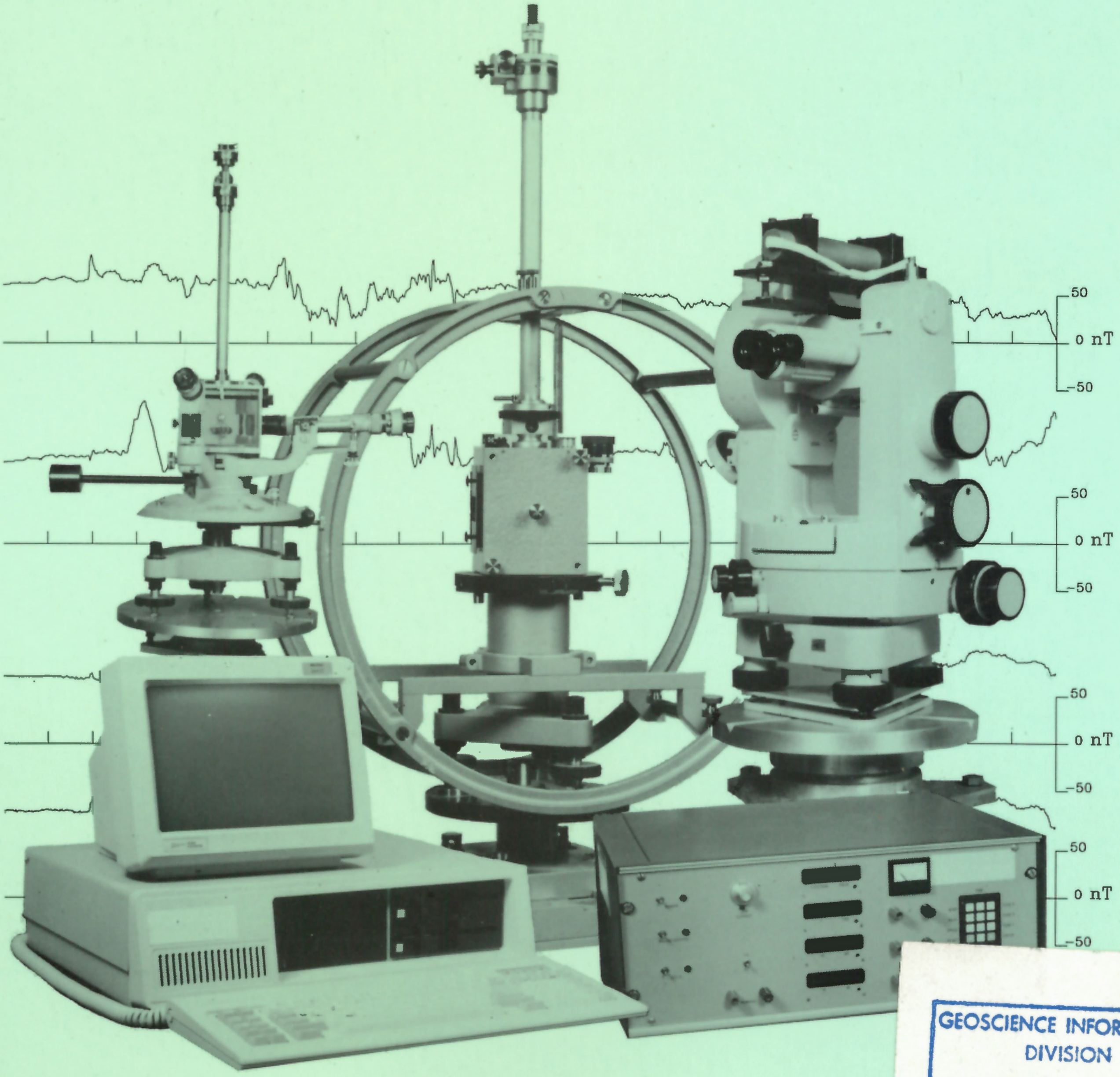
Geological Survey of Canada
Commission géologique du Canada

Proceedings of the International Workshop on Magnetic Observatory Instruments



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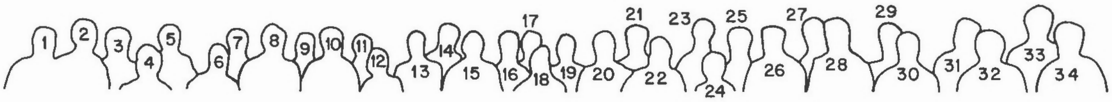

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FOREWORD

To the best of my knowledge, the concept of a working Workshop on magnetic observatory instruments originated in discussions between W.F. Stuart and C.G. Sucksdorff at the time of the International Union of Geodesy and Geophysics (IUGG) meetings in Hamburg in 1983. In the months that followed, Bill Stuart communicated the idea to the International Association of Geomagnetism and Aeronomy (IAGA) Working Group V-1, and we agreed that Ottawa might be a possible venue for a small specialist meeting of this kind. Space and facilities for magnetic measurements were available there at the Geomagnetic Laboratory of the Geological Survey of Canada. At Prague, the Working Group organized a special meeting to inform the IAGA community of the idea and to seek its support before proceeding with requests for formal approval and funding from IAGA and from the Canadian Department of Energy, Mines and Resources.

To make a long story short, the idea was well received in Prague, and with enthusiastic support from the scientific community, the necessary approvals and funding were readily obtained. We are indebted to IUGG, IAGA and the Geological Survey of Canada for their support and for permission to make use of the facilities of the Geomagnetic Laboratory at Ottawa.

This is the first time an international workshop on magnetic observatory instrumentation has been attempted. Its main objective was to provide a proper environment for testing the performance and specifications of new and currently available magnetometers and recording systems suitable for use in magnetic observatories. The intention was to bring together those who manufacture instruments and those who use them, in the hope that interactions and cross-fertilization would be beneficial to both groups. If this succeeded, and we believe that it did, then the efforts of all those who took part in the organization of these activities were well rewarded. We are most grateful to all participants who attended the meeting and contributed to its success by providing instruments and/or expertise in observatory measurements and procedures.

E.R. Niblett
Chairman,
IAGA Working Group V-1

1. INTRODUCTION

A PERSPECTIVE ON THE WORKSHOP

W.F. Stuart,[1]

It is appropriate at the very beginning of this working Workshop on Geomagnetic Observatories and Practice to thank those people who have made it possible. The Workshop will be very different from the usual international meeting, very much an experiment, and a great deal of courage was needed to accept the responsibility for hosting it.

I wish to thank Bill Hutchison (Assistant Deputy Minister of the Department of Energy, Mines and Resources), Ray Price (Director General of the Geological Survey of Canada), Jim Tanner (Chief Geophysicist) and Mike Berry (Director of Geophysics) for approving the suggestion to hold the meeting in Ottawa and for encouraging their staff to participate in it and in the preparations for it. Not least they must be thanked for allowing the Workshop to have use of the finest observing site in the world, the Geomagnetic Laboratory at Blackburn (Ottawa). Jim Tanner remarked that he regards it as a national asset; I believe that by the time this workshop is over it will be regarded as an international asset.

Ron Niblett (Chief Scientist of the Geophysics Division), Richard Coles (Head of the Geomagnetism Section), Doug Trigg (Head of Geophysical Instrumentation), Gerrit Jansen van Beek and Larry Newitt have done the local organization which made the Workshop possible. I thank them all for their commitment. Local Organizing Committee is far too feeble a term to describe the work that has gone into preparing for this Workshop, as you will see when we get to the Laboratory, and I would like to take the opportunity now to express gratitude on behalf of all the participants to all the members of the Geomagnetism and the Geophysical Instrumentation Sections for the work they have already done and the work they will still do, in order to make this meeting a success.

There are instruments here from seven commercial suppliers (Dowty, U.K.; GEM, Canada; Littlemore, U.K.; Narod, Canada; Scintrex, Canada; EDA, Canada; Thomson CSF, France) and privately from Denmark, Finland/Poland, Hungary, Netherlands, Peru, U.S.A. and of course from our hosts, Canada.

That list of credits explains very clearly the first objective of the Workshop: to allow those people who think they know how to make geomagnetic measurements to work with people who think they know how to make magnetometers so they can communicate problems to each other and talk about solutions.

Of course there will be some assessments made, but I hope that they will not only be 'of instruments by scientists'. I hope that scientific methods will also be questioned and that as some of the old fashioned instrumentation is being replaced by modern technology some of the old fashioned notions about observing practice and standards will be replaced by sensible ideas about resolution, stability and absolute accuracy which bear direct relationship to the research and commercial science which use geomagnetic data. This is not just an instrument testing workshop. The experience we gain working with the equipment which has been made available will certainly be valuable to everybody here, and if we can prepare a written summary of the proceedings of the next ten days it will be even more valuable to the observers at the 150 or so observatories which are not represented here and, perhaps more importantly, to the organizations which control and manage the observatories.

I think it is important that, as well as looking to our own parochial interests, we try to bear in mind the problems faced by almost all observatories in modern times. They can be summarized in the sense that science and communications are demanding digital data at a time when geomagnetism is regarded as old fashioned by governments and funding agencies. Specifically the geomagnetic observatories need completely new instrumentation and people with the new skills to operate them, but managing institutes think that it is too expensive.

Old fashioned can be taken to mean 'not worth keeping' or 'should be replaced by the new fashion'. We must make sure that it is the second view that is taken by those who fund the observatory community.

I do not believe that the costs need to be very high, if realistic targets are set for accuracy and stability and if sensible attitudes to data logging, preparation and quality control are adopted. I would like to think that, in the course of this Workshop, we can make an attempt to specify what the targets should be, and describe the sort of data processing which would be adequate.

I often have great difficulty in explaining the fundamental difficulty of the work of a geomagnetic observatory to people who say 'You have been measuring the field for 150 years, you should have the hang of it by now'. If anyone has a simple explanation which is valid I would be very pleased to hear it. The nearest I can get is to say that we are attempting to make measurements of something which is varying in a complex way with time using measuring devices which are not stable with time. Each measurement itself takes so much time that it must be corrected for the field's temporal variations between measurements and still attempt to achieve accuracy which is at or within the minimum noise limits of the instruments available.

That sounds quite impressive but it doesn't really say anything and rarely impresses anyone. What it means in practice is that the only way to know that an observatory is working properly is to make observations and recordings there for a long time, tens of years, and use the resulting data to study some aspect of the geomagnetic field, perhaps the regional field, or the secular variation or some aspect of external fields. Ninety-nine times out of a hundred the research cannot be done well with only one observatory. No matter how carefully an observatory is run it is only from feedback from research using its data and data from other observatories that its accuracy can be verified.

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[1] Chairman of Division V, IAGA

Not every observatory can be supported by research groups dedicated to monitoring its performance. Probably half of the total number in the world work in total isolation. An important thing for us to think about here is how to persuade their managing institutes of the value to the local country, as well as to the international community, of keeping each observatory running and of adopting the changes of technology which are certain to be required in the next decade. Part of the answer must be to provide a channel of communication back to them with feedback of information from the international scientific community and possibly to advise on the sort of research which they might look to. In this regard we, the observatory community, might consider asking the research community to adopt programs which support outlying magnetic observatories.

I believe that geomagnetism will come back into favour with funding agencies in the 1990s with large international research programs on Earth History and the dynamics of the Earth; there are already plans for an International Geosphere-Biosphere Program and one on Solar Terrestrial Physics, and at that time it will be more necessary than ever to have good global coverage on the ground in support of magnetic satellite surveys. It would be very useful if we could do something now to help the existing observatories to be ready to meet that demand when the time comes.

By way of encouragement to those of us who are more interested in the commercial return than the scientific, I do believe that the coming upsurge in geophysics will result in a sizeable market for high resolution low drift magnetometers and compact, simple data logging and processing systems. There may also be a substantial market for reasonably priced communications systems for data transfer.

This 'perspective' is possibly rather less specific than you had expected; I don't honestly believe that you really need me to state the obvious. Of course we will all look at the instruments and use them, but there is not much point to that unless we can use the things we learn to advise the scientific population in general. It is my hope that this very special gathering of people will produce some good and lasting advice and that the international community will act on it.

THE GEOMAGNETIC LABORATORY, OTTAWA

R.L. Coles

Surveys for a new site for a geomagnetic observatory and laboratory in the Ottawa area were carried out in the early 1960s. Conditions for the location were: a) the area had to be free from large natural magnetic anomalies; b) it had to be unaffected by artificial disturbances such as traffic, buildings, electrical and industrial operations; c) there had to be a reasonable guarantee that a suitable magnetic environment would persist for at least 50 years.

A suitable area was found on an east-west ridge of land, bounded on both the north and south by swamp and marshland. The ridge is a feature of Recent geology, and was at one time an island in the Champlain Sea. The soil is fluvial sand underlain by marine clay.

A railway line is located about 2km south of the site; trains are pulled by diesel locomotives. A second line to the north has been closed for some time and recently the tracks were removed. One square kilometre of land was reserved on the ridge, in the greenbelt surrounding the city of Ottawa. By agreement with the Canadian Forestry Service, limited reforestation was permitted within the area, such reforestation to be consistent with the operational requirements of the magnetic observatory and laboratories.

Construction of the magnetic laboratories complex was started in 1965 and was finished in 1968 (Fig. 1.1). Offices, test laboratories and workshops were housed in a main, single-storey building, to accommodate paleomagnetic and instrument development activities. A restricted-access, non-magnetic compound about 500 m by 600 m was located adjacent to the main laboratory (Figure 1.2). In the compound, 16 buildings were erected for specific purposes. The buildings are of concrete block and wood construction. Sand, gravel and other materials used in the construction of the buildings were carefully tested to be non-magnetic. All the aggregate used in the concrete was crushed limestone. Electrical fittings, heaters, door hardware, were all carefully selected to be non-magnetic. Buried power lines and signal cables, in two carefully separated conduits, connect all buildings in the compound with the main laboratory.

The Ottawa Magnetic Observatory currently consists of four of these buildings and a storage building. The variometer building (no.2; 6 m × 6 m) is divided into two rooms. One room houses the three-component fluxgate sensor assembly enclosed in an insulated, thermostatically-controlled box. The other room houses a proton precession magnetometer sensor. The electronics and recording systems for the variometer are housed in building no.3 identical in size to building no.2. Building no.4 (12 m × 5 m) houses the absolute instruments; the main pier is marble. A secondary fluxgate magnetometer is also operated in this building to provide data during intervals when the main variometer is not functioning. Building no.5 (12 m × 5 m) has been used as a test and calibration building until recently when an Elsec 8200 vector proton precession magnetometer was acquired. The continuous operation of this instrument precludes any other geomagnetic measurements in the building.

Figure 1.1 The Geomagnetic Laboratory, Anderson Road, Ottawa.

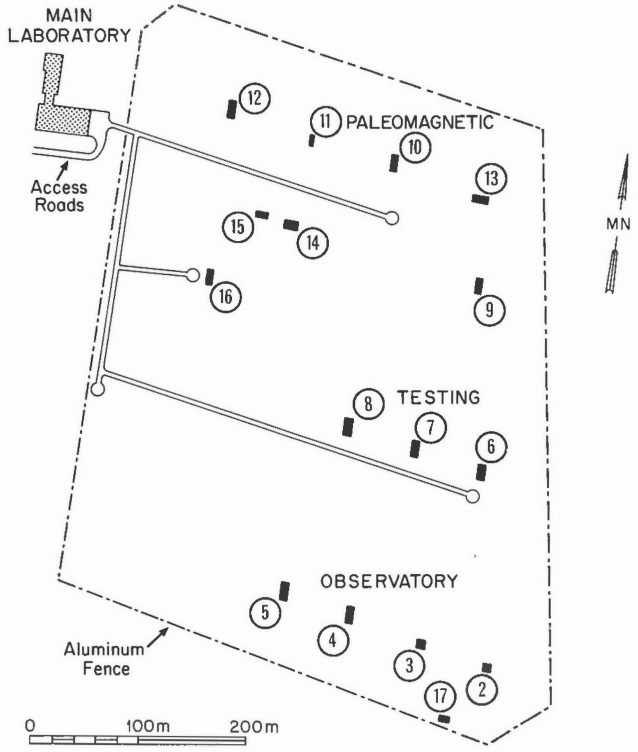

Figure 1.2 Plan of the Geomagnetic Laboratory and non-magnetic compound.

SUMMARY OF THE WORKSHOP

R.L. Coles

The International Workshop on Magnetic Observatory Instruments was held at the Geomagnetic Laboratory of the Geological Survey of Canada, 30 July to 9 August 1986. Forty-one individuals from seventeen countries participated in a series of instrument tests and discussions covering those aspects of geomagnetic observatory procedure that relate to present-day measurements and reduction of data. Twenty-nine magnetometers and data-recording systems were provided by seven commercial companies and by several research and government institutions.

The initial setting-up period was followed by an inspection tour for all participants during which each of the instrument operators described his equipment and demonstrated its use. Sensors and operating parts were displayed and owners responded to detailed queries from the group. This enabled the delegates to become familiar with the instruments in use and to realize the options available for comparative data analysis during the following days.

The tests carried out fell into two broad categories:

a) absolute measurements and comparisons
b) recordings of geomagnetic variations and their comparisons.

For absolute observations of the vector magnetic field, five different instruments were used in the measurement program and two more were available for demonstration. The local Ottawa Observatory records and absolute observations were available as a reference for the comparisons.

A number of the variometers provided analogue outputs as a convenience for quick comparisons. However, the main data sets were, in most cases, recorded digitally. Ottawa Observatory staff transferred data from individual instrument storage media to a format which was compatible with the computing facilities provided at the laboratory. The end product of the data reduction is a suite of files of the variations recorded by the various instruments, and made available on magnetic tape or diskette to the participants. The Ottawa Geomagnetism Group performed some initial analyses, using the local observatory recordings as reference.

The format of the Workshop was novel. Each day, after a few minutes spent on administrative matters, the participants were free to work on their own instruments, to learn the details of, and perhaps operate, instruments brought by other participants, or to exchange experiences and discuss problems in designing, manufacturing, or operating observatory instruments.

Although no formal talks or discussions were arranged prior to the workshop, specific intervals of time were set aside each day for informal discussions on topics of interest and relevance to the participants. Topics were proposed by the participants themselves. In addition to these identifiable discussions, numerous spontaneous sessions arose among interested participants.

Specific discussions took place on the following:

1. The meaning of absolute observations in geomagnetism
2. External magnetic fields
3. The Maria/Canopus program of NRC Canada
4. Geomagnetism in developing countries
5. The ideal variometer for magnetic observatories
6. Digital magnetic observatory data
7. Accuracies achievable at magnetic observatories

A full report on the proceedings of the Workshop is contained in this GSC paper.

ACKNOWLEDGMENTS

R.L. Coles

As Chairman of the Local Organizing Committee, I wish to express my thanks to my colleagues on this Committee for their considerable efforts and their endurance, during the preparations for the Workshop, during the hectic 10 days of the Workshop itself, and during innumerable subsequent hours spent collating and processing data gathered at the Workshop. I would also like to thank the technical and support staff at the Geomagnetic Laboratory. Their efforts were a major contribution to the Workshop, and have made a lasting impression on the participants. Without the enthusiastic team-work that went into all of this, the Workshop could not have been a success.

On behalf of the Workshop participants, and especially of the Local Organizing Committee, I would like to express our deep appreciation of the tremendous help and advice given to us by Carole Jones and Patricia Scott and their staff of the Tour and Conference Centre of Carleton University. In the preparations for the workshop, the social program, the accommodation and meals, their professional experience was of great value to us, and we thank them for the friendly way in which they provided so much support.

I thank all of the contributors to this documentary record of the Workshop, and also those who have reviewed individual reports. I particularly wish to thank Larry Newitt, Benoit St. Louis, and the editorial staff of the GSC for their help in checking and assembling this GSC paper on the Workshop.

2. THE SCIENTIFIC SETTING

SCIENTIFIC REQUIREMENTS FOR GEOMAGNETIC OBSERVATORY DATA

E.R. Niblett and R.L. Coles

Introduction

A standard magnetic observatory provides a continuous record of time variations of the earth's magnetic field, and precise values of its direction and intensity at a fixed location. Sucksdorff et al. (1979) have indicated that the basic requirements for a magnetic observatory are:

1. permanency of operation
2. baseline control of the variometer recordings by means of absolute observations of the magnetic field.

Permanency does not mean that an observatory must have operated since the time of Gauss and continue forever into the future. It does mean, for practical purposes, that the operation be continuous for a sufficiently long period that the station can provide annual mean values of the geomagnetic field which can be used for the derivation of secular change. Standard observatories normally attempt to achieve a precision of ± 0.1′ for declination and inclination measurements, and ± 1 nT for total force. For classical three-component photographic analogue magnetograms the standard recording speed is 20 mm/h, which permits resolution of magnetic variations at periods longer than about 100 s. Modern digital systems (such as described in this report) can output data at 10 s intervals or less, though 1 min data must also be available for permanent storage at world data centres.

Much modern research in geomagnetism does not require a knowledge of absolute field levels, but depends instead on detailed analysis of frequency, phase, amplitude and distribution characteristics of magnetic variations. Examples include studies of electromagnetic induction within the earth and studies of the physics of that part of the upper atmosphere which contains the ionosphere and magnetosphere. Akasofu and Kamide (1985) have discussed the applications of meridian chains of magnetic variation stations in the study of electrodynamic processes in the near-earth environment. Variometer stations without baseline control are usually operated for a limited period of time to meet the requirements of a specific experiment or campaign such as the International Magnetospheric Study (IMS) of the late 1970s. They provide neither the permanency nor the absolute levels which are the distinguishing features of the standard magnetic observatory.

Distribution of standard magnetic observatories

Chapman and Bartels (1940) listed 75 observatories for 1933 (Fig. 2.1), roughly a third of which were located in Europe, with the remainder of the world very sparsely populated. Huge gaps existed in Africa, central Asia, polar regions and, of course, the oceans. Sucksdorff et al. (1979) compiled a list of 210 standard magnetic observatories known to be operational in 1978 (Fig. 2.2) — almost a 3-fold increase in 45 years. The distribution of observatories remains highly irregular (Figs. 2.3, 2.4, 2.5) and has been controlled by political, financial and logistical considerations as well as by the underlying need for scientific data. The number of stations in the north and south polar regions has increased dramatically, however, during the last 30 years in response to scientific demands for high latitude geomagnetic data. The impetus for this effort was stimulated by the International Geophysical Year and by scientific satellite campaigns which demonstrated the unique characteristics of magnetic variations in auroral and polar regions and their importance in developing physical models of the structure and dynamical behaviour of the ionosphere/magnetosphere system. The global distribution of standard observatories is still heavily weighted in Europe's favour, while serious gaps remain in parts of Africa, Asia, Australia, Greenland and South America.

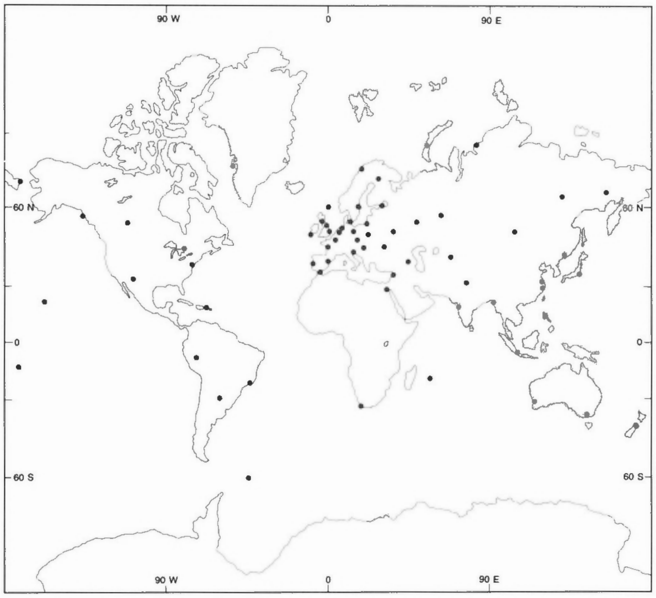

Figure 2.1 Distribution of geomagnetic observatories in 1933.

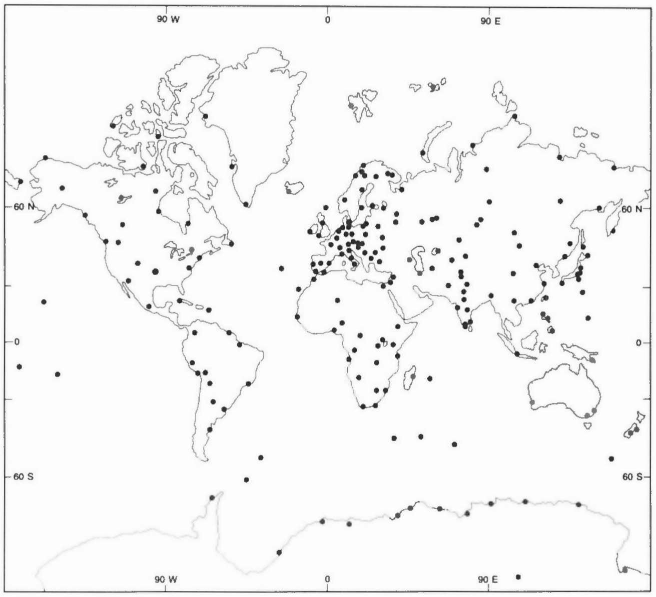

Figure 2.2 Distribution of geomagnetic observatories in 1978.

Figure 2.3 Distribution of geomagnetic observatories in 1987.

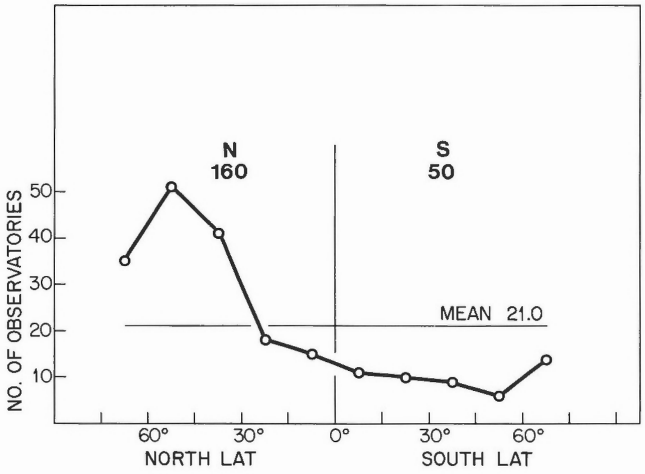

Figure 2.4 Latitudinal distribution of observatories.

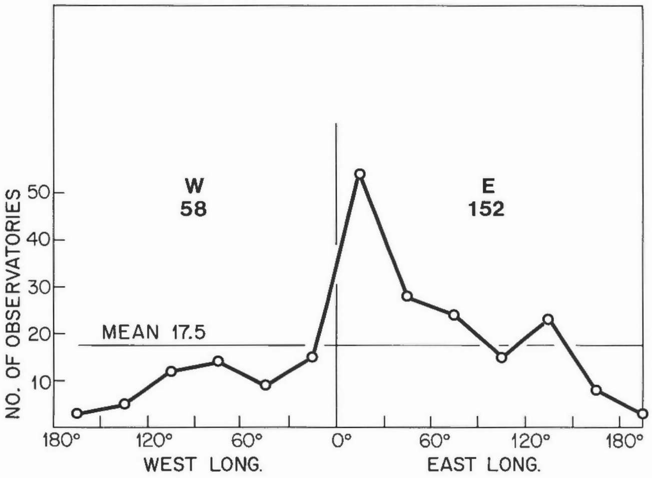

Figure 2.5 Longitudinal distribution of observatories.

Scientific requirements and applications for magnetic observatory data

Requirements for which absolute determinations and baseline control have been important.

1. Determination of mean annual values (and quiet reference levels) of at least three independent magnetic field components. These data are used for:
   - — derivation of secular change;
   - — updating of survey data used for regional magnetic charts and global field representations such as the International Geomagnetic Reference Field (IGRF);
   - — spherical harmonic analysis of the earth's main field, determination of the geomagnetic poles, the dipole component, the non-dipole component and associated drift characteristics.

   Knowledge of the distribution and secular variation of the main field at the earth's surface is essential for studies of the deep interior relating to physical properties and fluid motions in the core, electrical conductivity of the lower mantle and the origin of the geomagnetic field (Chapman and Bartels, 1940; Bullard et al., 1950; Rikitake and Honkura, 1985; also, the proposed research program SEDI (Study of the Earth's Deep Interior) submitted to the IUGG).
2. Standardization of compasses and calibration of magnetic instruments used in navigation, geophysical exploration and airborne surveys.
3. Comparisons of absolute field levels on the ground with those observed in satellites or other space vehicles. Comparisons of this kind are necessary for the verification of downward extrapolation of satellite data to ground level so that they may be usefully applied to the construction of magnetic charts and the derivation of secular change. Downward extrapolation from satellite heights is complicated by current flow in the ionosphere.
4. Determination of absolute undisturbed levels against which disturbance phenomena (auroral substorms, interplanetary magnetic field (IMF), and mid - to long-term effects such as Sq, L, Dst, seasonal variations) may be measured. For example, IMF polarity changes which are diagnostic of impending changes in substorm activity can be detected at high latitude observatories.
5. Reduction of repeat station values to a common epoch and correction of survey data for temporal variations of the geomagnetic field.
6. Studies of the long-term after-effects of major magnetic storms.

Scientific requirements and applications for which absolute field determinations and baseline control are not strictly necessary.

1. Study of the distribution and morphology of pulsations, irregular disturbances, magnetic storms and, indeed, all short period transient magnetic variations.
2. Study of relationships between geomagnetic disturbances and solar events.
3. Forecasts of geomagnetic activity.

4. Derivation of K, Kp, Ap and other indices of geomagnetic activity which are important in commercial and military applications and fundamental to scientific studies of ionospheric currents, auroras and energy dissipation in the ionosphere-magnetosphere system.
5. Developing planetary models of the structure and dynamical behaviour of the ionosphere and magnetosphere.
6. Studies of electromagnetic induction in the earth and of the conductivity of the crust and upper mantle.
7. Removal of short period time-variant fields from aeromagnetic survey data.
8. Hazards associated with magnetic disturbance fields — i.e., their effects on power transmission lines, pipelines, radio communications and space vehicles.

Will there be an on-going need for standard magnetic observatories?

The standard magnetic observatory operating on a permanent basis, and with careful measurement of absolute field values, has been an essential tool for maintaining up-to-date knowledge of the main field and its secular variation for over 150 years. Its output of recorded data, mean annual values and undisturbed field levels has provided important control for repeat station surveys and for ground and airborne surveys which produce data for magnetic charts and for global field models such as IGRF.

Does this work need to be continued in future years? Do we now know enough about the distribution of the geomagnetic field and its secular variation to consider closing standard observatories, depending instead on temporary recording stations and satellite measurements to meet future needs for mapping and research?

Space vehicles such as MAGSAT provide nearly uniform data acquisition over most of the globe and have substantially improved the quality of main field analysis. Cain et al.(1983) have shown that satellites can monitor secular variation as well as external field variations if they operate for long enough. However, such measurements require downward continuation through the E and F regions of the ionosphere where potential field laws are not generally valid. Further, the fields generated by currents in these regions cannot be distinguished by spherical harmonic analysis from the main field at satellite heights. Satellite measurements are therefore difficult to apply to the problem of mapping the main field and secular variation at the surface, the usual practice being to discard observations at all except the least disturbed times (Cain et al., 1983). It appears likely that a worldwide network of standard observatories will continue to be needed to maintain accurate reference measurements of the main field at the surface and to monitor long-term changes.

Knowledge of the intensity and global configuration of the geomagnetic field is important not only for magnetic charts and studies of physical processes in the earth's core. The dipole field also controls the structure, electrical properties and dynamical behaviour of the ionosphere/magnetosphere regions of the upper atmosphere. When the dipole component becomes vanishingly small (as happens frequently on a geological time scale during periods when the geomagnetic field reverses polarity) the ionosphere-magnetosphere system as we know it either ceases to exist or undergoes drastic modification. This near-earth environment plays a key role in the conversion of cosmic and solar radiation to other forms of energy. For example, when large geomagnetic and auroral storms occur, enormous quantities of electromagnetic and thermal energy are released in the polar upper atmosphere to produce intense electric currents throughout the magnetosphere and Joule heating of the ionosphere on a global scale. The ionosphere acts as a buffer zone which shields the surface from certain types of radiation, including primary cosmic rays, and presents boundary conditions for the chemistry of ionized atoms which control the composition of the atmosphere. It is, therefore, important to the ecology of many forms of terrestrial life (Parkinson, 1982). Substantial heating from energetic particles and ionospheric currents occurs in the D and E regions at atmospheric heights of 70-130 km. This heat appears to have little effect on day-to-day weather patterns (although some recent studies suggest that the effects may be more significant than previously thought), but long-term climatic changes are possible if these plasma regions undergo severe changes in ionization and electrical conductivity. Knowledge of long-term trends in the growth or decay of the dipole field and in global patterns of geomagnetic disturbance therefore has important implications for the near-surface environment as well as for the physics and chemistry of the upper atmosphere. The International Council of Scientific Unions (ICSU) and its constituent bodies are currently planning an interdisciplinary program named the International Geosphere-Biosphere Program to study complex physical, chemical and biological processes in the sun-earth system that determine its changes and are responsible for the origin and survival of life on Earth.

It should not be forgotten that standard magnetic observatories have always provided magnetic variation data for studies of aeronomy and electromagnetic induction in the earth. However, observatories are usually spaced too far apart to provide adequate resolution of current systems in either the upper atmosphere or the earth's interior. For this reason, observatory data are often supplemented with data from closely spaced networks, chains or arrays of magnetic variation stations to achieve satisfactory coverage. Such stations are normally established on a campaign basis for a predetermined time interval depending on the nature of the experiment. For example, satellite observations of magnetic and electric fields in various regions of the magnetosphere usually require simultaneous ground-based magnetometer data for comparison and interpretation of recorded events. International campaigns such as the IMS require several years of observations, and in locations near the auroral zone, where the magnetosphere is highly structured, arrays of magnetic variation stations are now operating on a semi-permanent basis (10 years or longer). Standard magnetic observatories are included in these variometer networks to provide absolute reference levels and variation data with guaranteed long-term stability.

Digital versus analogue data acquisition

The foregoing considerations imply a need for standard geomagnetic observatory data but say nothing about how they should be collected.

The rapid advances in computer technology over the past 30 years have had a profound and compelling impact on the way we record, store, use and communicate geomagnetic data. Some countries, Canada included, have opted to discontinue using the old reliable standard suspended magnet photographic systems and to replace them with sensors and recorders which produce and store their data in a digital format. A recent survey by Svendsen (pers. comm., 1985) revealed that 73 observatories worldwide are currently recording digitally. The advantages are obvious and have been discussed in detail by Serson (1977), Stuart (1984) and others. They include:

- Data no longer require conversion from analogue to digital form for long-term storage and retrieval in a data bank or at a WDC.
- Automated data acquisition procedures can be implemented at observatories which require less human intervention and therefore lower operating costs.
- Data may be transmitted from remote stations to headquarters in near real-time via satellite or telephone links. Raw data can be made available for processing and analysis as quickly as they are obtained.
- Daily editing and control procedures can be implemented from headquarters.
- Flexibility in manipulating outputs is greatly increased. For example, a Canadian digital observatory can output magnetic data at 1 s or longer intervals on command; it can also apply filtering algorithms and averaging to output 1 min values in conformity with IAGA recommendations and format.

There are also disadvantages:

- Analogue systems were formerly fairly standard throughout the world and procedures were well known and understood. Instruments were reliable and required only minor adjustment from one year to the next. Digital equipment is sophisticated, complex and costly, and often not easily repaired. Hardware and software require frequent updating. On a worldwide scale digital recording instrumentation is much more diversified than were the older analogue systems.
- There will always be a requirement for manual absolute observations at standard geomagnetic observatories, though modern vector proton precession magnetometers and other novel magnetometers may eventually reduce this aspect of human intervention.
- Highly skilled operators at the observatories are no longer needed, but electronics engineers and technical specialists are required at headquarters to keep a digital network going. Such personnel with experience in geomagnetic instruments may be difficult to find, particularly in developing countries.

In many countries the agencies which manage observatories are unwilling to replace their analogue systems with modern digital instrumentation because of the initial capital cost. In some, there are not enough highly-skilled technical people to undertake the task of upgrading an observatory to digital operation. In such cases it is a question of continuing to operate in a classical analogue mode, or closing down altogether. It is to be hoped that no country or agency will discontinue operation of a standard analogue observatory simply because it is felt that such equipment is out-of-date or obsolete. Analogue data still serve very well the main scientific requirements for studies of the earth's main field and its secular variation. These requirements do not depend on automated methods of acquisition, transmission and computation. Hourly, daily and annual mean values and activity indices will be needed for many years to come regardless of how they are obtained. Indeed, a higher overall standard of observation is often obtained in a well run analogue observatory than in its modern automated digital counterpart.

Having made a strong plea for countries to continue operating analogue recording systems in their observatories if digital methods are not readily available, it must be acknowledged that digital outputs are in ever-increasing demand by the user community. It seems inevitable that within a few years neither the scientific and commercial users nor the data collection agencies will have the time or facilities to deal with analogue data. It is important, therefore, that those concerned with the future of magnetic observatories use every possible means to encourage and expedite conversion to digital data acquisition in the world network.

Jankowski et al. (1984) have described a method of changing classical torque-balance variometers of the Bobrov type from photographic to electrical output by means of photoelectric converters. Examples of this kind of instrument were in use during this Ottawa Workshop (operated by the Poland/Finland group and the Hungarian group — Section 3). These torsion photoelectric magnetometers (TPM) have as high a standard of stability and performance as their photographic parent systems, and the conversion is not expensive. The method provides a practical alternative for magnetic observatories wishing to "go digital" but which do not have the resources to acquire and operate more sophisticated fully automatic systems using different physical principles.

Precision

The classical requirements for standard magnetic observatory data are concerned with magnetic charts, secular variation and global field representations which can be derived from spherical harmonic analysis. Long unbroken series of hourly mean values have also made it possible to determine harmonic coefficients of solar and lunar daily variations and other long period effects. For all of these applications, a precision of 1 nT for absolute magnetic force measurements and 0.1′ for declination and inclination has proven to be generally satisfactory. However, baseline values at any given time are usually less accurately known because of instrument drifts caused by temperature changes, pier tilting and other disturbing influences. Thus the mean hourly values, though usually quoted to the nearest nT or the nearest 0.1 min of arc in observatory reports, are seldom this accurate. A precision of 2 to 5 nT is perhaps a more representative figure for most places unless a very careful program of absolute observations is maintained. The classical scientific and mapping problems referred to above have been well served by data acquisition at this level and with a standard analogue recording speed of 20 mm/h. However, studies of 'jerks' and 'impulses' in secular variation, and effects of the solar cycle, have shown a need for an absolute accuracy of the order of 1 nT (e.g. Alldredge, 1982).

Absolute instruments with measuring precisions close to 1 nT or 0.1′ have been available for many decades and therefore provide a convenient standard in a worldwide network. However, for control of recording variometers it is usually necessary to combine absolute observations in order to convert the measurements to the component being recorded. For example, standardization of a Z-variometer baseline usually requires absolute measurements of F (proton precession magnetometer) and I (fluxgate D&I) and the derived values of Z will be less precise than either of the measured values. Detailed comparison measurements with a D-I fluxgate magnetometer, two quartz declinometers and a vector proton precession magnetometer have been reported by Kring Lauridsen (1985). He concluded from these and other comparison experiments that it is extremely difficult with currently available instruments to achieve an accuracy better than 1 nT in absolute measurements. In high latitude regions, a lower level of accuracy must be accepted for declination measurements because the horizontal field is relatively weak and highly variable.

