Notes on geomagnetic observatory and survey practice

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Preface

Between 1964 and 1968 Unesco and the World Magnetic Survey Board collaborated in organizing four geomagnetic advisory missions of experts who visited, successively, magnetic observatories and survey organizations in Africa, South America, the Middle East and South-East Asia. The principal objectives of these missions were to calibrate the standard geomagnetic instruments used for magnetic surveys in the countries visited, to collect information on the surveys already carried out or in progress and to give instruction where necessary in the use of geomagnetic survey instruments.

It will be recalled that the World Magnetic Survey was begun in 1958, under the auspices of the International Council of Scientific Unions (ICSU), as part of the programme of the International Geophysical Year (IGY). Its aim was to collect the data required for a full description of the Earth's magnetic field, leading not only to a better understanding of the origin of this field but also to more accurate magnetic charts for maritime and aeronautical navigation. A knowledge of the general magnetic field of the Earth, and its temporal variations, is also indispensable for the interpretation of the magnetic data acquired in prospection for certain minerals.

The experts who carried out the four advisory missions were unanimous in calling attention to the need for an up-to-date practical handbook on geomagnetic observatory and survey practice, intended for the use of the scientific and technical personnel engaged both in observatory and in field work. The present publication is an attempt to meet this need, and it is hoped that it will prove a valuable companion to those who have the task of keeping watch on the Earth's magnetic field and on its changes. The advent of new methods and techniques and the launching of satellites into outer space, far from diminishing the value of observations made at the Earth's surface, have indeed enhanced their importance and rendered indispensable a high standard of accuracy.

The Organization's thanks are due to Dr. Karl Wienert for having undertaken the arduous task of preparing the text and illustrations, a task for which he was specially qualified by his wide experience of geomagnetic work in many parts of *the world, and to the chairman and members of the World Magnetic Survey Board for their invaluable advice and assistance.*

The designations employed and the presentation of the material in this publication do not imply the expression of any opinion whatsoever on the part of the Secretariat concerning the legal status of any country or territory, or of its authorities, or concerning the delimitations of the frontiers of any country or territory.

Contents

Introduction

The advent of the space age has aroused widespread interest in geomagnetic research. As a consequence, the number of geomagnetic observatories has considerably increased during the last decade. Numerous installations are run by individuals who have not had the opportunity to receive intensive training at well-established observatories. In fact, the operators of most of the new observatories are usually inexperienced in the procedures and the attitude of mind which are necessary for maintaining an observatory at the standards nowadays required. Though many are trained physicists with adequate scientific background, in approach to observatory techniques they are in the best sense amateurs and it is this deficiency which leads to the results of their labours not being so perfect as the International Association of Geomagnetism and Aeronomy could wish.

From 1964 to 1968, Unesco and the World Magnetic Survey Board sent missions to Africa, South America, the Middle East and South-East Asia, in order to assess the situation of geomagnetic work there. Reports on these missions showed that the operation of a geomagnetic observatory is an art which cannot readily be learned from modern textbooks and manuals. Many of the old elaborate textbooks, observatory reports and survey publications, which in many respects were perfect 'Do it Yourself' instructions, are out of print. Hazard's *Directions for Magnetic Measurements* has recently been reprinted. Much of it is still valid but the progress of the last thirty years has not been dealt with. McComb's *Magnetic Observatory Manual* mainly describes work with the variometers, assuming that the reader is a fully trained geomagnetician. Fanselau's Handbook (volume II) deals with all aspects of geomagnetic work but is written in German. Discussions with young observatory workers have revealed that too little has been said about basic tradesmanship. In these circumstances the novice has to collect much experience at a high cost before he can produce useful and dependable results. This booklet is intended to fill part of the gap. Its layout is such that together with McComb's *Observatory Manual* it may provide advice to the novice in geomagnetic observational and processing techniques as well as to the intelligent technician. It will try to explain in simple terms and unambiguous language the basic principles of observatory operation and surveying and to stress important facts which are commonplace to the professional geomagnetician. In some instances it has been considered desirable not only to describe a procedure but also to say how it should not be done.

McComb's *Observatory Manual* was written at the end of the Gaussian and Lamontian period and just touched the La Courian age, which is still in full bloom. However, thirteen years ago, new methods, powerful beyond the imagination of numerous of those who handled magnets or even electric currents for geomagnetic measurements, were invented. It now seems that at the present time the methodology of geomagnetic measurements is in a turmoil. All three eras will be covered so that the reader may find his bearings himself. It will be shown how old (classical) methods can be efficiently combined with modern methods without undue financial outlay.

In order to damp a bit the enthusiasm for the new it may be stated that the classical methods are still and will continue for some time to be adequate when expertly handled. The difference between the methods is that with classical equipment the (good) observer is an integral part of the instrument while with modern equipment the technician may take his place. However, the critical scientist cannot be disposed of.

What is written in this text is not 'The Geomagnetician's Holy Scripture'. There is nothing more adverse to progress than considering something as standard and invariable. The methods described here are naturally more or less standard and are in use at numerous observatories but this does not exclude the possibility of improvement. The reader should use his imagination and, whenever he finds an improvement, he should put it to experimental (not only mathematical) test for some years and, when it has proved its value beyond doubt, introduce it without hesitation after having obtained sufficient overlap with the previous method.

Here we touch a subject which requires elaboration. Continuity and sufficient overlap when changing methods are essential for sound geomagnetic work. The worst the reader can possibly do after reading this text is to forget all he has done so far and to make a new beginning. Whenever he believes an observational or computational procedure to be at fault, he should continue with it and, at the same time, make observations or computations following the new method. He should carefully compare old and new results over several months, study the differences brought about by changing procedures, and keep thorough records of all the changes so that he can explain things properly in his observatory publications.

A word of warning is necessary. The creation of a geomagnetic observatory is an ambitious enterprise which entails considerable financial commitments. Even more of a burden is the maintenance of the installation and the processing of data. A full-scale standard observatory can neither be run by one individual nor can the work be coped with by part-time scientists and technicians. With efficient and inventive staff, a full-time scientist and two technicians will be adequate to handle the data output of a standard observatory in the sense of the

International Association of Geomagnetism and Aeronomy (IAGA), which includes the production of yearbooks and reporting to one of the world data centres. Research will hardly be possible. A staff of four, two scientists and two technicians, will permit a modest research programme. Practical experience has shown that there is very little point in trying with less, because the end will invariably be inadequate performance and hence frustration.

A geomagnetic observatory will not have its full capabilities immediately after the installation of the instruments. The magnets and suspension fibres of the variometers will undergo ageing that in the beginning will be speedy and often cause erratic changes of the base-line values. The ageing process may last several years. Furthermore, it will take time for the staff to develop proficiency in handling absolute or semi-absolute instruments.

The response to the invitation of the World Magnetic Survey Board for participation in geomagnetic ground surveying has been gratifyingly good. Contributions are coming in mainly from old institutions, observatories and survey departments, which have experience and tradition in this type of work. Yet, in spite of these contributions, large parts of the globe have still not been covered. Much more information is needed and the Board is anxious to further the work by giving all such advice and practical guidance as would seem of use to those taking part in the WMS project. One manual has already been issued, namely the *Instruction Manual on World Magnetic Survey* by E. H. Vestine (IUGG Monograph No. 11, English and French edition), but it is strongly felt that in addition to this general manual dealing with the scientific aspects of the project there is a need for a more elementary guide for people who would like to participate in the work, but who have little or no experience in geomagnetic survey practice, or who have had all their training at a geomagnetic observatory.

The novice in geodetic surveying is initiated in the practice of field work by a senior officer. He learns to overcome the various obstacles by watching his teacher. The beginner in geomagnetic surveying will usually be depending on his own inventiveness. As in observatory work, he will have to pay a high price for experience, learning continually from his mistakes. Therefore, a section of this text deals with practical difficulties and intends to show the beginner how to overcome them.

Another serious difficulty arises from the fact that the novice will search for examples of geomagnetic surveys in the literature and may try to copy one or the other of them because it appeals to him. He may, however, lack the equipment used in the example he has chosen to follow and since he has no chance of acquiring these particular instruments he assumes that he cannot do survey work. For this reason a chapter will be devoted to instruments and to useful combinations of them from the dearest to the cheapest and from the most convenient to the most unpractical. The reader will be able to judge whether the equipment which is at his disposal will make a useful combination or not. This section will also be of use to those who intend to purchase equipment.

Fortunately, geomagnetic surveying may in numerous instances be handled by a single man. Modern equipment, the progress of civilization and rapid means of transport have removed many of the hardships and hazards from which surveyors suffered in the old days. The cost of a survey in comparison to an observatory is low if the utmost in comfort is not wanted. Furthermore, the results of a survey, and with it something to look at with satisfaction, will be worked out in a couple of years after the field work has been completed. Finally, it may be mentioned that utmost accuracy is only required at secular stations; endeavours to be as accurate as possible may pay poor dividends, as can be inferred from the analysis of many ground surveys. However, this should not be interpreted as an invitation to slipshod work but as an indication of where efforts are rewarding.

It is advisable to contact the geodetic survey department before beginning a geomagnetic survey. Valuable advice will usually be obtained and in many instances the geodetic survey department may be able to supply an observation tent, camp equipment, a theodolite for azimuth observations, though perhaps not of the most recent type, and perhaps an accurate timepiece. The director of surveys or surveyor-general may even offer to include the planned geomagnetic survey in his own programme and in some countries this may be the most advantageous way of performing the task.

It is admitted that geomagnetic work as it is described here is not 'big science', which the gifted and ambitious young man is looking for. However, it is participation in the gear train of a great international enterprise. The results are often awaited with impatience at a scientific centre. A sound piece of work, be it an observatory yearbook published at the right time or a section of ground survey done with devotion, will certainly receive laudatory comments from the geomagnetic community. The lonely worker at a remote place may often think that his work passes unnoticed by the world. However, he can be assured that his efforts and his troubles are the main concern of organizers of international surveys.

The compilation of this text is mainly based on D. L. Hazard's *Directions for Magnetic Measurements*, R. Bock's *Praxis der magnetischen Messungen*, and publications of the Danish Meteorological Institute. In numerous instances reference has been made to McComb's *Magnetic Observatory Manual*, which should be in the possession of any serious observatory worker.

This manual has been under discussion since the end of 1964. It is the outcome of observations made at many new observatories during the afore-mentioned missions and experience collected elsewhere. Sincerest thanks are due to Dr. V. Laursen, Chairman of the World Magnetic Survey Board, to Dr. J. M. Stagg, and Mr. E. Kring Lauridsen, who not only took a keen interest in the preparation of the text but also read the manuscript and helped avoid faults and discrepancies. In numerous instances they suggested better approaches to poorly treated subjects. Dr. J. C. Cain, Goddard Space Flight Center, Greenbelt, Maryland, contributed five world magnetic charts of his Pogo (3/68) Model (Fig. 6-10). Figure 25 was reproduced with kind permission of Dr. P. H. Serson, Dominion Observatory, Ottawa.

Selection of an observatory site

1 The function of a geomagnetic observatory is to record the short- and long-period variations of the geomagnetic field in such a way that the information obtained is representative of a large area. This necessitates that at the observatory site: (a) the geomagnetic elements are 'normal', which means that the geomagnetic field at the observatory is not distorted by anomalies caused by abnormally magnetized geological bodies; (b) the subsoil of the surrounding area is fairly homogeneous in electric conductivity. A nearly horizontal stratification of the subsoil will satisfy this condition. For the same reason the observatory should be at least some tens of kilometres from any coast.

2 The first requirement can be ascertained by a simple geomagnetic survey. It suffices to ensure that at least one element has a fairly normal distribution over the area surrounding the observatory. If no detailed survey of the area has previously been made, a profile extending 30 kilometres north and south of the prospective site should be surveyed with a spacing between the stations of three kilometres. Usually one will measure the vertical or total intensity. The observed values plotted against distance should give an approximately straight, though inclined, line. If a second instrument for the observation of the diurnal variation at a fixed site is not available and the observations cannot be corrected, the line will show a modulation due to the diurnal variation. A certain correction may be obtained from Figure 11, which shows the diurnal variation of D, H and Z at different latitudes. In a similar way, a traverse from east to west should be surveyed. The results plotted against distance will give for vertical and total intensity either a horizontal or slightly inclined line. The site will be excellent if the anomalies (departures from a straight line) are less than 50 gammas. Anomalies of more than 200 gammas should be avoided. Two short profiles from north-west to south-east and from north-east to south-west up to a distance of 10 kilometres to each side of the observatory may be added.

3 The wide-spaced survey is followed by a dense survey of the observatory site proper. An area of 100 by 100 metres is marked by pegs from 10 to 10 metres and then surveyed. The diurnal variation can be allowed for by observing at a central point every thirty minutes. Select the area with the smallest gradients for the absolute house. If the four corner points of the absolute house differ by less than five gammas the site can be considered as perfect. Occasionally an ideal site may not be found in spite of an extensive search. Larger gradients may be tolerated under exceptional conditions. With gradients of more than 10 gammas per metre the proton magnetometer will fail to give reliable results. If large gradients are present the absolute instruments must always occupy exactly the same position.

If suitable instruments are not available at the planning stage, the geological survey department may be asked to do the reconnaissance survey either with a vertical-intensity field balance or, preferably, with a proton magnetometer. Especially in the close-spaced survey, the proton magnetometer will be very useful.

4 It is usually beyond the means of an observatory, in its initial phase of development, to find out whether or not the second requirement, namely, homogeneity in electrical conductivity of the earth, is fulfilled. The investigation of the underground conductivity would call for the simultaneous operation of several portable magnetographs in order to investigate whether or not transients such as bays and geomagnetic storms are recorded with the same amplitude and phase over an appreciable area. A substitute for this investigation may be a careful study of all geological information relating to possible deformations of the strata by faults and folding.

5 Sources of artificial disturbance of the geomagnetic field are DC electric railways and tramway lines. Starting and stopping of trains may be felt as far as twenty kilometres from an DC railway line. Under unfavourable conditions the disturbance may reach much farther. A IAGA Resolution recommends a minimum distance of thirty kilometres from a DC railway line.

The earth current may be heavily disturbed by AC power stations in the vicinity of an observatory because the stray currents between the various earthing points are partly rectified in the earth. When proton magnetometers are used, near-by broadcasting stations, ionosondes and UHF relay stations may cause heavy interference.

6 When selecting an observatory site, attention should be paid to practical aspects as well. A reasonably good road to the site and an adequate water supply are the minimum requirements. Electricity is not absolutely necessary but nevertheless very useful. Public transport—a bus stop or a railway station in the vicinity of the observatory—will be of benefit to the resident staff.

7 In the past, quite a number of geomagnetic observatories had to be shifted, owing to the development of near-by cities. It is therefore desirable to contact the planning authorities before the selection of a site is begun. After a good site has been found, it is desirable to obtain legislative protection for the observatory area. Furthermore, it is advisable to keep an eye on development activities in the vicinity of the observatory that may cause magnetic disturbances. A protest launched in the planning phase of a project may be successful but at an advanced stage of development negotiations will be of no avail.

Non-magnetic buildings

Building material and general layout

8 When planning the absolute house and the variometer house, careful consideration has to be given to the choice of building material. Kiln bricks are unsuitable because they are magnetic. Timber, limestone or sandstone may be used. It is good practice to test samples of building material by means of a field balance or a QHM (Quartz Horizontal Magnetometer) in the deflected position. When concrete is being used, test cubes may be produced. Modern heat-retaining insulating materials, which are nowadays much used in the construction of residential buildings and which are on the market under a large variety of trade names, may, if available, be used not only for lining the inner sides of the walls but also for the ceilings. The fittings of the doors, windows and shutters should be of brass or aluminium. The pins of the hinges will usually be of steel, as will be the locks, and may have to be accepted.

9 When using equipment such as QHMs, magnetic theodolites and BMZs (Balance Magnétométrique Zéro), it may be permissible to combine the absolute house and the variometer house in one unit. However, the trend towards vector magnetometers in absolute measurements calls for a separation of the two buildings, so that the fairly large bias fields required by vector magnetometers do not influence the variometers. Another question to be settled at the planning stage is whether the absolute house should be constructed as a large unit, housing a number of instruments, or whether it should be split up into a number of small pavilions. Examples of both types of layouts are available. The pavilion system is more flexible and permits the simultaneous operation of several instruments. One may start with one unit and add more units later as circumstances demand.

The variometer house

CONSTRUCTION

10 The variometer house should be constructed in such a manner that the highest possible degree of temperature stability is achieved. The usual argument that temperature stability is not required, because the variometers are temperature-compensated, is weak. It may be difficult even for experienced observers to obtain perfect temperature compensation. With residual temperature coefficients the labour of reduction is considerable if a daily variation of the temperature occurs in the variometer room. There exists also the possibility that residual temperature coefficients are not detected and therefore that the diurnal variation of the intensity components may be much distorted by the diurnal variation of the temperature in the variometer room. This source of error seems to be present in quite a number of installations.