Instruments have been available for some years with the ability to resolve magnetic field differences in the picotesla range. Examples include cryogenic magnetometers, rubidium vapour magnetometers, cesium magnetometers and ring-core fluxgates. These make excellent sensors for special purpose high resolution recording systems, but have not found much useful application as high precision absolute (or quasi-absolute) instruments at magnetic observatories. The ring-core fluxgate combined with a high quality proton precession magnetometer may have sufficient stability to improve the precision of absolute measurements to better than 1 nT.

A continuing problem with absolute instruments, whatever their magnetic precision, is that of levelling. Traditional techniques have relied heavily on operator skill and dedication, and on sensitive level bubbles. As technologies develop, the use of tiltmeters of sufficient precision and long-term stability, along with azimuth detectors, comes closer to reality.

Ongoing support for magnetic observatories

In these days of increased awareness of public and institutional spending, more and more magnetic observatories and their managing agencies are coming under pressure from restricted funding. This paper has attempted to review the many and diverse fields of scientific and technological endeavour which depend on geomagnetic data, and to indicate something of the nature of the contribution which magnetic observatories have made to fundamental knowledge about the earth and to practical applications such as navigation, surveys, mapping and geophysical exploration.

The concept of a global network began with widely distributed simultaneous magnetic observations organized by Von Humboldt early in the 19th century and solidified with the formation of the Gottingen Magnetic Union in 1834 by Gauss and Weber. Since then its continued development has been stimulated by improved methods and instrumentation (photographic recording was first introduced in 1847), by major international programs such as the Polar Years, IGY and IMS, and by greatly increased awareness of the scientific value of the data. In future years, a comprehensive, well-instrumented network will be essential for support of geomagnetic survey satellites, the International Geosphere Biosphere Program, SEDI and all new scientific initiatives concerned with the structure and dynamics of the earth and sun-earth environment. It is hoped that the planners of these new programs will continue to recognize the value of magnetic observatories and find ways to provide the financial support and human resources required to keep a well-equipped world network in operation.

References

Alldredge, L.R.
1982: Geomagnetic models and the solar cycle effect; Reviews of Geophysics and Space Physics, v. 20, no. 4, p.965-970.

Akasofu, S.-I. and Kamide, Y.
1985: Meridian chains of magnetometers as a powerful "remote sensing" tool in determining electromagnetic quantities in the ionosphere on a global scale; EOS, Transactions of the American Geophysical Union, v.66, no. 22, p.465-466.

Bullard, E.C., Freedman, C., Gellman, H., and Nixon, J.
1950: The westward drift of the earth's magnetic field; Royal Society of London, Philosophical Transactions, Series A, v. 243, no. 859, p.67-92.

Cain, J.C., Frayser, J., Muth, L., and Schmitz, D.
1983: The use of Magsat data to determine secular variation; Journal of Geophysical Research, v. 88, p.5903-5910.

Chapman, S and Bartels, J.
1940: Geomagnetism; v. I, Oxford University Press.

Jankowski, J., Marianiuk, J., Ruta, A., Sucksdorff, C. and Kivinen, M.
1984: Long-term stability of a torque-balance variometer with photoelectric converters in observatory practice; Geophysical Surveys, v.6, p.367-380.

Kring Lauridsen, E.
1985: Experiences with the D-I fluxgate magnetometer inclusive theory of the instrument and comparison with other methods; Danish Meteorological Institute, Geophysical Paper No. R-71.

Parkinson, W.D.
1982: Introduction to Geomagnetism; Elsevier Science Publishing Co.

Rikitake, T. and Honkura, Y.
1985: Solid Earth Geomagnetism; Terra Scientific Publishing Company, Tokyo, Japan.

Serson, P.H.
1977: Digital recording and telemetry of magnetic observatory data; (Abstract) IAGA symposium on magnetic observatory practice, Seattle, USA. EOS, Transactions of the American Geophysical Union, v.58, p.776.

Stuart, W.F.
1984: Introduction, Workshop on Geomagnetic Observatory and Survey Practice; Geophysical Surveys, v.6, p.217-220.

Sucksdorff, C., Nevanlinna, H., and Svendsen, K.L.
1979: Geomagnetic observatories 1978; Report SE-21, World Data Center A for Solid Earth Geophysics, Boulder, Colorado.

3. INSTRUMENTS AT THE WORKSHOP

Table 3.1 List of instruments

EPB AMOS III	GSC/EMR Ottawa
EPB D&I fluxgate	GSC/EMR Ottawa
EDA AMOS III	EDA Inc.
FM100B fluxgate	EDA Inc.
OMNI IV PPM	EDA Inc.
DIM-100 DI fluxgate	EDA Inc.
Elsec 8200 Vector PPM	Littlemore Scientific
Elsec 820 PPM	Littlemore Scientific
Elsec 810 DI fluxgate	Littlemore Scientific
Ring-core mag.	Narod Geophysics
Automatic observatory	USGS
Torsion photoelectric magnetometer	Institute of Geophysics, Poland, and Finnish Meteorological Institute
DIMARS quartz magnetometer	Eotvos Inst., Hungary
D&I fluxgate	Royal Netherlands Meteorol. Inst.
D&I fluxgate	Danish Meteorol. Inst.
Sokkisha Earth Inductor	Huancayo Magnetic Observatory
GSM10 PPM (Overhauser)	GEM
GSM11 PPM (Overhauser)	GEM
GSM18 PPM	GEM
GSM8 PPM	GEM
GSM9 PPM (Overhauser)	GEM
Ring-core mag. SAM3	Dowty
Ring-core mag. TAM3	Dowty
Differential 3-axis magnetometer	Dowty
Cesium vapour magnetometer	Scintrex
Proton precession magnetometer	Scintrex
Vector fluxgate magnetometer	Scintrex
D&I fluxgate	Inst. de Phys. du Globe
Triaxial fluxgate	Inst. de Phys. du Globe/ Thomson-Sintra

THE GEOLOGICAL SURVEY OF CANADA INSTRUMENTS

The GSC instruments and systems at the Workshop have been described in earlier publications (Trigg, 1970; Andersen, 1973, 1974; Trigg and Nandi, 1984; Jansen van Beek et al., 1986). In view of minimizing the text, only brief summaries are given here.

Automatic digital recording of magnetic data at Canadian geomagnetic observatories was introduced in 1969. The system was subsequently named AMOS I (Automatic Magnetic Observatory System) and has been described by Andersen (1974). The orthogonal elements X, Y, and Z are derived from three fluxgate sensors mounted in a Helmholtz coil system. One pair of coils continually nulls the principal horizontal component and the second pair, Z, so that the fluxgate operates in a relatively small field (less than 15 % of the total field) at all stations. A proton precession magnetometer measures F.

Figure 3.1 The Geological Survey of Canada AMOS III at the Ottawa Observatory.

AMOS I has now been replaced by AMOS III. AMOS III (Fig. 3.1), incorporating advances in electronics and computer technology, was developed and built by the Earth Physics Branch.

The objective of the AMOS III design was to incorporate the existing AMOS magnetometers into a new system based on a microcomputer control unit, providing upgraded digital data acquisition, and also improved system monitoring and diagnostic capability. Details of the AMOS III are given by Trigg and Nandi (1984). In the AMOS III, analog signals from the fluxgate magnetometer are presented to three independent digital voltmeters. Once per minute, digitally filtered values of X, Y, and Z, along with an F value, are stored in memory until sufficient data are available to write a record on the cartridge tape recorder. In the AMOS III software, two filtering algorithms are used. A detailed analytical derivation of the responses is given by Coles (1983)

Connection of a data terminal or personal computer via an RS232C serial interface built into the microcomputer allows an operator extensive control of the system. This capability represents a considerable expansion of the telephone verification system (TVS) described by Andersen (1973) and implemented on the AMOS I. The AMOS III TVS is described by Trigg and Nandi(1984). The microcomputer can retain diagnostic information for up to 5 days.

The D&I fluxgate magnetometer has been described by Trigg (1970) and is discussed further in section 4 of these Proceedings.

References

Andersen, F.
1973: Telephone verification system for automatic magnetic observatories; Publications of the Earth Physics Branch, v. 44, No. 5, Ottawa.

1974: An automatic observatory system; Publications of the Earth Physics Branch v. 44, No. 11, Ottawa.

Coles, R.L.
1983: Response functions for AMOS III digital filters; Earth Physics Branch, Division of Seismology and Geomagnetism, Internal report 83-2, Ottawa.

Jansen van Beek, G., Coles, R.L., and Newitt, L.R.
1986: Annual report for magnetic observatories — 1984; Earth Physics Branch, Geomagnetic Series No. 30, Ottawa.

Trigg, D.F.
1970: A portable D&I magnetometer; Earth Physics Branch, Geomagnetic Report No. 70-3, Ottawa.

Trigg, D.F. and Nandi, A.
1984: The Automatic Magnetic Observatory System AMOS III; Earth Physics Branch, Geomagnetic Series No. 27, 25 p. Ottawa.

THE EDA INSTRUMENTS CORPORATION MAGNETOMETERS

Tim Dobush, Paul Smith, and Bill Griffith,

EDA DIM-100 Declination and Inclination Magnetometer

Specifications

Measured quantities	Absolute angle of magnetic field declination and inclination and geographic north
Technique	Nulled fluxgate sensor parallel to optical axis of non-magnetic theodolite
Accuracy	± 3″ using two telescope positions (mean square error)
Null detector	Panel meter ± 15 nT full scale
Temperature range	−40°C to +50°C
Power requirements	Internal, four D6 cells, ±18 V
Theodolite	Zeiss/Jena 020A
Telescope	Erect image, 25x magnification
Automatic vertical index stabilization	Mean setting accuracy ±1″
Plate level sensitivities	30″/2 mm bubble travel on tubular level 8′/2 mm bubble travel on circular level
Optical plummet	Centering accuracy ±0.3 mm at 1.5 m
Horiz. and vertical circles:	86 mm diameter with 1′ micrometer graduation intervals and reading by estimation to 0.1′

EDA Fluxgate magnetometers FM100B and FM100C

Specifications

Measured quantities	Magnetic field variations in three orthogonal directions
Technique	High sensitivity oriented fluxgate sensors, zero nulled to ambient level
Range	
FM100B X, Y	0 to +40 000 nT, 2 ranges
Z	0 to +70 000 nT, 2 ranges
FM100C X, Y	0 to +40 000 nT
Z	0 to +70 000 nT
Resolution	
FM100B	0.4 nT
FM100C	0.4 %
Sensitivity	
FM100B	100 nT/volt
FM100C	10 000 nT/volt (10 nT/mV)
Null adjustment	Three precision 0 – 1000 graduated front panel locking potentiometers
Null meter	
FM100B	−500 to +500 units full scale
FM100C	−5000 to +5000 units full scale
Dynamic range	
FM100B	±1000 nT (10 volts) from baseline
FM100C	±100 000 nT (10 volts) from baseline
Noise envelope	less than 0.2 nT
Frequency response	
FM100B	less than 3 db from DC to 4.0 Hz
FM100C	less than 3 db from DC to 0.5 Hz
Temperature coefficient	less than 1 nT/°C
Temperature range	−40 to +50°C
Output	Three analogue voltages ±10 V, ±5 mA at less than 0.2 ohms
Power	4 watts at 115/230 Vac, or ±90 mA at ±14 to 28 Vdc
Sensor head level accuracy	450″ per division

EDA OMNI IV Tie-line magnetometer

The EDA OMNI IV proton precession magnetometer is microprocessor-controlled and has been designed to operate in four different modes:

1. As a self-correcting or tie-line magnetometer
2. As a portable field magnetometer
3. As a recording base station magnetometer
4. As a true simultaneous gradiometer (with a second sensor).

Specifications

Dynamic range	18 000 to 110 000 nT.
Tuning method	tuning value is calculated accurately utilizing a specially developed tuning algorithm
Automatic fine tuning	±15 % relative to ambient field strength of last stored value
Display resolution	0.1 nT
Processing sensitivity	±0.02 nT
Statistical error resolution	0.01 nT
Absolute accuracy	±1 nT at 50 000 nT at 23°C ±2 nT over total temperature range
Standard memory	up to 5000 data blocks in base station mode
Display	LCD 6 digit plus monitors
RS232 interface	2400 baud, 8 bits, 2 stop bits, no parity
Gradient tolerance	6000 nT per metre
Cycling time	Programmable from 5 seconds to 60 minutes in base station mode
Operating range	−40 to +55°C 0 – 100 % humidity weatherproof
Power	non-magnetic rechargeable sealed lead-acid or NiCad or disposable batteries, or 12 V DC for base station

EDA Automatic Magnetic Observatory System AMOS III

Specifications

FM-100C Three Component Fluxgate Magnetometer
as detailed above

PPM-105 Proton Precession Magnetometer

Sensitivity	0.1 nT standard, 0.01 nT optional
Dynamic range	18 000 to 99 000 nT
Tuning	Manual coarse augmented by microprocessor fine tuning
Temperature coefficient	less than 5 ppm from −10 to +40°C
Output	Simultaneous three overlapping analogue ranges, six digit BCD and six digit LCD front panel visual
Sensor	noise cancelling microprocessor tuned low inductance type; standard cable 100 m.

CPU-310 Central Control Unit

Digital master clock	0.0001 % accuracy
Microprocessor	COSMAC
Operator Interactive Control	24 key pad plus ENABLE
A/D converter	resolution to 1 nT, accuracy to ±1 nT
Communication interface	RS-232C, 300 to 9600 baud. 20 mA current loop, 110 baud
Display	Three 6 digit LEDs, switch selectable for X, Y, Z components
Memory	36K byte of internal, RAM and PROM
Sample rate	Normal set at 1 minute, 10 set per record Fast sampling from 1 to 30 seconds
Record length	336 BCD characters per record fast sample 620 characters per record
Measured parameters and computations	X, Y, Z components in nT; F in 0.1 nT; calculated resultant F from X, Y, Z; temperatures (four transducers) to 0.1°C; year, day, hour, minute, second (on fast sample only); station identifier; hourly means; hourly maxima and minima; 22 error codes and diagnostic reports.

MTR-125 Magnetic Tape Recorder

Tape	8.5 inch, 800 bpi
Capacity	4 months at standard operational program

PSB-350 Power Supply

Input	120 Vac 60 Hz or 240 Vac 50 Hz
Output	stable AC and DC supplies
Standby power	8 hour capacity from internal sealed lead-acid batteries.

THE LITTLEMORE SCIENTIFIC ENGINEERING CO. INSTRUMENTS

Cyril Chapman

ELSEC 8200 Automatic Magnetic Observatory

(This instrument is the property of Energy, Mines and Resources, Canada, and was included in the program with their kind permission.)

The ELSEC 8200 (also known as the Littlemore Vector PPM) is a system for recording the total field and variations in the angles of declination and inclination completely automatically. The system comprises a single proton precession magnetometer sensor set in a pair of Helmholtz coils (Fig. 3.2) and an electronics unit which controls the coil currents and magnetometer to produce a complete measurement every 30 seconds with a resolution of 0.1 nT. The results are displayed at the electronic unit and are available on 3 analogue channels whilst the digital output is via an RS232 interface for recording.

When used in conjunction with a theodolite-mounted fluxgate instrument (e.g ELSEC 810) for the absolute determination of D and I, the ELSEC 8200 provides a complete observatory variometer system where the results may be computed to be expressed in some other form such as D, H, and Z.

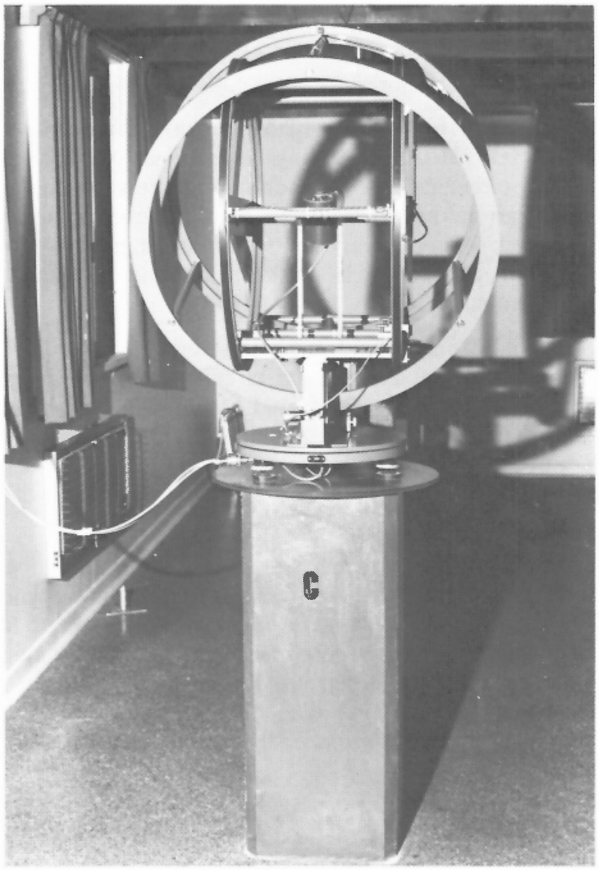

Figure 3.2 The Littlemore ELSEC 8200 vector proton magnetometer, at the Ottawa Observatory.

ELSEC Proton Precession Magnetometer Type 820

This magnetometer has a sensitivity of 0.1 nT and a wide range of operating modes which make it suitable as a part of a digital observatory system. A reading may be triggered from an external clock, an external contact or via the RS232 interface. Data may be stored internally, output in analogue or serial form and the tuning may be set from an external computer via the RS232 interface to enable its use in automatic vector measurements.

ELSEC Fluxgate D & I Theodolite Type 810

This instrument combines an accurate non-magnetic theodolite with a sensitive fluxgate element mounted with its magnetic axis coincident with the optic axis of the theodolite. The electronic unit has a 3.5 digit display which may be used as a null indicator for the absolute measurement of D and I. The digital readout also enables the components H and Z to be measured when used with a proton magnetometer as a reference.

NAROD GEOPHYSICS LTD. RINGCORE MAGNETOMETER S-100 VERSION

Barry Narod

Introduction

The initial impetus was provided by the U.S. Geological Survey, which required low-power, compact magnetometers for use in both ocean-bottom and temporary land installations. The S-100 instrument described here is the result of that development.

The sensor for this magnetometer uses three Infinetics Inc. S1000-C310JC-2239 ring-cores as its variable permeability elements, one for each of its three vector components. High thermal stability has been achieved by making all the coil support components from machinable ceramic (MACOR). The sensor is similar to the one developed by Mario Acuna of NASA for MAGSAT.

The S-100 instrument includes three circuit cards. The principal card contains all the circuitry to drive the ring cores, offset the main field, and amplify the sensor error signals. This card also includes S-100 I/O circuitry allowing the CPU for the S-100 bus to write offset values to registers on the card, thereby allowing automatic offset control.

The remaining two cards are a bus controller card with analog comparators and firmware to implement automatic offset control, and a three-channel anti-alias filter. The three cards and sensor comprise a stand-alone analogue triaxial instrument. When used with a data-logger for ocean-bottom or on-land use, the controller card is removed. Its function is replaced by the digitizer and CPU of the data-logger.

Design criteria

The design criteria may be summarized as follows:

1. General
   - — minimum complexity and power consumption
   - — electronics cards to IEEE-696 (S100) mechanical specifications (excluding thickness); to electrical specifications where possible or appropriate.
2. Magnetometer electronics card
   - — interfaces between sensor assembly and remainder of instrument
   - — configured as 7 write-only I/O locations in S100 bus
   - — accepts numerical (digital) offset information for each of three channels
   - — outputs 3 unbuffered, unfiltered analogue variometer signals, 50 Hz bandwidth, scale 1.0 V = 100 nT
   - — basic three-component magnetometer electronics (no output analogue filters, no offset controller function) occupies one full card.
3. Anti-alias filter specification
   - — selection of either 0.1 Hz or 0.5 Hz corner frequency by altering component header orientation
   - — 3 filter channels
   - — 3-pole filter
   - — maximally-flat amplitude (Butterworth) function
   - — low-impedance (buffered) output
   - — unity gain
4. Controller card specification
   - — CMOS CDP1802 microprocessor based
   - — six comparators set ±3.1 volts for autorange function, inputs on J2 from magnetometer card.
   - — fully interrupt driven software for minimum power consumption
   - — 9-bit, 2's-complement, 3-channel bin number data available on J1, maximum bin number: ±246
   - — +12 V to −12 V power conversion available on board.

System specifications

- — 3-component measurement of field
- — variometer resolution limit 0.01 nT in each axis
- — offset field step size 327.68 nT nominal, range limits ±256 × 327.68 nT
- — operation from nominal ±12 volt batteries
- — physical components configurable into two systems
  - — OBM subsystem
  - — stand-alone version

Specifications (Magnetometer card and sensor)

Bandwidth	−3 dB at 50 Hz, second order rolloff
Sensitivity	100 nT/volt
Output range	±10 volts
Offset range	±70 000 nT
Offset stability (sensor and electronics)	less than 0.010 nT/day ±10 ppm/deg (estimated)

Offset stability (sensor only)	±1 ppm/deg (estimated)
Offset accuracy	±5 % (estimated)
Noise (equivalent input)	1/f power spectral density, less than 5×10^{-5} nT^2/Hz at 1 Hz (measurement system limited)
Zero level drift (electronics only)	less than 0.07 nT/deg
Power requirements	±12 volts ±35 mA regulation +20 %, −10 %
Offset data — S-100/IEEE-696 output ports	seven in sequence
Maximum sensor cable length	10 m, or greater than 150 m with specially implemented cabling

Offset stability can be improved at the expense of higher power consumption (heated zener reference) to ±5 ppm/°C temperature sensitivity for the electronics.

USGS AUTOMATIC OBSERVATORY SYSTEM

A.W. Green, Jr., J.D. Wood, and L.R. Wilson

The system employs a ring core fluxgate magnetometer to obtain high quality three component magnetic variation data. A self-biasing ring core fluxgate is used because of its high resolution, excellent base line stability, and its ability to automatically change bias level in response to field changes. This new magnetometer, developed in co-operation with the University of British Columbia and the Pacific Geoscience Centre of the Canadian Geological Survey, has a resolution of 0.01 nT and a temperature coefficient of less than 0.1 nT/°C. This new fluxgate also incorporates a level detector, an up-down counter, and a digital-to-analogue converter to provide bucking, or bias, fields for each component in increments of 327.68 nT.

The analogue output for each component is a voltage proportional to the magnetic field variation about the bias level. If the variation exceeds ±327.68 nT, the self-biasing circuit automatically changes the bias level up or down in 327.68 nT increments. Each component also has a digital output in the form of a nine bit binary word which designates the bias level, or "bias bin number". For example, a bin number of +010011101, or +157, and a voltage −1.6591 volts on the Z component, would correspond to a Z field of $157 \times 327.68 - 165.91 = 51279.85$ nT.

Although the ring core fluxgate is a very stable magnetometer, it is not an absolute instrument. A high sensitivity proton magnetometer PPM 105 is used in an orthogonal bias coil arrangement to obtain daily, quasi-absolute measurements. The proton magnetometer and bias coils provide a means to periodically correct baseline values obtained from the ring core fluxgate and obtain quasi-absolute values of the magnetic field elements.

At the time of emplacement of the station, the inclination and declination angles of the bias coil system axis are very carefully measured. Theoretically, if the alignment of the axis remains unchanged, the system remains absolute (subject to certain errors in the actual measurements). In practice, however, such will probably not be the case, so the alignment of the coil system must be determined periodically. If the alignment varies in a linear or other systematic manner, due to pier settling or tilting, corrections can be made to maintain quasi-absolute values within satisfactory limits.

Geomagnetic data from the station can be transmitted in near real-time via telecommunications satellites and also recorded on tape cartridges at the remote station.

The transmitted (and recorded) data consist of:

1. Values, every 5 s, of H, D, Z (or X, Y, Z) amplitude variations about their respective bias base lines. Variation range is ±327.68 nT and the least count is 0.01 nT.
2. Bias base line levels, every 5 s, for each of the three components. (There are ±256 levels separated by 327.68 nT for each component.)
3. F values, every 30 s, from the proton magnetometer.
4. Temperature at the fluxgate sensing head, temperature at the fluxgate electronics, and time every 40 min.
5. A special sequence of five proton magnetometer readings occurring at 5 s intervals between normal 30 second proton magnetometer samples. These values (+I, −I, F, +D, and −D) constitute the quasi-absolute measurement sequence. This sequence occurs at 24 hour intervals, or on command.

Specifications

Instrument name	Narod Triaxial Fluxgate
Type	Self-biasing ring-core
Supplier	Narod Geophysical Ltd
Owner/operator	U.S. Geological Survey
Reliability	MTBF Unknown MTTR Unknown
Protected	Lightning No Humidity Yes Radio freq. interference No
Power	0.8 W Uninterruptible Yes
Export	Restrictions Yes
Cost	6000 $ U.S.
3 Component	Yes
Sensor construction	Orthogonal within ±6′ Stable to 1.2″/mo. 0.28″/°C
Resolution	0.01 nT
Dynamic range	±83 000 nT
Stability	< 0.3 nT/mo.
Passband	d.c. −0.5 Hz. (−3dB), 3-pole
Noise	0.004 nT rms in passband
Linearity	0.005 % of full scale
Timebase	1.0 s/mo., (a.c. line? No)
Sample rate	40 Hz. *
Measurement rate	60 s **
Storage	10 weeks
Temperature coefficient	Head 0.03 nT/°C Console 0.04 nT/°C

Temperature range	−20 to +50 °C
Temperature recording	Resolution 0.1 °C
Tilt sensors	?No Specs.
Azimuth sensors	? No Specs.
Comments:	±246 bias steps of 338 nT bias rate = 5 steps/s * to be changed to 5 Hz sample rate ** to be changed to 5 s measurement rate

INSTITUTE OF GEOPHYSICS, POLISH ACADEMY OF SCIENCES/FINNISH METEOROLOGICAL INSTITUTE TORSION PHOTOELECTRIC MAGNETOMETER (TPM)

Wojciech Turewicz, Chris Sucksdorff and Lasse Hakkinen

Advantages of TPM over classical magnetometers

Variometers with magnets suspended on fibres have been used in geomagnetic observatories for more than 100 years. In many, La Cour variometers are still in use, and all observers agree that these variometers are very reliable and easy to service and operate. The main disadvantage of this type of instrument is that a digital data logger cannot be directly connected to them.

It is possible to overcome this shortcoming by adding to classical variometers simple electronics, which do not affect any parameters of the instrument. Moreover, in this way, resolution, linearity, temperature coefficients and the bandwidth can be improved. The long term stability cannot be improved, but it is retained.

The Torsion Photoelectric Magnetometer type PSM is an instrument consisting of three torsion variometers with photoconverters and simple electronics. This instrument can detect signals of all magnetic variations needed in observatory practice. Using one instrument only, we can record micropulsations and long period variations of three elements of the magnetic field H, D, Z or X, Y, Z.

The electronics of PSM are comparatively simple, so the reliability of the instrument is high. Furthermore, the application of a modern digital logger makes it possible to avoid development of photographic paper. Thus the total amount of daily work needed for daily operation of PSM is less than for classical magnetographs.

Basic operational principle

The basic element of the photoconverter is the torsion variometer, whose magnet, suspended on fibres, responds to the magnetic field changes. A light beam from the illuminator falls on the variometer mirror rigidly connected to the magnet. The light beam reflected from the mirror illuminates the photodiode converter consisting of the two silicon photodiodes and a simple optical system.

The photocurrent from the photodiodes is transformed into voltage by a high-gain amplifier. The amplifier output is the output of the photoconverter. Part of the output current flows to a negative feedback coil so that the rotations of suspended magnets of the PSM become much smaller than in the classical variometer. Due to very strong negative feedback, the possible instabilities of electronic components or the sensor itself are automatically compensated, which makes the dynamic parameters of the PSM very stable.

Specifications

Instrument name	Torsion Photoelectric Magnetometer
Type	PSM
Supplier	Sensor and analogue part: Institute of Geophysics Pan, Poland Digital data logging part: Finnish Meteorological Institute
Owner/operator	Finnish Meteorological Institute Sucksdorff/Turewicz
Reliability	MTBF 2 years MTTR electronic — 2 days sensors — 1 month
Protected	Lightning. Yes Humidity. No Radio freq. interference. Yes
Power	2.5 W sensors and analogue part 6 W digital logging part all 12 volt Uninterruptible Yes Export Restrictions No
Cost	Sensor and analogue part 4500 $ U.S. Digital data logging part 10000 $ U.S.
3 Component	Yes
Sensor construction	Orthogonal within ±3.0′ Stable to 0.2″/mo. 0.2″/°C
Resolution	0.01 nT
Dynamic range	±3000 nT
Stability	1 nT/mo.
Passband	d.c. −5 Hz. (−3dB), 4-pole
Noise	0.01 nT rms in passband
Linearity	0.1 % of full scale
Timebase	1 s/mo., (a.c. line? No)
Sample rate	1 Hz.
Measurement rate	2 s and several hours
Storage	1 week at 2 samples/min
Temperature coefficient	Head 0.2 nT/°C Console 0.2 nT/°C
Temperature range	10 to 50°C
Temperature recording	Resolution 0.01°C
Tilt sensors	No
Azimuth sensors	No
Frequency response:	flat (0.1 %) from dc to 5 Hz optional — from dc to 0.2 Hz

Recording outputs:	dc output for any type of recorder, ac output for recording micropulsations temperature output all outputs ± 10 V full scale
Sensitivity of dc out:	from 2 mV/nT to 200 mV/nT in 5 ranges
Sensitivity of ac out:	from 10 mV/nT to 4 V/nT in 15 ranges
Comments:	1. Instrument consists of 3 blocks: sensors, analogue block, digital logging block 2. analogue block is provided with two filters: a) l.f b) h.f. (5 Hz) for pulsation studies

EOTVOS INSTITUTE DIMARS QUARTZ MAGNETOMETER

L. Hegymegi, L. Drimusz, and Z. Koros

Introduction

DIMARS is a microprocessor-based observatory system for digital recording of the Earth's magnetic field (Figures 3.3, 3.4). The system contains measuring and controlling electronics, the variometers, a temperature sensor, a clock-/calendar unit and a floppy disk drive.

Magnetic variometers

The torsion fibre quartz variometers are equipped with a feedback and a calibration coil system. The UV light beam reflected from the magnet/mirror is converted into an electric signal by a UV photosensor. When the magnetic field varies, a current proportional to the detected signal is fed back to the coil to create a compensation field which opposes the deflection of the magnet. The electric signal proportional to this current is measured.

Any type of variometer with an electrical output can be used as a signal detector, but the system accuracy basically depends on this part.

The variometer calibration is carried out by the system itself. Three different currents in the positive and negative directions are sent to the coils of the variometers and the current magnitude is measured together with the variometer output signal. The proton magnetometer is connected to the system by a serial link.

Electronics

The A/D converter measures the output signal of the variometers at 2 s intervals. The measured values are averaged and stored every 10 s and mean values are calculated every minute. The minute mean values are recorded and stored in memory for further calculations. Hourly mean values are calculated from the minute mean values. The maximum and minimum values of each channel, including that of the proton magnetometer, and their times of occurrence are continuously monitored and stored for each day. At the end of the day, the daily mean values are calculated. At the end of the month, the monthly mean values are calculated. In the 24 hour period following the end of the month, all the mean values for the preceding month can be recorded without any loss of data. The system has a built-in capability to start and operate rapid-run recording automatically. This recording starts when the variation in the H component fulfills the conditions:

$$H > A/10 \text{ min or } H > B/1 \text{ h}$$

where A and B are preprogrammed values by the operator and H is the actual change in the H component. The rapid-run recording can be terminated by the operator.

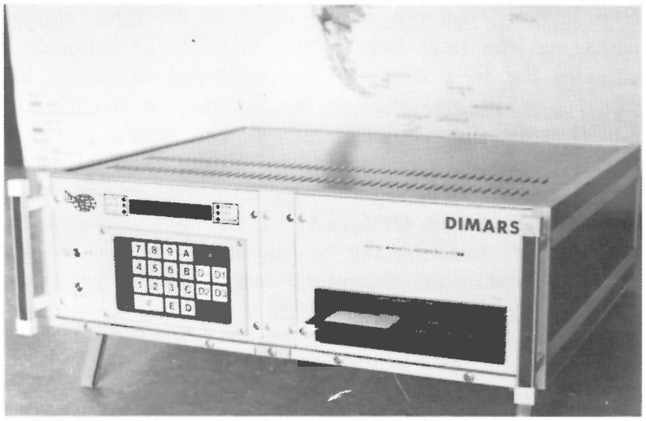

Figure 3.3 The DIMARS observatory system, from the Eotvos Institute, Hungary.

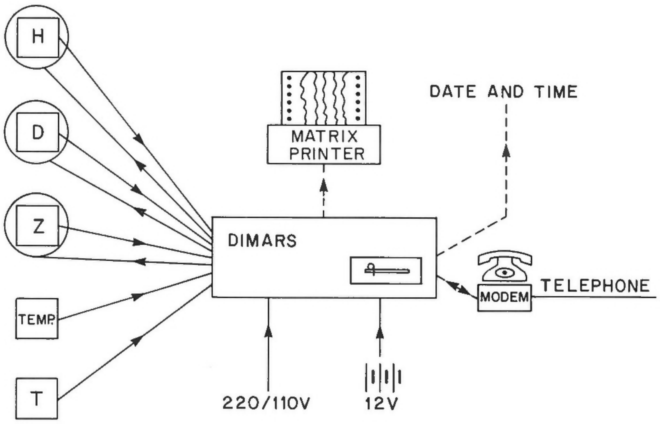

Figure 3.4 Diagram of the DIMARS system.

Recorders

The system has a built-in 5.25 inch floppy-disk drive. The diskette holds two files. The first file contains the header with identification data for the station, date and time, baseline values, temperature of the sensors and calibration data. After the header, there are the series of the 10 min blocks. The first record in the block contains the date, time and the temperature. This is followed by ten data records containing the minute mean values of the three components and the total field. The other file is optional. It contains the 10 s values of the rapid-run recording. Because of the limited space on the diskette, the first file is in ASCII while the second is binary. The system has multipurpose parallel Centronics type output. This gives the possibility of connecting a dot matrix printer or a magnetic tape recorder to the DIMARS. All the data measured and recorded or stored by the equipment can be sent to this output. Furthermore, the printer can be used to produce a real-time synthesized magnetogram.

System operation

DIMARS operates from the mains or batteries. For interruptions of the mains, it has built-in batteries to supply power to the clock/calendar and to the memory. During power failures, the system stops the measuring but all the data previously recorded and memorized are conserved. When the power comes back, the recording proceeds.

The recorded data, in the case of attended operation, can be obtained by changing the diskette. If only the one-minute data are on the diskette, one diskette contains 8 days of data. In the case of both normal and rapid-run recording, 4 days recording are on one diskette.

The DIMARS has a serial port for a modem. This gives the possibility of operating it via a telephone line. In a full-duplex mode all the keyboard commands can be activated remotely, and all the data recorded and memorized by the system can be obtained on a terminal. The data transmission can be repeated any time and after a successful data transmission the transmitted data can be deleted from the diskette.

Main technical characteristics

- number of input channels: 5 (H,D,Z,F,T), differential, floating
- input resistance: 1 megohm
- input amplitude: ±2 V
- maximum common mode input noise: 4 V
- digital input: RS232C (1200 Baud, 7 bits, 2 stop bits, no parity)
- calibration output: 3 programmable current outputs
- calendar output: RS232C (1200 Baud, 7, 2, N)
- remote terminal connection: RS232C (duplex, 300/1200 Baud, 7, 2, N)
- digital recorder output: 8-bit parallel, Centronics type
- self-contained recorder: 5.25 inch floppy disc, IBM-PC/XT/AT
  MS-DOS (360 Kb) format
- power supply: 110/220 V 50/60 Hz AC or 12 V DC 40 W
- dimensions (mm): 420(w) × 140(l) × 340(h)
- sensors
  - 3-component Bobrov-type quartz variometers
  - dynamic range: ±1000 nT
  - linearity: 0.5 %
  - temperature coefficient: < 0.5nT/°C
  - stability: < 1 nT/mo

  Product of IZMIRAN, U.S.S.R.

THE D-I FLUXGATE MAGNETOMETER OF THE ROYAL NETHERLANDS METEOROLOGICAL INSTITUTE, DIVISION OF GEOPHYSICS

J.H. Rietman

Introduction

The D-I fluxgate magnetometer has been developed by the Division of Geophysics of the Royal Netherlands Meteorological Institute (RNMI) for the absolute measurement of the declination D and the inclination I at the Geomagnetic Observatory at Witteveen and for the geomagnetic survey of the Netherlands.

Description of the instrument

The magnetometer consists of a fluxgate sensor fixed parallel to the optical axis of a non-magnetic Zeiss 010A theodolite. The sensor is the Fluxgate LFG-A13, manufactured by Pandect Instrument Laboratory (formerly Kelvin-Hughes). The electronics have been built by the Division of Geophysics of the RNMI. The schematic circuit diagram is given in Figure 3.5. The output of the sensor is displayed on a digital voltmeter. All components of the electronics (except for the digital voltmeter) have been assembled in an aluminum carrying case.

Principle of operation

The instrument is used as null detector. When the output of the sensor is zero, the actual geomagnetic field is perpendicular to the sensor. The sensor is first rotated in the horizontal plane. There are four positions of the sensor in which the output of the sensor is zero (magnetic east and magnetic west with the sensor under and above the telescope). By using the readings of the horizontal circle of these four positions, the misalignment of the fluxgate sensor relative to the axis of the telescope and the sensor offset are both cancelled. This procedure yields the direction of Magnetic North. For the calculation of the Declination the direction of Astronomical North has to be determined.

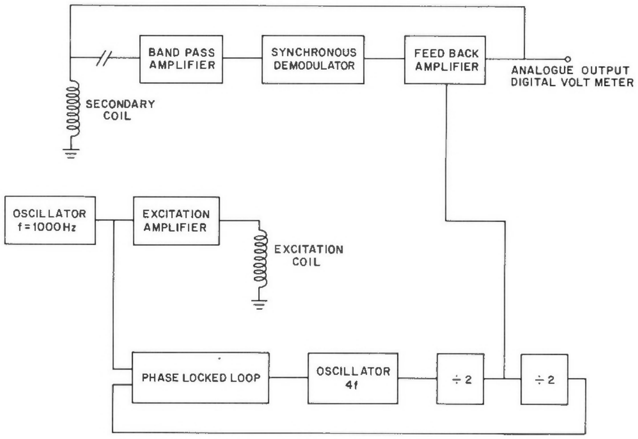

Figure 3.5 Diagram of the DI fluxgate from the Royal Netherlands Meteorological Institute.

When the sensor is rotated in the meridian plane the four zero positions are perpendicular to the direction of the total field F and the inclination I can be calculated directly.

The intensity of the total geomagnetic field is measured by a proton precession magnetometer (PPM). The intensity of the total field together with the declination and inclination give the intensity of the horizontal and vertical components of the earth's magnetic field.

Specifications

Theodolite: Zeiss Jena 010A (Non-magnetic)
Fluxgate sensor: Pandect Instrument Lab. type LFG-A13
Electronics: Null detector: resolution 0.1 nT,
±200 nT full scale
Power consumption: ±18V/60mA and 9V/5mA
Passband: DC — 3 Hz
Temperature coefficient: not measured
Accuracy: ±5″ for D and I

DANISH METEOROLOGICAL INSTITUTE DI-FLUXGATE

E. Kring Lauridsen, and O. Rasmussen

The Danish DI fluxgate consists of a fluxgate magnetometer with digital output mounted on a Jena 010 non-magnetic theodolite. Practical details and theory of the instrument are contained in a report by Kring Lauridsen (Experiences with the DI-fluxgate magnetometer inclusive theory of the instrument and comparison with other methods: Danish Meteorological Institute, Geophysical Papers R-71, Copenhagen, 1985).

HUANCAYO MAGNETIC OBSERVATORY SOKKISHA EARTH INDUCTOR MAGNETOMETER

Oscar Veliz

Instrument description

Theodolite earth inductor D,I magnetometer
Sokkisha GSI First Order No. 40

Principle of operation

A cylindrical small search coil is rotated at a rate of 10 turns per second by using a rotating handle at the centre of the nonmagnetic theodolite. The output of the AC generated signal comes to zero when the rotating axis is adjusted completely parallel to the direction of the earth's magnetic field. The direction of the geomagnetic field can be read out by the horizontal and vertical circles, and the declination and inclination can be determined to an accuracy of 0.1′.

The output signal of the rotating coil is fed into a high gain, low noise amplifier whose output is displayed by a calibrated LED bar indicator.

Composition

- Non-magnetic theodolite and rotary detector coil
- Amplifier unit
- Observing LED display

Specifications

Theodolite		
Telescope	Length:	186 mm
	Aperture:	40 mm
	Magnification:	16 X
	Image:	inverted
Horizontal circle:	Graduation:	20′
	Vernier:	2′
	Estimation:	0.2′
Vertical circle:	Graduation:	20′
	Vernier:	2′
	Estimation:	0.2′
Levels:	Horizontal:	10″/2 mm
	Vertical:	10″/2 mm
Detector		
Type:	Rotating search coil, enamelled copper winding	
DC resistance:	45 kΩ	
Diameter:	20 mm	
Electronic amplifier		
Type:	Solid state IC	
Bandwidth:	10 Hz ± 2 Hz	
Gain:	110 dB	
Power:	12 V DC	
Temperature:	−20 to +50°C	

THE GEM SYSTEMS INCORPORATED MAGNETOMETERS

Ivan Hrvoic

GSM-10 Proton (Overhauser) Memory Magnetometer

Resolution	0.1 nT
Absolute accuracy	0.2 nT
Range	20 000-100 000 nT, automatic tuning, manual override
Gradient tolerance	Up to 5000 nT/m
Operating modes	
Manual	Automatic storage of label, time and date, magnetic field, error code
Base station	3 s to 24 h intervals, automatic storage of time, date, magnetic field and error code
Storage capacity	
Manual	2700 readings standard, 5350 or 8060 optional
Base station	7300 readings standard, 14 770 or 22 220 optional (18 h operation at 3 s intervals)
Power consumption	2 W per reading, 300 mW stand-by
Power source	12 V, 2.2 Ah lead-acid rechargeable batteries standard, others optional
Operating temperatures	−40 to +60°C

Comment	Presently there is no on-line (reading by reading) transfer of data to a mass storage medium; to be available later.

GSM-11 Continuous Proton (Overhauser) Magnetometer

Resolution	0.01 nT for up to 10 readings/s
Noise envelope	0.01 nT for 1 reading/s 0.02 nT for 2 readings/s 0.05 nT for 5 readings/s 0.1 nT for 10 readings/s
Reading intervals	Selectable in steps of 0.1 s from 0.1 to 9.9 s
Absolute accuracy	0.5 nT: time base stability 1 ppm over −35 to +55°C, aging 1 ppm per year
Tuning	Wideband system, no tuning
Range	20 000 to 100 000 nT
Operating temperatures	−35 to +55°C
Power consumption	22-32 V, 15 W average, 25 W maximum
Continuous signal	Non-decaying proton precession frequency is generated by means of the Overhauser Effect. This allows for an uninterrupted measurement of magnetic field, in contrast to a sampling feature of the classical proton magnetometer
Analogue output	3 channels — magnetic field, coarse — magnetic field, fine — fourth difference (a noise measure) Analogue scales are fully programmable on all three channels from 1-10 000 nT full scale
Digital output	Seven digit BCD, serial RS232C and parallel IEEE-488(GPIB) ports
Visual output	Dot matrix LCD, 7 digit magnetic field in nT, status indication and four digits of noise level (4th difference)
Comment	Highest class proton magnetometer available

GSM-18 Proton Memory Magnetometer

Resolution	0.1 nT
Absolute accuracy	0.5 nT
Range	20 000-100 000 nT, automatic tuning
Gradient tolerance	Up to 5000 nT/m
Operating modes	
Manual	Automatic storage of label, time, magnetic field, error code
Base station	3 s to 60 min intervals, automatic storage of time and magnetic field
Storage capacity	
Manual	2700 readings standard, 5350 or 8060 optional
Base station	7300 readings standard, 14 770 or 22 220 optional (18 h operation at 3 s intervals)
Power consumption	8 W per reading 300 mW idle 30 mW standby
Power source	12 V 2 Ah Nicad rechargeable batteries standard, others optional
Operating temperatures	−40 to +60°C
Comment	Presently there is no on-line transfer of data to a mass storage medium; to be available later.

GSM-8 Proton Magnetometer

Resolution	1 nT or 0.5 nT optional
Accuracy	1 nT over operating range
Range	20 000-100 000 nT in 23 overlapping steps
Gradient tolerance	Up to 5000 nT/m
Operating modes	Manual pushbutton: new reading every 1.85 s, display active between readings Cycling: pushbutton initiated, 1.85 s period Selftest cycle: pushbutton-controlled 7 s period
Output	Visual: 5 digit 1 cm high LCD, visible in any ambient light Digital: multiplied precession frequency and gating pulse Analogue: 0-99 nT (optional)
External trigger	Permits externally triggered cycling with periods longer than 1.85 s. (cycling faster than once per second optional)
Power requirements	10-18 V DC, 8 W per reading
Power source	Internal: 12 V 0.75 Ah NiCad rechargeable battery, 3000 readings when fully charged External: 12-18 V
Operating temperatures	−40 to +55°C
Comment	An inexpensive total field standard

GSM-9 Proton (Overhauser) Magnetometer

Resolution	1 nT or 0.5 nT optional
Accuracy	1 nT over operating range
Range	20 000-100 000 nT in 23 overlapping steps
Gradient tolerance	Up to 5000 nT/m
Operating modes	Manual pushbutton: new reading every 1.85 s, display active between readings Cycling: pushbutton initiated, 1.85 s period (optional) Selftest cycle: pushbutton controlled, 7 s period

Output	Visual: 5 digit 1 cm high LCD, visible in any light Digital: Multiplied precession frequency and gating pulse, 0.5 nT resolution Analogue: 0-99 nT (optional)
External trigger	Permits externally triggered cycling with periods longer than 1.85 s (cycling faster than once per second optional)
Power requirements	10-18 V DC, 1W per reading, 3mA standby current
Power source	Internal: 12 V 0.45 Ah NiCad rechargeable battery, 15 000 readings between chargings Alternatively: Disposable Lithium battery pack (internal) good for over 250 000 readings; 10 D size Alkaline batteries good for over 150 000 readings External: 12-18 V
Operating temperatures	−40 to +55°C
Comment	Very low power total field standard

DOWTY ELECTRONICS LTD (DOMAIN MAGNETICS)

Ian Bell and Mike Hellard

Single Axis (SAM 3) and Three Axis (TAM 3) Magnetometers

Fluxgate probe(s)

In either the SAM 3 or TAM 3, the individual fluxgate probe consists of a ferro-magnetic ring core wound with a toroidal excitation winding. This assembly is housed within a moulded bobbin and then overwound with a solenoidal sense winding. An additional field reset solenoidal winding is fitted to the fluxgate for field compensation and calibration purposes. It is independent of the sense winding but has the same magnetic axis. The sense axis of the probe is defined by the axis of the solenoidal sense winding. The fluxgate is environmentally protected and totally encapsulated.

Magnetometer electronics

The magnetometer operates using the second harmonic fluxgate principle in a closed loop configuration. Field proportional signals produced by the fluxgate are of an amplitude modulated double sideband suppressed carrier type. These signals are effectively an unbalanced flux signal and are detected by and connected to a signal processing circuit via the sensing winding. The processing circuit translates the field proportional signal down to a base band. Application of a reset current closes the circuit loop and nulls the field at the fluxgate to nominally zero under static conditions. Use of high forward gain with heavy feedback ensures good linearity and stable performance.

Specifications

Dynamic range	Maximum 100μT or ±10 V dc Output corresponds to full scale of appropriate output range setting
Noise (pk.to pk.) dc to 10 Hz bandwidth	Not greater than 1 nT standard typically 0.3 to 0.5 nT
HF cut-off frequency	1, 10, 100, 1000 Hz switched
LF cut-off frequency	dc
Drift	Better than 0.5 nT/°C
Temperature coefficient of solenoidal transfer function	−16.7 ppm/°C
Output ranges with range set at X1	3, 10, 30, 100, 300, 1000 nT
Output ranges with range set at X100	300, 1000, 3000, 30 000, 100 000 nT
Operating temperatures	0 to +50°C standard −50 to +70°C optional
Field compensation	±100 nT
Power supply	240 V 50/60 Hz internal NiCad rechargeable pack 110 V 60 Hz optional
Battery life	15 hours before recharge
Comments	Probes available to give a X5 and a X10 multiplication factor on ranging i.e. 500μ T and 1 mT full scale

3-axis Differential Magnetometer DMAG 3

Specification summary

Dynamic range	±100 μT
Bandwidth	dc to 10 Hz
Ranges	−10 to +10 nT −100 to +100 nT −1000 to +1000 nT Auto
System noise	Not greater than 0.5 nT pk to pk
Resolution	Not greater than 0.25 nT
Accuracy	±1 % of full scale reading or ±0.5 nT whichever is greater
Orthogonality	±0.1° (mechanically to 0.25°)
Temperature range	Storage −10 to +45°C Operating +5 to +35°C

SCINTREX CORPORATION

John Buckle and George Tibenski

At this Workshop, three Scintrex sensors were interfaced into a data-acquisition system, with graphic trace outputs and a nine track digital recording:

1. Cesium vapour optically-pumped magnetometer with sensitivity of 0.01 nT cycling up to 10 times per second and recording scalar total field.
2. Proton precession magnetometer MP3, with sensitivity of 0.1 nT and internal memory for up to two weeks on one minute recording.
3. Vector fluxgate magnetometer orientable into X, Y, or Z planes, with resolution of 0.001 nT, analogue output interfaced to A/D converter.

INSTITUT DE PHYSIQUE DU GLOBE DI FLUXGATE

D. Gilbert

Full details of this instrument are given in section 6.

Measurement principle
- Fluxgate sensor used as a zero detector for measurement of D & I
- Fluxgate sensor used in a compensated field for measurements of the components H, X, Y or Z.

Theodolite: Carl Zeiss Jena model 010B (non-magnetic version)
- average angular error ±1″ (horizontal and vertical circles)
- sensitivity of the tubular level: 1 mm of movement of the bubble is equivalent to 10″
- estimated leveling accuracy ±1″ (mean stabilization error of the pendulum ±0.3″
- weight: 4.8 kg.

Fluxgate sensor:
- length 80 mm, outer diameter 18 mm (double saturated core)
- output sensitivity: 2 mV/nT
- dynamic range: ± 350 nT
- noise: 0.2 nT peak to peak from 0.5 Hz to DC
- temperature coefficient: less than 0.05 nT/°C in zero field
- sensor error: less than 2 nT

Measurement electronics and display unit:
- control indicator: display resolution 0.1 nT, linearity 10^{-3}
- bandwidth: 0.5 Hz to DC
- linearity of compensation current: 10^{-5}
- range of measurement (compensation method): $\pm 10^{5}$ nT
- temperature coefficient: less than 0.2 nT/°C for a compensated field of 50 000 nT

Power source: sealed lead-acid battery (12 volts, 4 ampere-hours): consumption of 100 mA/12 V
Operating temperature: −10 to +45°C
Weight: 7 kg.

INSTITUT DE PHYSIQUE DU GLOBE/THOMSON-SINTRA TRIAXIAL FLUXGATE VARIOMETER

D. Gilbert and J.-J. Periou

Details of the design, construction and operation of this instrument are presented in section 7.

Specifications

Instrument name	Variomètre Triaxial à vannes de flux
Type	VFO 31
Supplier	Thomson-Sintra, Brest, France
Owner/operator	Institut de Physique du Globe de Paris Institut de Physique du Globe de Strasbourg
Reliability	MTBF 10 years MTTR 1 day
Protected	Lightning No Humidity Sensor No Electronics Yes Radio freq. interference No
Power	Sensor 4 W Sensor plus logger 12 VA/220 volts Uninterruptible Yes limit 12 h, battery 12 v 4 Ah
Export Restrictions	None
Cost	$23 000 U.S. in 1984
3 Component	Yes
Sensor construction	Discrepancy between geometric axis and magnetic axis of core: < 5′ Orthogonal within < 10′ Stable to < 2″/mo. < 1″/°C
Resolution	0.1 nT
Dynamic range	±1000 nT ±2000 nT (option)
Stability	< 1 nT/mo.
Passband	d.c. — 0.5 Hz. (−3dB), 1-pole
Noise	0.1 nT rms in passband 0.1 nT p-p from 0.001 to 0.5 Hz
Linearity	0.1 % of full scale
Timebase	1 s/mo.
Sample rate	5 Hz.
Measurement rate	60 s.
Storage	> 8 weeks
Temperature coefficient	Head < 0.15 nT/°C Console < 0.08 nT/°C for compensation of 50 000 nT
Temperature range	0 to 40 °C
Temperature recording	See comments
Tilt sensors	See comments
Azimuth sensors	See comments
Sensor error	< 10 nT
Compensation of permanent component	±79 900 nT
Dimensions of sensor	length 100 mm, diameter 20 mm
Sensor constant	0.15 µA/nT
Excitation frequency	2 kHz
Excitation current	120 mA peak to peak
Detected 2F harmonic level	3.5 µV rms/nT
Offset current of current generator	< 1nT
Output sensitivity	5 mV/nT

Comments:

The National observatory of Chambon la Forêt has operated 1 variometer since 1979.

The observatories of the Terres Australes et Antartiques françaises have operated 4 variometers since 1972.

There have been 2 breakdowns to note, both after lightning.

The variometers are installed either in thermostatically controlled shelters or in insulated buildings (vault). At Chambon la Forêt, the mechanical level was only verified 5 years after installation at the time of realignment in the magnetic meridian. After having leveled the variometer and clamped it in the meridian, the values of the baselines of D and H were evidently modified but the baseline of Z remained identical to its value before adjustment.

Characteristics of digital acquisition system

Analogue inputs from fluxgate magnetometer
- number of analogue channels: 8
- nominal input level: ± 5 V
- input impedance: 1000 megohms
- analogue/digital converter: dual slope integrator principle with automatic zero correction
- rejection of 50 Hz series mode signals: better than 50 dB
- duration of integration of voltage to be measured: 40 ms
- duration of a measurement cycle: 70 ms
- dynamic range: ±10 000 points
- precision: $\pm 10^{-4}$ ±1 unit

Digital input from proton magnetometer
- temperature compensated 5 MHz oscillator
- stability 10^{-7}/day, 5×10^{-7} from 0 to 50°C
- sampling: 2, 10, 20 seconds and 1, 2, 10-20 minutes

Output coding: binary coded decimal

System:
- incremental 7 or 9 track digital magnetic tape recorder
- cassette recorder
- printer

Monitoring: selective day, hour, measurement display of components of the fluxgate and proton magnetometers.

THE CJ6 MAGNETIC THEODOLITE AND THE CTM-302 THREE-COMPONENT FLUXGATE MAGNETOMETER OF THE INSTITUTE OF GEOPHYSICS, ACADEMIA SINICA, CHINA

Liu Chang-Fa

(NOTE: These instruments were not brought to the Workshop but were described to the participants.)

Introduction

The Institute of Geophysics, Academia Sinica, was established in 1950. Since that time, our institute has designed and manufactured some high quality geomagnetic instruments for magnetic observatories and magnetic field surveys, such as the Type 57 Variometer and Type CB3 Variometer, Type CJ6 Magnetic Theodolite and Type CTM-302 Three-component Fluxgate Magnetometer. At present, these instruments are working at magnetic observatories and variation stations. We have designed a new Automatic Magnetic Observatory System in recent years.

CJ6 Magnetic Theodolite

This instrument can accurately measure the declination D and the horizontal intensity H of the geomagnetic field, which provide a rapid means of determining the magnitude and direction of the magnetic field in conjunction with a proton magnetometer. The instrument consists of a declinometer and a quartz horizontal intensity magnetometer. Both of them use the same horizontal optical circle which has a reading system similar to the standard optical theodolite; it is easy to read the angles. The theodolite (designed by Du Ling and Wang Xiu-Shan) is made of copper, copper-aluminum alloy and other materials having very weak magnetism. It is convenient to carry and to operate in the observatory or in the field.

Specifications

Measured quantities	Declination D and horizontal intensity H
Accuracy	D ±0.2′ (mean square error) H ±1.5 nT (mean square error)
Temperature range	−15 to +40°C
Power supply	9 V DC
Telescope	8x magnification, objective aperture 20 mm with 3° field of view
Plate level sensitivities	Tubular level 30″/2mm Circular level 8′/2mm
Weight and dimensions	Net 6.5 kg, 256 × 141 × 428 mm

The Type CJ6 magnetic theodolite has been used at magnetic observatories and repeat stations in China. It has also been used to make absolute observations at Port Moresby magnetic observatory in Papua New Guinea during the Total Solar Eclipse on 11 June 1983. The CJ6 is stable in operation and convenient to operate, and costs about the equivalent of $US 3000 each in China.

The CTM-302 three-component fluxgate magnetometer

The accurate recording of X, Y, and Z component variations of the geomagnetic field can be obtained by the CTM-302 magnetometer. This instrument consists of a compact electronic console, 30 meter cable and fluxgate sensor. The output ranges of X, Y, and Z are all ±10 volts. It can provide multichannel analogue recording or cassette-tape recording for regular and rapid variations. The fluxgate sensor has been compensated for temperature. The magnetometer (designed by Liu Shi-Jie) is very stable and convenient to operate.

Specifications

Measured quantities	Relative variations of X, Y, and Z of geomagnetic field provided on analogue recording or cassette tape recording
Range	X & Y 0 to ±50 000 nT Z 0 to ±70 000 nT
Resolution	0.1 nT
Sensitivity	10 mV/nT
Dynamic range	±800 nT (8 volts) from baseline
Noise level	Less than 1 nT/°C
Frequency response	0 to 2.5 Hz (−3 db)
Temperature coeff.	Less than 1 nT/°C
Temperature range	0 to +35°C
Monitor	0 to ±500 nT (full scale)
Filter	Lowpass from 0 to 2.5 Hz bandpass from 600 s to 400 ms
Power supply	AC 50 Hz, 220 V or DC ±18 V, 3.5 W
Weight and dimensions	Net 20 kg, 220 × 350 × 220 mm sensor 520 × 410 × 180 mm console

The CTM-302 fluxgate magnetometers will be incorporated into the new Automatic Magnetic Observatory Instrument System. It is expected that with this system, the quality of geomagnetic observations in China will soon be improved.

4. ABSOLUTE INSTRUMENTS

A COMPARISON OF ABSOLUTE INSTRUMENTS AND OBSERVATIONS CARRIED OUT DURING THE IAGA WORKSHOP

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Introduction

During the Workshop on Magnetic Observatory Instrumentation it was demonstrated that it is now possible to construct magnetometers which have low temperature coefficients and good long term stability. (See, for example, the description of the Thomson-Sintra instrument, the Narod instrument and the Polish torsion photo-electric magnetometer.) The deployment of these magnetometers in observatories is bound to improve our knowledge of the absolute level of the magnetic field at any given time because of the reduced instrument drift between absolute observations. On the other hand, although the magnetometer may be stable, the pier on which it rests will still be subject to changes in tilt and azimuth. The amount of pier movement depends on the type of pier construction, the type of soil or bedrock on which it is constructed, and climatic conditions. A discussion of some of these factors, as applied to Arctic observatories, has been given by Jansen van Beek and Loomer (1982). They give examples in which changes in observatory baselines of almost 100 nT over a period of several months may be attributed to pier movements. Similar problems have been encountered in the French Antarctic observatories.

Frequent absolute observations, then, will continue to be required regardless of the type of magnetometer used. In addition, the new generation of magnetometers may place even greater demands on the absolute observer and his equipment. Many magnetometers now record with a precision of 0.1 nT, with noise figures low enough to justify this precision. It is unlikely that many observatories in the world can achieve an accuracy of 0.1 nT during an absolute observation. Delegates to the Workshop were not unanimous in their opinions as to whether 0.1 nT absolute accuracy is even necessary; nor did they agree on the probability of obtaining such accuracy on a routine basis.

Description of instruments

Given the continued, and perhaps increasing, importance of absolute observations it is not surprising that a great deal of interest in absolute instruments and their use was shown by delegates to the Workshop. In fact, a total of 16 absolute instruments were either displayed or demonstrated. Of these, seven were proton magnetometers and will not be discussed further in this report. The remaining 9 instruments consisted of the following:

D&I Fluxgate Magnetometer (Danish Meteorological Institute, DMI)
D&I Fluxgate Magnetometer (Royal Netherlands Meteorological Institute, RNMI)
D&I Fluxgate Magnetometer (Geological Survey of Canada, GSC)
D&I Fluxgate Magnetometer (Institut de Physique du Globe, IPG)
Sokkisha Induction Magnetometer (Geophysical Institute of Peru, GIP)
D&I Fluxgate Magnetometer (Littlemore Scientific)
Quartz Declinometer (Danish Meteorological Institute)
Quartz Horizontal Magnetometer (Danish Meteorological Institute)
D&I Fluxgate Magnetometer (EDA Instruments Inc)

The last four instruments listed above were displayed only. The first five were used in a series of comparative observations.

Instrument descriptions have been given by the responsible delegates in section 3. However, a few additional comments about the four D&I magnetometers used in the comparisons are in order.

All instruments consist of a fluxgate sensor mounted on a "non-magnetic" theodolite. The DMI, the RNMI and the IPG all use a Zeiss-Jena 010A or 010B; The GSC uses a Zeiss-Jena 020A. Both models are direct reading theodolites; the former, however, has scales graduated to 1″ (or 0.2 mgrad); the latter has scales graduated to 1′, with an estimated reading accuracy of 0.1′. The level bubble on the 010B is graduated at 20″ per division; that of the 020A, 30″ per division. The magnification of the telescope for the former is 30X, and for the latter, 25X. Thus it should be possible to level, sight and read the 010B more accurately than the 020A.

Both models feature automatic vertical circle stabilization; that is, the reading of the vertical circle is given with respect to a small pendulum, not the alidade. Thus, in theory, precise levelling of the instrument is not necessary. However, tests carried out at the IPG indicate that a greater scatter in the observations results when the instrument is not levelled precisely.

All theodolites were mounted with fluxgate sensors, many of which were commercially manufactured. The associated magnetometers were all designed and manufactured by the responsible institute. More complete details have been given elsewhere in these Proceedings. At least two companies manufacture complete units (also described elsewhere), so that it is not necessary for potential users to develop and manufacture their own systems.

A warning should be given to current and potential users of "non-magnetic" Zeiss-Jena theodolites. It cannot be assumed that these instruments are completely non-magnetic. It has been the experience of some of the participants that these theodolites arrive from the manufacturer with at least some small parts (springs, clamps, clips, screws, etc.) possessing a magnetization great enough to affect observations. If the magnetic part is in the base, it is essential that it be removed. The effect of a magnetic part in the body of the theodolite or in the telescope can be eliminated, theoretically, by observing with the sensor in four different positions, but it must be remembered that the offending magnetization can change in strength during the observation, and may not be completely eliminated by this procedure. Each instrument should be thoroughly checked, and offending parts replaced, before it can be safely used.

It is an interesting fact that six of the nine instruments listed above are D&I fluxgate magnetometers. The D&I fluxgate magnetometer has been in use as a field survey instrument since at least 1947 (Serson and Hannaford, 1956), and has been in use as an absolute instrument in some Canadian observatories since 1948. However, it appears that the instrument did not gain wide acceptance as an observatory instrument even as late as 1970, as witnessed by the fact that it is not even mentioned in Wienert's (1970) text on geomagnetic observatory and survey practice. However, over the past several years its use has increased and recent comparisons against classical standards indicate that comparable precision and accuracy can be obtained (Bitterly et al., 1984; Kring Lauridsen, 1985). For example, comparisons have been made over the past five years with classical observations made with a Cambridge inclinometer and over the past two years with measurements made using a Littlemore vector proton magnetometer using Serson's method. The measurements, although not made on the same pier, are convincing since differences are on the order of 1 nT.

The assemblage of several of these instruments, all from different institutes, in one location offered a good opportunity not only for the comparison of instruments but also for the comparison of observational techniques.

Observational procedures

The D&I magnetometer is essentially used as a null detector. In the horizontal plane, the sensor will indicate a null when it is perpendicular to the magnetic meridian. There are four possible sensor positions in which this is possible. By observing in all four positions, errors due to misalignment of the coil as well as coil offset resulting from remanent magnetization of the coil and from the electronics are eliminated. The mean of the four horizontal readings and the sighting of a known reference mark before and after the observations gives, after a simple calculation, the angle of declination. When the sensor is placed in a plane parallel to the magnetic meridian, (90° from the mean position just determined) a null will be detected when the sensor is positioned perpendicular to the direction of the field vector. Again, observations are normally made with the sensor in all four possible positions although it can be shown that only two positions are actually necessary to eliminate coil misalignment and offset errors (Kring Lauridsen, 1985). The mean of the four vertical circle readings gives the value of the inclination of the magnetic field.

These steps are fundamental, but the actual observing technique and the subsequent method of baseline calculations varied from observer to observer. It is worthwhile to describe briefly these methods.

The observers from the IPG and the RNMI employed similar techniques. For each sensor position, a null was obtained at the time at which the observatory magnetometer sampled the field; in this case, on the minute. Baselines (for D) were calculated without timing errors simply by taking:

$$D_{bl} = \bar{D}_{abs} - \sin^{-1}(\delta\bar{D} / H_{abs})$$

where $\bar{D}_{abs} = \frac{1}{4}(D_{t1} + D_{t2} + D_{t3} + D_{t4})$ and

$$\delta\,\bar{D} = \frac{1}{4}(\delta D_{t1} + \delta D_{t2} + \delta D_{t3} + \delta D_{t4})$$

Observations of I were made in a similar fashion.

The observers from the DMI used a slightly more complicated technique. Instead of rotating the sensor until an exact null was obtained, they set the horizontal circle on a fixed value close to the null position. Then, at even minute intervals, the meter deflection was recorded. Three values were recorded before the sensor was moved to the next position. A baseline value was calculated for each coil position as follows:

$$D_{bl}(1) = D_{abs}(1) + \sin^{-1}(\bar{S}\,(1)/H_{abs}) - \delta\bar{D}\,(1)s_D$$

where $\bar{S}$ is the average meter reading (after correcting for sign) and sD is the magnetometer sensitivity. (If the magnetometer output is in nanoteslas, one can more accurately use $\sin^{-1}(\delta\bar{D} / H_{abs})$ in place of $\delta\bar{D}\,s_D$). The final baseline is the average of the four individual baselines:

$$D_{bl} = \frac{1}{4}(D_{bl}(1) + D_{bl}(2) + D_{bl}(3) + D_{bl}(4))$$

The observer from the GSC did not null the instrument simultaneously with the magnetometer sampling. Instead, readings in the four positions were obtained as quickly as possible, and a single time, taken at the midpoint of the the observation, was noted. In calculating the baseline, an average of three variometer values, approximately centred on this time, was used.

$$D_{bl} = \bar{D}_{abs} - \sin^{-1}(\delta\bar{D} / H_{abs})$$

where $\bar{D}_{abs} = \frac{1}{4}(D_1 + D_2 + D_3 + D_4)$

and $\delta\bar{D} = \frac{1}{3}(\delta D_{t-1} + \delta D_t + \delta D_{t+1})$

This method is inherently less accurate than the other two methods. Also, the use of a Jena 020A theodolite instead of the more precise 010B decreased the accuracy. These difficulties are compensated for by taking six sets of observations, at least twice as many as done by the other observers.

The principle of operation of the Sokkisha magnetometer is, as already described, different from that of the fluxgate. Nevertheless, four separate readings are necessary for a complete observation of D or I. The observer from the GIP noted the start time and the end time of a set of observations. In calculating the baseline, the average value of the variometer data sampled during the time interval was used.

$$D_{bl} = \bar{D}_{abs} - \sin^{-1}(\delta\bar{D} / H_{abs})$$

where $\bar{D}_{abs} = \frac{1}{4}(D_1 + D_2 + D_3 + D_4)$

and $\delta\bar{D} = 1/(T_2 - T_1 + 1) \sum_{k = T_1}^{T_2} \delta D_k$

Program of observations

At the beginning of the Workshop a schedule was drawn up in which each observer would make two sets of observations per day in the Ottawa Observatory absolute building, one on Pier A, and one on Pier E. This would provide up to 12 observations per instrument for comparison. It soon became apparent that this schedule could not be maintained because numerous other Workshop activities placed great demands on the time of most observers. Instrumental problems further reduced the number of observations. Adjustments to theodolite bases had to be made to allow them to be used on Pier E; the Sokkisha instrument could not be used on Pier A because its side-mounted telescope could not be sighted on the azimuth mark. A critical factor which affected those observations which could be done was the contamination of the observatory building with extra instruments and boxes, not to mention the constant stream of visitors anxious to observe and discuss methods of observations.

Another problem arose in choosing a variometer for the calculation of baselines which could then be compared. Data were available on a daily basis from only three magnetometers: the Thomson-Sintra fluxgate, the ELSEC vector PPM and the AMOS fluxgate. The Thomson-Sintra magnetometer, inherently a very stable instrument, was mounted on an outside pier, making it subject to greater than normal pier tilt and temperature variations. The ELSEC 8200 vector PPM was housed on an inside pier, but the building was not temperature controlled. In addition, neither instrument operated continually, and both were subject to frequent inspection by numerous interested delegates. The Ottawa Observatory AMOS ran continuously, but appears to have undergone some unusually rapid drifts during the Workshop.

For all these reasons, the results tabulated in the following section do not comprise proper instrument comparison comparable to those carried out periodically by the Nordic countries. Rather they can be viewed as a "worst-case scenario"; that is, a measure of how well observations can be made under adverse conditions.

Results

The baseline values calculated from each instrument by an observer using his normal method of reduction are given in Tables 4.1 to 4.6 and are plotted in Figures 4.1 to 4.3. Results are presented for each of the three magnetometers mentioned previously since each presented different advantages. The Thomson-Sintra system was set up to record D, H and Z, the components which are recorded at most observatories throughout the world. This system is described in more detail in section 7. The vector PPM recorded D, I and F, the same components which are observed with the D and I magnetometer and the Sokkisha instrument. The AMOS recorded X, Y and Z in nanoteslas allowing errors in the different components to be compared directly.

Observer 1 is from the GSC; Observer 2, from the IPG, Observer 3 from the RNMI; Observer 4 from the DMI; Observer 5 is a second observer from the GSC using the same instrument; Observer 6 is from the GIP.

Table 4.1 Thomson D, H and Z baselines — Pier A

		D_{b1} (345° +)			
Date	Obs1	Obs2	Obs3	Obs4	Obs5
Aug 1	40.61				—
Aug 2					40.71
Aug 3					—
Aug 4	39.47	39.45	39.39	39.70	—
Aug 5	38.98	39.45		39.00	38.78
Aug 6		39.35	39.30		
Aug 7				39.33	39.21
				39.13	
Aug 8			39.33	39.03	38.65
		H_{bl} (16800 nT +)			
Date	Obs1	Obs2	Obs3	Obs4	Obs5
Aug 1	34.7				—
Aug 2					38.0
Aug 3					—
Aug 4	41.2	40.7	39.1	38.8	—
Aug 5	38.7	41.7		38.4	38.9
Aug 6		41.5	40.0		
Aug 7				40.8	41.7
				41.2	
Aug 8			40.3		42.6
		Z_{bl} (54900 nT +)			
Date	Obs1	Obs2	Obs3	Obs4	Obs5
Aug 1	29.2				—
Aug 2					30.3
Aug 3					—
Aug 4	28.8	28.7	29.0	28.0	—
Aug 5	29.0	28.6		28.5	29.5
Aug 6		27.2	27.8		
Aug 7				29.3	29.6
				29.1	
Aug 8			28.5		29.1

Table 4.2 Thomson D, H and Z baselines — Pier E

		D_{b1} (345° +)		
Date	Obs2	Obs3	Obs4	Obs6
Aug 4	39.25	—	39.32	39.15
Aug 5	39.10	39.22	38.93	39.09
Aug 6				
Aug 7				39.29
				38.97
		H_{bl} (16800 nT +)		
Date	Obs2	Obs3	Obs4	Obs6
Aug 4	43.0	—	42.0	41.5
Aug 5	43.4	40.7		44.6
Aug 6				
Aug 7				42.5
				45.2
		Z_{bl} (54900 nT +)		
Date	Obs2	Obs3	Obs4	Obs6
Aug 4	30.3	—	30.7	30.3
Aug 5	30.4	29.7		29.8
Aug 6				
Aug 7				31.2
				29.1

Table 4.3 ELSEC D and I baselines — Pier A

D_{b1} (345° +)

Date	Obs1	Obs2	Obs3	Obs4	Obs5
Aug 1	—				—
Aug 2					—
Aug 3					—
Aug 4	35.51	35.50	35.48	35.63	35.62
Aug 5	35.43	35.81		35.40	35.16
Aug 6		—	—		
Aug 7				—	—
				35.54	
Aug 8			36.32		35.51

I_{bl} (72° +)

Date	Obs1	Obs2	Obs3	Obs4	Obs5
Aug 1	—				—
Aug 2					—
Aug 3					—
Aug 4	51.92	51.87	51.99	51.91	51.85
Aug 5	51.99	51.69		51.98	51.92
Aug 6		—	—		
Aug 7				—	—
				51.78	
Aug 8			51.85		51.72

δF (nT)

Date	Obs1	Obs2	Obs3	Obs4	Obs5
Aug 1	—				—
Aug 2					—
Aug 3					—
Aug 4	−8.6	−8.2	−8.3	−8.6	−8.3
Aug 5	−8.6	−8.3	−8.4	−8.7	−8.2
Aug 6		—	—		
Aug 7				—	—
				−8.4	
Aug 8			−9.3		−8.0

Table 4.4 ELSEC D and I baselines — Pier E

D_{b1} (345° +)

Date	Obs2	Obs3	Obs4	Obs6
Aug 4	35.31	35.37	35.39	35.38
Aug 5	35.41	35.37		35.37
Aug 6				
Aug 7				—
				35.45

H_{bl} (72° +)

Date	Obs2	Obs3	Obs4	Obs6
Aug 4	51.76	51.85	51.86	51.76
Aug 5	51.64	51.78		51.55
Aug 6				
Aug 7				—
				51.56

δF (nT)

Date	Obs2	Obs3	Obs4	Obs6
Aug 4	−6.4	−6.3	−6.0	−6.2
Aug 5	−6.0	−6.2		−5.8
Aug 6				
Aug 7				—
				−7.1

Table 4.5 AMOS X, Y and Z baselines — Pier A

X_{b1} (nT)

Date	Obs1	Obs2	Obs3	Obs4	Obs5
Aug 1	123.2				121.9
Aug 2					122.6
Aug 3					122.6
Aug 4	123.4	124.0	121.6	123.6	123.9
Aug 5	122.0	125.2		121.5	121.9
Aug 6		126.7	124.7		
Aug 7				125.7	125.9
				127.6	
Aug 8			126.6		126.7

Y_{bl} (nT)

Date	Obs1	Obs2	Obs3	Obs4	Obs5
Aug 1	72.2				67.9
Aug 2					71.3
Aug 3					71.1
Aug 4	72.7	74.0	74.0	74.9	70.1
Aug 5	72.2	74.7		72.9	69.4
Aug 6		75.9	75.7		
Aug 7				75.2	72.6
				76.6	
Aug 8			75.5		70.5

Z_{bl} (nT)

Date	Obs1	Obs2	Obs3	Obs4	Obs5
Aug 1	−87.3				−88.2
Aug 2					−87.8
Aug 3					−88.6
Aug 4	−88.0	−87.7	−88.0	−86.6	−87.9
Aug 5	−87.6	−88.2		−86.5	−88.0
Aug 6		−84.8	−85.8		
Aug 7				−85.3	−86.4
				−86.3	
Aug 8			−90.7		−89.7

Table 4.6 AMOS X, Y and Z baselines — Pier E

Y_{b1} (nT)

Date	Obs2	Obs3	Obs4	Obs6
Aug 4	126.6	125.5	125.9	125.0
Aug 5	126.9	125.9		128.6
Aug 6				
Aug 7				127.1
				130.4

Y_{bl} (nT)

Date	Obs2	Obs3	Obs4	Obs6
Aug 4	72.1	72.5	73.1	72.2
Aug 5	72.4	73.8		72.8
Aug 6				
Aug 7				74.1
				73.7

Z_{bl} (nT)

Date	Obs2	Obs3	Obs4	Obs6
Aug 4	−85.4	−86.2	−85.4	−86.4
Aug 5	−85.9	−86.6		−86.8
Aug 6				
Aug 7				−84.1
				−84.9

A least-squares straight line was fitted to each set of baselines listed in the tables for the time interval 0001 UT Aug 4 to 2400 UT Aug 8. The lines are plotted on the figures. In most instances a straight line appears to be an adequate representation of trend; an exception is the AMOS Z baseline.

The standard deviations of the observed baselines about each curve are given in Table 4.7. D and I values are shown in nanoteslas as well as minutes to facilitate comparison between components.