11 The ideal variometer room is a room with absolutely constant temperature. This can be achieved by heating and temperature control, which will be dealt with later. Second best is a room in which the diurnal variation of the temperature is inappreciable. There will be a slow seasonal variation of the temperature, with slight accelerations and retardations dependent on the weather conditions. Residual temperature coefficients of the intensity variometers will find expression in a slight and slow change of the base-line values with temperature. In the following paragraphs some structures will be described which will achieve this aim.

12 The most simple approach toward construction of a variometer house is an excavation on the shadow face of a slope, as shown in Figure 1. The walls and the roof may consist of stone masonry or concrete. The roof may be a sixty-degree arc or semicircular arc. The moderate width of the variometer room, usually 2 to 2.5 metres, allows construction without reinforcement. In earthquake-prone areas the roof may consist of railway sleepers. Preservation of the timber against decay and, in certain regions, against white ants is necessary. A generous cover of asphalt mixed with sand or gravel will make the roof watertight. The slope is restored to its original shape by covering the building with a stone or earth filling. A cover of concrete will take care of the rain water. A concrete-lined ditch on the up-slope side for diverting rain water will be a useful addition. Drains below the floor will keep the walls dry. If a slope is not available the building may be constructed above or partly above and partly below the ground. In the latter case, drainage may pose some problems (Fig. 2). Buildings of this type will not show any diurnal variation of the temperature in the variometer room. A seasonal peak-to-peak variation of 40 degrees centigrade of the outside temperature will cause a peak-to-peak variation of 6 to 8 degrees centigrade in the room, with a considerable lag in phase against the outside temperature.

13 This method of construction is especially suitable in countries with cheap labour. Stone masonry will dry after a few weeks, provided the walls remain unplastered. However, variometer houses constructed of concrete will remain humid for at least ten years if covered up soon after construction, even in a dry

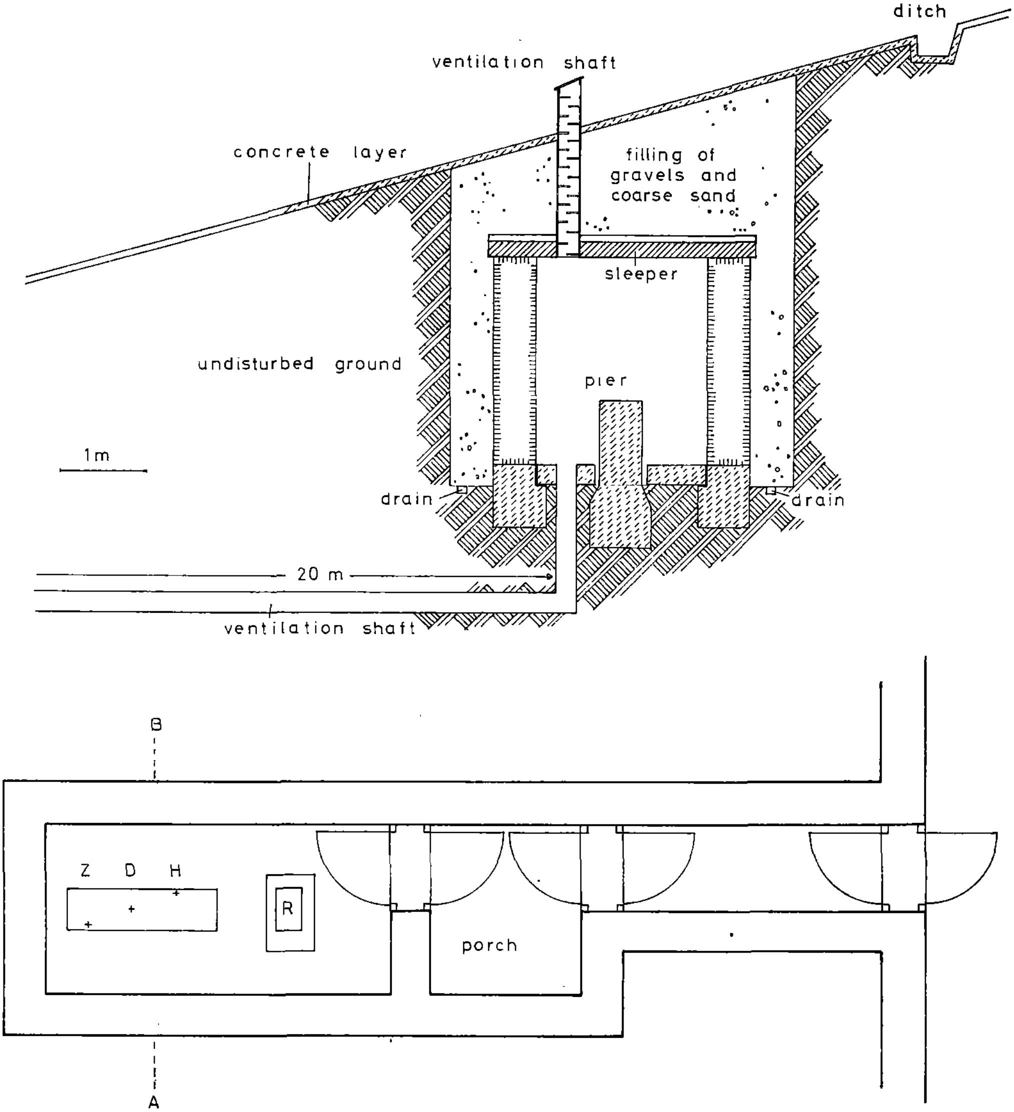


FIG. 1. Variometer house constructed in a slope.

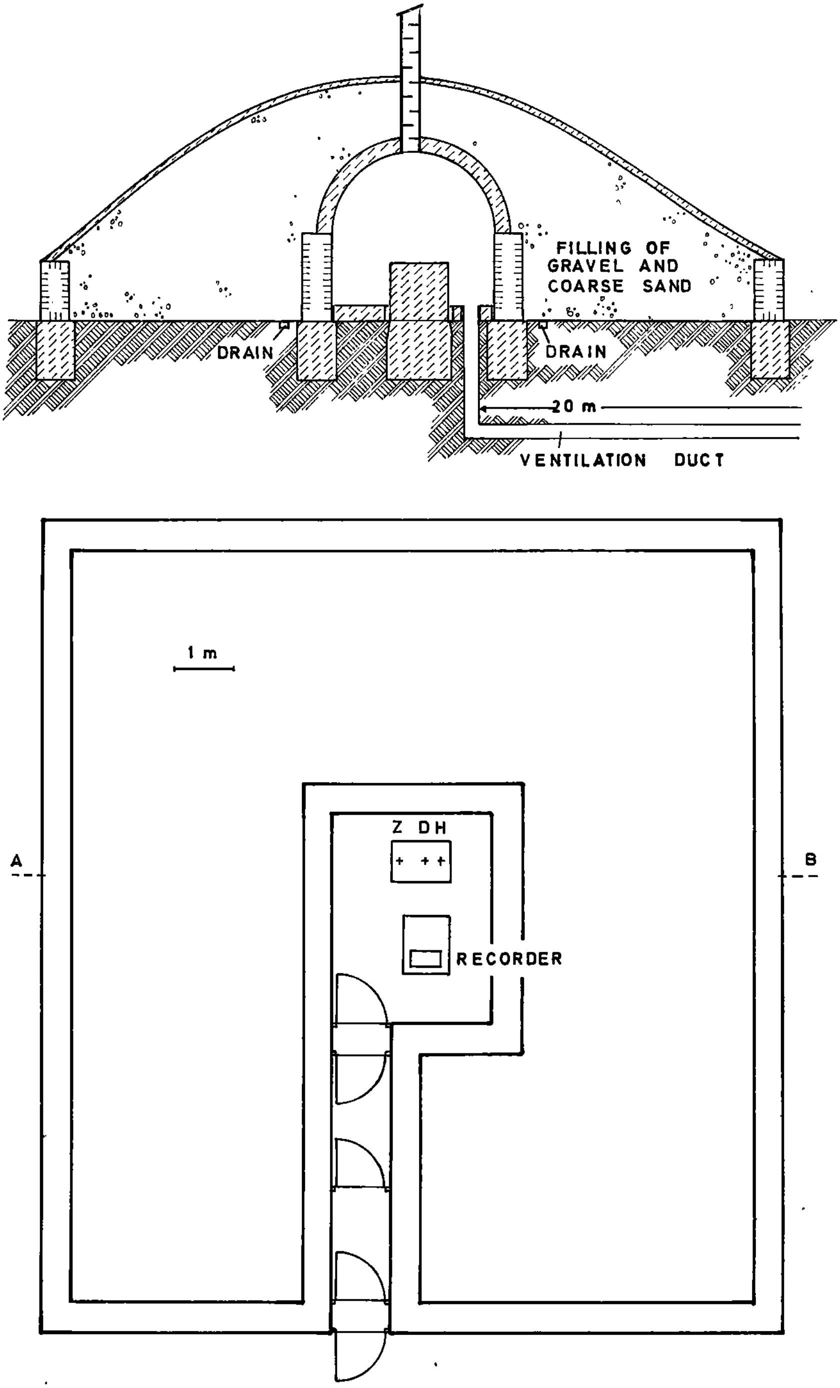


FIG. 2. Variometer house constructed above the ground.

climate. It is advisable to leave a concrete structure open for two years in order to accelerate the drying process. Even then, it may be necessary to apply heating and ventilation. More effective is a small de-humidifier which may dry the building within two years.