Table 4.7 Standard deviation of observed baselines

	Thomson Pier A	Thomson Pier E	ELSEC Pier A	ELSEC Pier E	AMOS Pier A	AMOS Pier E
D(')	.26	.138	.27	.029		
(nT)	(1.3)	(0.7)	(1.4)	(0.1)		
H(nT)	1.2	1.0				
Z(nT)	0.6	0.7			1.6	0.8
I(')			.089	.083		
(nT)			(1.5)	(1.4)		
X(nT)					1.3	1.2
Y(nT)					2.1	0.6
δF(nT)			0.3	0.3		

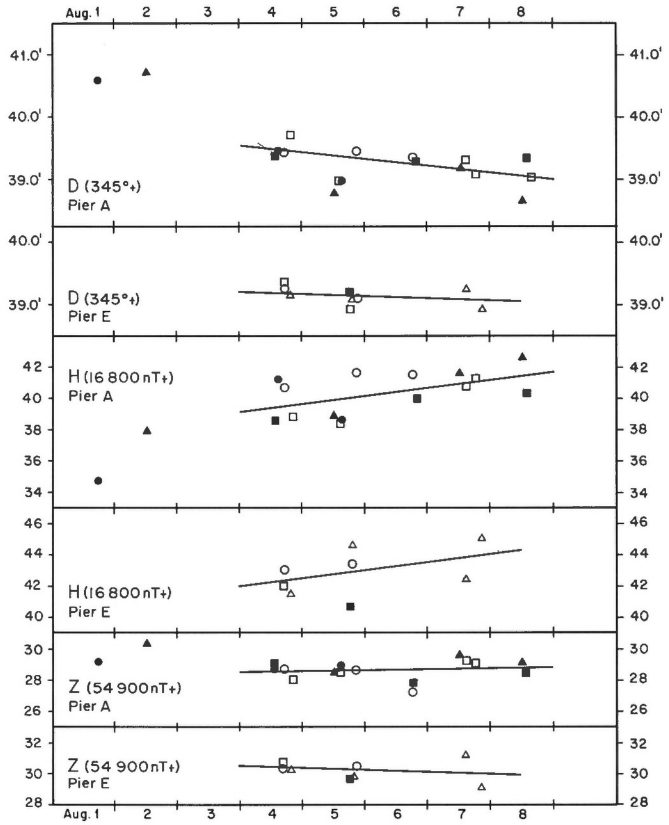

Figure 4.1 Baseline determinations for the Thomson-Sintra magnetometer derived from absolute observations taken during the Workshop on Pier A and Pier E. The solid lines are the least-squares fits to the individual baselines. Observations made by Observer 1 are denoted by ●; Observer 2, ○; Observer 3, ■; Observer 4, □; Observer 5, ▲; Observer 6, △.

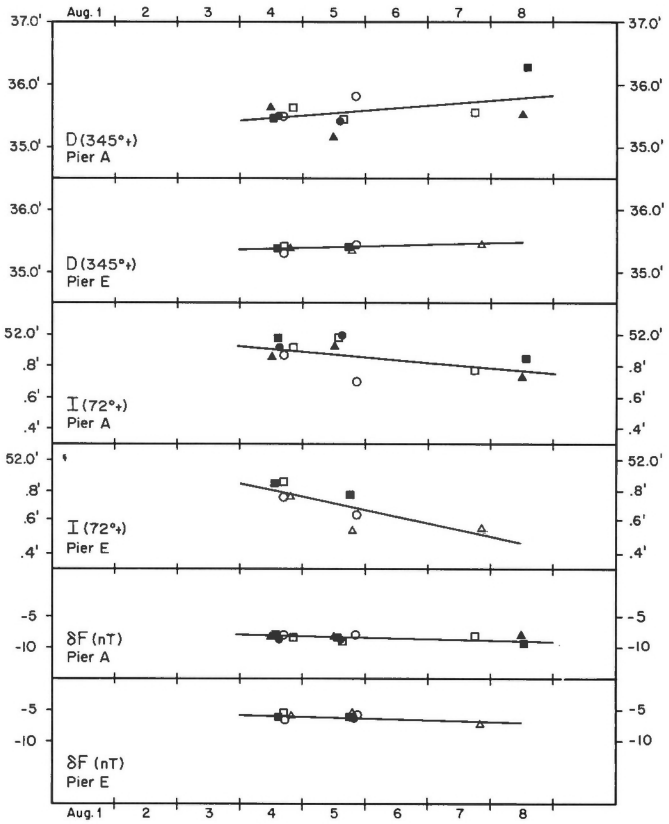

Figure 4.2 Baseline determinations for the ELSEC vector PPM. See Figure 4.1 for an explanation of symbols.

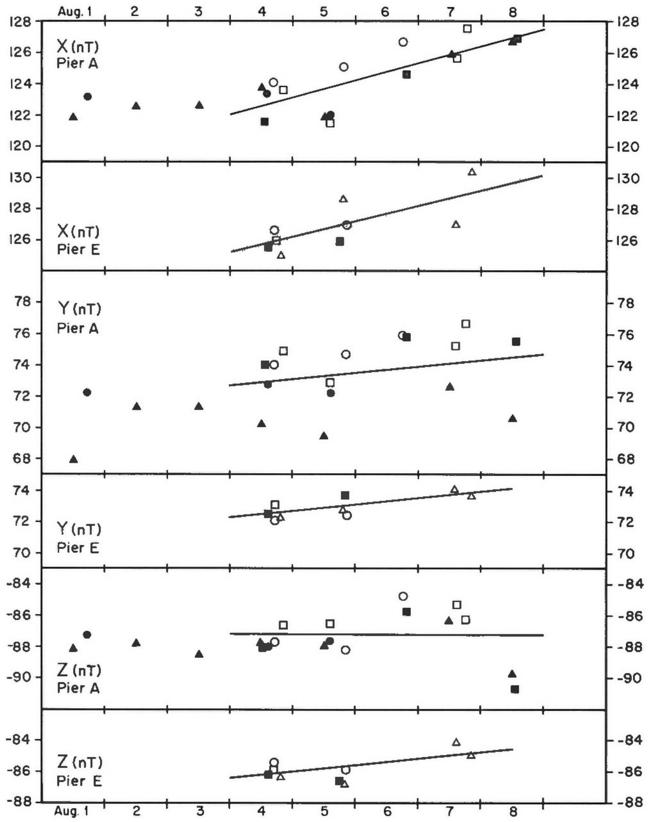

Figure 4.3 Baseline determinations for the Ottawa AMOS. See Figure 4.1 for an explanation of symbols.

Table 4.7 shows that the standard deviations of baselines calculated using Pier E absolutes are normally less than those calculated using Pier A absolutes. However, the two data sets are not directly comparable since they contain observations done by different observers at different times, and since many more observations were done on Pier A than on Pier E. Further discussion will concentrate on the Pier A baselines since more of them were carried out.

The standard deviations (Pier A) ranged from a low of 0.6 nT (Thomson Z) to a high of 2.1 nT (AMOS Y). On the whole, the AMOS baselines exhibited a larger scatter than either the Thomson-Sintra or the ELSEC baselines. However, calculating F-statistics shows that only the scatter in the AMOS Z baseline is significantly larger at the 95 % level of confidence. This is due to the fact that a straight line is not a good fit to the observed baselines.

It is common practice to consider the standard deviation of the baselines as a measure of the observational error. Errors of from 1 to 2 nT are considered by many observers to be excessive (see, for example the report by Sucksdorff and Kuwashima, in section 6). Some of the factors which might contribute to this excessive scatter, such as contamination of the absolute building, have already been mentioned. Such factors are impossible to quantify and might vary from observation to observation.

Also to be considered is the possibility that systematic differences exist between the instruments. However, unless a source of magnetization remains in an instrument this seems unlikely. A comparison of numerous instruments at the IPG has shown no differences at the level of resolution of the instruments. Moreover, Figures 4.1 to 4.3 show that differences between baselines obtained by different observers do not remain constant from day to day. For example, the Thomson-Sintra D baselines obtained by Observer 1 and Observer 2 differ by only 0.02′ on Aug 4; on Aug 5, they differ by −0.47. Likewise, AMOS X baselines obtained by Observer 3 and Observer 5 differ by −2.3 nT on Aug 4, and −0.1 nT on Aug 8. The most consistent indication of a systematic difference is seen in the AMOS Y baseline; here, observations by Observers 2 and 3 are consistently high; those by Observer 5 are consistently low. However, the effect is not nearly as pronounced in the Thomson-Sintra and ELSEC D baselines, nor is it apparent in the Pier E baselines. In fact, the ELSEC D baselines, determined from Pier E, have a standard deviation of only 0.03′, an indication that differences between the instruments must be quite small. Systematic differences, then, are unlikely to account for the large scatter in baselines.

Since the same observations were used to compute baselines for all three magnetometers, the plots of the observations about the regression line should show very similar patterns. However, an examination of Figures 4.1 to 4.3 shows some striking differences. As an example, consider the D baselines (Pier A) obtained by Observer 2 on Aug 4 and Aug 5. For the Thomson-Sintra magnetometer, the baselines are the same on the two days; however, for the ELSEC magnetometer, the baselines differ by 0.31′. As a further example, consider the Thomson-Sintra and AMOS Z baselines. On Aug 7, Observer 4 made two observations. The Thomson baselines calculated from these observations differ by 0.2 nT, but the AMOS baselines differ by 1.0 nT.

It is probable, then, that much of the dispersion in the observed baselines is due to rapid drifts in the triaxial magnetometers. A further indication of this is obtained by calculating the RMS difference from the least-squares baseline on a daily basis. In many instances, there appears to be a direct correlation between the RMS difference and the interval of time (δT) over which absolute observations were made. This is shown in Table 4.8 for all days on which at least 3 observations were made.

Table 4.8 Daily RMS Differences

	Aug 4	Aug 5	Aug 6	Aug 7
Thomson				
δT	4.0 h	8.1 h	4.4 h	1.9 h
D	.14′	.32′	.10′	.34′
H	1.3	1.5	0.5	
Z	0.4	0.5	0.3	
AMOS				
δT	5.4 h	8.1 h	4.4 h	
X	1.0	1.7	1.0	
Y	1.7	2.2	0.8	
Z	0.6	0.8	0.6	
ELSEC				
δT	5.4 h	8.1 h		
D	.07′	.27′		
I	.05′	.14′		

August 5 is the date with the greatest dispersion so let us examine it more closely. The ELSEC and Thomson-Sintra D baselines and the AMOS Y baselines for that day are plotted in Figure 4.4. Also plotted are temperatures measured in the shelter placed over the Thomson-Sintra sensor. The official air temperature, obtained from the Ottawa weather office, is also shown. The correlation coefficients between the baselines and the shelter temperature (ρs) and the baseline and the air temperature (ρa) are also shown on the figure. All correlations are very high, although correlations with the air temperature are higher. The highest correlation is between the AMOS baseline and air temperature. However, these temperatures do not necessarily correspond to the temperatures at the magnetometers or their sensors. For example, it is known that on Aug 5, the AMOS sensor temperature remained constant over the day to within ±0.5° C. The temperature of the magnetometer electronics, in a different building, was not recorded continually, but it is believed that it did not vary by more than a couple of degrees. However, it has been found that the AMOS electronics exhibits a temperature coefficient of approximately 5 nT/°C in the Y component; thus an increase in temperature of only 1°C over the course of the day, provided it is approximately in phase with the outside air temperature, would account for the observed baseline drift.

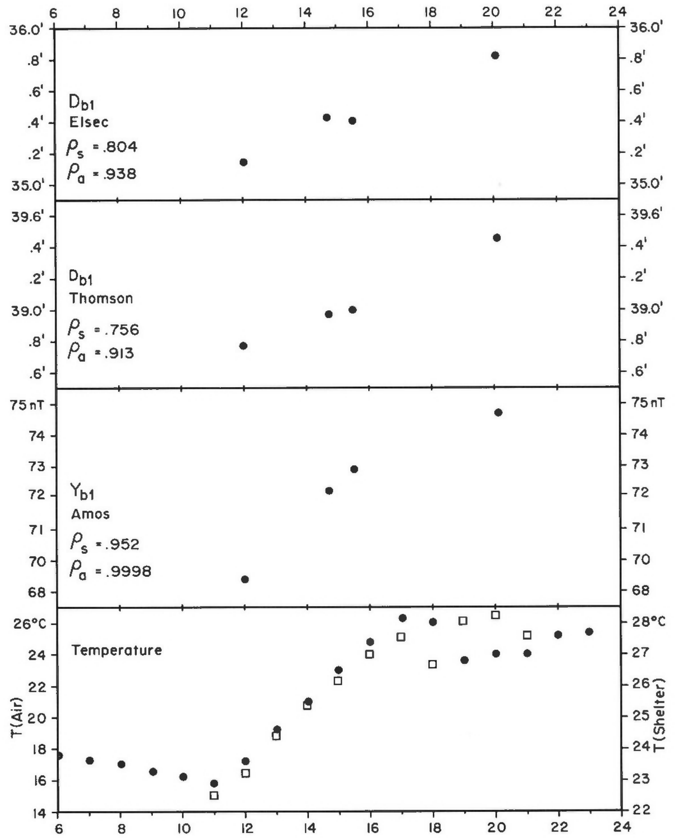

Figure 4.4 Variations in ELSEC D, Thomson-Sintra D, and AMOS Y baselines with time on 5 August 1986. Also shown is the variation in temperature in the shelter which housed the Thomson-Sintra sensor (solid circles), and the variation in the open air temperature (open squares).

The Thomson-Sintra instrument has quoted temperature coefficients of less than 0.15nT/°C for both the sensor and the electronics console. If we assume that the temperature of the sensor, in its shelter, increased approximately 4° and the temperature of the console, which is in the open, increased by approximately 10° during the day, the increase in the D baseline would be approximately 2.1 nT, or 0.42′. The observed increase is 0.67′, but the open-air temperature variation is only an estimate.

At the time of writing, nothing is known about the temperature coefficient of the ELSEC vector PPM, nor about the change of temperature in its building.

This analysis is a good example of the effect of temperature, although a similar effect can be seen on Aug 4 for the AMOS Y and Thomson-Sintra D baselines. Temperature effects in the other two components are not as obvious, but could account for at least some of the observed baseline dispersions.

Conclusions

Conditions at the Workshop proved to be less than ideal for a precise comparison of absolute instruments for several reasons: possible magnetic contamination of the building, insufficient time to do an adequate number of observations, and the lack of a sufficiently stable magnetometer. It is obvious that the Ottawa AMOS does not have sufficient temperature stability to allow comparisons with an accuracy of a fraction of a nanotesla, a fact that was not fully appreciated beforehand. The Thomson-Sintra, and probably the ELSEC would have provided this stability had they been installed on proper piers in a thermally stable environment.

It is apparent that in any future Workshop a first-class magnetometer must be installed before absolute comparisons begin. It may also be beneficial to continue the series of absolute observations for a few days after the official end of the workshop when distractions are less.

Various countries conduct absolute instrument comparisons on a routine basis. Input from these countries before the Workshop would have been beneficial, and this expertise should not be overlooked during the planning of a future workshop.

The results of our comparison indicate that under adverse conditions baselines can be determined with errors of from 1 to 2 nT. It is highly probable that under more favourable conditions errors of less than 1 nT would have been obtained with both the D & I magnetometers and with the Sokkisha magnetometer, although the observations allow no comment to be made on the ultimate accuracy of these instruments. It is difficult to detect with any confidence any systematic differences between instruments or observers because of the instability of the triaxial magnetometers used. However, if such differences exist, they must be small.

One of the most important features of the Workshop was the opportunity it presented for the observers and other delegates to compare different observing techniques. If this leads to the eventual improvement of methods at even a few magnetic observatories the whole exercise can be considered worthwhile.

References

Bitterly, J., Catin, J.M., Schlich, R., Folques, J., and Gilbert, D.
1984: Portable magnetometer theodolite with fluxgate sensors for earth's magnetic field component measurements; in Geomagnetic Observatory and Survey Practice, ed. W.F. Stuart; Geophysical Surveys, v.6, p.233-239.

Jansen van Beek, G. and Loomer, E.I.
1982: Annual report for magnetic observatories-1979; Geomagnetic Series No. 22, Energy Mines and Resources, Ottawa.

Kring Lauridsen, E.
1985: Experience with the DI-fluxgate magnetometer inclusive theory of the instrument and comparison with other methods; Danish Meteorological Institute, Geophysical Papers R-71, Copenhagen.

Serson, P.H. and Hannaford, W.L.W.
1956: A portable electrical magnetometer; Canadian Journal of Technology, v.34, p.232-243.

Wienert, K.A.
1970: Notes on Geomagnetic Observatory and Survey Practice. UNESCO, Paris, 217 p.

5. COMPARISONS AMONG DIGITAL VARIOMETERS

DATA EDITING

G. Jansen van Beek and L. R. Newitt

Introduction

The discussions which took place during the Workshop and many of the reports contained in these Proceedings concern timely and relevant topics such as absolute control and variometer stability. However, little was said, while the Workshop was in progress, with regard to data editing or data processing.

Data editing in itself is a rather unglamorous and unexciting job when the data are free from format and quality (spiking) errors. This was true for much of the Workshop data. Nevertheless some useful guidelines were developed during the processing of the data. A brief discussion of each particular data set will be given, followed by information on the Workshop output data format and recommendations for any future Magnetic Observatory Workshop which may emphasize digital data and their processing.

Multi-component data sets

Geological Survey of Canada

Data processing for the AMOS and ELSEC VECTOR PPM was routine. Both systems enjoyed the advantage of having been in operation well before the Workshop.

Repairs to the ELSEC VECTOR PPM were effected by C. Chapman at the beginning of the Workshop. The repair consisted of the replacement of a chip in the data IO section of the electronics and did not affect the stability or the sensitivity of the variometer.

The AMOS recorded the X, Y, Z and F components and the VECTOR PPM recorded the D, I and F components of the Earth's magnetic field. Both co-ordinate systems were different from the D, H, Z and F co-ordinate system used by all other Workshop participants. Therefore, the data were rotated using the following formulae:

$$\delta D = \sin^{-1}(Y/H) - QD$$

$$\delta D' = H\sin^{-1}(\delta D)$$

$$H = (X^2 + Y^2)^{1/2}$$

$$I = \sin^{-1}(\delta I'/F) + Ibl$$

$$Z = F\sin(I)$$

$$H = F\cos(I)$$

where: δD = variation of the declination in angular units,

QD = quiet level of the declination in angular units,

$\delta D'$ = variation of the declination in nT,

H = horizontal intensity in nT,

X = northward component of the magnetic field in nT,

Y = eastward component of the magnetic field in nT,

$\delta I'$ = variation of the inclination in nT,

Z = vertical component of the geomagnetic field in nT,

F = total force of the magnetic field in nT,

I = inclination in angular units,

Ibl = instrument baseline for the inclination in angular units.

When the plots of the rotated data sets were laid onto each other, it was noted that the ELSEC VECTOR PPM rotated data and the AMOS MKIII rotated data showed apparent sensitivity differences. Comparisons with other data sets recorded in D and H gave inconclusive results as to which variometer was at fault. Nevertheless, both rotated data sets as well as the original data sets have been included in the Workshop Data File.

EDA Instruments Inc.

The four-component data from the EDA AMOS were recorded on a tape deck and tape supplied by EDA. The tape was processed by the Geophysics Division. Reading the tape brought back many memories of the tape problems experienced when processing data from the then Earth Physics Branch AMOS MKI. Tape problems can usually be identified by the gradual deterioration of the data as time progresses. Unfortunately, this is evident in the EDA AMOS data set and accounts for the missing data towards the end of the recording period.

U.S. Geological Survey

Data processing was done in the home institution in Denver, Colorado as several attempts to transfer data from the data collecting Personal Computer of the USGS to another PC failed at the time of the Workshop.

The USGS PC was damaged in shipment to Boulder but data recovery from the hard disk was very high (considering that eventually the hard disk had to be placed into another PC). Nevertheless, some of the original binary packed data were damaged. In some instances the minus/plus data bits were not recovered resulting in an occasional sudden reversal of the direction of increase on the component plots, examples of which are shown elsewhere in these Proceedings.

Finnish Meteorological Institute/Polish Institute of Geophysics

The data were processed on-site by the Workshop participants from Finland. The processing resulted in data sets of averaged or spot values at sampling intervals of 60 seconds, 10 seconds and 5 seconds.

This variometer was deliberately subjected to the greatest possible temperature variation. Unfortunately, not all temperature data were recovered.

Institut de Physique du globe de Paris

A portion of the THOMSON-SINTRA magnetic variation data was collected directly on a data collecting platform with a data sample interval of 8 seconds. Another portion of the one-minute data (3 to 6 August) has been keypunched from the data listings provided by M. Daniel Gilbert. The data were processed by the Geophysics Division.

Eotvos Institute, Budapest

The DIMARS data were processed on site by the Hungarian participants at the Workshop. As the output from the magnetometer was not directly readable in nanateslas, the sensitivities of the data were later adjusted by the Geophysics Division by comparison with the POLE/FIN data provided by the Finnish Meteorological Institute.

Dowty Electronics Ltd.

The DOWTY data were collected at a sample interval of 8 seconds and processed by the Geophysics Division, in a manner similar to that used for the Thomson-Sintra data.

One component data

The one component data which have been placed in the Workshop Data File are those data which were contained in the internal memories of the various Proton Precession Magnetometers. The data were transferred into the Personal Computers and onto floppy diskettes using a commercial communications protocol package (CROSSTALK). Data processing was done by the Geophysics Division.

Comments on the data processing

Data editing was restricted as much as possible to rearranging the data into a uniform data format. Data spikes or offsets were removed only if they upset the plotting programs. Only in the EDA 4-component data was it actually necessary to filter the data and to perform character replacements in order to salvage as much of the data as possible.

Even though the manipulation of the data with regard to quality was kept to a minimum, the editing process was complicated as each data set had its own format and its own hidden pitfalls such as non-printable characters. Large mainframe computers tend to ignore extra carriage returns and linefeeds but PC's, using present day Fortran compilers, do not have that level of sophistication.

An effort was made to null fill (null values are those greater than 800 000) short periods of missing data. Therefore, data files are always continuous but not necessarily filled with real data. Wherever large gaps existed in the data (large in the sense of the number of data points), a new header record has been issued even though that may mean that there exist two header records for a given day and data set.

A visual indication of the availability of the multicomponent data is given elsewhere in the Proceedings.

Data format

After consulting with a number of persons skilled in data collecting/editing or knowledgeable in Personal Computer architecture, it was decided to use the following file structure:

- — the file contains fixed length records of 1024 characters each;
- — each record is to be read under format control as 128I8;
- — record fill is with 999999s;
- — each day of data is initiated by a header record containing the relevant data information;
- — the header record is followed by two records which contain the temperature data in units of 0.1 °C;
- — the temperature records are followed by an integer number of records sufficient to contain all of the data for the interval described by the start and stop times found in the header record, i.e. data for each of the component(s) listed in the header record are written in turn (note: component description is not contained in the data records);
- — the data interval is continuous within the start and stop times defined in the header record;
- — null values are those that are greater than 800000.

The header record contains the following data information:

Data item	Description
1	— IAGA station identifier (for Ottawa it is 45284);
2	— data set identifier;
3	— day of the month;
4	— number of the month;
5	— year;
6	— sequential day of the year;
7	— start hour of the data (UT);
8	— start minute of the data (UT);
9	— start second of the data (UT);
10	— end hour of the data (UT);
11	— end minute of the data (UT);
12	— end second of the data (UT);
13	— magnetic data sampling interval in seconds;
14 — 21	— component indicators, the presence of a component is indicated by the numeral one, otherwise the indicator contains a zero;
14	— X component;
15	— Y component;
16	— Z component;
17	— D, declination in nanoteslas;
18	— H, horizontal intensity;
19	— F, total force;
20	— I, inclination in nanoteslas;
21	— other;
22	— numeric factor by which the data have been multiplied;
23	— temperature data sampling interval in seconds;
24 — 128	— null fill with 999999s.

The data set identifier may be parsed into BMMII where: B is the building number in the Ottawa Observatory Compound;

MM is the manufacturer or the owner institute number,
01 — GSC AMOS MKIII
02 — EDA Instruments Inc.,
03 — USGS
04 — Littlemore Scientific Engineering Co.,
05 — Finnish Meteorological Institute,
06 — Institut de physique du globe de Paris (Thomson-Sintra triaxial fluxgate);

07 — GEM Systems Inc.,
08 — Eotvos Institute, Budapest (DIMARS)
09 — Dowty Electronics Ltd.,
10 — Scintrex Ltd.
and II is the data set number.

For example, the data set identifier 50401 would be for an instrument in Building no. 5, the manufacturer is Littlemore and the data is identified as data set number 1.

The Workshop data tape

A data tape containing the final temperature and magnetic variation data has been compiled and is available for distribution. The order and a description of the data sets follow:

	Data set identifiers	Description
1.	80801	DIMARS 1-minute data,
2.	80901	DOWTY 8-second data,
3.	30201	EDA AMOS 1-minute data,
4.	30102	GSC AMOS MKIII 10-second data,
5.	80701	GEM GM6743 PPM 5-second data,
6.	80703	GEM GM6747 OVERHAUSER PPM 5-second data,
7.	81001	SCINTREX MP3 PPM 1-minute data,
8.	80202	EDA OMNI4 PPM 5-second data,
9.	80202	EDA OMNI4 PPM 10-second data,
10.	30101	GSC AMOS MKIII rotated 1-minute data,
11.	30101	GSC AMOS MKIII 1-minute data,
12.	60503	POLE/FIN 5-second averaged data,
13.	60504	POLE/FIN 10-second averaged data,
14.	60505	POLE/FIN 10-second spot data,
15.	60502	POLE/FIN 1-minute spot data,
16.	60501	POLE/FIN 1-minute averaged data,
17.	70601	THOMSON-SINTRA 8-second data,
18.	30301	USGS 1-minute data
19.	50401	LITTLEMORE VECTOR PPM rotated 30-second data,
20.	50401	LITTLEMORE VECTOR PPM 30-second data,
21.	70601	THOMSON-SINTRA keypunched 1-minute data,
22.	80702	GEM GM6746 OVERHAUSER PPM 5-second data.

NOTE: The uniqueness of each data set is given by the data set identifier and the other parameters contained in the data header records.

Recommendations

For any future Magnetic Observatory Workshop which has to deal with a variety of digital data, the authors would make the following recommendations:

1. If the data are to be processed by the host organization in semi-real time, then samples of the digital data should be submitted at least two months in advance of the Workshop.
2. Records should end on a simple carriage return (ASCII 13_{10})/line feed (ASCII 10_{10}) combination. The addition of extra un-printable characters (ASCII 00_{10} to 31_{10}) results in a programmer's nightmare.
3. Data should be in ASCII code and suitable for correction by means of a screen editor preferably running on a PC. This also means that geomagnetic variations as described by the numbers should have meaning to the person doing the editing. Careful thought will have to be given to data packing to preserve data "legibility".
4. Data sets which are to be used for comparison purposes should remain at one sampling rate. Averaging of the data may always be done at a later date, given a sufficiently high data rate.

It is the authors' opinion that recommendations 2 and 3 have general application. Specifically, applications software contained within the instrument processors should be written so that the resultant data are user friendly.

COMPARISONS AMONG DIGITAL VARIOMETER SYSTEMS

R.L Coles and D.F. Trigg

Introduction

During the Workshop, data were recovered from 7 digital variometer systems operating all or part of the time. In this paper, we present some initial observations based on largely qualitative comparisons among the several data sets obtained from these instruments. Figure 5.1 shows the relative locations of the instruments in the non-magnetic compound. The legend on Figure 5.1 indicates the code for each instrument that we will be discussing in the paper. The sensors for TS, UR, EA, were mounted on concrete piers set in the ground outdoors with insulating boxes over them. The sensors for PF and EL were mounted on concrete piers which themselves were mounted on the concrete floors of Buildings no.6 and no.5, respectively.

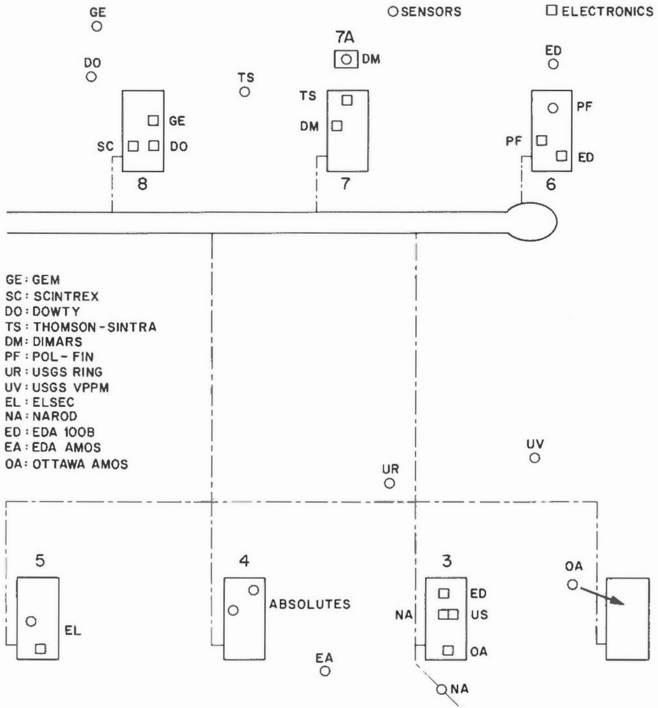

Figure 5.1 Layout of instruments in the non-magnetic compound during the Workshop.

The DM sensors were mounted on brass bolts attached to the concrete slab floor of the insulated fibreglass hut (Building no.7A). The OA sensors on their permali base were fixed to the concrete slab floor of Building no.2. Temperatures at the sensors were monitored for all instruments except EL. Data recording electronics for all instruments resided in buildings. With the exception of preamplifiers for TS and UR, sensor electronics also resided in the buildings.

The fluxgate magnetometer sensors in the Canadian Magnetic Observatory Network are oriented in geographic co-ordinates, north, east and vertically down. This is to maintain consistency across the network, which straddles the agonic line and surrounds the north magnetic dip pole. The Ottawa system OA, therefore, recorded X, Y, and Z components. The Ottawa vector PPM system, EL, is aligned to measure delta D, delta I and F.

For practical expediency during the Workshop, other participating instrument sensors were aligned relative to the magnetic meridian, and they recorded D, H, and Z. At Ottawa, the mean value of D for 1986 was 345°40.0′.

For purposes of comparing variometer data sets, the OA XYZ data and EL DIF data were rotated into the DHZ frame, as discussed in the previous report.

Data availability

Figure 5.2 indicates the approximate intervals for which digital data were available to the Workshop participants. (Note: more complete data sets may be available in some instances from specific instrument operators.) Many difficulties were inherent in assembling such a collection of diverse systems. Simultaneous magnetic and temperature data for most systems were available for only limited intervals between days 215 and 218. At this point, we should mention that there were many challenges encountered in bringing all these data sets into a common format for display and distribution, ranging from format conversions to detection and removal of non-printing characters. These difficulties are discussed more fully in the previous report.

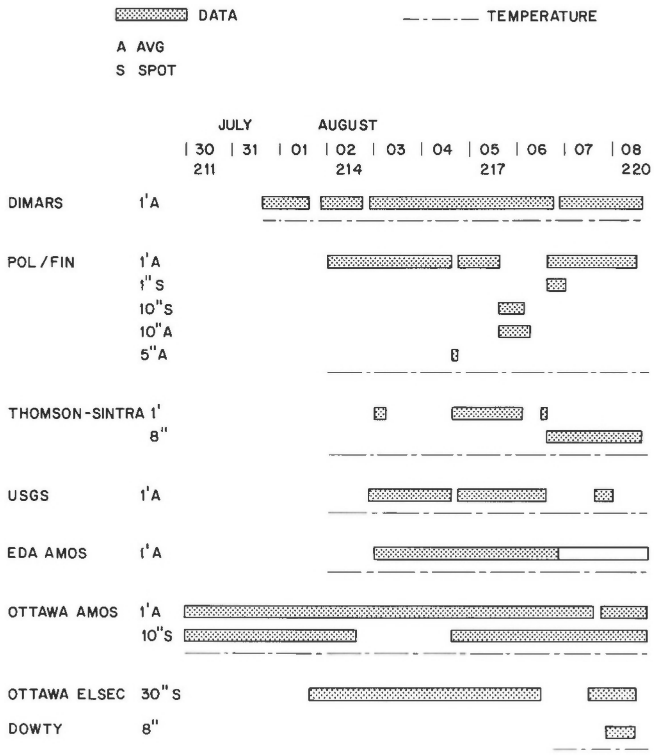

Figure 5.2 Availability of 3-component digital data recorded during the Workshop.

It must also be recognized that because of the temporary nature of some of the installations, data continuity, recording and quality may not be as good as would be obtained from a permanent installation. This has to be taken into consideration in drawing conclusions about the various instruments.

Reference data set

Although it is perhaps presumptuous to choose a priori one of the instruments as a reference against which to compare the others, some kind of temporary standard is useful. From a visual examination of plots of the data, it was evident that the best tracking of traces occurred between EL and OA, and TS and OA. OA was maintained at the most constant temperatures (air-conditioned rooms). We therefore have determined differences between each instrument and OA. Figure 5.3 shows, as an example, data differences for day 217. (Note that any features resulting from drifts or irregularities in the reference trace OA will show as common features in all difference traces.)

As most of the systems were recording at 1-minute intervals for most of the time, the difference comparisons have been made at that sampling interval. In the case of EL, the basic 30-second data were decimated to 1-minute sampling.

Local inconsistencies in the data

Empirical calibrations were made for DM by comparing with PF using large signal excursions, because sensitivity values were not available.

Mistracking of short period signals in some instruments was evident at several places. Some of this can be a result of incorrect calibrations, and would show up as common activity on difference traces during active periods. Another cause can be misalignment of the sensors. This may have occurred as a result of the temporary nature of most of the installations. Lack of orthogonality between sensors may also be a factor.

In the case of UR, some mistracking is known to be a result of difficulties in extracting data encoded in a packed binary format from a computer damaged in shipment. This specifically manifests itself as sudden inversions of portions of traces.

An offset found on all Z difference traces shortly after 2200 UT on day 217 has to be attributed to OA, although the offset cannot be positively identified on the OA trace because of geomagnetic activity at the time.

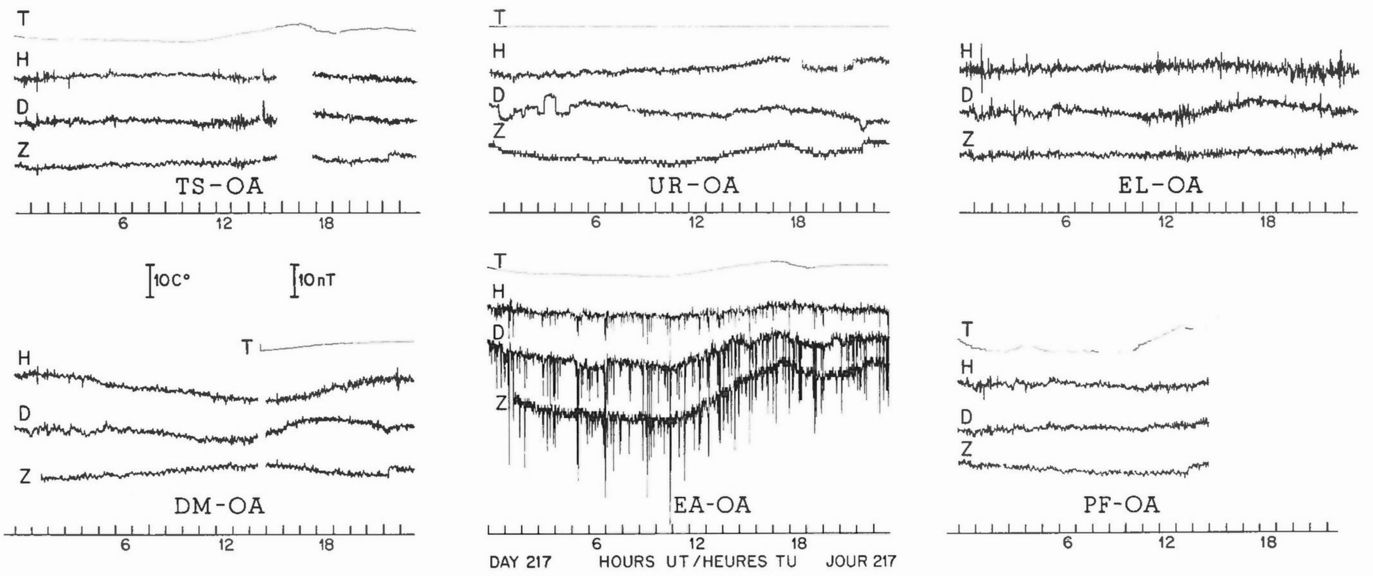

Figure 5.3 Differences between Workshop variometers and the reference variometer (Ottawa AMOS III) for day 217. T refers to temperature, H to horizontal component, D to declination and Z to vertical component. Instrument codes are as defined in Figure 5.1.

Data spikes were observed on some traces. The causes cannot readily be identified, but some may result from temporary power supplies, others from inquisitive participants, and still others from faulty instruments or recorders.

The relatively large high-frequency content in the EL-OA plots most likely is because the EL data are essentially spot values derived from a sequence of vector PPM measurements, whereas the OA data are filtered 1-minute averages.

The spikiness on the EA-OA plots results is of concern, and is most likely due to problems with the EA fluxgate magnetometer or the analogue-to-digital conversion in the EA system, because comparison plots of the F data from the PPM in the EA system do not show a similar spikiness.

Long term drifts

Our first step was to examine all traces for common features and consider whether or not these features should be attributed to OA. We were aware of the possibility that some correlations could be negative. In fact, all D difference traces show similar patterns, sometimes superimposed on other drifts. Accordingly, we have attributed to OA a portion of the drift in the D differences. OA tracked very well with EL and TS in H and Z. We are confident that OA had very low drift in these components over the interval under study.

DM was installed in a good thermal environment and its temperature profile shows much smoother variations, but lagging the outdoor temperatures by about 4 hours (Fig. 5.4). The Z and H difference traces show definite correlations with the sensor enclosure temperature (about 3nT/°C for H, and about 1nT/°C for Z). The D difference trace shows a quite different character, similar to D difference traces for other systems. We conclude therefore that the D temperature coefficient was low and that much of the apparent drift on the D plot is properly attributable to OA. The compensation for temperature in H

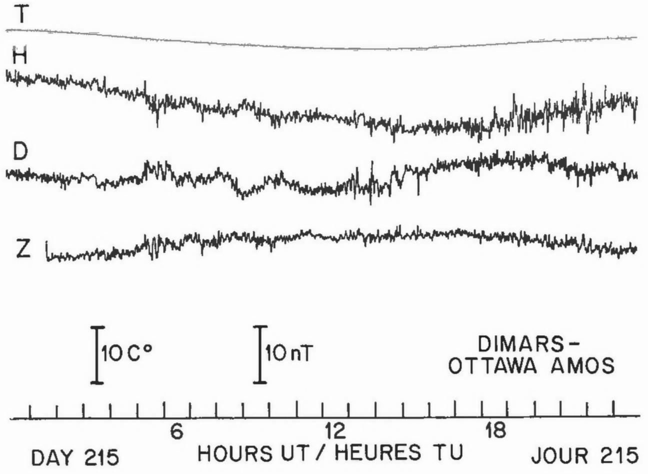

Figure 5.4 Differences between Hungarian DIMARS torsion photoelectric magnetometer and Ottawa AMOS III on day 215.

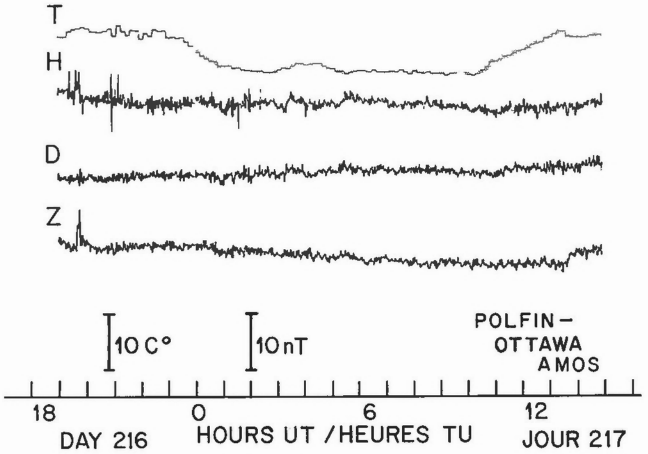

Figure 5.5 Differences between the Poland/Finland torsion photoelectric magnetometer and the Ottawa AMOS III on days 216-217.

and Z for the DM system appears not to have been adequate, possibly because of the temporary nature of the installation.