14 Variometer houses constructed completely of timber are described by McComb in the *Magnetic Observatory Manual* and by Fleming (1939). Instead of sawdust, glass wool may be used. Variometer houses of this type may be partly protected against the sun by painting them white, by constructing them in a forest, or by planting fast-growing trees around them.

TEMPERATURE CONTROL

15 If electricity is available the temperature of the variometer room may be controlled. A certain control may be afforded by manual switching of heater groups. The ultimate answer to temperature-stability problems is the installation of an automatic temperature control.

16 A simple and reliable temperature sensor is the contact thermometer. Its contact will carry up to 15 milliamperes and may be used to turn on an AC mercury relay which can be kept near the variometers because it does not build up disturbing fields. Transistor switches, which load the thermometer contact less, are equally good but since they require DC relays they have to be kept at a safe distance from the variometers.

Contact thermometers have to be made to order. They are either equipped with several contacts for different temperature levels or else a separate thermometer has to be used for each temperature level.

17 Thermistor bridges are cheaper than contact thermometers. They can be adjusted over a wide temperature range. From time to time the bridge circuit will have to be readjusted because, owing to ageing of the bridge components, the temperature level at which the power relay is actuated shifts slowly.

18 The best place for the temperature sensor is at the level of the variometer magnets and fairly near to them. The sensor should react quickly to temperature changes so as to avoid objectionable fluctuations in temperature.

19 The decision about the level at which the temperature of the variometer room should be kept may present somewhat complex problems. If the variometer room has been in use without temperature control for several years, the maximum temperature to which the room can rise is known. However, when the room is heated, the thermal behaviour will be disturbed and the control temperature should be set several degrees centigrade higher than the maximum observed temperature; otherwise, the room temperature may rise beyond the control temperature. If economy in power consumption is important, the control temperature may be adjusted, in steps of two or three degrees, in accordance with the outside temperature. The number of steps should not be carried too far because each shift of temperature level may be accompanied by a break in the base-line values of the variometers, often with annoying after-effects. Three steps is about the upper limit.

20 The heater elements should be mounted so as to be regularly spaced along the walls and slightly above the floor level of the variometer room. Radiator spirals wound on ceramic cylinders with light-bulb sockets are very convenient heater elements. Long wires of suitable resistance pose some problems with regard to insulation and safety of operating personnel. Red carbon filament bulbs are also in use but do not last long when frequently switched on and off.

21 The ideal temperature control would be a device which regulates the power dissipation in the heater circuit in infinitesimal steps. This requires complicated electronics and is not absolutely necessary. With an automatically switched heater circuit, best results will be obtained when the on and off periods are approximately equal. This may be achieved by providing a second heating circuit whose power dissipation is manually controlled, by turning radiators on or off as required for obtaining the desired characteristic of the automatically switched circuit.

It may be pointed out that an automatic temperature control will be useful only with a reliable power supply. Frequent power failures will cause more trouble than a free-running temperature in the variometer room.

HUMIDITY CONTROL

22 Next to temperature, the control of the humidity in the variometer room poses problems, especially in underground structures. Humidity is the worst enemy of recording balances, except for the Godhavn balance which can be perfectly sealed. Less sensitive to high relative humidity are quartz fibres of D and H variometers. The humidity also affects the sensitivity of the photographic paper. When the paper is brought into the room in a dry state the strength of the traces will decrease considerably towards the end of the record. The relative humidity in the variometer room is certainly too high if the photographic paper which was put on the recorder drum in a brittle state is soft when being removed after 24 hours. A large stock of photographic paper should not be kept in a humid variometer room. However the paper should be left a few days in the room before it is used, in order to avoid the fading of traces and undue changes of dimensions.

23 A prerequisite for an efficient humidity control by simple means is a ventilation system such as that shown in Figures 1 and 2. During the cold season the room temperature will be higher than the outside temperature. Therefore, the air will escape through the ventilation shaft in the ceiling and will carry away humidity. Outside air will enter the ventilation duct where it is warmed up. Its relative humidity will decrease. It will enter the variometer room in a fairly dry state and therefore be able to absorb humidity and carry it away through the shaft in the ceiling. If the room is heated, ventilation will be enhanced. Circulation of the air will cease when the outside temperature rises to the level of the room temperature. It is then advisable to close all ventilation ducts. In a moderate climate, with appreciable differences between summer and winter temperatures, the system will work well. In a tropical climate, with no substantial seasonal temperature variation, ventilation may be maintained by heating.

24 In a damp climate, a ventilation system may fail to keep the relative humidity in the variometer room at a reasonable level. In such a case, a de-humidifier has to be installed. If the plant is kept at a distance of four to five metres from the nearest variometer and not moved, it will not influence the variometers. The efficiency of a de-humidifier depends on the ambient temperature. Simple refrigeration units will keep the relative humidity of a room below 50 per cent at temperatures above 16 degrees centigrade. At lower temperatures, the level of the relative humidity will rise. At 12 degrees, the refrigeration unit will freeze and will no longer extract water from the air. A 25-watt bulb mounted near the cooling system will prevent freezing but cannot improve the efficiency appreciably. A small de-humidifier will remove about a gallon (4.5 litres) of water per day.

The absolute house

25 For reasons which have been mentioned in paragraph **9**, the absolute house should be at least 50 metres from the variometer house. Whereas the variometer house is a necessity, the absolute house may not be required in the initial phase of development of an observatory in a favourable climate. A peg driven into the ground in the shadow of a tree may mark the observing position. The next stage may be a reed roof supported by a light timber framework. In a severe climate and with complex equipment, the observer as well as the instruments will need more protection, which means that a solid structure is required.

26 The absolute house or pavilion should be constructed in such a way that it gives access to as much daylight as possible. Numerous large windows will satisfy this condition. The windows should be provided with shades or shutters so that the sun cannot shine on the instruments in use. It is very helpful to paint the walls of the room white. If QHMs and BMZs are used, a skylight may be useful but it causes difficulties in construction of the roof. The normal solution is to install electric lights, covered by heat-retaining filters, in the ceiling. If no filters are available, one will have to wait 20 to 30 minutes after having switched on the lights so as to allow the instruments to attain thermal equilibrium. In an absolute house, temperature stability is not essential, though desirable. It suffices if the house offers protection against rapid changes of the outside temperature. Figure 3 shows a small pavilion with one pier.

27 Instrument piers should be well founded. The best foundation is bed-rock. If this is not accessible, one may proceed to make an excavation, one metre square and one metre deep, in undisturbed ground, to set the pier vertically in the middle of the excavation and to fill the pit with concrete. The floor of the room should be arranged so as not to touch the piers and the ground around them, in order to prevent tilting or shaking of the piers when the observer is walking about in the room. This is achieved by placing the floor boards on beams which rest with their ends on the foundations of the walls. For instruments which have to be used on tripods, a pier of 120 by 120 centimetres should be provided, its surface being flush with the floor but not in contact with it.

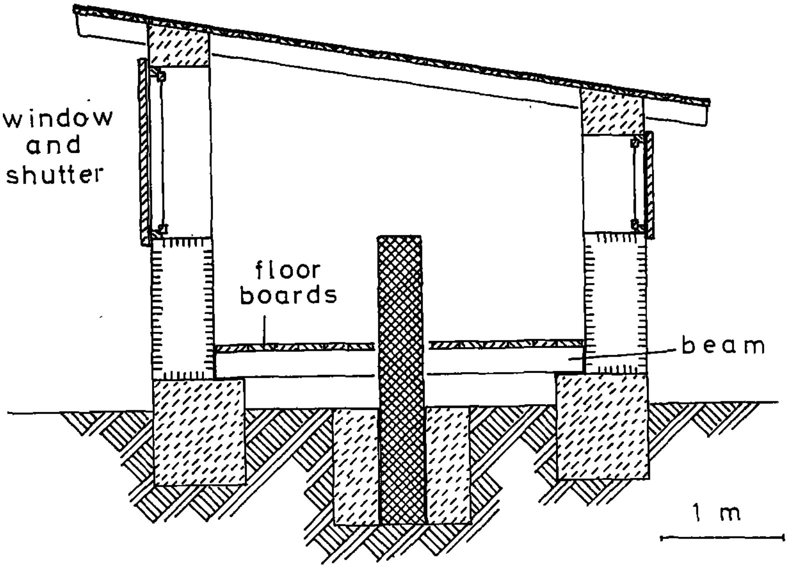


FIG. 3. Pavilion for absolute measurements.

28 If a BMZ is used at the observatory the top of the pier may have a shape as depicted in Figure 4. Cement four non-magnetic brass or aluminium rods vertically at the corners of the pier and install on top of the rods a marble plate with a hole of 8 centimetres diameter in its centre. The plate is held in position by nuts. Naturally, other instruments can be used on the same pier.

29 Piers, which should be of perfectly non-magnetic material, may be of circular or square cross-section. A diameter of 30 centimetres or a cross-section of 30 by 30 centimetres will take any ordinary geomagnetic instrument. A Schmidt theodolite or an earth inductor requires a pier cross-section of 40 by 40 centimetres. The height of the piers is a matter of taste. If the observer prefers to sit while observing, a height of 90 centimetres from the floor level to the top of the pier is about right. When standing, a height of 110 to 120 centimetres will be convenient for an observer of medium height.

30 The pavilion shown in Figure 3 will be sufficient for a small observatory. The reader will find descriptions of absolute houses in the literature. A small absolute house with two piers is described in McComb's *Observatory Manual.*

31 When constructing the absolute house, care should be taken that from the declination pier two azimuth marks are visible, one at a distance of more than one kilometre, and another at a distance of 150 metres, the latter serving for observations when the visibility is poor. One of the marks should be near the horizontal plane through the top of the pier so that declination observations can be made with QHMs.

32 Magnetic materials, especially magnets, BMZs, box compasses of earth inductors and galvanometers, except for those of the astatic type, should be in

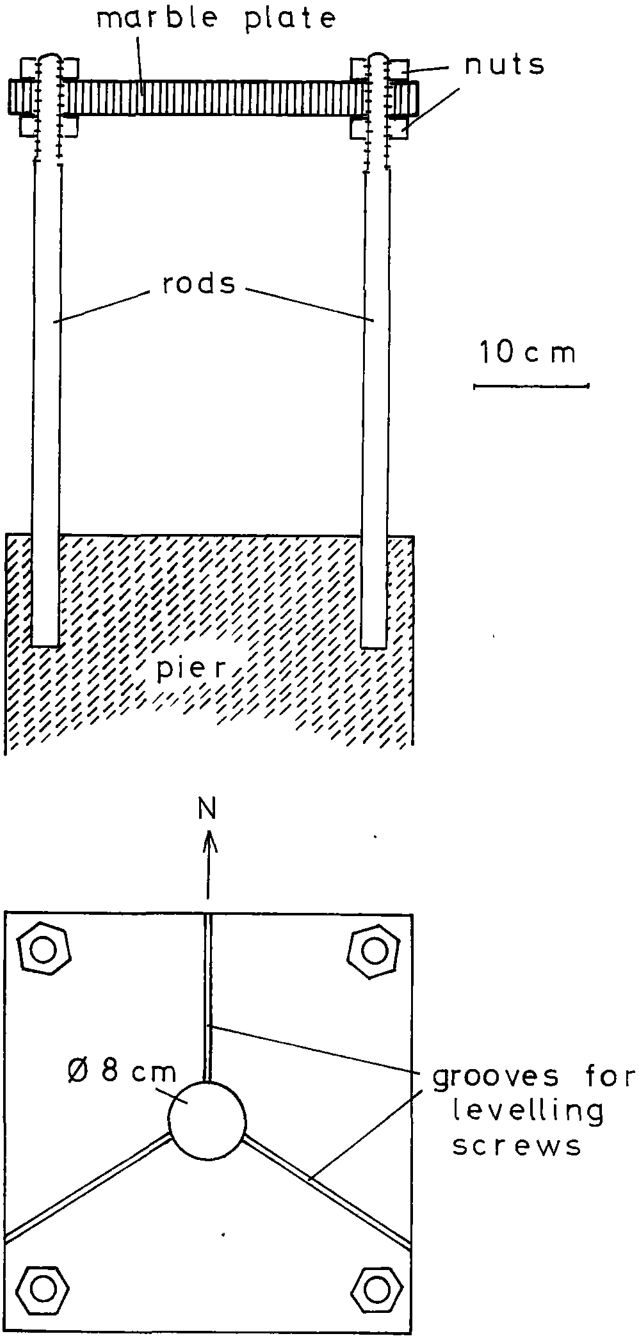


FIG. 4. Pier for BMZ observations.

the absolute house only when being used for observations. At all other times, they should be stored in a hut of 2.5 by 2.5 metres floor area, about 20 to 30 metres from the absolute house. This hut may also accommodate the chronograph for recording oscillations of magnets and the electronics of the proton magnetometer. Windows are not necessary. The door should be strong, so as to make access difficult to possible burglars. The building should be provided with ventilation holes (covered with wire gauze) near the floor and the ceiling so that the temperature inside the room does not rise much above the outside temperature. For the same reason the roof should be well insulated thermally.

Electrical installation

33 Normally, electricity will be available at the observatory. The Power may be distributed to the houses by conventional conductors on poles. Underground twin-cable ducts may equally well be used, one duct taking the power line while the other contains the signal cables. Low-voltage (4, 6, and 12 volts) AC points at various places are useful, especially at the piers where lamps may be connected for illuminating instrument circles and telescope eyepieces without danger to the operating personnel. The step-down transformer may be housed in the office building.

34 A power line should be earthed only at one point, preferably far from the absolute and variometer houses in order to prevent stray currents in the ground from disturbing the site. The precautions which will have to be taken in this case are prescribed by safety regulations which vary from country to country.

35 To ensure continuity in recording during power failures, a storage battery of 6 to 8 volts and a capacity of 40 to 60 ampere-hours is required, and may have its place in the variometer house. The battery is kept under trickle charge and always connected to the light circuit of the magnetograph. Between the battery and the trace lamp of the magnetograph, a transistorized voltage regulator may be used. The same battery may be used for the various signal functions, for instance, to actuate the time-mark relay and for the chronograph when oscillations of a magnet are observed.

36 If electricity from a public power supply is not available, a small motor generator is required for charging the batteries. Two sets of batteries will be useful. Ordinary lead accumulators are more efficient than alkaline batteries but deteriorate more rapidly. Alkaline batteries will last many years and require little service. Their unfavourable discharge voltage characteristic necessitates a voltage regulator for the trace lamp of the magnetograph or else frequent checking and readjustment of the lamp voltage by the operator.

Definitions

37 The Earth's magnetic field or, in modern usage, the geomagnetic field resembles, at a first approximation, the field produced by a magnetic dipole situated at the Earth's centre. The axis of the magnetic dipole makes an angle of $11\frac{1}{2}^\circ$ with the earth's axis of rotation and cuts the Earth's surface at the geomagnetic poles. This simple model provides the basis for the terms 'geomagnetic coordinates', 'geomagnetic equator' and 'geomagnetic meridian', which will be used later.

38 The actual magnetic field of the Earth departs from the above model. The actual magnetic poles are situated where the lines of force are perpendicular to the Earth's surface as observed by the dip needle. Therefore, the magnetic poles are also called dip poles. The dip equator or magnetic equator is situated where the lines of force are horizontal as observed with the dip needle. The magnetic meridian is the projection of the actual line of force on the horizontal plane.

39 The geographic positions of the poles are:

	Latitude	*Longitude*		*Latitude*	*Longitude*
North geomagnetic pole	78.5° N.	69° W.	North magnetic pole	75.5° N.	100° W.
South geomagnetic pole	78.5° S.	111° E.	South magnetic pole	66.5° S.	140° E.

The geomagnetic poles are antipodes. The positions of the magnetic poles are given for epoch 1965.0 on the world magnetic charts of the U.S. Hydrographic Office. North and south indicate the geographical position of the poles, not their polarity.