Weak correlations with temperature were found for the PF-OA difference traces for Z and H. The D difference trace showed little variation and therefore suggests that the PF D component drifted in a fashion similar to OA. A second plot (Fig. 5.5) shows a more complete temperature cycle.

TS and OA tracked closely over most of the interval, within about 1 nT except for a period around 1800 UT on day 217, where differences in D of about 2 nT were found. These latter differences, as noted above, are most likely attributable to OA. A second plot (Fig. 5.6) shows more completely the drifts for a complete day.

UR difference traces show correlations with outside temperature. The sensor temperature, monitored by two independent systems (one in the USGS system, the other set up by the Workshop technicians), was surprisingly stable. The drifts that occurred appear to be related to the electronics which were exposed to large temperature variations. Figure 5.7 shows the effects for the period when temperatures in the electronics room were monitored.

Considerable drifts were observed for the EA difference traces. The electronics were in the same environment as those of UR. The drift in H was less than 1 nT/°C, for D it was about 2 nT/°C, and for Z about 3 nT/°C. We have no way of distinguishing between sensor and electronics drifts.

Unfortunately, temperature data for EL are not available for the period of the Workshop. However, because EL is now a permanent part of the Ottawa observatory installation, we have been able subsequently to monitor carefully the temperatures and field differences for EL and OA. During February 1987, a specific temperature test was carried out. The Ottawa AMOS (OA) was maintained at stable temperatures (sensors were at a constant 23°C; the electronics were nominally between 23 and 24 °C, although heater fluctuations caused some minor short term effects of about 3 hours period). The temperature of the vector PPM (EL), including sensor, coils and electronics, was varied slowly and widely over a period of 10 days.

The results are shown in Figure 5.8. A distinct correlation between temperature and delta D is found, with a temperature coefficient of about -0.6 nT/°C. Less distinct, but indicative, is the effect on delta H, with a coefficient of the order of -0.2 nT/°C. Any temperature effect (small) on delta Z is obscured by noise or other effects.

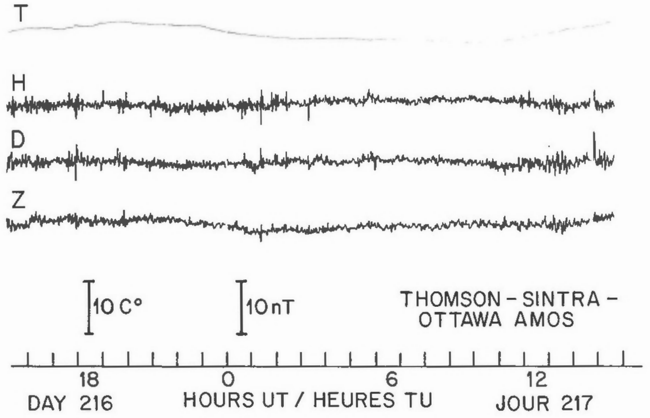

Figure 5.6 Differences between the French Thomson-Sintra fluxgate magnetometer and the Ottawa AMOS III on days 216-217.

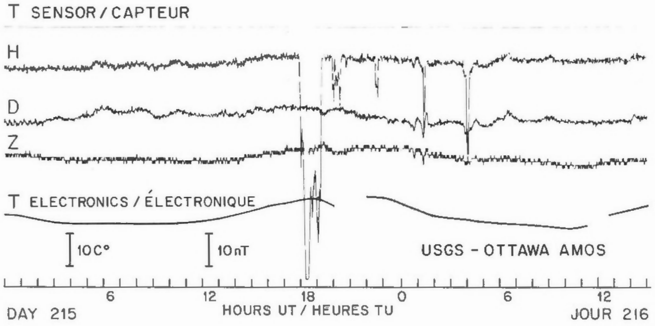

Figure 5.7 Differences between the U.S. ringcore magnetometer and the Ottawa AMOS III on days 215-216.

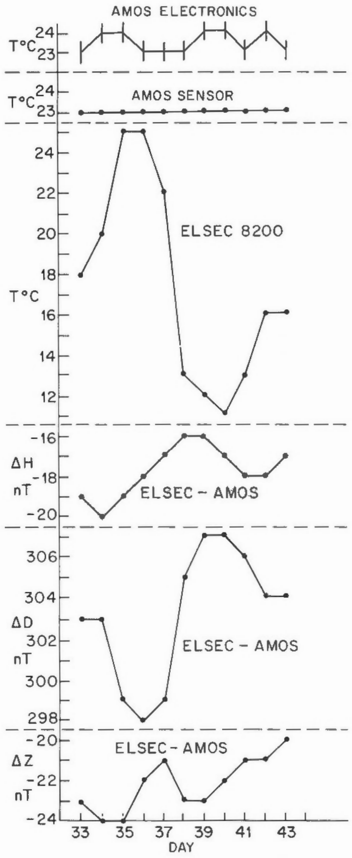

Figure 5.8 Effects of temperature on the ELSEC 8200 vector proton magnetometer, between days 33 and 44, 1987.

EL tracked well with OA during the Workshop period, except for D. As noted above, we have attributed the variation in D differences largely to OA.

Proton precession magnetometers

Proton precession magnetometers are commonly considered to be absolute instruments (see, however, the comments of W.F. Stuart in section 7). The primary intent of this report has been to look at some comparisons between variometers, but it was felt useful to consider some similar comparisons among proton precession magnetometers. Several of the PPMs at the workshop operated for long periods (Ottawa AMOS PPM, EDA AMOS PPM, ELSEC 8200, ELSEC 820, Scintrex MP3, USGS PPM) while others were set up in a more portable mode (the several GEM PPMs and the EDA Omni IV).

We will not display any plots of these data, since inspection of the data showed that the various data sets were in remarkably good agreement, with a few exceptions. One of the several electrical storms that occurred during the workshop caused a fault in the Ottawa AMOS PPM with the result that, although the long-term averages were not affected, there was an increase in high-frequency noise superimposed on the signal. Some of the portable PPMs showed a considerable number of spikes in the data. The cause of these is not known.

However, the real question that should be addressed in PPM comparisons — that of absolute accuracy — could not be dealt with at this workshop. It is a matter for manufacturers and users to develop systematic calibration procedures involving several instruments, taking heed of the comments in section 7.

Conclusions

In conclusion, we should comment on several effects that can cause serious errors in the measurement of the magnetic field. In the past, a somewhat cavalier approach has been taken by some in addressing these effects. Nonetheless, we cannot ignore them.

The most obvious effect, as emphasized in the results shown in this report, is that of temperature. Temperature changes can affect not only the characteristics of fluxgate or other sensors, but also the dimensions of coils (especially large ones) and, very importantly, the electronics associated with the sensors. Analogue electronics devices are inherently temperature-sensitive, and this includes analogue-to-digital converters. Ambient-field cancellation circuitry is prone to temperature problems.

Critical to the accurate determination of the magnetic field, and to take full advantage of the excellent sensitivities available, is the thorough testing and calibration of the temperature characteristics of magnetometers, not simply by using the design and construction specifications but by actual on-site measurements and comparisons.

Temperature compensation methods are often dependent on ambient-field strength, whether they be in the form of magnets, or currents in coils, or other. It may be critical in the installation of an otherwise straightforward piece of equipment that temperature compensation be carefully checked at the permanent site.

Tilting of sensors is another serious problem, both on the long term and on the short term. Tilts can occur as a result of, among other causes, uneven temperature changes in the pier mounting. In fact, some of the drifts seen in some of the instruments at the Workshop may have resulted from movements of the recently installed outside piers, rather than from direct effects of temperature on the magnetometers. No instruments presently measure tilt variations. Such recordings and subsequent correction of data for tilt effects is the next logical step for magnetic observatory systems.

6. STANDARDS ACHIEVABLE AT MAGNETIC OBSERVATORIES

Important but sensitive questions that are often raised at discussions of magnetic observatories, and which were again raised at this Workshop, are:

1. How good should a magnetic observatory be?
2. Can we classify observatories into first-class, second class, and so on? Should we do this?

Essentially, the science requirements should govern the answer to the first question and are addressed, at least in part, by Niblett and Coles in their article in this volume.

The following articles present some further examples and thoughts related to these questions.

[Editor]

WHAT STANDARDS ARE ACHIEVED BY A FIRST-CLASS FULLY-STAFFED MAGNETIC OBSERVATORY?

C. Sucksdorff and M. Kuwashima

Abstract

Based on experience especially in the Nurmijarvi Geophysical Observatory and also from other Scandinavian observatories, it is shown that in a fully-staffed magnetic observatory an accuracy of 1 nT is achieved in all components of the magnetic field. For that, absolute measurements with standard instruments once a week are enough, and the recording of the data and the data handling require only moderate-priced equipment and one person's work. Applying very sophisticated instrumentation and very careful checking systems, the accuracy can be made several times higher, as the example from the Kakioka Magnetic Observatory shows. Here the absolute value of the gyromagnetic ratio of protons is the limiting factor of the absolute accuracy of the measured and recorded data.

Introduction

Research into the mechanism and cause of the geomagnetic field and its variations is based on recordings of the components of the field at magnetic observatories, the number of which exceeds 200 at the moment, on measurements at repeat stations and on magnetic surveys. The final accuracy of surveys and measurements at the repeat stations depends on the accuracy of the observatory values, because these are used in the reduction and calibration of other measurements. Highest possible accuracy is the goal in all geomagnetic measurements, since the year-to-year change is small, usually a few tens of nanoteslas per year, and the phenomena to be studied, e.g. the "jerks" and "impulses" in the secular variation and effects of the sunspot cycle on the induced currents inside the earth, have amplitudes typically of the same order of magnitude or smaller. This shows that an absolute accuracy of the order of 1 nT or preferably even better is a must in geomagnetic observatory work. In the following we will show that the accuracy of 1 nT can be achieved rather easily in a staffed observatory using standard, not very expensive instrumentation. The Nurmijarvi Observatory in Finland is presented as an example of such a station. The Kakioka Observatory stands as an example of today's highest possible standard.

The Nurmijarvi Observatory

Instrumentation

The Nurmijarvi Geophysical Observatory (lat. 60°30.5′ N, long. 24°39.3′E) can be called fully-staffed in spite of the fact that there are only 4 people working at the station. To run the magnetic station requires one person's work full-time on average. Usually there are two or three people at work during the weekdays, and only one part-time on weekends. The observatory runs, besides the magnetic station, several other recordings, e.g. seismic, ionospheric and some meteorological, which keep the personnel fully-occupied. Three of the persons live near the observatory so that, in case of need, servicing of the instruments is usually also available outside of office hours.

The absolute instruments at the observatory are:

- Proton precession magnetometers (2 Elsec, 1 Polish PPM).
- Crystal clock (Rohde and Schwarz) which is used, for example, to control the crystals of the proton magnetometers.
- One horizontal Helmholtz coil (82 cm diameter) placed on an Askania Reisetheodolite for vector-proton measurements of H and Z (Serson's method of adding and subtracting about twice H).
- One Zeiss 010A theodolite (accuracy 1″) with fluxgate sensor by Geoinstruments Ky. for the measurement of D and I.
- Four classical declinometers, which are no longer used much because the fluxgate theodolite seems to give more easily the required accuracy of 0.1′ in D.
- Five QHM's which are used mainly in comparison measurements between observatories and in field measurements.

For the continuous recording of the field there are in the recording room, where the temperature is kept constant within 0.2°C:

- One set of La Cour variometers with photographic recording of X, Y, and Z components, sensitivities 8.05, 3.95 and 7.82 nT/mm, respectively (the original normal recording, installed in 1952).
- Two sets of torsion photoelectric magnetometer (TPM), described elsewhere in this publication in connection with comparison of recording magnetometers in Ottawa 1986, producing one-minute mean values (60 samples per minute) and spot-values at full minutes. One of the instruments is for normal use, having somewhat higher sensitivity and lower dynamic range; the other one has a dynamic range of +6000 nT, thus being able to record the biggest magnetic storms. The second TPM is also used as a back-up for the other one. Both have a memory unit capable of storing about one week of one-minute mean and spot values. A Data General DG 1 microcomputer is used to read the data from the memories and to write the data onto diskettes in final 0.1 nT units. The microcomputer also produces the hourly mean values, the values for the times of absolute measurements, etc. and prints out the data needed. It is also used to change the baseline values or sensitivities when necessary. The final handling of the data is done in Helsinki main office using the computer of the Finnish Meteorological Institute, which also prepares the standard magnetic tapes in IAGA format to be sent to the WDC's.

The accuracy of the absolute measurements

The accuracy of the data produced in an observatory is based on the accuracy of the absolute measurements. The absolute accuracy of the so-called "absolute measurements" is again based on the accuracy of the basic physical units used and on the accuracy of their measurements in connection with the magnetic "absolute measurements".

The total intensity F is measured with proton precession magnetometers. Here the basis is the gyromagnetic ratio of the proton (μ), adopted by IAGA in 1960 to be 2.67513×10^8 radians/tesla.s, or 0.0425760 Hz/nT, or 23.4874 nT/Hz. According to the recent absolute measurements of this value μ has an error smaller than 10^{-4} nT/Hz, which means that μ is known with sufficient accuracy for the measurements of F with an accuracy of 0.2 nT. The frequency of the crystal of the proton magnetometer, usually of the order of 10^5 Hz, has to be known with the corresponding accuracy, which is easy to control by feeding, say, 2 kHz from a good crystal clock into the sensor connection of the magnetometer.

At Nurmijarvi the Elsec proton magnetometers resolve 0.25 nT and the PPM 0.1 nT, so that F is known with an accuracy of better than 0.5 nT. In comparisons of magnetic instruments, which are organized every year in one of the Scandinavian countries, the proton magnetometers are also compared and the errors, after correcting for the possible change of the frequency of the crystal, are found to be small, of the order of 0.25 nT. The measurement of the components of F is made using two different methods: vector-proton measurement and DI-fluxgate.

As shown, for example, in Wienert's book on observatory practice (Wienert, 1970), the critical point in vector-proton measurement is the verticality of the vertical axis. In Nurmijarvi there is a level with a sensitivity of 4″ per division fixed on the horizonta coil. The level and also the current in the coil are kept as constant as possible. The possible small changes in turning the coil are taken into account the calculations, as presented in the yearbooks of Nurmijarvi. The frequency of the crystal is controlled before and after each measurement. The vector-proton method has been in use at Nurmijarvi since 1969.

The DI-fluxgate has been in use since 1984. The measurement requires rather more skill than the vector proton method, but, when applied by an experienced observer, seems to give rather easily an accuracy of 6″ in D and 3″ in I. This means that at Nurmijarvi, in a field of 15 000 nT in X, 1200 nT in Y and 49 000 nT in Z, an accuracy of better than 1 nT in X, 0.5 nT in Y and 0.5 nT in Z is obtainable. That these accuracies are real has been confirmed in several ways. As mentioned before, the standards have been between the Scandinavian countries once a year for many years. There the differences between the observatory standards have been found to be within on nanotesla. Another check is the use of different, independent methods for the determination of the different components. For example, D has been the most troublesome component before the development of the DI-fluxgate. Thus it has been measured with four different declinometers, one of them the Askania precision declinometer, based on another method. Finally, the scatter of the results of the absolute measurements indicates the precision (not necessarily absolute accuracy) of the measurements. The standard deviations of the absolute observations for the years 1981-85 are given in Table 6.1.

Table 6.1. Standard deviations of the absolute measurements at the Nurmijarvi Observatory 1981-85

		1981	1982	1983	1984	1985
X	nT	0.62	0.58	0.57	0.70	0.58
Y	nT	0.54	0.85	0.66	0.31	0.35
Z	nT	0.57	0.52	0.40	0.64	0.53

The accuracy of the recorded data

Before the direct digital recording which started in its present form in 1983, the Nurmijarvi Observatory produced only hourly mean values, which were hand-scaled and check-scaled from the normal La Cour magnetograms. Here the accuracy of the baseline values can be assumed to be the same as the accuracy of the absolute measurements, i.e. about 1 nT, because the scatter of the determined baseline values very seldom exceeded 0.5 nT. In rescaling, a difference of 0.2 mm was usually accepted in the hourly mean values. This means that the absolute accuracy of the hourly mean values has been about 2 nT, except during disturbed times, during which the accuracy has been somewhat lower. After starting the digital recording, the hand-scaled values were compared with the digitally produced ones, accepting the same differences as before. The final accuracy of the hourly mean values can be expected to have improved, however, to better than 2 nT, even during disturbed times, because of the high stability of the TPM baseline values and its ability to cope with disturbed times. Today, two digitally recording TPM's check each other and the La Cour magnetograms are used only as an additional check during quiet periods or if there are spikes to be found in the digital recordings.

According to the absolute measurements of the baseline values of the TPMs, the change of the baselines has been typically 2 to 3 nT per year. This allows us to conclude that the accuracy of the digitally produced one-minute values, as well as the hourly, daily, and annual mean values is about 1 nT.

Figure 6.1 shows a typical comparison of the data produced by the two TPMs in the variation room at the Nurmijarvi Observatory. We can see that the differences are small, very seldom 1 nT, and the mean values are typically the same in both recordings.

In TPMs the 2000-fold feedback keeps the magnets in fixed positions in practice. So, if the magnets of the different components have been oriented correctly in orthogonal X, Y, and Z directions, no corrections are needed between the components. In Nurmijarvi Observatory there is a coil-house, with three orthogonal coil systems (accuracy better than 1′) and a homogeneous field (within 10^{-5}) of 30 cm in diameter to check the orientations of the magnetometer sensors and also to determine the scale values with high accuracy. The sensors have to be correctly oriented with an accuracy of 4′ to have no more than 1 nT effect from a change of 1000 nT in another component.

We have tried to show above that it is possible to run a magnetic recording station rather economically and with high enough accuracy for most demands in the field of geomagnetism. It is important to have the observatory

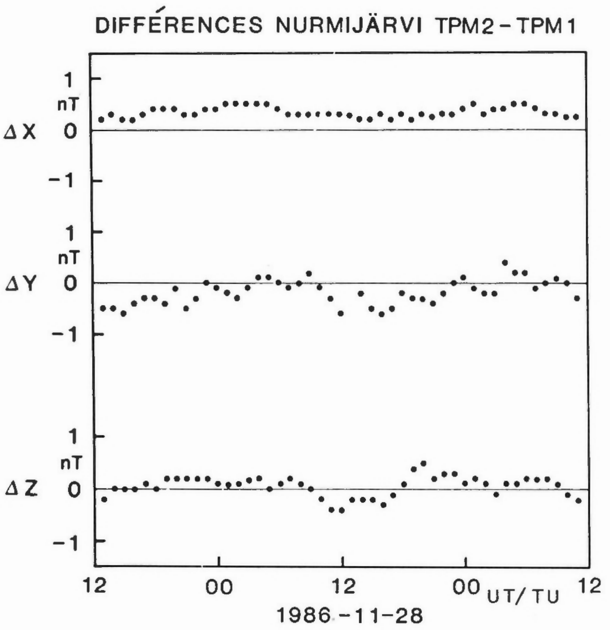

Figure 6.1 Difference of X,Y, and Z hourly mean values as recorded with two torsion photoelectric magnetometers (TPM) at Nurmijärvi.

staffed. But because the running of the magnetic station needs less than one person's continuous work on average and a fully-staffed station means some four persons at least, it is practical to collect several programs at the same observatory. In the case of Nurmijarvi, there are about 20 different recording or observing programs from different institutes going on. It is important, naturally, that there is at least one person in the observatory experienced in magnetic absolute measurements. It is also important to the quality of the data produced that there is somebody in the observatory or nearby who continuously uses the data and so has an acute interest in its quality.

The Kakioka Magnetic Observatory

The Japanese magnetic observatory section belongs to the Japanese Meteorological Agency (JMA). JMA consists of about 5000 persons, while the Japanese magnetic observatory section consists of about 50 persons and has 7 magnetic observatories. The Kakioka Magnetic Observatory (lat. 36°13′ 45″N, long. 140°11′ 23″E) is the standard observatory in Japan, where the KASMMER (Kakioka Automatic Standard Magnetometer) system has been employed since 1972. About 8 persons work to support the KASMMER system. The Memambetsu Magnetic Observatory (lat. 43°54′30″N, long. 144°11′35″E) and Kanoya Magnetic Observatory (lat. 31°25′14″N, long. 130°52′56″E) are the branch observatories of Kakioka, and are classed as first-class observatories. Their observatory work consists of the absolute observations and variation observations similar to those at Nurmijarvi as mentioned above. Four people work at Memambetsu and Kanoya.

The Kakioka Magnetic Observatory also has 4 unstaffed stations, which are Iwaki (IWK), Matsuzaki (MTZ), Omaezaki (OMZ) and Chichijima (CBI). Those observatories consist of a proton magnetometer for the observation of the total force (F) and a fluxgate magnetometer for the observation of the variations (H,D,Z). The measurement of the magnetic data is carried out every minute and then stored in computer readable memory (PROM for example). Absolute observations are carried out every two or three months.

Outline of KASMMER

The KASMMER system consists of four parts, which include four optical pumping magnetometers for the observation of the H, Z, D, F components, a fluxgate magnetometer as a supporting system for the optical pumping magnetometers, a calibration system for the optical pumping magnetometers, and a computer system. The main characteristic of the KASMMER system is that it can measure absolute values of the various components of the geomagnetic field at every second.

Four optical pumping magnetometers measure the magnetic fields of horizontal intensity (H), vertical intensity (Z), azimuth of declination (D) and total field intensity (F). The optical pumping magnetometers carry out measurements at every second with a resolution of 0.1 nT; they employ a cesium oscillator as the sensing element to produce an output signal whose frequency is proportional to the ambient magnetic field intensity. The cesium sensor is positioned at the centre of the Helmholtz coil pairs which produce a suitable bias field to measure appropriate magnetic components H, D, and Z.

As discussed below, the stability of the optical pumping magnetometer ultimately depends upon the undesirable changes in inclination of the bias Helmholtz coil. The Helmholtz coil system is set on a granite pillar whose cross-section is an octagon of diameter 60 cm. The length of the pillar is 2.8 m of which nearly half is buried in the ground. The bottom of the pillar is fixed on an octagonal non-magnetic concrete foundation reinforced by brass rods.

In the observation of the D-component, the sensor of the optical pumping magnetometer detects the Hy component. The direction of H_y makes an angle of 60° eastward from the mean magnetic meridian. The perpendicular components, Hx in the horizontal plane and Z in the vertical plane, are eliminated by the two orthogonal Helmholtz pairs. A calculation of the D- component is carried out by the relation

$$D = \cos^{-1}(H_y/H) - \Theta$$

where Θ is about 60°.

Each Helmholtz coil system has two separate windings, a main winding and an auxiliary one, whose diameters are 600 and 500 mm, respectively. The main winding supplies a constant field determined at the initial adjustment, whereas the auxiliary one cancels the time variation of the natural field by the feedback method. The fluctuation of the bias current supplied to the Helmholtz coil is kept at less than 1×10^{-6} A in the range of ambient temperature 15 – 30°C.

For supporting the optical pumping magnetometer, a very reliable fluxgate magnetometer has been installed in 1983. The temperature drift coefficient of this magnetometer is less than 0.1 nT/°C for example.

The calibration system for the optical pumping magnetometer corresponds to the absolute observation system in usual magnetic observatories. The calibration system consists of a magnetic theodolite for the observation of declination (D) and inclination (I), and a proton magnetometer for the observation of the total field intensity (F). The magnetic theodolite is named DI-72 because it measures D and I and was installed in 1972. The proton magnetometer is named MO-PK (Magnetic Observation by Proton magnetometer at Kakioka). The DI-72 determines D and I with an accuracy of one second. The main parts are a Helmholtz coil mounted on the theodolite and a rotating coil set at the centre of the theodolite. The Helmholtz coil creates a magnetic field Fc whose intensity is approximately equal to the ambient geomagnetic field intensity F, which is to be measured. The direction of Fc is approximately equal to that of F at the initial stage of the observation. The observer successively changes the direction of Fc to become just the reverse of that of F. The observer thus tries to align the direction of Fc along that of F in order to minimize a vector dF where

$$dF = Fc + F.$$

Using this null method, declination (D) and inclination (I) are determined as the directions of the Helmholtz coil. The AC signal of dF is amplified by a low-noise amplifier and then displayed on a synchroscope. The observer adjusts the direction of the Helmholtz coil by means of two tangent screws while watching the synchroscope figures.

Accuracy of the KASMMER system depends upon the accuracy of the calibration and the absolute observations. Figure 6.2 shows the results of the absolute observations on the KASMMER system (DI-72 and MO-PK). The observational results of absolute observations are presented by means of standard deviation for the period 1978-83. As shown in the figure, the standard deviation has been kept to within 0.02′ with D and I, and within 0.2 nT for H and Z. During the period 1981-82, part of KASMMER was renewed. As shown in Figure 6.2, the standard deviation has become smaller, about 0.015′ for D and I, and about 0.1 nT for H and Z, respectively. A 95 % reliability is expected to be 0.0146′ and 0.118′ for the D and I components, and 0.117 nT and 0.102 nT for the H and Z components, respectively.

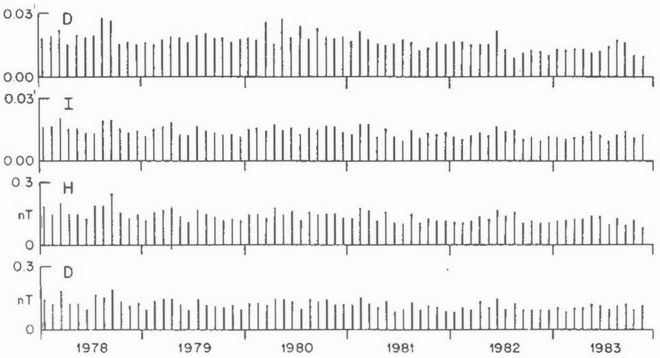

Figure 6.2 Standard deviations of absolute observations from Kakioka Magnetic Observatory.

Data acquisition system

The data acquisition system of KASMMER consists of two mini-computers, one for on-line processing and the other for off-line processing. The computers are the E-600 system manufactured by Hitachi Manufactory, Japan. The on-line computer has 128K words memory with disk system of 19M words; the off-line computer has 256K memory with disk system of 38M words. Realtime routine processing by the on-line computer includes continuous acquisition of data every second from the optical pumping magnetometer and data every minute from the supporting fluxgate and proton magnetometers. The on-line computer also carries out confirmations of the data quality. It can store the 1-second data for a period of 8 days and the minute data for up to 45 days. Also, a one-minute data value at 01min is derived from 60 data values recorded every second from 00min30s to 01min29s. One-minute data values from the fluxgate magnetometer (VH, VZ, VD) are also derived by a similar method. One-minute values from the proton magnetometer, FP, are obtained as instantaneous values on the minute.

The confirmation of the quality of one-minute data is carried out very carefully. Trigonometric check is employed at first, using the data FO, H, and Z from the optical pumping magnetometer and using the relation $A = FO - (H^2 + Z^2)^{\frac{1}{2}}$. If any one of the calculated values A exceeds a given limit (usually 0.2 nT), a special mark is attached to the data. An inappropriate value should be replaced after detailed examination. After the trigonometric check, a variation check is employed by judging from the apparent rate of change from one data point to the next. If any one of the changes exceeds a given limit (5 nT usually), a special mark is attached to that data point, and the value replaced as appropriate after detailed examination. Finally, a comparison check is employed between the data from the optical pumping magnetometer and that from the fluxgate magnetometer and the proton magnetometer. If any one of the differences between two kinds of data exceeds the given limit (usually 0.2 nT), again the data point is marked and replaced as appropriate after detailed examination. After these checks, one-minute data are compiled to the magnetic tape as are the data of the optical pumping magnetometer.

The off-line computer is used at times when the on-line computer is in trouble, and is also used with non-routine and research work.

Calibrations for the data of the optical pumping magnetometer are carried out from the results of the absolute observations made once or twice a week. Calibration values for the optical pumping magnetometer are defined as follows

CF = FO (optical) − FP (absolute)
CH = H (optical) − H (absolute)
CZ = Z (optical) − Z (absolute)
CD = D (optical) − D (absolute)

After correction by the calibration values CF, CH, CZ, CD, the one-minute data of the optical pumping magnetometer are adopted as the KASMMER data. Therefore, the stability of the KASMMER data depends upon the stability of the calibration values, CF, CH, CZ, and CD.

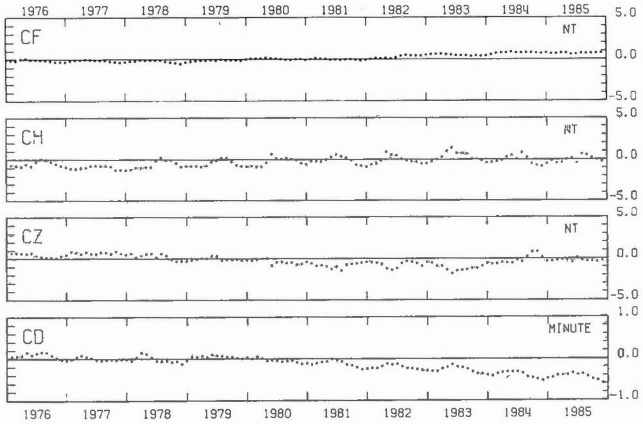

Figure 6.3 Calibration values for the KASMMER system at Kakioka Magnetic Observatory.

Table 6.2 Accuracy of KASMMER (standard deviations)

	F	H	Z	D	I	Hy
	nT	nT	nT	′	′	nT
C-value	0.045	0.215	0.165	0.0275	0.0195	0.245
Absolute value	0.059	0.117	0.102	0.0147	0.0118	—

Figure 6.3 shows the monthly means of CF, CH, CZ, CD for the period of 1976-85. As shown in the figure, the variation of CF is less than 1.0 nT for the ten years period. Considering the results for the standard deviation, stability of CF is expected to be 0.045 nT.

Variances of CH and CZ are slightly larger than that of CF, due to the orientation change of the bias Helmholtz coil which adds the bias compensation field to detect a specified component of the magnetic field. An annual variation of CH and CZ shown in Figure 6.3 is attributed to an annual change of inclination of the Helmholtz coil.

Distributions of the errors of CH, CZ, CD and CI show that 95 % of the measured values of the H-component fall within 0.215 nT of the mean; the corresponding value for the Z-component is 0.165 nT, for the D-component 0.0275′, and for the I-component 0.0245′. In conclusion we have confirmed that the KASMMER system has a capability as a magnetic observatory as summarized in Table 6.2.

The KASMMER one-minute data have been sent to WDDC since 1976 with an IAGA format on 1600 bpi magnetic tape. The KASMMER data have also been used extensively for various purposes, including earthquake prediction, volcanic activity, and radio-wave propagation conditions.

Reference

Weinert, K.A.
1970: Notes on geomagnetic observatory and survey practice; UNESCO, Paris, 217 p.

ABSOLUTE MEASUREMENTS OF THE EARTH'S MAGNETIC FIELD IN FRENCH OBSERVATORIES: RESULTS OBTAINED WITH THE PORTABLE THEODOLITE FLUXGATE MAGNETOMETER FOR THE PERIOD 1979-86

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Abstract

A portable theodolite magnetometer for measuring elements of the Earth's magnetic field was produced using a fluxgate probe mounted on the telescope of a 1-second non-magnetic theodolite. The measurement electronics, of original design, make it possible to carry out directional measurements in association with a proton magnetometer. The values obtained for declination and inclination (using the zero field method) are equivalent to absolute measurements, the precision being better than 5 seconds of arc. Direct measurement in nanoteslas of any component of the geomagnetic field (compensation method) involves a simple, precise procedure for calibrating the apparatus with reference to a proton magnetometer. This is a pseudo-absolute determination. These measurements of intensity in a given direction are particularly appreciated in polar observatories, where determination of weak horizontal fields with QHMs often seems to be a tricky business. The precision obtained for measurements of intensity remains of the order of a nanotesla. The projected performance is confirmed by observatory results. The portable theodolite fluxgate magnetometer is proposed as a reference apparatus for magnetic observatories. It is also very well suited for all magnetic surveys in the field.

Introduction

The elements of the Earth's magnetic field (intensity and vector components) are measured systematically in all magnetic observatories. The calculation of the average field, the determination of secular variation and the preparation of magnetic maps largely depend on these determinations.

Even quite recently, the most commonly used systems for measuring elements of the magnetic field employed mobile equipment consisting of a suspended magnet (QHM, BMZ, torsion balance). These devices are awkward to handle, and require frequent calibration. Equipment of the induction inclinometer type, like the Cambridge inclinometer, the DI72 inclinometer of the Kakioka Observatory (Yanagihara et al. 1973), or the equipment proposed by Usher and Reid (1978), supply an absolute value of inclination, but are tricky to use in the observatory and are not adapted to field measurements in most cases.

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The use of proton or optical-pumping magnetometers to determine vector components involves the use of complex setups. These are often bulky (coils), and incompatible with the requirements of measurement in the field. Tetani(1941) suggested and tried out the idea of using, for the measurement of declination and inclination, a single apparatus consisting of a fluxgate type probe operating as a zero detector and mounted on a non-magnetic theodolite. Various setups of this type were subsequently proposed, in particular by Meyer and Voppel (1954), Serson and Hannaford (1956), and Trigg (1970). This method, while attractive, has not become really widespread, primarily because of errors introduced by the inherent defects in fluxgate sensors and the inadequate resolution of the non-magnetic theodolites available on the market. The progress made since 1960 in the area of fluxgate magnetometer performance, and the possibility of making sufficiently non-magnetic some 1-second theodolites that had recently appeared on the market, led us to study a setup of this type in 1976. During our study of this equipment, the major criteria considered were as follows:

- Resolution and precision better than 3 seconds of arc for measurements of declination and inclination.
- Production of stable, reliable and low-power electronics
- Noise of the sensor and electronics assembly less than 0.2 nT p-p.
- Measurement methodology permitting the elimination of the influence of instrumental errors.
- Simplicity of operation in the field.
- Possibility of measuring, additionally, the intensity of the magnetic field in a given direction.

The first five examples of this new portable theodolite magnetometer were constructed and tested between 1977 and 1980 at the Institut de Physique du Globe of Paris (Cantin et al. 1979). The first instrument constructed has been used regularly at the observatory of Chambon-la-Forêt since 1980. In January 1981, the next four devices were installed in the observatories of Port-aux-Français (Kerguelen), Port Alfred (Crozet archipelago), Martin de Viviès (Amsterdam I.) and Dumont d'Urville (Adélie Land) in the French Austral and Antarctic Lands. The Institut de Physique du Globe de Strasbourg has been constructing and marketing this magnetometer since 1981 (14 examples are in service in 1986).

Other teams have developed equipment of this type: Fisher et al (1979), Lauridsen (1985), and Rietman of the Royal Netherlands Meteorological Institute. At present, three manufacturers are also offering devices of this type: the "DIM100 Declination and Inclination Magnetometer" by EDA Instruments Inc.; the "Portable Fluxgate Declinometer and Inclinometer type 810" by Littlemore Scientific Engineering Company; and the "MAG-01" by Bartington Instruments Ltd. Fluxgate theodolite magnetometers are gradually replacing traditional instruments, and are being adopted as absolute reference equipment.

Description of the equipment

Non-magnetic theodolite

The accuracy of measurements of declination (D) and of inclination (I) depends directly on the resolution of the theodolite. It should be remembered that the determination of the magnetic field's H and Z components to an accuracy of ±1 nT requires that the value of I be known to within three seconds of arc, if one supposes that the total field is known to an accuracy of ±0.5 nT. To obtain the desired precision, a "second" theodolite must be selected. The 010A theodolite manufactured since 1971 by Carl Zeiss Jena had the required optical characteristics: average accuracy of ±1 second, inclination compensator operating on the pendulum principle and giving an adjustment accuracy of 0.3 seconds. However, this model was not entirely non-magnetic. Consequently, in 1976, in collaboration with the Zeiss Jena representative in France, we proceeded to replace some of the parts and mechanical sub-assemblies of the standard 010A theodolite model. For our application, the disruptive field resulting from a permanent residual magnetization, or from a magnetizing effect induced by the ambient field, must be less than 0.2 nT at the sensor mounted on the telescope of the theodolite. The parts involved in the 010A theodolite's construction were produced using the non-magnetic alloy ARCAP (volume susceptibility K is less than 8×10^{-4} SI) provided by the Special Metals Department of Lyon Alemand Louyot. For the first theodolite so modified, tests for non-magnetic properties were carried out before assembly. At the present time, Zeiss Jena directly supplies the 010B theodolite in a non-magnetic version (Revue d'Iena, 1981/2, p. 69). A non-magnetic lighting device may be fitted to the theodolite for reading graduated circles.

Fluxgate sensor and measurement electronics

In 1976, we asked the Thomson-CSF D.A.S.M. Corporation to design a fluxgate sensor that would be mounted on the telescope of the 010A prototype theodolite. The sensor produced was of the "parallel" type, with two saturable cores. Its construction characteristics are the result of a compromise between the need to have a compact sensor (ease of adaptation and possibility of movement for reversals in the course of measurement), and the need to preserve enough resolution to allow use of the sensor as zero detector. The probe must also have good mechanical stability (absence of deformation in the course of measurement). Quartz was selected as the material to produce the chuck that supports the two permeable cores and the windings. The external dimensions of the sensor have a length of 80 mm and a diameter of 18 mm.

The sensors constructed between 1976 and 1986 used mumetal saturable cores; since 1986, Thomson-CSF has delivered sensors whose cores are of amorphous material. The spectral noise density of these new sensors is given in Figure 6.4; the total noise of the magnetometer is 400 pT^2/Hz at 100 seconds and 80 pT^2/Hz at 10 seconds. The limit of resolution of the equipment is thus between 0.1 and 0.2 nT, a value quite compatible with the resolution of the best observatory variometers. The sensor is mounted on the telescope of the theodolite by means of a polyphenylene oxide base (Noryl, loaded with 30 % fiberglass). The sensor is covered by a casing that provides adequate mechanical and termal protection when the sensor is in use.

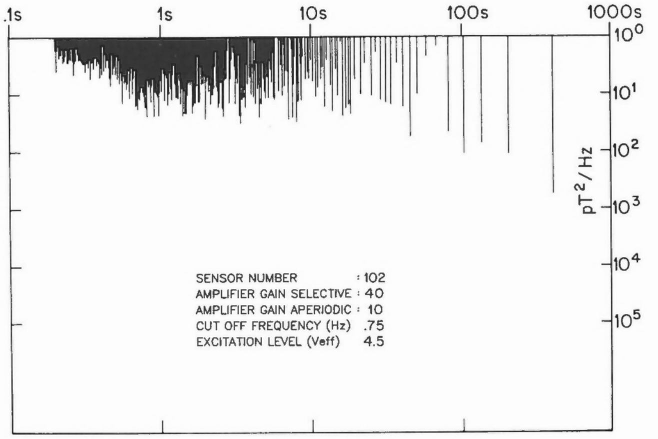

Figure 6.4 Spectral noise density of the IPGS portable theodolite magnetometer.

The measurement electronics, designed and produced by Cantin (1980), are housed in a carrying case and comprise the following elements:

- — A "magnetometer" circuit consisting of the excitation oscillator, the sensitive amplifier, the synchronous demodulator and the control amplifier. The control amplifier is associated with an anti-saturation circuit that supplies the feedback current required to permanently maintain the sensor in a virtually zero fiels for ambient magnetic field values between 100 and 100 000 nT.
- — An ultralinear compensation current generating circuit used for direct measurements of components.
- — A digital voltmeter allowing the display, in tenths of a nanotesla, of field variations measured along the axis of the sensor.
- — A 12 volt, 4 ampere-hour sealed lead battery providing independent operation for more than 10 hours.