40 The position of a place of observation is described by the geographic latitude φ and the geographic longitude λ. The geographic coordinates of a point of observation should be known to the nearest tenth of a minute of arc. A third desirable quantity is the elevation above sea level of the point of observation.

41 The geomagnetic coordinates describe the position of a point of observation with respect to the magnetic dipole. The geomagnetic latitude Φ and the geomagnetic longitude Λ are derived from the geographic coordinates of the point of observation and of the north geomagnetic pole, by means of a simple transformation (McNish, 1936). The geomagnetic meridian is the great circle through the

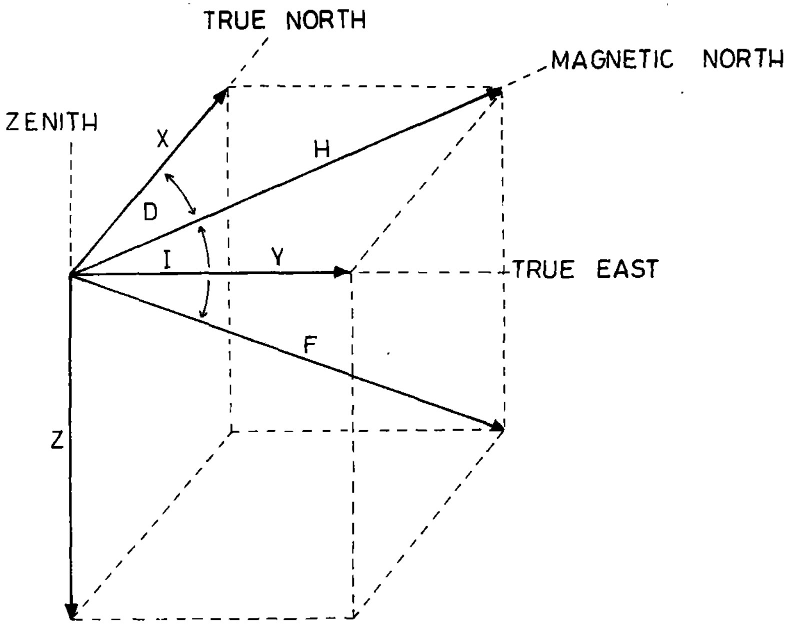


FIG. 5. Components of the geomagnetic field vector.

geomagnetic poles and the place of observation, and makes the angle Ψ *with* the true (geographic) meridian.

42 The angle which the line of force at a point of observation makes with the horizontal plane is the inclination I, also called dip (Fig. 5). I is positive when the geomagnetic field vector is directed downward (i.e. in the northern hemisphere), and varies between + 90° at the north magnetic pole and − 90° at the south magnetic pole (Fig. 7).

43 The scalar magnitude of the geomagnetic field vector is called the total intensity F, which is always positive and varies between 0.25 gauss (symbol: Γ; 1 gamma = 1γ = 0.000 01 gauss) in South America and 0.80 gauss near the north magnetic pole (Fig. 10).

44 The projection of the geomagnetic field vector on the horizontal plane is the horizontal intensity H which is always positive and can assume values between zero at the magnetic poles and 0.40 gauss at the magnetic equator (Fig. 8).

45 The projection of the geomagnetic field vector on the vertical is the vertical intensity Z which is zero at the magnetic equator, + 0.60 gauss at the north magnetic pole and − 0.70 gauss at the south magnetic pole (Fig. 9).

46 The vertical plane containing H is the magnetic meridian. The plane perpendicular to H is the magnetic prime vertical. The angle made by the magnetic meridian and the true north meridian is the magnetic declination D which is positive or 'east' when the magnetic meridian is east of the true north meridian.

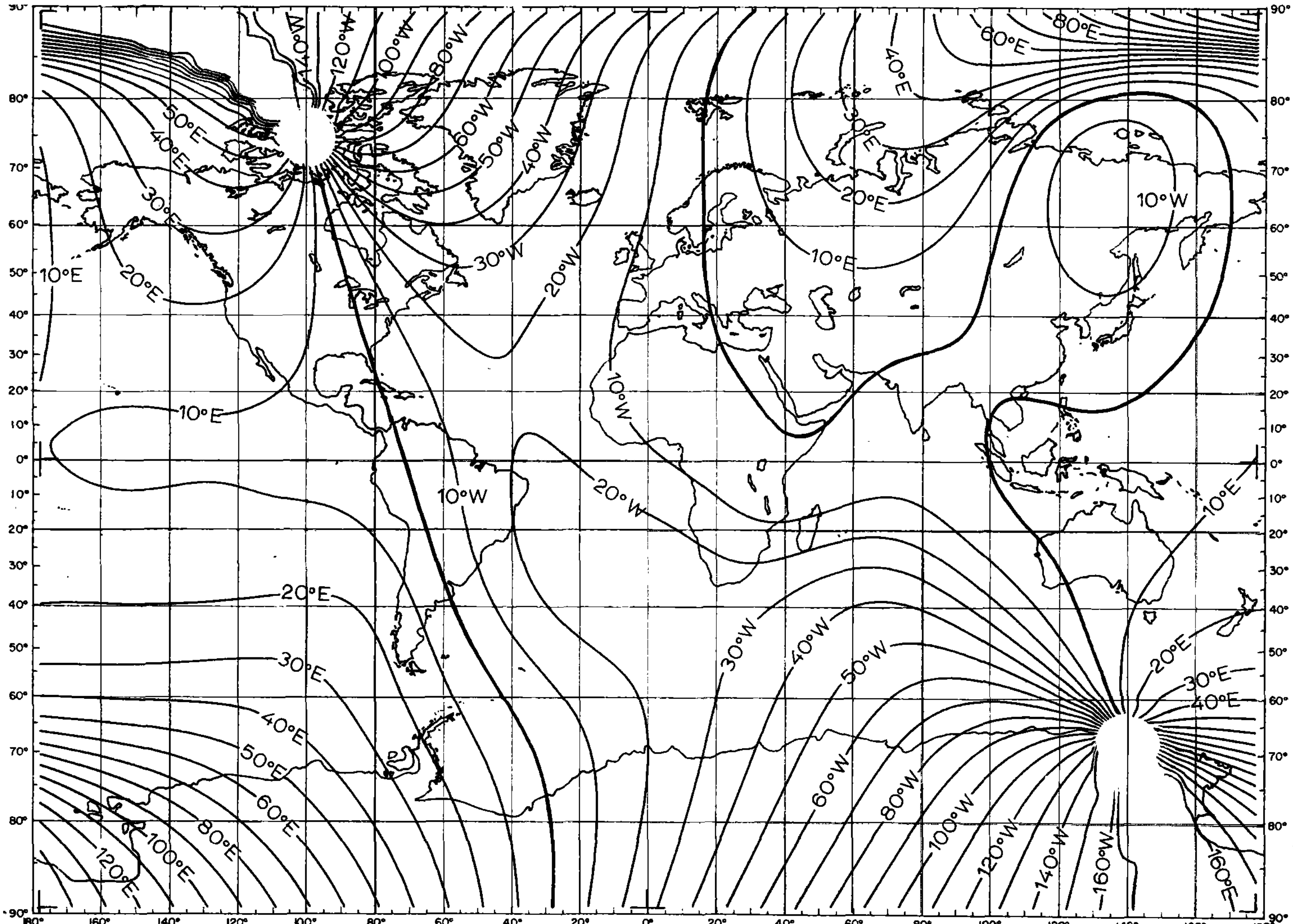
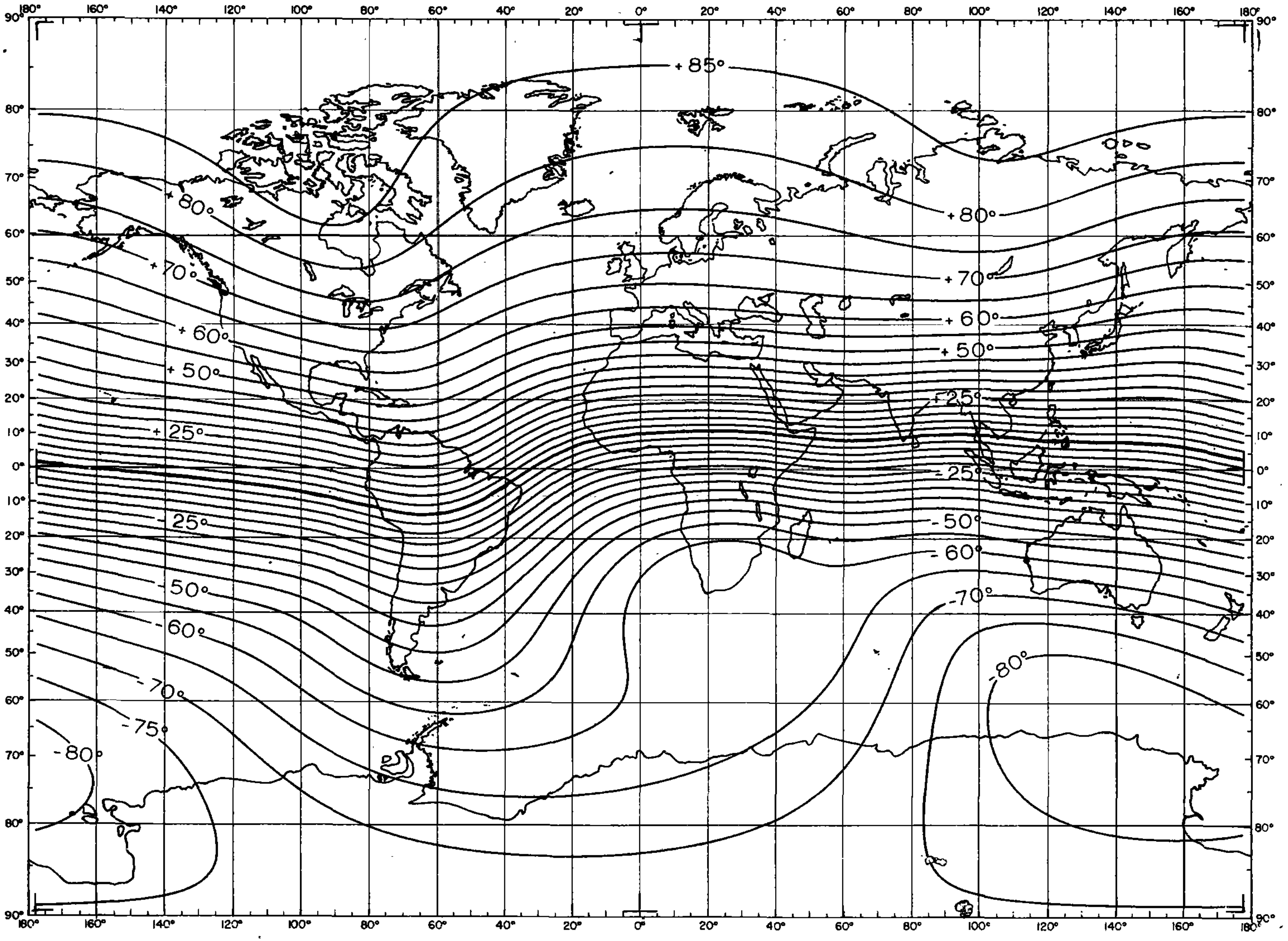


FIG. 6. Magnetic declination, in degrees of arc, epoch 1965.0. Cain's Pogo (3/68) model.


180°
160°
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50°
60°
70°
80°
90°
+85°
+80°
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+70°
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+50°
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-80°
-80°

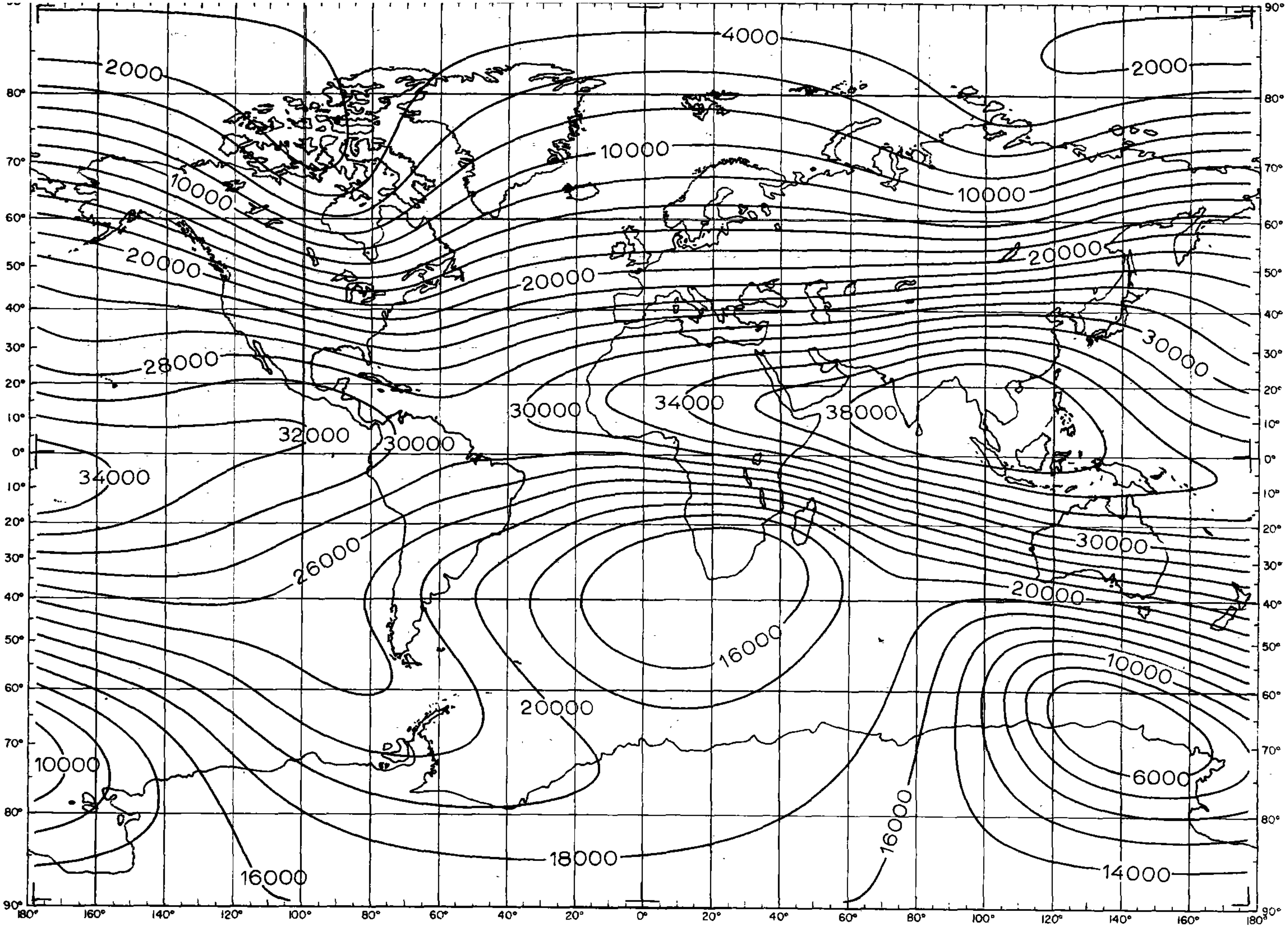
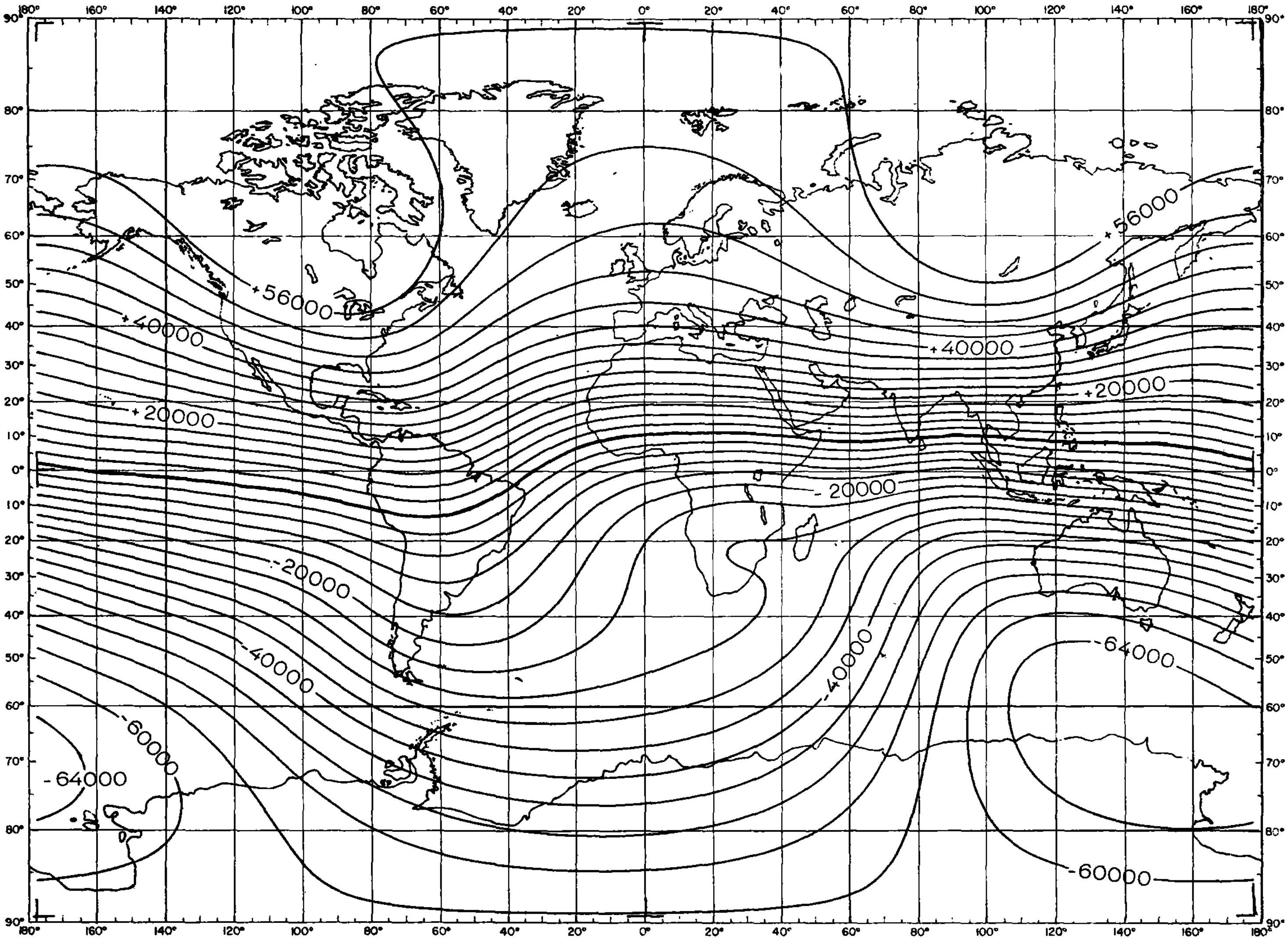