The schematic for the measurement electronics is shown in Figure 6.5. The electronic box must be placed at least 1.5 metres from the theodolite so that measurements will not be disturbed. The operator makes convenient use of a small repeater box that allows direct reading of the sensor signal value and the time of measurement. This case is sufficiently non-magnetic to allow it to be placed in the immediate proximity of the theodolite. The whole equipment array comprising theodolite, sensor, measurement electronics and repeater box is represented in Figure 6.6.

The major characteristics of this equipment have already been given elsewhere (Bitterly et al. 1984). The complete specifications are given elsewhere in section 3. The general theory and methodology of measurement are set forth in the "instructions for use" of the equipment (internal document of the Institut de Physique du Globe de Paris, 1980, unpublished).

The theory of measurements of declination and inclination with this type of theodolite magnetometer has recently been re-examined in detail by Lauridsen (1985), who also analysed the major defects and errors that can affect the accuracy of the determinations. It should be emphasized that the measurement method used only eliminates associated instrumental errors directly if they may be considered constant for the whole duration of a measurement. Drifts or mechanical instabilities of thermal origin can nevertheless affect the precision of the determinations. By careful selection of materials to construct the fluxgate sensor and its bases we have been able to reduce mechanical deformations caused by temperature fluctuations. In general, defects of non-coincidence between the magnetic axis of the sensor and the optical axis of the telescope can be reduced to less than 30 seconds of arc, through adjustment of the sensor support. The value of these residual errors is calculated by the operator for each series of measurements; in addition, a control criterion is provided for the mechanical stability of the whole system. The drifts of electronic origin also have to be taken into account. The fluxgate sensor is used as a zero field detector (measuring D and I), and its output characteristics must remain stable during measurements. The optimum adjustment of the excitation circuit and detection circuit makes the effect of magnetometer circuit drifts negligible. However, for a fluxgate sensor placed in a zero field, the output signal is not strictly zero. The value of this offset can be easily estimated by algebraic calculation of the means of the measurements obtained by positioning the sensor parallel and antiparallel to the field to be measured. This offset is on the order of a few nT. Primdahl (1979) showed that the sensor error can vary through a process of magnetic hysteresis, as a function of the value of the magnetic field along the sensor axis. We have therefore produced an anti-saturation circuit that allows the probe to operate continually in virtually zero fields. In this condition, the probe error may be considered as stable regardless of the position taken by the telescope during the reversals required by the method of measuring D or I; it does not influence the accuracy of the measurements.

For magnetic surveys in the field, measurements of the horizontal and vertical components (H, X, Y, Z) are often useful, and complementary to the measurements of D and I. For certain "polar" observatories, direct measurement of X and Y becomes a necessity. The theodolite has been adapted for the direct measurement, in nT, of the magnetic field in any direction. For this measurement to be possible, one must apply a permanent compensation current to the sensor; this current cancels out the major part of the field to be measured. Knowledge of the exact value of the compensated field, and measurement of the residual field seen by the sensor, make it possible to calculate the value of the magnetic field in the direction considered, provided that one develops a measurement procedure that allows elimination of effects associated with the above-mentioned instrument errors (sensor offset, site and azimuth errors).

A "parallel" arrangement with two saturable cores avoids any particular difficulties in measuring the residual field seen by the probe. For this magnetometer with feedback, the linearity between the detected signal and the actual field is better than 1 nT for a range of 1000 nT, if the whole core is subject to a homogeneous excitation field at an adequate level and if the loop gain is high. On the other hand, in order to determine the value of the compensated field exactly, one must have a stable, ultralinear compensation generator whose calibration may be easily checked. A generator of this type was built and incorporated into the magnetometer case. Linearity, which is better than 10^{-5}, is obtained by filtering a pulse train of

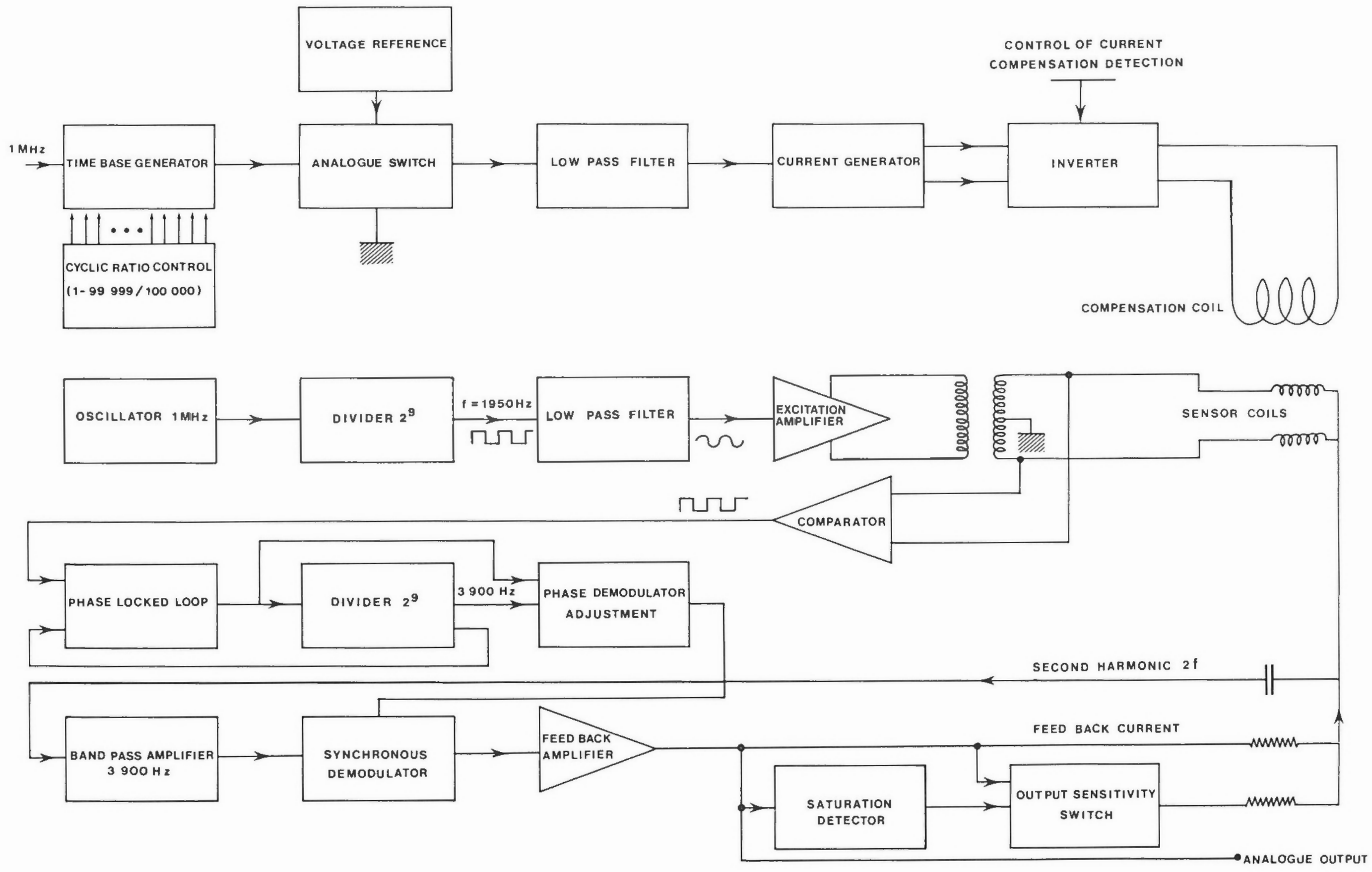

Figure 6.5 Schematic diagram of the portable magnetometer theodolite.

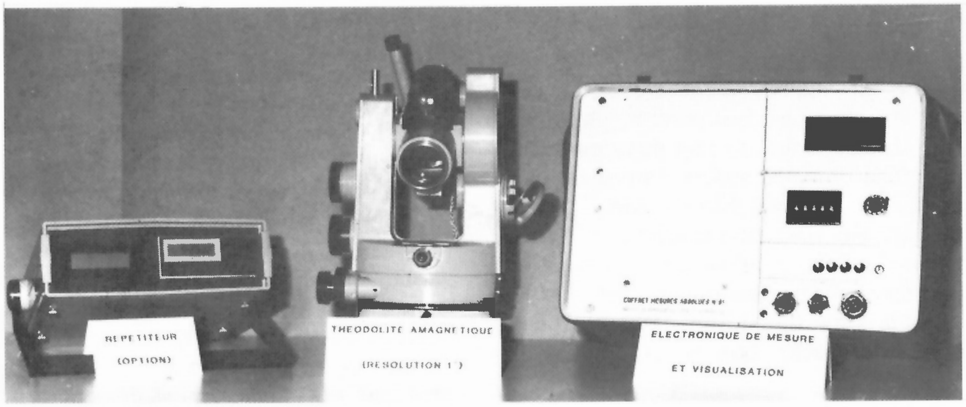

Figure 6.6 Display of the IPGS portable theodolite magnetometer equipment.

precisely adjustable duty cycle. The compensation current is strictly proportional to the duty cycle and to the value of the reference voltage. This generator does not require adjustment, and its linearity is not likely to deteriorate. The thermal stability of the generator is better than 1 ppm/°C, and its long term stability is on the order of 20 ppm per year.

The calibration of the compensation current is done by comparing, at the same moment, the value of the total field measured with the fluxgate theodolite and the value of the total field measured with a proton magnetometer. The correction factor for the compensation current is determined by four reversals of the sensor oriented in the direction of the total field. In order to position the axis of the probe in this direction, one first orients it in the magnetic meridian perpendicularly to the direction of the total field (search for electrical zero). From this position, one merely has to make a rotation of 90° in the vertical plane to orient the probe in the direction of the total field. The residual orientation error of the sensor's magnetic axis in relation to the direction of the total field does not produce any appreciable calibration errors if it is less than

10 minutes of arc. The approximate value of the sensor error can easily be monitored on the basis of the four readings performed. One observes that the extreme variations of the value of the calibration coefficient are less than 2×10^{-5} for one hour of operation.

Measurements of H, X, Y, and Z are made immediately after the calibration of the current generator. The usual four reversals of the sensor-telescope system are made in order to eliminate instrument defects. The measurement of two components, including preliminary calibration, is carried out in less than 20 minutes.

Results obtained for measurement of declination and inclination

Estimate of instrumental error

The major causes of error in measurements of D and I are as follows:

- Estimation of readings of the theodolite's circles by the operator; ±1 second of arc in the best of cases
- The resolution of the fluxgate magnetometer (consisting of the sensor and the electronics); the overall noise of the sensor is less than 0.2 nT
- Systematic errors linked to the reduction of absolute measurements by the use of data recorded by the variometer. The resolution of the triaxial variometer is 0.1 nT
- Systematic errors introduced by the use of measurements of the total field F to calculate baselines Ho and Zo from measurements of inclination. The resolution of the proton magnetometer is 0.25 nT, and its absolute precision is ±1 nT
- Accidental errors depending on the operator or uncertainties associated with the existence of a magnetic field gradient at the place of measurement.

It is possible to make an overall estimation of instrumental error by analyzing the baseline values calculated for pairs of declination and inclination measurements carried out at the observatory's reference pier. The difference calculated between two successive measurements of D (or of I) is representative of the error; as these measurements are generally made 5 minutes apart, one can eliminate possible drifts of the variometer. For 155 pairs of Do, Ho, and Zo determinations calculated at the observatory of Port Alfred (Crozet) in 1985, we obtain:

Component	Max. difference	Mean difference	
D	15″	4.5″	(st. dev. 3.8″)
H	1.1 nT	0.3 nT	(st. dev. 0.25 nT)
Z	0.8 nT	0.25 nT	(st. dev. 0.5 nT)

These results show that instrumental error remains below 5 seconds of arc for measurements of D and I, which corresponds to an error of the order of 1 nT for values of H and Z calculated on the basis of measurements of I and F.

Direct comparison of the portable theodolite magnetometer with common standards: precision and reliability of measurements

At the observatory of Chambon-la Forêt, an analysis of the data available for the period 1979-80 had shown good agreement between determinations made with the theodolite magnetometer and the conventional standards of the observatory, namely measurements made with the Cambridge inclinometer, the QHMs and the Brunner theodolite. The calculated mean differences were 11 seconds for the declination, 1 nT for the horizontal component and 0.3 nT for the vertical component. However, we noted (Bitterly et al., 1984) that these residual deviations must not be considered significant, because they were of the same order of magnitude as the probable instrumental errors associated with the conventional systems. In November 1983, at the observatory of Brorefelde, a first series of comparative measurements were made between a portable theodolite magnetometer of the Institut de Physique du Globe de Paris and the proton-vector system used at Brorefelde. Lauridsen (1985) noted that when these QDs and the D-coil were compared with a French DI-flux in November 1983, there was practically agreement between all instruments.

In order to illustrate and more clearly define this conclusion, we have compared the results of 186 series of measurements made over a period of 18 months at the observatory of Chambon-la-Forêt. The portable theodolite magnetometer used reference pier P1 of the observatory and the proton-vector magnetometer was installed on an auxiliary pier P3.

Figure 6.7 shows the baseline values of Ho and Zo calculated for each instrument, along with the corresponding differences. The mean differences for 1985 are as follows:
1985 Ho vector-ppm (P3) − Ho DI-flux (P1) = −0.4 nT (s.d. 1.3 nT)
1985 Zo vector-ppm (P3) − Zo DI-flux (P1) = +0.7 nT (s.d. 0.8 nT)
The total field difference between Pier P3 and Pier P1 is −0.9 nT ± 0.3 nT.

The mean differences calculated for the first six months of 1986 are slightly different: for Ho, we obtained −0.6 nT and for Zo, −0.7 nT. The replacement on 11 February 1986, of the proton magnetometer used in the coil system on pier P3 can reasonably explain this change; at this date the discontinuity in the Zo values is clearly visible in Figure 6.7.

There is excellent agreement between the H and Z values calculated using the portable theodolite magnetometer and those obtained with the proton-vector magnetometer system. The observed deviation is less than 1 nT, and remains stable over the whole 18 month period considered. This result shows that the accuracy of measurement of H and Z is better than ±1 nT, and that the portable theodolite magnetometer is an accurate, reliable instrument.

Results obtained for the direct measurements of the components X, Y, and Z by the compensation method: analysis of measurements made at the observatory of Dumont-d'Urville (Terre Adélie) in 1985

The magnetic observatory of Dumont d'Urville is located 160 km from the position of the south magnetic pole (1986 location), in an area of more or less continual magnetic

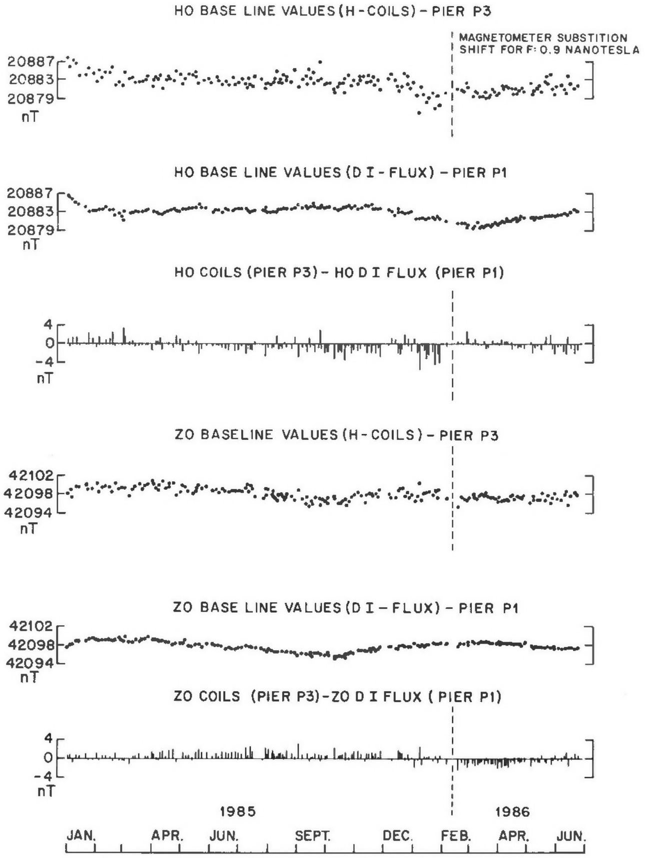

Figure 6.7 Baseline values for the Chambon la Forêt magnetic observatory January 1985 to June 1986, using both the DI theodolite magnetometer and the vector proton magnetometer.

disturbance. Its particular location complicates the task of the observer responsible for absolute measurements. Conventional measurements of D and I are not feasible in a place where the elements of the geomagnetic field had the following mean values (in 1985): X = 1288 nT, Y = −445 nT, Z = −69 873 nT and F = 69 886 nT.

In Terre Adélie, the portable theodolite magnetometer is used for the direct measurement of the X, Y, and Z components (compensation method), in association with a Geometrics G816 magnetometer specially adapted to obtain a resolution of 0.25 nT.

Figure 6.8 shows the baseline values Xo, Yo, and Zo, and the difference Fo of total field, existing between the variometer hut and the absolute measurement hut. A seasonal change of the baselines is observed for the X and Y components. This effect is due, at least in part, to the instability of the variometer pier, whose variations of inclination (up to 45 seconds of arc in the East-West direction) are detected through periodic monitoring of two levels. The seasonal effects observed seem to be in direct correlation with changes in the average temperature of the subsoil.

It should be noted that the location of the Dumont d'Urville Observatory, which was installed for the International Geophysical Year in 1957, was dictated by logistical considerations. (Unfortunately, this site is on a very large local magnetic anomaly.) The antarctic observatory of Scott Base is indeed in a comparable situation, and similar effects have been noted there (Rodgers, 1980). In these conditions, it is clear that absolute measurements must be taken regularly and often. The portable theodolite magnetometer installed in Terre Adélie since 1981 is particularly well suited to this objective. In 1985, an analysis of 124 pairs of determinations made during the year showed that the average error of baseline values may be estimated at 0.6 nT (the maximum deviation observed between two consecutive measurements t1 and t2 is 2.3 nT).

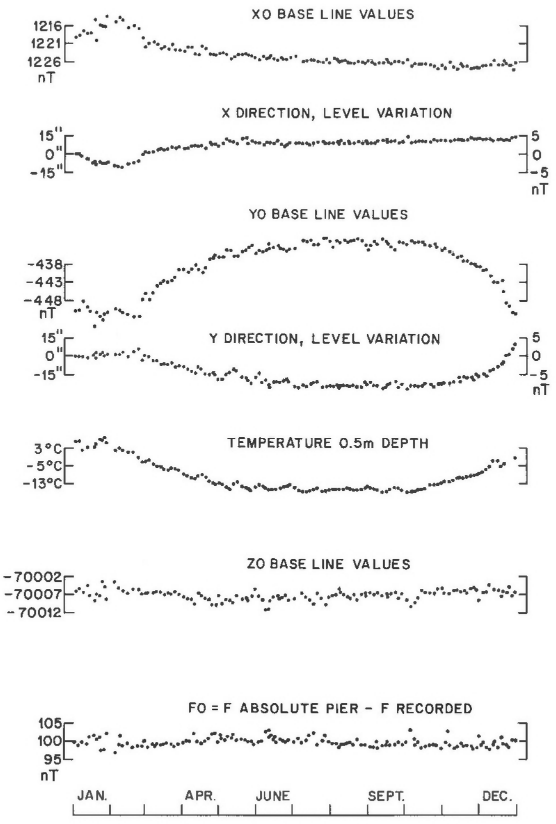

Figure 6.8 Baseline values, variations of level, and temperature for 1985 from Dumont d'Urville Magnetic Observatory.

1985 deviation	Max. deviation	Mean error	RMS
Xo(t1)-Xo(t2)	2.3 nT	0.6 nT	0.4 nT
Yo(t1)-Yo(t2)	2.3 nT	0.5 nT	0.5 nT
Zo(t1)-Zo(t2)	2.0 nT	0.7 nT	0.5 nT

Because of the particular situation of the Dumont d'Urville Observatory, the values of Z and F are directly comparable (the "difference" between Z and F is only 13 nT). The values of Z0 and F0 presented in Figure 6.8 are perfectly correlated. This illustrates the stability of the magnetometer's compensation current generator for strong fields (70 000 nT) and thus all the more so for weaker compensated fields (1300 nT for the horizontal component). In calculating the mean of 248 determinations of Zo for 1985, one obtains a standard deviation of 1.4 nT. This value may be definitely considered as representing the accuracy of the direct measurements of components carried out in Terre Adélie with the portable theodolite magnetometer.

Use of the portable fluxgate theodolite magnetometer for measurements in magnetic repeat stations

The portable magnetometer was first used for surveying in the field in 1982, when France's magnetic repeat stations were reoccupied (Gilbert and Le Mouel, 1984). Although the performance in observatories was known, it was decided that for this campaign, the conventional QHM and Chasselon theodolite devices would be maintained. A new proton magnetometer (with a resolution of 0.25 nT) was used in association with these devices to measure components.

The French network comprises 32 stations, which are reoccupied every five years. On the benchmark in each station, five to ten determinations of D and I were made with the fluxgate theodolite. These were complemented by two intercalated series of measurements of H with the QHM and of D with the Chasselon theodolite. The optical characteristics of the 010B theodolite permit the determination of the azimuth of the reference mark (using the method of determining the sun's hour angle) with an accuracy of ± 20 seconds of arc. Measurements of F were made systematically at the same time as the measurements of the components, using an auxiliary station point located 15 m from the benchmark. Care was taken to determine the total field difference between the measuring point above the benchmark and the location of the auxiliary point. In each station, the proton magnetometer was compared with a second magnetometer having the same precision. All measurements (D, I, and F, except for the data gathered by the Chasselon theodolite) were made to the nearest minute in time, hence simultaneously with the "magnetic field" information provided by the triaxial variometer of the reference observatory.

The reduction of the measurements was done on the basis of data supplied by the fluxgate triaxial variometer VFO 31 installed in 1978 at Chambon-la-Forêt. The performance of the theodolite magnetometer and the reduction procedure used allowed considerable improvement in the accuracy of the determinations of the reduced values, as is shown by the comparison of the resultant uncertainties estimated for the reoccupations of 1977 and 1982.

Uncertainty in	1977	1982
D	2.5′	1′
H	7 nT	4 nT
Z	–	3.5 nT
F	7 nT	4 nT

These uncertainties result from measurement errors at the stations, from errors in the determination of the element considered at the observatory, and from errors in reducing transient variations. The resultant uncertainty estimated above should again be considerably reduced during the next campaign (1987) through systematic recording, over 48 hours, of variations in the components of the magnetic field at the station. The digital data obtained will make it possible to reduce measurements locally by referring them back to the hour when the daily variations at the station and at the observatory are closest to the average level.

In early 1986, the Institut de Physique du Globe de Stasbourg carried out a campaign of magnetic measurements in the French sub-Antarctic islands (station of American Bay in the Crozet Archipelago, station of Port Jeanne d'Arc and of the Baie de l'Observatoire in the Kerguelen Islands, and the station on Ile Saint Paul). The equipment used included a portable fluxgate theodolite magnetometer with its accessories, and independent equipment for measuring and recording the total field F. The accuracy of the reduced measurements is of the same order as those of the French national survey.

During these two campaigns, the observers appreciated the ease with which the portable theodolite magnetometer may be used on an isolated site. It is remarkable that even in these conditions, which were relatively difficult, a series of measurements of declination and inclination was made in less than 15 minutes.

Conclusions

Fourteen units of the portable theodolite magnetometer for measuring elements of the geomagnetic field have been built. Seven permanent magnetic observatories have been using it as a reference for several years. It is an absolute, accurate and reliable device. As a zero field detector, it can be used to measure declination and inclination with an accuracy greater than five seconds of arc. When a compensation method is employed, the theodolite magnetometer then functions as a pseudo-absolute device that is easy to calibrate in association with a proton magnetometer. In this case, it allows measurement of any component of the Earth's magnetic field with an accuracy of the order of a nanotesla. Setting up the apparatus at a station and taking measurements do not require any more precautions than those that are usually necessary for the utilization of a "seconds" theodolite. Measurements can be made rapidly and easily. Thanks to these characteristics, on can propose this fluxgate theodolite magnetometer as a replacement for conventional devices used in magnetic observatories, and for carrying out field measurements at magnetic repeat stations or magnetic surveys.

Acknowledgments

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References

Bitterly,J., Cantin,J.M.,Schlich,R., Folques,J., and Gilbert,D.
1984: Portable magnetometer theodolite with fluxgate sensor for Earth's magnetic field component measurements; Geophysical Surveys, v.6, p.233-239.

Cantin, J.M., Gilbert, D., Bitterly, J., and Schlich, R.
1979: Magnétomètre portatif pour la mesure de la déclinaison et de l'inclinaison du champ magnétique terrestre; Communication presented at the XVII General Assembly of IUGG, Working Group V-1, Canberra, December 1979.

Cantin, J.M.
1980: Méthode et appareil de mesure du champ magnétique terrestre; Diplôme d'ingénieur D.P.E., Ecole Nationale Supérieure de Radioélectricité et d'Electronique Appliquée, Cergy Pomtoise, October 1980.

Fischer, G., Schnegg, P.A., and Sesiano, J.
1979: A new portable vector magnetometer for geomagnetic surveys; in A New Geomagnetic Survey of Switzerland. Geophysical Series, Commission Suisse de Géophysique, no.19, p. 13-17.

Gilbert, D. and Le Mouel, J.L.
1984: Observations magnétiques, réseau magnétique de répétition de la France, 1982; Fascicule no. 50, Institut de Physique du Globe de Paris, p.1-34.

Lauridsen, E.K.
1985: Experiences with the DI fluxgate magnetometer inclusive theory of the instrument and comparison with other methods; Danish Meteorological Institute, Geophysical Papers R 71, p.1-23.

Meyer, O. and Voppel, D.
1954: Ein Theodolit zur Messung des erdmagnetischen Feldes mit der Förstersonde als Nullfeldindikator; Deutsche Hydrographische Zeitschrift, v.7, p.73-77.

Primdahl, F.
1979: The fluxgate magnetometer; Journal of Physics E: Scientific Instruments, v.12, p.241-253.

Rodgers, T.A.
1980: Seasonal variations in the La Cour baselines values at Scott Base, Antarctica; IAGA News, International Association of Geomagnetism and Aeronomy, no. 18, p.108-112.

Serson, P.H., and Hannaford, W.L.W.
1956: A portable electrical magnetometer; Canadian Journal of Technology, v.34, p.232-243.

Tetani, M.
1941: Nuovo metodo di misura della declinazione e delle inclinazione magnetica; La ricerca scientifica, v.20, p.1135-1140.

Trigg, D.F.
1970: A portable D and I magnetometer; Geomagnetic Laboratory Report, no. 70-3, Earth Physics Branch, Energy Mines and Resources, Ottawa, Canada.

Usher, M.J. and Reid, J.P.
1978: An absolute vector magnetometer; Journal of Physics E: Scientific Instruments, v.11, p.1169-1172.

Yanagihara, K., Kawamura, M., Sano, Y., and Kuboki, T.
1973: New standard magnetic observation system of Kakioka (KASMMER); The Geophysical Magazine, v.36, p.236-243.

STANDARDS AT UNSTAFFED OR PARTIALLY-STAFFED OBSERVATORIES

R.L. Coles, G. Jansen van Beek and L.R. Newitt

An important point to make clear at the outset is that whether an observatory is fully-staffed, partially-staffed, or unstaffed is not a fundamental criterion regarding the quality of the data from that observatory. A properly designed, installed and operated unstaffed observatory can in principle meet the same standards as a fully-staffed station. Given the necessary money, technologies exist to do that. In reality, of course, a less-than-fully-staffed observatory is often seen as a way of saving money, or at least of saving person-power. Even in this less-than-ideal state, automatic digital observatories have the potential for performance on a par with the best fully-staffed stations.

We will consider as unstaffed stations those that are visited by an operator less than once a month. Fully-staffed stations will have an operator on duty every day. Partially-staffed stations fall between these bounds.

With older technologies, it is true that the ability to detect and repair faults promptly at partially or unstaffed stations was not as great as at fully-staffed stations, with consequent loss of data or data quality. Problems could arise with the magnetometer, the recorders, or the environment, and prompt action was not always possible at the site. With the advent of daily telephone links to observatory systems (such as those operating in Canada), the downtime at partially or unstaffed stations can be reduced, and the quality upgraded. In recent years, the reliability of electronic equipment has also improved. The Canadian network of 12 standard observatories, for example, has as a whole a greater than 98 % data recovery rate.

Less-than-fully-staffed means, of course, that absolute determinations may often suffer, with a corresponding decrease in the absolute control of the data. With the latest technology, this too may become less critical. Improved variometer instrument stabilities, coupled with better environmental control and monitoring, while not eliminating the need for absolute measurements, can at least decrease the frequency of such measurements. Such improvements are to the advantage of all observatories, whatever their mode of staffing.

A good physical installation, i.e. the stability of the mounting pier, is critical for accurate measurements. A highly stable variometer requires a highly stable pier.

Given adequate instruments and environment (with remote monitoring if necessary), the crux of the matter rests on the availability of a sufficiently trained and competent technician close to the observatory who can, on a schedule, carry out absolute determinations and who can visit the station to carry out repairs when required (mostly diagnosed from headquarters). Not uncommonly, there is difficulty in obtaining and retaining such a person, especially if the observatory is in a remote location with a severe climate.

For almost two decades Canada has operated a network of partially-staffed automatic observatories in a variety of environments and employing contract operators with varying degrees of skill and dedication. Our experience has shown that it is possible to obtain data of a quality on a par with data from many fully-staffed observatories. This can be seen in the plots of the Victoria Y and Meanook X baselines (Figure 6.9). The rms scatters of 1.0 and 1.3 nT, respectively, are typical also of those for other components at these stations.

Over the years, we have experienced most of the problems which can beset a partially-staffed network. The large amount of magnetic disturbance often present at polar cap and auroral observatories may have an adverse effect on absolute observations. At a fully-staffed observatory, the operator would be expected to delay absolute

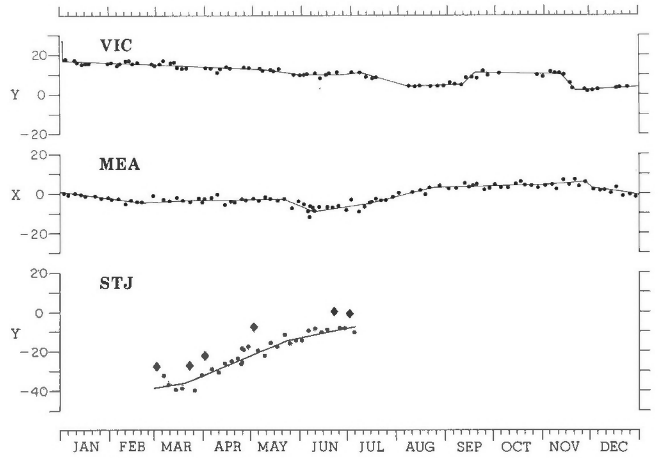

Figure 6.9 Baseline values for Victoria, Meanook and St.John's Magnetic Observatories for 1986. Dots represent measurements made by regular observers; the diamonds represent measurements made by a relief operator at St. John's.

observations until magnetic disturbances have subsided. At partially-staffed observatories, this is generally not so. Contract operators normally visit the observatories at fixed times, and few are willing to make several return trips for the purpose of making absolute observations under optimum conditions.

At some high Arctic observatories, such as Resolute Bay, the process of taking absolute observations is further complicated by the low value of horizontal intensity. Observations of declination under these conditions require extra skill and care and an understanding of the principle of the instrument, which many part-time observers may not possess.

Where magnetometer sensors or the associated electronics have significant temperature coefficients, temperature stability in an observatory building is critical. The lack of a full-time operator can make it more difficult to achieve the desired stability at some observatories. To partially overcome this problem in the Canadian network, the sensors at all our observatories have been thoroughly insulated in controlled-temperature enclosures; however, it has been more difficult to stabilize the temperature of the electronics which have been found to have a significant temperature coefficient.

Another type of problem is illustrated in the 1985 baseline plots for St John's Observatory (Fig. 6.9). The bold dots denote observations made by the back-up operator. It is obvious that a systematic difference exists between his observations and those of the regular operator. The difference is greatest in the Y baselines, which indicates that the problem occurs with the D observations. Again this is a problem which relates directly to the competence and experience of the observer. Such problems are extremely difficult to resolve since the observatories are normally visited once a year by headquarters personnel, and funds are seldom available for unscheduled trips.

The challenge, then, lies with the scientists and engineers to produce yet a new generation of automatic digital observatory systems, with true absolute control (i.e. relative to geographic co-ordinates, not arbitrary, or seasonally moving, approximations thereof) that minimize the skill level required by local operators. The greatest degree of skill is definitely required for the absolute measurements. Until this is reduced, the costs of operation will remain high, and the absolute control of the data subject to serious loss of quality.

7. SPECIAL TOPICS

THE PROBLEMS FACED BY DEVELOPING COUNTRIES IN ADOPTING DIGITAL RECORDING AT MAGNETIC OBSERVATORIES

D.R.K. Rao

[Editor's note: At the request of several participants, an informal discussion session was arranged during the Workshop, under the leadership of D.R.K. Rao. His summary of the session follows.]

Introduction

The discussion fell into three parts:
1. The reasons for converting from analogue to digital.
2. The instrumentation and data processing equipment which may be involved.
3. How the International Community can assist the less developed countries.

Analogue to digital conversion

A summary of the arguments for replacing classical methods of operation with digital ones includes:

A. Scientific and commercial users require geomagnetic records in digital form almost exclusively.

B. Digital recording allows all the data preparation (including Year Books where required) to be done easily, quickly, and accurately without the need for tedious hand-scalings and manual tabulations. Many observatories fall behind in the calculation and publication of their data, and often do not clear the backlog. Digital data processing would eliminate this problem.

C. There is a recurrent cost in manpower and materials (photographic paper and chemicals) which would be saved by the adoption of digital data. This would offset the initial capital cost of installing digital equipment. In addition many countries have difficulty in maintaining stocks of photographic paper of the correct size and quality.

D. The adoption of digital data by an observatory represents a technological advance which can be used elsewhere in the country, and which lays a foundation for the development of commercial and scientific research in the country. It is felt that digital technology is a much more powerful catalyst, in this respect, than classical observations.

Hardware requirements

The basic requirements for a digital data acquisition system are:

A. Variometer sensors which produce an electrical output proportional to field change

B. Analogue to digital conversion

C. A suitable data logging system

D. A data processing computer.

It was generally agreed that each country should decide about the choice of data logger and computer in the light of the local computing facilities and the local availability of spare parts and servicing for computers and peripheral equipment. However, it was recommended that flexibility of use should be considered as a priority in making the choice and it was noted that systems based on personal computers are very cheap and convenient. These computers are also easy to learn and use. The basic data processing system consists of a microcomputer (comparable to personal computers) with a suitable input/output device to read data from the data logger, preferably with floppy and hard disk connections, a graphics terminal for quality control, a printer and a plotter for analogue records.

International help

Software is needed for the routine data processing and quality control (for mean value tables, analogue plotting and data transfer to bulk storage or main frame computing facilities). It was considered that it would be impossible to devise standard software which will work on all computers, but it was thought that operators with established experience could provide copies of the primary programs for the assistance of personnel in the developing countries.

Technical and computing training for personnel in the developing countries continues to be a major difficulty which must be overcome before digital installations can be adopted worldwide. It was recommended that institutions wishing to adopt digital data should always seek advice from an institution which has established its ability to make digital recordings well. The two institutes should then attempt to find funding from national or international agencies to support training at the advanced institution for technical staff from the developing observatory.

It was also recommended that established institutes should assist by performing some pre-delivery inspection or test of equipment purchased by countries which are not confident of the level of their technical skill.

There are over 100 observatories which do not yet operate digital equipment to the standard of a geomagnetic observatory. These are, for the most part, located in developing countries in low and equatorial latitudes. The data from these observatories are crucial to producing accurate mathematical models of the main field and its secular variation, which are essential for international navigation and which are the basis of fundamental research on the Earth's core and the dynamical history of the Earth and in modelling the Earth's magnetosphere. It was recommended that scientists in the developing countries should collaborate to formulate an international project using the special position of these observatories to study outstanding questions of the global geomagnetic field or equatorial aeronomy. It was recognized that future survey magnetometers on satellites will need ground reference data of the highest quality in digital form from equatorial regions and will, in return, supply valuable data for a program of research on equatorial aeronomy.

The Interdivisional Commission of IAGA which deals with problems of developing countries was asked to take some action to help geomagnetic observatories. An example of the kind of help that is needed is a list of the international funding agencies which may support observatories in the change to digital recording either in the purchase of equipment or in providing funds for training. There are many cases where developed institutions have helped developing countries. IAGA should prepare a list of these, together with the type of help and the name of any international body involved, and circulate it to the standard magnetic observatories with the recommendation that the director of any observatory which wants help or guidance writes first to a developed institution to establish a collaboration and for assistance in finding an international funding agency which can help.

DEFINITIONS OF TERMS USED IN THE DESCRIPTION OF SPECIFICATIONS FOR GEOMAGNETIC INSTRUMENTS

Barry Narod

Introduction

Certain inconsistencies have been noted in the usage of terminology related to geomagnetic engineering, and it was felt useful to define a number of terms specifically. These terms are in common use for comparisons of the performances of geomagnetic instruments.

Units of H:
The basic SI unit for H is ampere/metre [A/m]. The old unit, oersted, corresponds to $(10^3/4\pi)$ A/m.

Units of B:
The basic SI unit for B is [tesla]. Since the permeability of free space has been defined to be $4\pi \times 10^{-7}$ H/m, the relation between B and H units is:

[tesla] = $(4\pi \times 10^{-7}$ H/m$) \times$ [A/m].

The old unit [gauss] equals 10^{-4} [tesla]. The [gamma] equals 10^{-9} [tesla], or the [nanotesla].

Terms of performance:

Sensitivity

Sensitivity of an instrument is defined as the ratio (or its inverse) of the output in engineering units to the input signal in physical units. An example of this would be an analogue variometer sensitivity which might be 100 nT/volt.

Signal strength

Geomagnetic variations are inherently broad-band in nature, i.e. the signal does not form sharp spectral lines. Thus signal strength must be qualified by the frequency band in question. For a complete description of signal strength this feature should be taken to the limiting case of incremental bandwidth. The most precise statement of signal strength is in the form of a power spectrum, in which signal power spectral density (PSD) is plotted as a function of frequency. A common unit for PSD in geomagnetism is [nT × nT/Hz]. Amplitude spectral density is the square root of power spectral density.

Resolution

Resolution is the smallest change in signal that can be distinguished by an instrument. Resolution is usually a function of noise, and thus is a function of the frequency band.

Precision

Precision is the smallest increment by which an instrument reports its estimate for the physical parameter that it measures. For digital outputs this is the physical unit corresponding to a change of the least significant bit.

Accuracy

Any instrument used to provide a measure of a physical parameter provides an estimate for the (unknown) true value of that parameter. Accuracy is the difference between that estimate and the true value. Since the latter is never known, accuracy itself is at best an estimate, usually derived through engineering experience.

Dynamic range

Dynamic range is the ratio, usually expressed in dB, of the maximum signal swing which an instrument is able to follow, to the resolution of the instrument. Alternately, it may be expressed as a range described by these two values, e.g. (0.1 nT to 1000 nT). As with resolution, dynamic range can be frequency band dependent. This parameter is usually defined without range switching.

Instrument noise

Noise in an instrument has the same characteristics as does signal strength. It is generally expressed as equivalent noise at the instrument input, in terms of the physical units of the signal. As with signal strength, noise is properly expressed as a power spectral density function.

Signal-to-noise

Signal-to-noise is the ratio, usually expressed in dB, of signal strength to instrument noise, when both are expressed as power spectral densities. Resolution, signal strength, instrument noise and signal-to-noise can all be functions of frequency.

ABSOLUTE OBSERVATION OF F BY PROTON MAGNETOMETER

W.F. Stuart

During one of the discussion sessions at the Workshop, Emil Kring-Lauridsen suggested that:
'An absolute measurement of a recorded magnetic element is a measurement of the element performed within a short interval of time and with an accuracy at least of the order of the resolution of the recording instrument, and with some consideration of its stability.'

Although it attempts to address the questions of measuring accuracy versus variometer resolution and also the time factor, the definition was considered to describe a laboratory measurement rather than an observation which is intended to convey the scientific significance of the magnetic field of the Earth at a point, which may be influenced by several anomalies and under the influence of complex external disturbance fields. In the context of geomagnetic observatories, these considerations seem to be important.

The word "absolute" implies a fixed-for-all-time value which can be determined (for all time), and in that respect is perhaps not the best one to use in geomagnetism. It also implies measurement in absolute units of mass, length and time. The classical methods of Gauss satisfied the latter criterion, but fail, in the context of high resolution recording, to be acceptable because of the time taken in making measurements. Modern thinking is that methods of observation which do not involve a complex series of amendments for temporal variations offer the safest route to achieving reliable base line data in support of variometers. Since all the values of the geomagnetic field that are used in science are computed from the variometer records, it is essential that the accuracy and stability of baselines is recognized as the raison d'être for absolute measurements.

Variometers normally measure components of the magnetic field, and so "absolute" determinations of direction are important in the establishment of baselines. The scalar intensity of the magnetic field is also required, and one instrument that approaches an "absolute" device is the proton precession magnetometer.

IAGA adopted the proton standard in 1960 (International Association of Geomagnetism and Aeronomy, 1960) recognizing that the precession of protons in water constitutes an absolute measure of field magnitude in terms of a well known atomic constant. The gyromagnetic ratio adopted is 2.67513×10^8 radians/tesla.second. Modern practice recommends the use of the proton magnetometer, with coils to obtain H and Z, together with a suspended magnet system or fluxgates in null positions to determine D.

Proton magnetometer frequencies are in the range 1 to 3 kHz in the Earth's magnetic field, and with a signal-to-noise ratio of 100 it is possible to approach the ultimate precision of the atomic constant, i.e. 0.2 nT. Signal processing techniques (synchronous frequency multiplication or microprocessor controlled gating) offer direct reading proton magnetometers which claim to operate at a resolution of 0.1 or 0.01 nT. It must be borne in mind that these resolutions are not absolute accuracies.

The true absolute accuracy of any value produced by a proton magnetometer depends on:

1. The signal-to-noise ratio of the signal from the proton samples.
2. The actual gyromagnetic ratio of the sample (e.g. protons in water, protons in paraffin, etc.).
3. The gyromagnetic ratio used by the manufacturer in designing the electronics.
4. The frequency standard used in the frequency-counting circuitry.

The standard error of the proton gyromagnetic ratio is 3 ppm and limits the precision of any single geomagnetic measurement to between 0.1 and 0.2 nT. In order to achieve and maintain the ultimate precision, frequencies used in the magnetometer electronics should be set to an accuracy of at least 1 ppm and have a stability in the long and short term of at least 0.1 ppm. Because crystals do experience drifts, and to eliminate sources of error in manufacturing or due to misadventure, it is important to verify standard frequencies to these precisions, and desirable to check them from time to time. It is helpful to make comparisons between proton magnetometers but:

(a) Two proton magnetometers of the same design may have the same systematic error.
(b) A difference between two proton magnetometers does not establish which, if either, is correct.

Each magnetometer should be supplied with a fact sheet, preferably rivetted to the instrument case, on which critical electronic parameters (frequencies, multiplying factors, etc.) are listed together with the fluid used for a proton sample and the gyromagnetic ratio used in the design. Variations in gyromagnetic ratio of 10-20 ppm occur with different fluids. Systematic baseline errors of 1 nT or more can result from not taking these into account.

Systematic errors were common in the old inverted count electronic systems due to drift of standard frequency. Standard frequency oscillators have improved to the point where this should not occur but drift within the phase lock loops of direct reading instruments creates the same effect. Offset errors of several nanoteslas have been found.

In general, signal-to-noise deterioration shows as erratic readings and as such indicates the limit of absolute accuracy; it can also produce a bias in the resultant readings. The source of undue noise should be investigated because it suggests excessive field gradients or RF interference. In these circumstances offset values are possible.

References

International Association of Geomagnetism and Aeronomy
1960: Comptes Rendus de la XII Assemblée Générale de l'UGGI; Helsinki, p. 129-130.

SPECIFICATIONS OF AN IDEAL VARIOMETER FOR MAGNETIC OBSERVATORY APPLICATIONS

D. Trigg[1]

An attempt was made to anticipate future needs of scientists making use of magnetic observatory data. An instrument which conforms to the specifications would provide the means for a significant advance in the state-of-the art of recording and analyzing data on the Earth's ambient magnetic field. Resolution, stability and frequency response would be sufficient to provide a higher quality data set than could be achieved using current instruments.

Considerable discussion took place about attributes of the ideal magnetic observatory variometer before actual specifications were addressed. All present agreed the

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[1] Discussion convenor

instrument should be "rugged" but found this difficult to quantify. Such things as resistance to shock and durability under environmental extremes come to mind.

Precautions should be taken against some of the problems known to cause instruments to malfunction or fail. We experienced one of these problems during the Workshop in the form of thunderstorms, whose effects caused loss of data. Good instruments should be protected against pickup of damaging lightning-induced transients both on their own cabling and on power lines. Many observatories are located near radio transmitters and the ideal magnetometer should be shielded against radio frequency interference.

Cost was also difficult to deal with, and while a target figure of under $15K US is listed below it represents only a wish, not a specification. The same may be said about having no export controls on the instrument. One which meets the specifications outlined below would most certainly come under export restriction by some countries.

One area of performance that has received relatively little attention is long-term stability, probably because it has been difficult to separate from temperature and orientation effects. A very stable instrument will alleviate the need for frequent "absolute" measurements.

Section 5 of this report, showing comparisons between variometers deployed during the Workshop, reveals that problems exist with temperature dependency. It is expensive to provide a thermal environment that is stable year-round, and the equipment required invariably requires much maintenance effort. It is much more desirable that the variometer itself be insensitive to temperature changes of both the electronics and the sensors.

No instruments at the Workshop recorded tilt or azimuth changes. Such angular measurements are deemed advisable. Orientation changes of a sensor orthogonal to a field of 60 000 nT will generate approximately 1 nT error per 3 seconds of arc. The components most affected naturally will vary with location. At high latitudes the ground freeze/thaw cycle is known to move piers and buildings. Tilt and azimuth errors will contaminate horizontal components there much more than Z, with horizontal errors containing a [Z sin(tilt)] term plus at worst an [H sin(az)] term. Note that by definition Z is unaffected by azimuth errors. At low magnetic latitude, problems with angular displacements can be expected to be less severe both because of the lack of freeze/thaw and because field values are smaller. Here Z will be contaminated by an [H sin(tilt)] term and horizontals by at worst an [H sin(az)] term.

Undaunted by all the above considerations, the Workshop participants came to a consensus on a self-consistent set of target specifications outlined below:

Consensus on specifications
— Ideal observatory variometer

Rugged	
Reliable	MTBF = 24 mo.
	MTTR = 1 day
Protected	Lightning
	Humidity
	Radio freq. interference
Power	< 100 W
	Uninterruptible
Export	No restrictions
Cost	< $15K U.S.
3 Component	
Sensor construction	Orthogonal within ± 30′
	Stable to 0.3″/mo.
	0.3″/°C
Resolution	0.1 nT
Dynamic range	> ±3000 nT
Stability	0.25 nT/mo.
Passband	d.c. – 1 Hz. (–3dB), 4-pole
Noise	0.03 nT rms in passband
Linearity	0.1 % of full scale
Timebase	1 s/mo., (not a.c. line)
Sample rate	10 Hz.
Measurement rate	5 s
Storage capability	6 weeks
Temperature coefficient	Head < 0.1 nT/°C
	Console < 0.1 nT/°C
Temperature range	–20 to +50 °C
Temperature recording	± 0.25 °C (every 10 min.)
Tilt sensors	Resolve 1″ (every 10 min)
	Stability 1″/mo.
Azimuth sensors	(as for tilt)

MBTF — mean time before failure
MTTR — mean time to repair

A sample specification blank follows that observatory operators or suppliers are invited to use and send to R.L. Coles, as a co-ordinator of such information. Such an information bank may be of interest to those who are establishing new digital observatories, especially in developing countries. Manufacturers may also be interested in using it as a guide in their brochures.

Please return completed form to:

Richard Coles,
Geophysics Division,
Geological Survey of Canada,
1 Observatory Crescent,
Ottawa, Ontario, K1A 0Y3
CANADA

Telex 053317
Telephone (613) 995-5487

Specifications — Observatory Workshop Instruments

(Use numbers or Y/N, as appropriate)

Instrument name	____________________
Type	____________________
Supplier	____________________
Owner/operator	____________________
Reliability	MTBF ________ (Mean Time Before Failure) MTTR ________ (Mean Time To Repair)
Protected against	Lightning ____ Humidity ____ Radio freq. interference ____
Power	____ W Uninterruptible ____
Export	Restrictions ____
Cost	______ $ U.S.
3 Component?	____
Sensor construction	Orthogonal within ± ____ minutes of arc Stable to ____ seconds of arc/mo. ____ seconds of arc/°C
Resolution	____ nT
Dynamic range	± ____ nT
Stability	____ nT/mo.
Passband	d.c. to ____ Hz. (−3dB), ____-pole
Noise	____ nT rms in passband
Linearity	____ % of full scale
Timebase	____ s/mo.,
Sample rate	____ Hz.
Measurement rate	____ s
Storage	____ weeks
Temperature coefficient	Head ____ nT/°C Console ____ nT/°C
Temperature range	____ to ____°C
Temperature recording	Resolution ____ °C
Tilt sensors	Specs. ____________________
Azimuth sensors	Specs. ____________________
Other	____________________ ____________________

Comments: ______________________________

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DIGITAL RECORDING OF VARIATIONS IN THE EARTH'S MAGNETIC FIELD IN FRENCH OBSERVATORIES: DESCRIPTION OF EQUIPMENT AND RESULTS FOR THE PERIOD 1972-86

J. Bitterly[1], J.M. Cantin[1], J. Burdin[1], R. Schlich[1], J. Folques[1], and D. Gilbert[2]

Abstract

Continuous recording of variations in the Earth's magnetic field is carried out in the French magnetic observatories with a triaxial fluxgate variometer and a proton precession magnetometer. The resolution of the fluxgate variometer is 0.1 nT, its long-term stability is better than 1 nT per month and drifts of thermal origin remain below 0.25 nT/°C. The resolution formats the signals delivered by the sensors. The magnetic field information (H, D, Z, F or X, Y, Z, F) is recorded on different media: magnetic tape, minicassette or diskette. The data are preprocessed in real time in a microcomputer associated with the recording device. The instantaneous difference between the total field values calculated on the basis of the three elements (H, D, Z or X, Y, Z) supplied by the fluxgate variometer and the values given directly by the proton magnetometer is less than 1 nT in 95 % of cases.

The system described here has been operating continually since 1972 in the high-latitude French magnetic observatories. Since 1979, it has also been used in the national magnetic observatory of Chambon-la-Forêt.

Introduction

The main task of a magnetic observatory is to calculate instant values and hourly, monthly and annual averages of various elements of the geomagnetic field, to analyze recorded disturbances and to keep a record of this information.

Rapid monitoring and use of the collected data requires equipment that meets the following criteria:
- — A reliable, low-power sensor that is easy to install.
- — Digital acquisition of signals by an independent device.
- — Recording of the data on a medium that allows direct processing of the data in a computer.
- — Visual display and testing of data in real-time on the observatory site.

Serson (1957) described a triaxial field station using fluxgate sensors. Various semi-automatic observatory systems were subsequently developed. In particular, the geomagnetism laboratory of the Earth Physics Branch at Ottawa produced several versions of the system known as AMOS (Automatic Magnetic Observatory System) between 1969 and 1974 (Andersen, 1969, 1974; DeLaurier et al., 1974). At the same time, the Institut de Physique du Globe de Paris was studying a device for digital recording of variations in the geomagnetic field, intended as a replacement of the magnet variometers installed in the high-latitude French magnetic observatories. The prototype of this new apparatus was installed in 1972 in the magnetic observatory of Port-aux-Français in the Kerguelen Islands (Schlich et al., 1974). Similar fluxgate variometers were installed in the observatories of Dumont d'Urville (Terre Adélie) in 1973, of Port Alfred (Crozet) in 1974 and of Martin de Vivies (Amsterdam Island) in 1980. In 1979, a similar device was installed in the national magnetic observatory at Chambon-la-Forêt. It is now the observatory's reference equipment. Equipment derived directly from this system was incorporated into the French mobile station in 1976, for recording geophysical data (Perrault et al., 1978).

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[1] Institut de Physique du Globe de Strasbourg

[2] Institut de Physique du Globe de Paris

Description and characteristics of the fluxgate triaxial variometer

Details of the electronics

The progress made since 1970 in the areas of reliability, stability and resolution of fluxgate magnetometers has led us to favour this type of directional sensor. To avoid unwieldy equipment and to ensure simplicity of use, we rejected nuclear resonance or optical pumping magnetometers associated with coil systems.

Between 1969 and 1971 a triaxial variometer was developed in collaboration with the Thomson Sintra A.S.M. Corporation, which,in 1971, built and marketed the VFO 31 type variometer that we have adopted. This is a "parallel" type sensor with two saturated cores. The major characteristics of the variometer are given in section 3 of these proceedings.

In order to attain the projected performance, it was necessary to limit the influence of the major causes of defects that generally affect the operation of fluxgate sensors. Defects of electronic origin are mainly associated with the existence of a sensor error (the sensor placed in a zero field delivers a residual signal), with the instability of the compensation current, and with the lack of homogeneity of the compensated field. The influence of these various parameters on the performance of two saturated cores has been analyzed in detail by Primdahl (1979). As far as the VFO 31 variometer is concerned, this analysis has been summarized by Bitterly and Cantin (1979), in an internal report of the Institut de Physique du Globe de Paris. We summarize below the actions taken in the development of the VFO 31 circuitry.

— Compensation current generator circuit: The stability of the compensation current depends primarily on the stability of the reference voltage. It is essential to select diodes having a temperature coefficient better than 2 ppm/°C. The amplifiers used for the current generator must have a drift less than one microvolt/°C.

— Excitation and amplification detection circuits: At the level of the electronics associated with the sensor, the appearance of an error signal can be due to: (1) The variation of the excitation signal (an effect of approximately 1 nT for a variation of 1 mA p-p in the excitation current and for a compensation field of 100 000 nT). (2) The phase variation, dependent on temperature, of the selective amplifier or the 2F phase detector relative to the excitation signal F. The circuits used during the trials of the VFO 31 variometer limited the sum of these effects to less than 0.15 nT/°C for a compensation field of 100 000 nT. It was necessary to reduce the level of the second harmonic in the excitation signal to less than 75 dB; under these conditions the sensor error is on the order of a few nT and remains constant with time.

For magnetometers with two saturable cores operating in a compensation field it is observed, in addition to the 2F harmonic related to the field to be measured, the presence of a 2F quadrature harmonic due mainly to the inhomogeneity of the compensation field. The amplitude of this 2F quadrature signal is at the same time proportional to the level of the excitation current and the intensity of the compensation field. If the compensation field is not homogeneous the phase variations of the selective amplifier or of the phase detector, with respect to the excitation signal, bring about the demodulation of this 2F quadrature harmonic and thus create an error signal. For the sensors used, the amplitude of this error signal is approximately 1 nT per degree of phase variation of the selective amplifier or phase detector for a compensation field of 100 000 nT and an excitation current of 120 mA p-p. These faults have been eliminated by designing, on the one hand, an excitation circuit whose signal level is constant, and, on the other hand, selective amplifier and phase detector circuits having a good temperature stability. The geometric characteristics of the compensation coils have been optimized to obtain a compensation field as stable and homgeneous as possible.

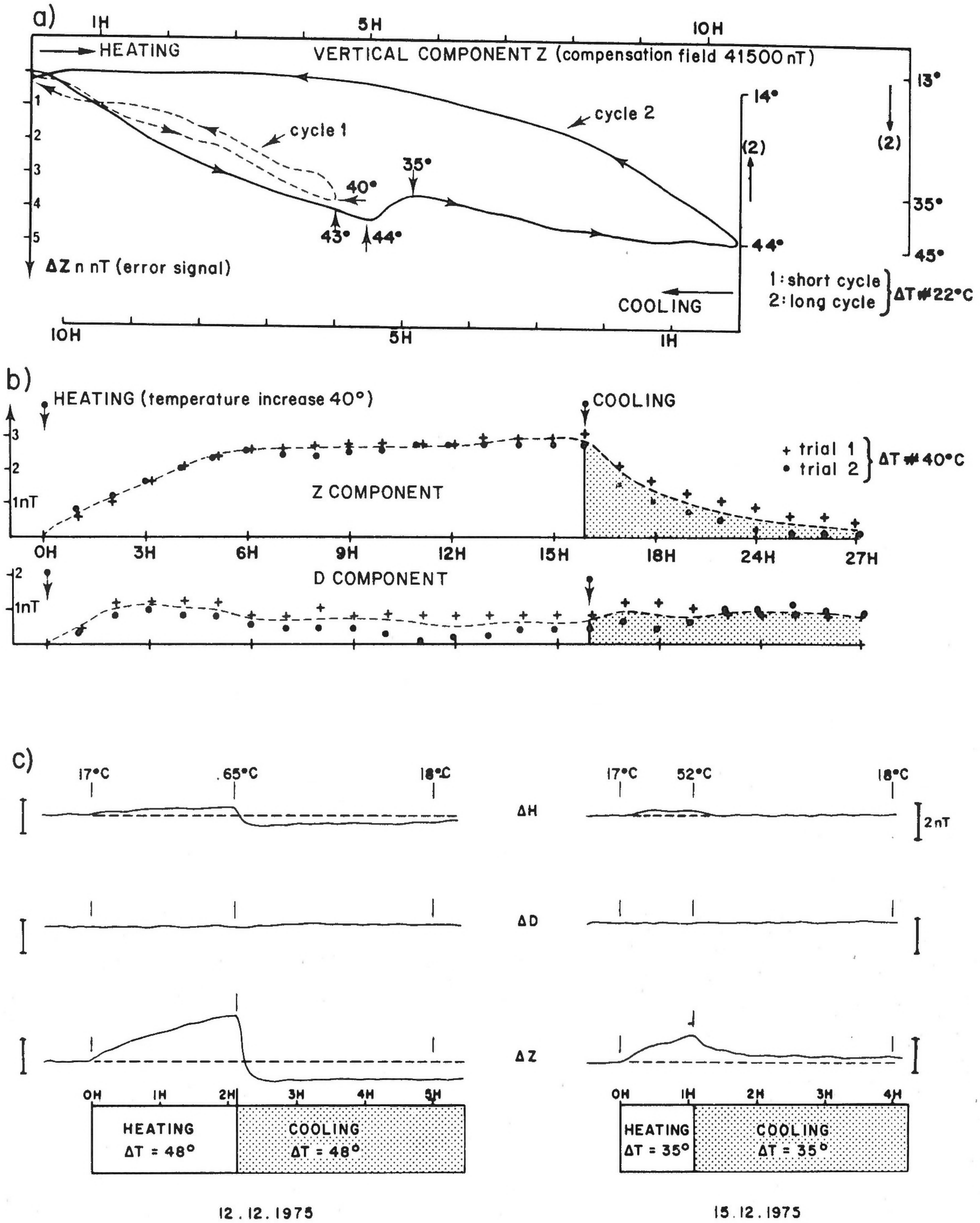
Drifts of thermal origin

The study of the thermal stability of the variometer, and the experimental determination of the temperature coefficients of different parts of the assembly were carried out simply by using two VFO 31 magnetometers whose outputs were connected in opposition. This differential test assembly permits the elimination of the natural variations of the magnetic field; one of the sensors is chosen as a reference while the other is subjected, in whole or in part, to controlled thermal variations with amplitudes of about 40°C. The amplitude of the thermal drifts depends on the mechanical stability of the sensor; particular care has been taken in the choice of material and in the mechanical construction of the triaxial sensor support assembly. The best results were obtained by using CER-VIT, a vitreous ceramic manufactured by Owens Illinois Inc., for producing the base, and by using a block of quartz to machine the chuck that holds the permeable cores and supports the compensation solenoid. These materials, which have a coefficient of expansion of the order of 5.10^{-8}, permit the construction of a sensor which is not very sensitive to deformations of thermal origin.

For convenience, the temperature coefficients of the different parts of the assembly were determined separately; that is, the sensor itself, the associated electronics, and the compensation circuits. Figure 7.1 shows the results obtained for several heating-cooling cycles. The good reproducibility of the curves from one cycle to the next as well as the return to the starting point to better than 1 nT for the difference signal observed at the end of the cycle confirms that the coefficients determined are significant. The results obtained are shown in Table 7.1; they show that the cumulative effects of temperature variations are always less than 0.25 nT/°C for a compensated field of 50 000 nT.

Noise

The noise of the VFO 31 variometer is attributed essentially to the sensor; in essence, the noise power spectrum of the electronic circuits is less than 25 $pT^2 Hz^{-1}$ in the band considered. The noise measurements were made for a



Temperature coefficient of console : D component (compensation zero) 0.00 nT/°C
H component (compensation 21 000 nT) 0.02 nT/°C
Z component (compensation 41 500 nT) 0.08 nT/°C

Figure 7.1 Temperature calibration tests for the VFO 31 magnetometer.

Table 7.1 Summary of temperature coefficients in nT/°C

Sensor			**Variometers**			
	A101	A102	CSF1	CSF2	CSF3	CSF4
D component	.05 ± .03	.03 ± .02	.04 ± .02	.06 ± .03	.06 ± .03	.05 ± .02
H component	.07 ± .03	.02 ± .02	.04 ± .03	.08 ± .04	.08 ± .02	.06 ± .02
Z component	.04 ± .04	.05 ± .02	.07 ± .04	.12 ± .05	.17 ± .04	.10 ± .03
Electronics						
D component	.02 ± .01	.02 ± .01	.04 ± .02	.02 ± .02	.01 ± .005.	005 ± .001
H component	.04 ± .02	.03 ± .02	.03 ± .02	.08 ± .08	.02 ± .01	.015 ± .008
Z component	.07 ± .03	.05 ± .02	.03 ± .02	.08 ± .05	.05 ± .01	.013 ± .005

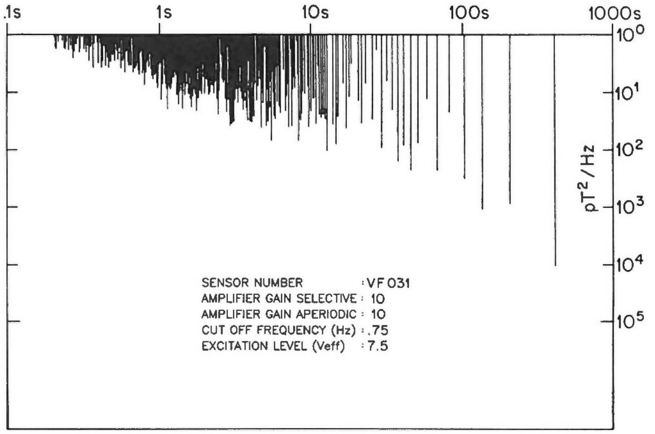


Figure 7.2 Spectrum of noise density for the VFO 31 magnetometer.

basic sensor placed in a mumetal shield having an attenuation coefficient for ambient field variations on the order of 200. The noise power spectrum of the sensor is shown in Figure 7.2; it was calculated following a method similar to that adopted by Candidi et al. (1974). The general appearance of this spectrum, in the 0.0025 to 1 Hz band, is similar to the results given by Snare and McPherron (1973); the noise power spectrum, calculated at 100 s, is 900 $pT^2H_z^{-1}$. It can be estimated that the overall noise of the variometer is less that 0.1 nT p-p from 0 to 1 Hz.

The proton precession magnetometer

A conventional arrangement is to associate a triaxial sensor with a proton precession magnetometer, which gives the value of the intensity of the total field. This redundant information permits control testing of the sample data (X, Y, Z or H, D, Z). This configuration was adopted, and a proton magnetometer (Geometrics G816 or ELSEC 770) completes the system. This magnetometer was specially altered and adapted to obtain a resolution of 0.25 nT, and to operate according to a remote control protocol. A coaxial cable supplies power, allows the measurement to be triggered and transmits the pulse train corresponding to the measurement (the number of pulses transmitted is equivalent to the value of the total field expressed in quarters of a nanotesla). The proton magnetometer sensor is equipped with shielding that limits the effects of interference of radioelectric origin.

Digital recording apparatus

The fluxgate variometer (sensor and associated electronics) and the proton magnetometer are installed in a non-magnetic, temperature-regulated hut. The amplitude of the thermal variations within the hut is less than 2°C. The digital acquisition system and recording equipment are installed in a location that may be several hundred metres from the sensors.

The acquisition system used was designed and built in 1971 by the Magnetic Observatories Department of the Institut de Physique du Globe de Paris (Bitterly et al., 1976). It receives the signals delivered by the triaxial variometer and proton magnetometer sensors. This equipment uses CMOS technology. The sensor-acquisition system can function independently for more than 12 hours (using a 12 volt, 4 ampere-hour battery). The principal functions of this digital acquisition system are as follows:

- — Generating time information.
- — Multiplexing analogue signals (H, D, Z).
- — Analogue/digital conversion of the signals.
- — Formatting the signals for recording.
- — Triggering the measurement of the total field F, and transmission of the pulse train corresponding to the measurement.
- — Formatting all digital information for recording (BCD).
- — Generating control signals for the incremental magnetic recorder or for the minicassette recorders.

For each component, the fluxgate variometer supplies a voltage proportional to the variations of the field to be measured. This voltage is transformed into digitial information by a "double ramp" converter, which delivers a pulse train. The number of these pulses is equal to the value of the field to be measured, expressed in tenths of a nanotesla. The proton magnetometer is triggered by a command generated by the digital acquisition system at the end of each X, Y, Z or H, D, Z sampling.

The pulse train from the analogue/digital converter or the proton magnetometer is counted and memorized. The serializer simultaneously receives all digital information from the day hour and measurement counters. For each measurement, it delivers successively, at a rate of 100 Hz, the characters to be recorded in BCD code.

A control and monitoring box provides a link between the digital acquisition system and the continuous advance tape unit (9 tracks, 800 bpi). This box comprises an 8-bit microprocessor and a 16K (octal) memory, which ensures twenty hours of independent operation. A printer allows display of control or error messages (permanent operation in the "log book" mode).

The magnetic field information is recorded sequentially in the order H, D, Z, and F. The observatory's identifier, the date and the time are added to these data every twenty minutes. Time precision is of the order of 0.5 seconds.

A 32 K microcomputer and a floppy disk drive complete the measurement chain. It is thus possible to carry out a real-time verification test of the consistency between the instantaneous values of the total field Fi* reconstituted from three elements and the total field values measured with the proton magnetometer. In practical terms, the difference dFi = Fi* − Fi is calculated every minute; for each group of 20 measurements, the mean dFi value and the corresponding standard deviation are calculated. The consistency criterion adopted is expressed by the relationship (dFi − mean dF) < 2E.

Values that do not meet this criterion are tabulated.

The characteristics of the digital acquisition system are summarized in section 3. A summary of the complete measurement sequence is given in Figure 7.3. The system as a whole was presented to the 17th General Assembly of the IUGG at Canberra (Bitterly et al., 1979).

Major operating results for the period 1972-86

Estimation of long-term stability

The stability of the triaxial variometer can be estimated by analyzing the values calculated for its baselines in each observatory. The origin of long-term drifts may be mechanical (e.g. instability of the triaxial base) or electronic (variation of sensor error, changes in reference voltage). In our case the portion of these drifts which are of mechanical origin can be considered very small, as is shown by the baseline values calculated for 304 measurements of declination made between March 1985 and November 1986 at the Chambon-la-Forêt Observatory.

Mean value of D: Do =	−3°43′34″	standard deviation = 7″
Extreme values	−3°43′16″	(minimum)
	−3°43′49″	(maximum)

The histogram in Figure 7.4 represents the distribution of differences from the mean value of Do for this period. During this period, the average rate of change of Do baseline values as a function of time is always less than 15 seconds of arc per month. This result is confirmed by analysis of 13 years of continuous operation of the VFO 31 sensor installed at the Port-aux-Français Observatory in 1972 (see fascicules entitled "Observations magnétiques faites à l'Observatoire de Port-aux-Français", published by Institut de Physique du Globe de Paris, 1972, 1979, and by the Institut de Physique du Globe de Strasbourg since 1980). See also Table 7.2.

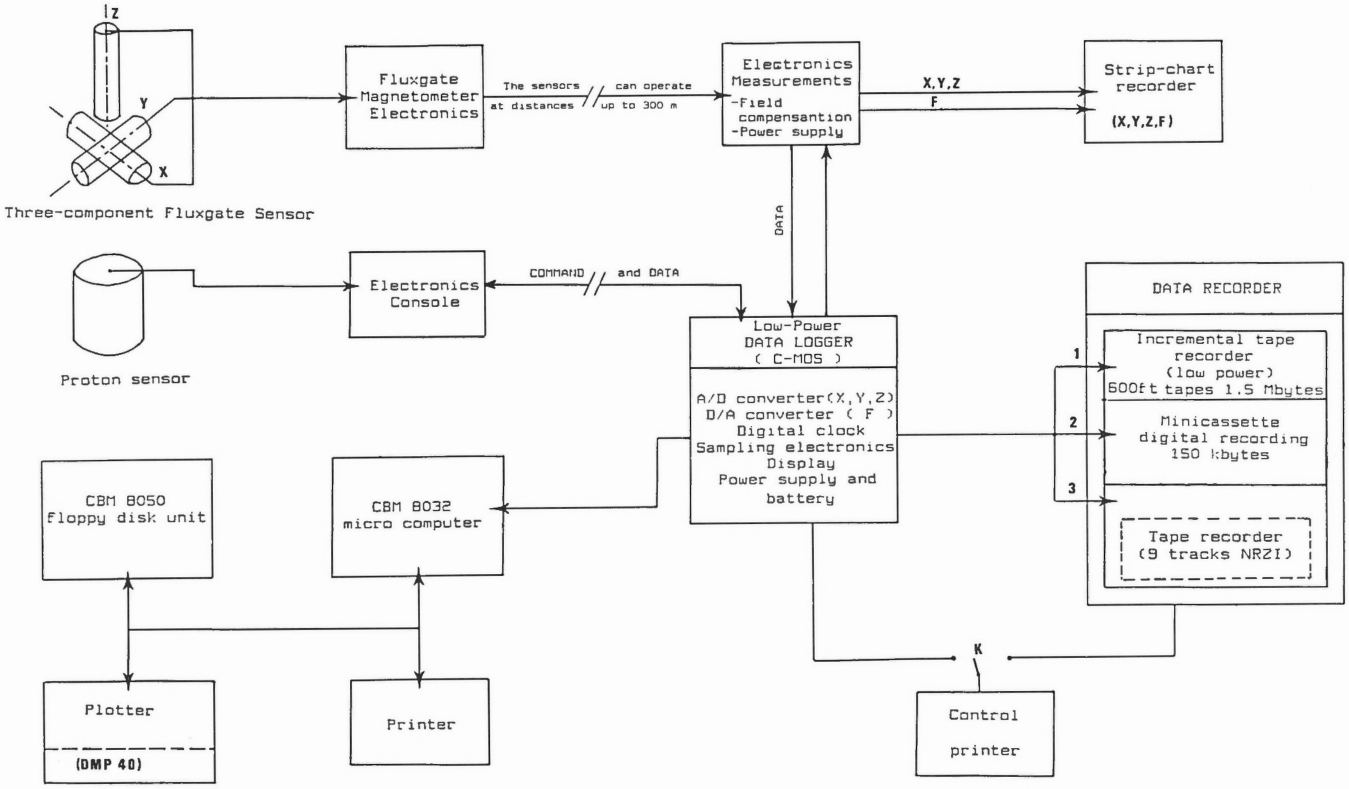
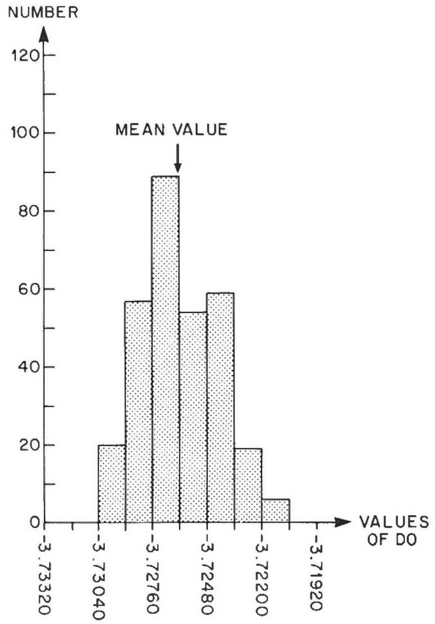


Figure 7.3 Block diagram of IPG digital magnetic observatory system.



BASE VALUES D_0 FOR PERIOD
MARCH 1985 – NOVEMBER 1986

DISTRIBUTION OF DEVIATIONS FROM THE MEAN
HISTOGRAM BASED ON 304 MEASUREMENTS
MEAN VALUE OF D_0 :−3 .7262°
MINIMUM VALUE :−3.7303°, MAXIMUM VALUE :−3.7211°
HISTOGRAM INTERVAL : 5" (EQUIVALENT TO 0.5 nT)

Figure 7.4 Histogram of base values of declination Do for Chambon la Forêt.

For the H and Z components, we know that the long-term stability of the Ho and Zo baseline values corresponding to the sensor's electrical zero mainly depends on the characteristics (homogeneity, stability) of the compensation field created to cancel the major portion of the geomagnetic field along the sensor axis.

At Chambon-la-Forêt for the period from March 1985 to November 1986 (280 series of measurements), the following results were obtained:

Mean value of H: Ho =	20883.1 nT, standard deviation 1.4 nT
Extreme (min)	20879.5
(max)	20885.0
Mean value of Z: Zo =	42097.4 nT, standard deviation 0.9 nT
Extreme (min)	42095.4
(max)	42099.9

One notes a weak seasonal variation of Ho and Zo baseline values that may reach 1.5 nT/month. The annual amplitude of thermal variation in the variometer is on the order of 5°C. However, despite the above noted facts, it remains difficult to determine the relative importance of the various electronic causes giving rise to this change.

In order to illustrate and quantify more precisely the concept of the VFO 31 variometer's long-term stability, we decided to analyze the baseline values at the Dumont d'Urville Observatory in Terre Adélie for the years 1984 (119 measurents) and 1985 (136 measurements). At this observatory, which is located 160 km from the south magnetic pole, the value of the Z component is very close to value of the total field.

For 1985, the annual values are:

Z = −69873 nT
F = −69886 nT
X = −1288 nT
Y = −445 nT

Figure 7.5 represents the values calculated respectively for Zo and for the difference of the total field existing between the variometer hut and the absolute measurement pier. This value is called Fo. It can be seen that the mean value of Zo in 1984 (−70007.1 nT) is within 1 nT of the mean value of Zo in 1985 (-70007.9 nT). The standard deviation was equal to 1.4 nT for these two consecutive years. These results and the close correlation observed between the residual fluctuations of Zo and those of Fo (reference proton magnetometer) show the remarkable stability of the VFO 31 variometer. In conclusion, we may state that in all cases, this long-term stability is better than 1 nT/month.

Failure rate

Since 1972 the mean failure rate of equipment installed in the French magnetic observatories amounts to:

- One failure every three years for the fluxgate variometer.
- Two failures per year for the digital acquisition system. The percentage of missing digital data, on an annual basis, is always less than 0.6 %.

Accuracy of the calculated field values

An overall estimation of the accuracy of the instantaneous values calculated from data supplied by the variometer VFO 31 may be obtained by comparing the value of the total field calculated on the basis of three elements (H, D, Z or X, Y, Z from the fluxgate) with the value measured directly by the associated proton magnetometer. This comparison has been systematically carried out since 1974 in the French austral observatories. The discrepancy associated with these determinations is less than 1 nT in 95 % of cases. In only less than 2 % of cases are the discrepancies greater than 2.5 nT.

Conclusion

The equipment described above has been operating in the French magnetic observatories since 1972, without interruption or significant incident. The selection of sensors made at that time (fluxgate combined with proton magnetometer) is unquestionably justified for equipping a magnetic observatory, given the sensors' simplicity of use and reliability, and the performance they deliver. Recent developments in the field of compatible microprocessors and microcomputers suggests the feasibility of a new generation of automatic magnetic observatories.

Table 7.2 High-latitude French magnetic observatories

Dumont d'Urville (Terre Adélie)	DUM	66°40'S,	140°01'E	75.6°S,	230.9°E	1973
Port-aux-Français (Kerguelen)	KGL	49°21'S,	70°12'E	56.5°S,	127.8°E	1972
Port Alfred (Crozet)	CZT	46°28'S,	51°52'E	51.2°S,	109.4°E	1974
Martin de Vivies (Amsterdam Island)	AMS	37°59'S,	77°34'S	46.5°S,	141.3°E	1980

The operation of the high latitude French magnetic observatories is the responsibility of the Territoire des Terres Australes et Antarctiques Françaises. These observatories are under the scientific responsibility of the Institut de Physique du Globe at Strasbourg.

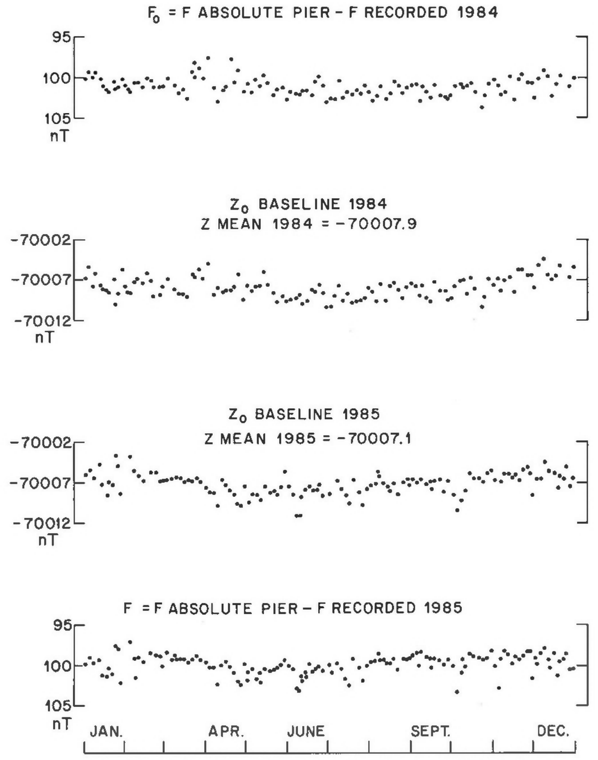


Figure 7.5 Baseline values for the triaxial variometer at Dumont d'Urville, 1984 and 1985.

References

Andersen, F.
1969: An automatic observatory (abstract); IAGA Bulletin No. 26, p.106.
1974: An automatic observatory system; Publications of the Earth Physics Branch, Ottawa, Canada, v.44, p.249-259.

Bitterly, J., Cantin, J.M., and Schlich, R.
1976: Enregistrement numérique des variations lentes du champ magnétique terrestre; A paper presented at the roundtable on systems for measuring magnetic and electric fields, Garchy, March 17-18, 1976. Report CRG/CAPT/03/1976, p.13.
1979: Enregistrement numérique des variations du champ magnétique dans les observatoires français de hautes latitudes; in Program and Abstracts, XVII IUGG General Assembly Canberra 1979, p.342.

Bitterly, J. and Cantin, J.M.
1979: Les magnétomètres 'fluxgate'; A paper presented at the seminar on magnetic sensors, Einsieg-Steen, Grenoble, November, 1979. Report CEPHAG No.18/80, p. 42-46.

Cadidi M., Orfei, R., Palutan F., and Vannaroni G.
1974: FFT analysis of a space magnetometer noise; IEEE Transactions on Geoscience Electronics (U.S.A.), v.GE-12, p.22-28.

DeLaurier,J.M., Loomer,E.I., Jansen van Beek,G., and Nandi,A.
1974: Editing and evaluating digitally recorded geomagnetic components at Canadian observatories; Publications of the Earth Physics Branch, Ottawa, Canada, v.44, p.235-242.

Medford, L.V., MacLennan, C.G., Rosenfeld, P.E., Lanzerotti, L.J., and Acuna, M.H.
1981: Low-power portable data acquisition system and its use in geomagnetic measurements; IEEE Transactions on Geoscience Electronics, v.GE-19, p.122-128.

Perrault, S. et al.
1978: French mobile station for recording geophysical data: description, initial results of the conjugated campaign in association with GEOS-1; ESA SP-135, June 1978, p.73-83.

Primdahl, F.
1979: The fluxgate magnetometer, Journal of Physics E: Scientific Instruments, v. 12, p. 241-253.

Schlich, R., Bitterly, J., Benzoni, A., and Halleguen, P.
1974: Observations magnétiques faites à l'observatoire de Port-aux-Français (Kerguelen), 1972; Fascicule of the Institut de Physique du Globe de Paris, p.1-53.

Serson, P.H.
1957: An electrical recording magnetometer; Canadian Journal of Physics, v.35, p.1387-1394.

Snare, R.C. and McPherron, R.L.
1973: Measurement of instrument noise spectra at frequencies below 1 Hertz; IEEE Transactions on Magnetics, v.MAG-9, no. 3, p.232-235.

Trigg, D.F.
1975: A high-capacity low power data logger; Publications of the Earth Physics Branch, Ottawa, Canada, Geomagnetic Series No.1, p.1-11.

Trigg, D.F., Serson, P.H., and Camfield, P.A.
1971: A solid-state electrical recording magnetometer; Publications of the Earth Physics Branch, Department of Energy, Mines and Resources, Ottawa, Canada, v.41, no.5, p.67-80.

8. CONCLUSION

In the ten days, or so, of the working Workshop a great deal was done outside the basic aim of operating a diverse set of instruments in one place over a fixed period of time. Exchange of views took place on all sorts of subjects related directly and indirectly to the principal objective. The wide range of subjects represented those particular concerns which were most pressing in the minds of each individual present. Engineers wanted to define observatory functions in technical terms. Manufacturers wanted to highlight production and testing. Observers were concerned about accuracy and reproduceability. Administrators were worried about staffing and training.

Most of these subjects do not receive airing at conventional international meetings and it is in this respect that the working Workshop was thought by all who attended it to be an enormous success. Most of those who were present recommend further working Workshops usually emphasizing rather more particular aspects of the instrumental and technical side of basic geomagnetism. The consensus seems to be that another general Workshop should occur in 4 to 6 years but that one addressing data capture, processing and presentation should take place within 2 to 3 years.

The open structure of meetings was generally successful in exploiting the expertise present and in encouraging individuals to elaborate on problems or opinions and also to address common issues which arose from the instrument work which was going on. Some topics would have been better treated by a more formal procedure, perhaps with a review given by invitation followed by discussion focussed on quite specific aspects of the topic. Some introductory talks about the physical principles of sensors and their practical operating characteristics would, in hindsight, have helped discussion of current and future trends or recommendations. It was very clear that the host institution has a great deal to contribute to this element of the work. One lesson learned at Ottawa is that in a working Workshop the host institute does as much work as all the other participants combined, not only in providing facilities and technical support but also in talking about problems, which can be of their own making or brought in by participants, and identifying the strengths and weaknesses of the instruments which are used.

The Geophysics Division of the Geological Survey of Canada did a magnificent job of providing facilities and manpower at all working levels of the Workshop, as well as doing the essential promotion and the management of the domestic arrangements. The contributions of its staff to discussions were essential. The GSC learned a great deal from the Workshop, a point for future hosts to consider, and profited greatly from the intense effort of its members of staff before, during and after the meeting. Hosting the meeting called for preparation of the site to accommodate many instruments, provision of electrical power, shelters and mechanical bits and pieces and provision of computer facilities to create common data files by which data from a wide variety of instruments recording on various media in various formats could be compared. Not all of the problems could be anticipated and the success of the Workshop depended entirely on the ability and the willingness of GSC staff to deal promptly and pleasantly with situations as they arose.

The observing community is a very isolated one. In general, observers do not attend IAGA meetings and not many IAGA scientists take an interest in or have responsibility for observational work. It would have been useful to have had one or two more scientists at the meeting specifically to review applications of observatory work. The Workshop was much more successful at attracting the attendance of observers. If this is a true conclusion, working Workshops should be held regularly. The isolation felt by observers who have little or no access to IAGA meetings was very strongly expressed as was their feeling that IAGA does not do enough for the observing community by way of advice or material assistance.

On the commercial front the meeting brought out the value of communication between users and manufacturers. At the beginning of the meeting each group seemed to think that its requirements or constraints were not compatible with the others'. By the end of the meeting it became clear that even the idealized aspirations of observers are achievable with modern commercial instruments, and at reasonable cost. It was also apparent that the observing community (and those performing experimental geomagnetism) represents a substantial market for sensors and data logging/processing equipment.

A generation gap was identified which is represented by older observers who have many years of actual experience using theodolites and absolute instruments and younger observers who, though competent, are still learning or re-inventing techniques. Most countries have personnel in one category or the other, not both. The Workshop brought these together to the obvious advantage of each. The generation gap also showed between those using classical absolute instruments and those using fluxgate 'null' methods, and both schools of thought benefitted from the ensuing exchange of views.

The Geophysics Division staff drew up some conclusions about how the Workshop could have been improved with the benefit of hindsight.

1. Although a Program Committee is necessary and should contain a rounded international membership, the onus for preparations, including identifying scientific issues in advance, falls almost entirely on the local organizers.
2. It is not possible to anticipate the instrumental work or the scientific discussions totally (e.g. there was an unexpected concentration by Europeans on absolute observations).
3. More disciplined instrument operation is needed. On set days instruments must be left strictly alone to operate undisturbed. All adjustments must be notified and documented. There should be one or two days for setting up and fiddling and for ad hoc ideas to be conceived. Such ideas should only be adopted at a fixed time after prior open discussion.
4. It takes 2 or 3 days to settle all the instruments down, so the Workshop should begin on a Monday to ensure availability of full technical support.
5. Temperature must be monitored in all rooms, on all sensors and on all electronics which may have a relevant thermal coefficient.
6. Absolute buildings must be treated with the full respect given to them in observatory conditions.
7. A limited range of data formats must be specified by the hosts to contributors. It may even be desirable to set a single standard data format because it is easier for each designer to translate to a standard than for hosts to make all the transformations. It would be useful for IAGA to consider guidelines for such a standard data format in view of changing computer preferences.
8. Early commitment of attendance is needed from scientific and commercial interests to optimize the chances of success in operation and data management.

Finally, the site at Ottawa was ideal for this first working Workshop not only because of the number of magnetically clean buildings but also of the adjacent workshops, offices and meeting areas. Dedicated computing facilities (with peripherals) were also on site as were all the personnel (scientific, technical and clerical) who were needed day by day in the organization, management and proceedings of the Workshop. These are almost minimum requirements and any institution willing to host a future working Workshop should measure its capability against that of the Geophysics Division of the GSC and would be advised to consult the GSC staff for advice.

W.F. Stuart

APPENDIX 1

A bibliography of magnetometers

This bibliography is the latest in a series, and does not contain references already listed in the previous editions:

Primdahl, F.
1970: Bibliography of fluxgate magnetometers; Publications of the Earth Physics Branch, Ottawa, 41, no. 2.

Serson, P.H. and Primdahl, F.
1972: Bibliography of magnetometers; Publications of the Earth Physics Branch, Ottawa, 43, no. 8.

The bibliography has grown out of one prepared by Fritz Primdahl, of the Danish Space Research Institute. Copies of his bibliography were made available at the Workshop in Ottawa, and it was subsequently suggested that it would be useful to include it in the proceedings. By consultations with a number of people associated with the Workshop, we have added some additional references, including some on proton precession magnetometry and D&I fluxgate theodolites. However, the vast majority of references were collected by Fritz Primdahl, and we acknowledge our indebtedness to him.

[R. L. Coles]

Abadeer, W. W. and Ellis, D. M.
1971: Magnetic field detection using coherent magnetization rotation in thin magnetic film; Journal of Applied Physics, v. 42, p.1439-1440.

Acuna, M. H.
1974: Fluxgate Magnetometers for outer Planets Explocation; IEEE Transactions on Magnetics, MAG-10, p.519-523.
1980: The MAGSAT precision vector magnetometer; Johns Hopkins APL Technical Digest, v. 1, p.210-213.
1981: MAGSAT – Vector magnetometer absolute sensor alignment determination; NASA Technical Memorandum 79648, Goddard Space Flight Center, Greenbelt, Maryland 20771, U.S.A.

Acuna, M.H. and Ness, N.F.
1975: The Pioneer XI High Field Fluxgate Magnetometer; Space Science Instrumentation, (Netherlands), v.1, no. 2., p. 177-178.

Acuna, M. H., Scearce, C.S., Seek, J. B. ,and Scheifele, J.
1981: The MAGSAT vector magnetometer — a precision fluxgate magnetometer for the measurement of the geomagnetic field; NASA Technical Memorandum 79656, Goddard Space Flight Center, Maryland, 20771, U.S.A.

Adams, D. F., et al.
1976: Vector magnetometer design study of a triaxial fluxgate sensor design demonstrates that all MAGSAT vector magnetometer specifications can be met; Final Report, N77-13390, Ball Brothers Research Corporation, Aerospace Division, Time-Zero Laboratories, 1488 W, 178th st., Gardena, CA90247, U.S.A.,173 p.

Afanasenko, M. P., Berkman, R. J., Bondaruk, B. L., and Itchkovich, A. B.
1974: Multiple component magnetic field intensity meter with a ring ferromagnetic probe; Otbor i Peredacha Informatsii (USSR), No. 41, p.92-98.

Afanasiev, J. V.
1984: Calculation of maximum field strength for ferroprobe excitation; Measurement Techniques (Transl. from Russian); v. 27, p. 551-554, Plenum.

Afanasiev, J. V., and Bushuev, L. J.
1978: Three component ferroprobe; Pribori I Sistemi Upravlenia, no. 1, p. 29-31, (in Russian).

Alex, T. K.
1977: High precision magnetometer using COSMOS circuits; Electronic Engineering, v. 49, p.27-28.

Andersen, F.
1973: Telephone verification system for automatic magnetic observatories; Publications of the Earth Physics Branch, v.44, no. 5.
1974: An automatic magnetic observatory system; Publications of the Earth Physics Branch, v. 44, no. 11.

As, J. A.
1973: The compensation method for measuring the components of the Earth's magnetic field; Zeitschrift fur Geophysik, v. 39, p. 303-311.

Auster, V.
1984: Geomagnetic absolute measurements with a nuclear resonance theodolite at the Adolf Schmidt Observatory in Niemegk; Geophysical Surveys, v. 6, p. 269-270

Barker, R. C.
1965: On the analysis of second-harmonic modulators; IEEE Transactions on Magnetics, MAG-1, p. 337-341.

Behannon, K. W., Acuna, M. H., Burlaga, L. F., Lepping, R. P., Ness, N. F. and Neubauer F. M.
1977: Magnetic field experiment for Voyager 1 and 2; Space Science Reviews, v. 21, p. 235-257.

Bell, M. E.
1979: 3 axis fluxgate magnetometer sensor; Canadian Patent Application, Filed on or about Jan. 9/79, File No. 265-6950-2. Canada Patents and Developments Ltd., 275 Slater Street, Ottawa, Canada, K1A OR3.

Bergmark, T.
1984: Experience of geomagnetic field recording with a fluxgate magnetometer having a bridge sensor; Geophysical Surveys, v. 6, p. 381-391.

Berkman, R. J., and Sinitskii, L. A.
1962: On the maximum possible gain of a magnetic modulator having an output at twice the frequency, and means of realizing it; Automatika i Telemekhanika, v. 23, p. 1385-1392.

Berkman, R. J., et al.
1972: The ferroresonant excitation regime for magnetic modulators and ferroprobes; Geofizicheskaya Apparatura, (U.S.S.R.), No. 50, p. 20-28.

Bittel, H.
1969: Noise of ferromagnetic materials; IEEE Transactions on Magnetics; MAG-5, p. 359-365.

Bitterly, J., Cantin, J. M. Schlich. R. and Folgues J.
1984: Portable magnetometer theodolite with fluxgate sensor for Earth magnetic field component measurements; Geophysical Surveys, v. 6, p. 233-239.

Brankoff, K.
1960: Aufbau eines Magnetfeld Messgerätes nach dem Oberwellenverfaren; Nachrichtentecknik, v. 10, p. 247-256.

Brown, R. E.
1972: A miniature fluxgate magnetometer with sub-gamma noise (DIGEST); IEEE Transactions on Magnetics; MAG-8, p. 589.

Burger, J. R.
1972a: The theoretical output of a ring-core fluxgate sensor; IEEE Transactions on Magnetics; MAG-8, p. 791-796.
1972b: Comments on "Sensor noise in low-level flux-gate magnetometers"; IEEE Transactions on Magnetics; MAG-8, p.797-798.

Cahill, L. J., Jr.
1963: A study of the outer geomagnetic field; IEEE Transactions on Nuclear Science, NS-10, p. 10-19.

Candidi, M., Orfei, R., Palutan, F. and Vannaroni G.
1974: FFT analysis of a space magnetometer noise; IEEE Transactions on Geoscience Electronics (USA), GE-12, p. 23-28.

Chamalaun, F. H. and Walker, R.
1982: A microprocessor based digital fluxgate magnetometer for geomagnetic deep sounding studies; Journal of Geomagnetism and Geoelectricity, v. 34, p. 491-507.

Chiron, G., and DeLapierre, G.
1979: Description of a thin film directional magnetometer; IEEE Transactions on Magnetics; MAG-15, p. 1815-1817.

Coon, C. W.
1965: Thermally cycled magnetometer; NASA U.S. Patent 3.564.401, Aug. 1965.

DeLaurier, J.M., Loomer, E. I., Jansen van Beek, G. and Nandi, A.
1974: Editing and evaluating digitally recorded geomagnetic component at Canadian observatories; Publication of the Earth Physics Branch, Ottawa, v. 44, no. 9.

Drosdziok, S.
1973: Magnetometersonden kleinster Abmessungen zur Messung kleiner Magnetfelder, (ATM); Arkiv für technisches Messen, Blatt V391-12, p 189, Lfg. 453.

Drozhzhina, V. I., and Retov, Y. J.
1973: A simple ferroprobe magnetometer; Soviet Journal of Nondestructive Testing, (U.S.A.), v. 9, p. 102-103.

Dyal, P. and Gordon, D.I.
1973: Lunar surface magnetometers; IEEE Transactions on Magnetics, MAG-9, p. 226-231.

Forbes, A. J., and Riddick, J.C.
1984: The Digital recording system operated at the UK magnetic observatories; Geophysical Surveys, v. 6, p. 393-405.

Gao, Z.-C. and Russell, R.D.
1987: Fluxgate sensor theory: stability study; IEEE Transactions on Geoscience and Remote Sensing, GE-25, p. 124-129.

Gise, P. E., and Yarbrough, R. B.
1975: An electrodeposited cylindrical magnetometer sensor; IEEE Transactions on Magnetics, MAG-11, p. 1403-1404.
1977: An improved cylindrical magnetometer sensor: IEEE Transactions on Magnetics, MAG-13, p. 1104-1106.

Goldschmidt, R.
1910: Die Verkleinerung der Hystereseverluste durch Ströme hoker Frequenz und das Verhalten des Eisens bei Längs — und Quer-Magnetisierung; Electrichnische Zeitschrift, Heft 9, p. 218-221.

Gordon, D. I., and Brown, R. E.
1972: Recent advances in fluxgate magnetometry; IEEE Transactions on Magnetics MAG-8, p. 76-82.

Gordon, D. I., and Lundsten, R. H.
1970: Low field magnetometer sensor of high stability; Revue de Physique Appliquée, v. 5, p. 175-177.

Gordon, D. I., Brown, R. E. and Haben, J. F.
1972: Methods for measuring the magnetic field; IEEE Transactions on Magnetics, MAG-8, p. 48-51.

Gordon, D. I., Lundsten, R. H., Chiarodo, R. and Helms, H. H. Jr.
1967: A highly stable fluxgate magnetometer for space exploration; Symposium on Space Magnetic Exploration and Technology, Reno, Nevada, Aug. 28-30, 1967. (Univ. of Nevada and NASA/AMES Research Center).

Gore, W.
1974: Analysis and design of a fluxgate magnetometer; Publication No. 78-1445, Institute of Geophysics and Planetary Physics, UCLA.

Hedgecock, P. C.
1974: Magnetometer experiments in the European Space Research Organization's HEOS satellites; Space Science Instrumentation, v. 1, p. 61-82.
1975: A correlation technique for magnetometer zero level determination; Space Science Instrumentation, v. 7, p.83-90.

Hegymegi, L., and Drimusz, L.
1984: An intelligent digital magnetic recording system; Geophysical Surveys, v. 6, p. 317-321.

Heinecke, W.
1978: Fluxgate magnetometer with time coded output signal of the sensor; IEEE Transactions on Instrumentation and Measurement, IM-27, p. 402-405.
1981: Magnetfeldmessung mit Saturationskernsondenmagnetometern; Technisches Messen, v. 391-13, 48, p. 3-9.

Heppner, J. P., and Boroson, H. R.
1966: Wide range linear fluxgate magnetometer; U.S Patent Office 3.258.687, 28 June 1966.

Higuchi, T.
1970: A statistical mode of core noise in half-wave push-pull magnetic amplifiers; IEEE Transactions on Magnetics, MAG-6, p. 847-849.
1971: Experimental study of core noise in various ferromagnetic materials; IEEE Transactions on Magnetics, MAG-7, p.316-319.

Ions, H. R., and Schwec, L. J.
1972: Magnetic thin film magnetometers for magnetic-field measurement; IEEE Transactions on Magnetics, MAG-8, p.61-65.

Jankowski, J., Marianiuk, J., Ruta, A., Sucksdorff, C., and Kivinen M.
1984: Long-term stability of a torque-balance variometer with photoelectric converter in observatory practice; Geophysical Surveys, v. 6, p. 367-380.

Kelly, J. M.
1951: Magnetic field measurement with peaking strips; Review of Scientific Instruments, v. 22, p. 256.

Kerr, D.
1972: A direct reading, total feed-back, high performance airborne fluxgate magnetometer; Proceedings of the Institution of Radio & Electronic Engineers Australia, v. 33, p. 339.

Kono, M., Koyanagi, M., and Kokubin S.
1984: A ring-core fluxgate for spinner magnetometer; Journal of Geomagnetism and Geoelectricity, v. 36, p. 149-160.

Kring Lauridsen, E.
1980. Absolute measurements with proton magnetometers in stationary coils; Danish Meteorological Institute, Geophysical Papers, Copenhagen, R-57.
1984: Absolute measurements of D by means of a proton magnetometer; Geophysical Surveys, v. 6, p. 223-232.
1985: Experiences with the DI-fluxgate magnetometer inclusive theory of the instrument and comparison with other Methods; R-71, Geophysical Papers, Danish Meteorological Institute, Copenhagen.

Kuwashima, M., and Sano, Y.
1984: Improved Kakioka Automatic Standard Magnetometer (KASSMER); Geophysical Surveys, v. 6, p. 357-365.

Langvagen, E. N.
1975. A ferroprobe with rotating field excitation; Geofizicheskaya Apparatura (USSR), no. 5, p. 31-37.

Lepping, R. P., and Ness, N. F.
1978: An extension of the dual magnetometer method for use on a dual spinning spacecraft; Journal of Geophysical Research, v. 83, p. 2211-2215.

Ledley, B. G.
1970: Magnetometers for space measurements over a wide range of field intensities; Revue de Physique Appliquée, v. 5, p.164-168.

Luhr, H., Thurey, S., and Klocker, N.
1984: The EISCAT magnetometer cross; Geophysical Surveys, v. 6, p. 305-315.

Marshall, S. V.
1973: Impulse response of a fluxgate sensor — application to lightning discharge location and measurement; IEEE Transactions on Magnetics, MAG-9, no. 3, p. 235-238.
1977: Using an inverter to measure magnetic fields; IEEE Transactions on Magnetics, MAG-13, p. 1116-1118.

McPherron, R. L., and Snare, R. C.
1978: A procedure for accurate calibration of the orientation of the three sensors in a vector magnetometer; IEEE Transactions on Geoscience Electronics, GE-16, no.2, p.134-137.

McPherron, R. L., Coleman, P. J., Jr., and Snare, R. C.
1975: ATS-6 UCLA fluxgate magnetometer; IEEE Aerospace Electrical Systems, AES-11, p. 1110-1116.

Medford, L. V., Maclennan, C. G., Rosenfeld, P. E., Lanzerotti, L. J., and Acuna, M. H.
1981: Low-power portable geophysical data acquisition system and its use in geomagnetic measurements; IEEE Transactions on Geoscience and Remote Sensing, GE-19, no. 3, p. 122.

Meitzner, W.
1965: Zur Anwendung der Förster-Sonde bei Gesteinsmagnetischen Arbeiten; Zeitschrift für Geophysik, p. 332-344.

Meloni, A., Molina, F., Palangio, P., Taccetti, Q., and DeSantis, A.
1984: Automatic digital recording of geomagnetic elements by means of a proton precession magnetometer; Geophysical Surveys, v. 6, p. 339-350.

Mizuno, Y., Fukui, F., Hashimoto, M., and Takada M.
1987: Stability of vector proton magnetometer at Memambetsu Magnetic Observatory; Memoirs of the Kakioka Magnetic Observatory, Japan, v. 22, no.1.

Mohri, K., Takeuchi, S. and Fujimoto, T.
1981: Sensitive magnetic sensors using Wiegand-type ribbons; IEEE Transactions on Magnetics, MAG-17, No. 6, p.3370-3372.

Mohri, K.
1984: Review on recent advances in the field of amorphous-metal sensors and transducers; IEEE Transactions on Magnetics, MAG-20, No. 5, p. 942-947.

Morton, B. R., and Suckau, K. P.
1976: A micro power fluxgate magnetometer for remote operations; MONITOR-Proceedings of the IREE Australia, v. 37, p.272-277.

Musmann, G., and Maier, A.
1972: Das Förstersondenexperiment E2 in HELIOS A und B; GAMMA, v. 21, 133 p.

Naito, Y., Tomoda, Y., Uchiyama, A., Ohkura, Y., Nagayama, Y., and Takahashi, Y.
1984: Geomagnetic observations at the Sagami Trough by use of a new type of three-component ocean bottom magnetometer; Journal of Geomagnetism and Geoelectricity, v. 36, p.239-256.

Narod, B. B. and Russell, R. D.
1984: Steady-state characteristics of the capacitively loaded fluxgate sensor; IEEE Transactions on Magnetics, MAG-20, no. 4, p. 592-7.

Narod, B. B., Bennest, J. R., Strom-Olsen, J.-O., Nezil, F., and Dunlap, R. A.
1985: An evaluation of the noise performance of Fe, Co, Si, and B amorphous alloys in ring-core fluxgate magnetometers; Canadian Journal of Physics, v. 63, p. 1468-1172.

Ness, N. F.
1970: Magnetometers for space research; Preprint x-690-70-78, (NASA TM X-63887), available from: Clearinghouse N70-25202.

Neubauer, F. M., et al.
1986: The Giotto magnetic-field investigations; in The GIOTTO Mission, ed. R. Reinhard and B. Battrick, ESA SP-1077, ESA Publications Division.

Owen, T. R. E., and Sik, J. M.
1972: A three component fluxgate magnetometer for sea-bottom use; Oceanology International '72, p. 37-40, Department of Geodesy and Geophysics, Cambridge University, England.

Pedersen, B. O.
1960: Phase-sensitive detection with multiple frequencies; IRE Transactions on Instrumentation, I-9, p. 350-355.

Pelen, J.
1966: Un Nouveau Magnetometre de Restitution D'Attitude; Sciences et Industries Spatiales, (Suisse); v. 2, p.55-64.

Pelen, J., Guillemin, G., and Schillinger, A.
1969: Le Magnetometre de Restitution d'Attitude du Satellite Aurorae; L'Onde Électrique, v. 49, p. 442-448.

Pellerin, C. J. Jr., and Acuna, M. H.
1968: Two axis fluxgate magnetometers; US Patent Office 3,571,700, Dec. 1968.
1979: A Miniature Two-axis Fluxgate Magnetometer; NASA TN D-5325, National Aeronautics and Space Administration, Washington D.C., U.S.A.

Peters, T.J.
1986: Automobile navigation using a magnetic fluxgate compass; IEEE Transactions on Vehicular Technology, VT-35, p.41-47.

Podsklan, J., and Kovac, I.
1984: One year experience with the CMVS 2 magnetic variation station; Geophysical Surveys, v. 6, p. 335-338.

Ponomarev, Y. F.
1975: Conversion coefficient of even-harmonic ferroprobes with longitudinal excitation; Defektoskopiya, no. 1, p. 49-56.

Power, J. J.
1973: A digital offset fluxgate magnetometer for use in remote geomagnetic observatories; University of California, Los Angeles, Institute of Geophysics and Planetary Physics, AD-777 885, IGPP-1247-37,AFCRL-TR-73-0603, F19628-72-C-0175.

Primdahl, F.
1970: A ferrite core fluxgate magnetometer; Danish Meteorological Institute, Geophysical Papers, R-12.
1973a: Comments on "The theoretical output of a ring core fluxgate sensor"; IEEE Transactions on Magnetics, MAG-9, p. 708.
1973b: Fluxgate sensors, principles and properties; Danish Meteorological Institute, Geophysical Papers, R-36.
1979: The fluxgate magnetometer; Journal of Physics E: Scientific Instruments, v. 12, p. 241-253.

Primdahl, F., and Jensen, P. A.
1982:9 Compact spherical coil for fluxgate magnetometer vector feedback; Journal of Physics E: Scientific Instruments, v. 15, p. 221-226.
1987: Noise in the tuned fluxgate; Journal of Physics E: Scientific Instruments, v. 20, p. 637-642.

Reutov, Y. J.
1973: A ferromagnetic probe magnetometer with rectangular excitation; Defekloskopiya, v. 9, no. 2., p. 34-38.

Roy, J. L., Robertson, W. A. and Keeping, C.
1969: Magnetic "field free" spaces for paleomagnetism and other studies; Canadian Journal of Earth Sciences, v. 6, p.1312-1316.

Russell, C. T.
1974: Apollo particles and fields subsatellite magnetometer experiment; Final Report for NASA Contract NAS 9-12236, N74-33265.
1978: The ISEE 1 — and 2 fluxgate magnetometers; IEEE Transactions on Geoscience Electronics, GE-16, p. 239-242.

Russell, R. D., Narod, B., and Kollar, F.
1983: Characteristics of the capacitively loaded fluxgate sensor; IEEE Transactions on Magnetics, MAG-19, p.126-130.

Saito, T., Sakurai, T., Yumato, K., and Tamura, T.
1980: Magnetometers for geophysical use. Part I. Fluxgate magnetometer with a 0.5 m length two-core sensor; Science Reports of Tohoku University, Ser. 5, v. 27, no. 2, p.85-93.

Saito, T., Sakurai, T., Yumoto, K., Tamura, T., Seto, M., Hayasaka, T., and Aoyama, I.
1980: Magnetometers for geophysical use. Part 2. Test of twelve kinds of ring core; Journal of Geomagnetism and Geoelectricity, v. 32, p. 649-659.

Sanderson, T. R.
1972: A three-axis magnetometer with digital readout, suitable for balloon borne apparatus; Nuclear Instruments and Methods, v. 105, p. 371-376.

Scarzello, J. F., and Usher, G. W., Jr.
1977: A low power magnetometer for vehicle detection; IEEE Transactions on Magnetics, MAG-13, p. 1101-1103.

Scarzello, J. F., Lenko, D. S., Brown, R. E., and Krall, A. D.
1978:9 SPVD: a magnetic vehicle detection system using a low power magnetometer; IEEE Transactions on Magnetics, MAG-14, p. 574-576.

Schlich, R., Bitterly, J., Deininger, R., and Denier, P.
1975: Observations magnétiques faites à l'Observatoire de Dumont d'Urville Terre Adélie 1974; Institut de Physique du Globe, Univ. Pierre et Marie Curie, Paris, France.

Schonstedt, E. O.
1963: Adjustable magnetic core; U.S. Patent Office, 3,076,930.
1965: Magnetic flux directing cylindrical core having a plurality of serially arranged interruptions; U.S. Patent Office, 3,168,696.
1969a: Magnetic field sensor including means to minimize permanent magnetization; U.S. Patent Office, 3,426,269.
1969b: Core assembly of prefabricated parts for a magnetic field sensor; U.S. Patent Office, 3,439,264.
1975: Magnetic locator having sensor units with two-piece housings and tubular cores; U.S. Patent Office, 3,909,704.
1976: Magnetic locator having improved sensors; U.S. Patent Office, 3,961,245.

Schulz, G., and Carstens, U.
1979: A period measuring proton magnetometer with a direct readout; Deutsche Hydrographische Zeitschrift, v. 32, p.119-125.

Schwarts, W., and Nelms, W. L.
1969: Mechanical aspects of the Lunar Surface Magnetometer; 3rd Aerospace Symposium, p. 133-138, (Available from Clearinghouse N69-11816).

Scouten, D. C.
1970: Barhausen discontinuities in the saturation region; IEEE Transactions on Magnetics, MAG-6, p. 383-385.
1972: Sensor noise in low-level fluxgate magnetometers; IEEE Transactions on Magnetics, MAG-8, p. 223-231.

Seek, J. B., et al.
1974: GSFC Magnetic field experiment explorer 43; NASA TM X 70 609, 52 p, N74-19089.

Serson, P. H.
1973: Instrumentation for induction studies on land; Physics of the Earth and Planetary Interiors, v. 7, p. 313-322.
1974: Compact bias coil systems for geomagnetic measurements; Publications of the Earth Physics Branch, Ottawa, v. 44, p. 243-247.

Serson, P. H. and Primdahl, F.
1972: Bibliography of magnetometers; Publications of the Earth Physics Branch, Ottawa, v. 43, no. 8.

Shirae, K.
1984: Noise in amorphous magnetic materials; IEEE Transactions on Magnetics, MAG-20, p. 1299-1301.

Shturkin, D. A.
1971: Some peculiarities of ferromagnetic probes with longitudinal excitation in measuring magnetic fields over a wide intensity range; Defektoskopiya, No. 6., p. 76-89.

Sitbon, P., and Crespin, J.
1971: Un Magnétométre Pour Ballon Plafonnant; L'Onde Electrique, v. 51, No. 1, p. 44-48.

Skillmann, T. L.
1970: ATS-E magnetic field monitor instrumentation; GSFC, Preprint X-645-70-54.

Smit, J.
1959: The reversible permeability in a biased state; in Ferrites, Chapter. 13, section. 49.1, p. 260-262, Wiley and Sons.

Smith, E. J. and Sonett, C. P.
1976: Extraterrestrial magnetic fields: achievements and opportunities; IEEE Transactions on Geoscience Electronics, GE-14, p. 154-171.

Snare, R. C. and Means, J. D.
1977: A magnetometer for the Pioneer Venus Orbiter; IEEE Transactions on Magnetics, MAG-13, p. 1107-1109.

Snare, R. C. and McPherron, R. L.
1973: Measurement of instrument noise spectra at frequencies below 1 Hertz; IEEE Transactions on Magnetics, MAG-9, p.232-235.

Snare, R. C., Peters, D. J., Coleman, P.J., Jr., and McPherron, R.L.
1973: Digital data acquisition and processing from a remote magnetic observatory; IEEE Transactions on Geoscience Electronics, GE-11, p. 127-134.

Stuart, W. F.
1972: Earth's field magnetometry; Reports on Progress in Physics, v. 35, p. 803-881.
1984: Geomagnetic Observatory and Survey Practice; editor, reprinted from Geophysical Surveys, v. 6, D. Reidel, Dordrecht/Boston.

Stumm, W.
1973: Techniken der Messung Magnetischer Felder und ihrer Anwendung; Messen und Prüfen, v. 9, p. 29-33, 83-86.

Takeuchi, S. and Harada, K.
1984: A resonant-type amorphous ribbon magnetometer driven by an operational amplifier; IEEE Transactions on Magnetics, MAG-20, p. 1723-1725.

Takeuchi, S., Ichioka, S., and Harada, K.
1973: Analysis of mechanism of orthogonal fluxgate thin-film magnetometers; Electrical Engineering in Japan, v. 93, no. 1, p. 130-136.

Theile, B, and Lühr, H.
1976: Magnetfeldmessungen an Bord von Höhenforchungsraketen; Raumfahrtforschung, nr. 6, p. 301-305.

Trenkeer, G.
1972: Verfahren zur Electrichen Messung Magnetischer Felder; Messen und Prüfen, v. 8, p. 535-538, 624-627, 705-708, 793-797.

Trigg, D. F. and Nandi, A.
1984: The automatic magnetic observatory system AMOS III; Earth Physics Branch, Ottawa, Geomagnetic Series, no. 27.

Valet, J.-Y.
1970: Utilisation d'une couche magnétique mince pour la mesure des champs magnétiques très faibles; Centre d'Etudes Nucléaires de Grenoble, Rapport CEA-R-3930.

Van Bree, J. L. M. J., Poulis, J. A., and Hooge, F. N.
1974: Barkhausen noise in fluxgate magnetometers; Applied Scientific Research, v. 29, p. 59-68.

Verma, J. K. D., Raju, V., and Aggarwal, M. D.
1972: Measurement of magnetic field; a bibliographical review; Nuclear Instruments and Methods, v. 104, p. 545-574.

Voppel, D.
1972: The proton vector magnetometer at Wingst Observatory; Deutsches Hydrographisches Institut, Erdmagn. Jahrb. v. 17, p. 133-149.

Washino, S. and Ura, K.
1973: A ring-core type fluxgate magnetometer operating at 4.2 K; Japanese Journal of Applied Physics, v. 12, no. 5, 766.

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Former head of Instrumentation,
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Spouses in attendance

Madame Gilbert
Mrs. Hrvoic
Madame Periou
Mrs. Svendsen

Local Organizing Committee	**Geophysics Division, GSC/EMR**
Richard Coles (Chairman)	Head, Geomagnetism
Ron Niblett	Chief Scientist
Doug Trigg	Head, Geophysical Instrumentation
Gerrit Jansen van Beek	
Larry Newitt	

Technical and Support Staff at the Geomagnetic Laboratory

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Glenn Brown
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Bob Schieman
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APPENDIX 3

Impressions from participants

During the Workshop, participants were invited to submit a few paragraphs describing their impressions of the workshop, including suggestions where they felt them appropriate. Some of the comments contained common themes and it is these that Dr. Stuart has largely emphasized in his concluding remarks in Section 7. However, it was felt that since individuals had taken the time to express themselves, sometimes on points that were not raised by anyone else, a compilation of some of the detailed comments should be included in the Proceedings. With minor changes, only to alleviate language problems, some of these comments follow (with their sources). The participants all commended the workshop itself and the organizers.

Most helpful was to be able to discuss the instruments with commercial instrument producers. It was also interesting to see how difficult it was to have the "compatible" microcomputers understand each other. **(Sucksdorff and Hakkinen).**

In our Division of Geophysics only a few people are interested in or have experience with magnetic observatory instruments. For me therefore the workshop was an excellent opportunity to meet people who work in the field of geomagnetic instrumentation and to see the developments which are going on in other countries (**Rietman**).

The ability for industry to mix with the specialist end-user is always of great value and so was the case here. You have helped us learn a lot, subject our equipment to "in the field" environments and above all raised a lot of questions (**Bell and Hellard**).

I think that this kind of experience must be repeated as frequently (and conveniently) as possible, trying to maintain the informal way of interchanging opinions and experiences (**Orozco**).

I hope this (kind of) Workshop is held often, to discuss the problems of common interest on ideal automatic magnetic observatories, and to exchange experience and learn from each other so that we can raise the measured accuracy in magnetometers (**Liu Chang-fa**).

I had expected it to be successful but I can say it exceeded my expectations. . . The only things I can think of that would have made the workshop even more valuable would have been if there had been additional instruments from several other important national systems, such as Japan, Australia, and South Africa — and if there had been more shoppers from other countries (**Svendsen**).

It is felt that while the status of the delegates was ideal, their numbers were a little disappointing. This was obviously not the fault of the organizers but an effect of the general economic climate **(Chapman).**

From a manufacturer's perspective, there are very few venues where we can sit with many of our end-users and discuss in a "non-confrontational" atmosphere, the pros and cons of the instrumentation that we supply. I felt that your workshop allowed the users and manufacturers to meet on common ground to discuss not only the current equipment available, but what we are jointly going to strive for in equipment needed in the future (**Smith**).

It offered an insight into the operation of a modern magnetic observatory with a massive amount of data being taken and processed. We also noticed a shortcoming through a lack of well-defined standards for data formats, processing and presentation. We would also like to suggest graded standards for the instrumentation performance, i.e. recommended standards for the first class, second best and just satisfactory operations (**Hrvoic**).

Absolute measurements — Based on today's technology, I have to state that there is no sense to continue the discussion on this matter and, for the sake of history and evolution, I would suggest we save this terminology for the proton precession measurements (PPM). In conclusion I would say that the term "absolute" is an anachronism. **(Turewicz).**

Observatories contemplating adopting digital recordings should not necessarily opt for the best or most comprehensive system on the market. It is better to choose a simpler one, even if it is less than ideal, and use it to develop operating procedures and skills. The local commercial availability of computer hardware, peripherals and software are as important as the system specification in terms of observatory standards **(Stuart).**