FIG. 8. Horizontal intensity, in gammas, epoch 1965.0. Cain's Pogo (3/68) model.


180° 160° 140° 120° 100° 80° 60° 40° 20° 0° 20° 40° 60° 80° 100° 120° 140° 160° 180°
90° 80° 70° 60° 50° 40° 30° 20° 10° 0° 10° 20° 30° 40° 50° 60° 70° 80° 90°
+56000
+40000
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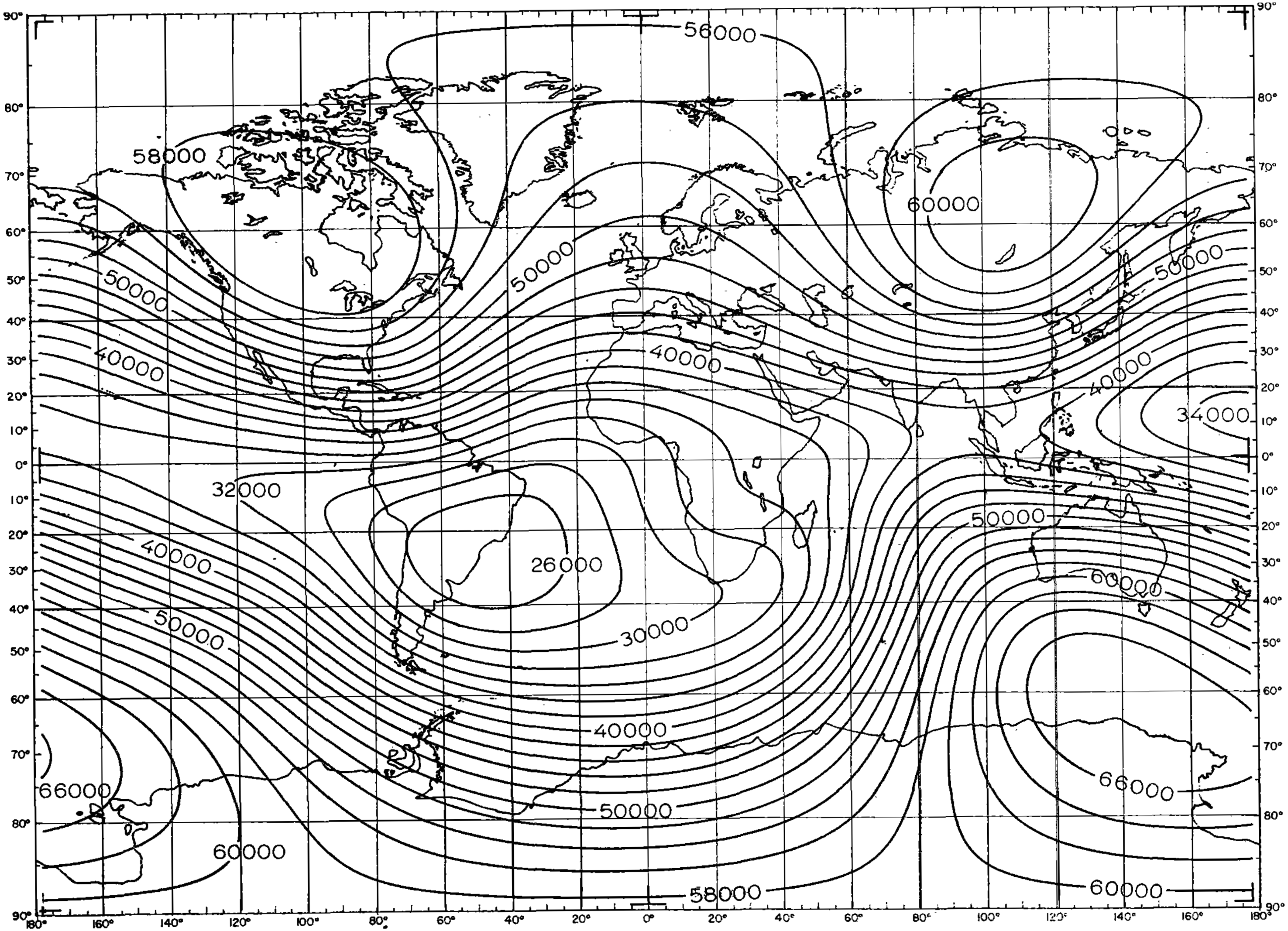

FIG. 10. Total intensity, in gammas, epoch 1965.0. Cain's Pogo (3/68) model.

Near the magnetic poles, D may vary from + 180° to − 180°. At lower latitudes D is confined to ± 30° (Fig. 6).

47 The projection of H on the true meridian is the geomagnetic north component X, which is nearly always positive except for small areas near the magnetic poles.

48 The projection of H on the true east direction is the geomagnetic east component Y. The geomagnetic east component is positive when directed eastward and is of the same algebraic sign as the magnetic declination.

49 The following is a summary of the symbols and the mathematical relations between the various quantities:

D = declination; H = horizontal intensity; X = geomagnetic north component;
I = inclination; Z = vertical intensity; Y = geomagnetic east component.
F = total intensity

$$\begin{array}{llll} \sin D = Y/H; & \cos D = X/H; & \tan D = Y/X; & H^2 = X^2 + Y^2; \\ \sin I = Z/F; & \cos I = H/F; & \tan I = Z/H; & F^2 = H^2 + Z^2; \end{array} \qquad (1)$$
$$F^2 = X^2 + Y^2 + Z^2.$$

By means of the above formulae, transformation of the D, H, I system to the X, Y, Z system and vice versa is possible; for example, X = H cos D; Y = H sin D; Z = H tan I; etc. From simple considerations it follows that, for the complete determination of the geomagnetic field vector, three elements or components have to be measured, of which none can be derived from the other two. Combinations of components for field surveying, and their merits and disadvantages, will be discussed later.

50 From the above formulae a whole family of formulae for small changes can be derived by differentiation. Instead of the operator d which indicates infinitesimal steps, Δ is used, which means that the steps may be substantial, say up to 50 or 100 gammas. For the application of the formulae the conversion of small angular changes of D and I to gammas and vice-versa is made as follows:

$$\begin{array}{ll} \Delta D^{(\gamma)} = H^{(\gamma)} \sin 1' \, \Delta D^{(')} & \Delta D^{(')} = \dfrac{1}{H^{(\gamma)} \sin 1'} \Delta D^{(\gamma)} \\ \Delta I^{(\gamma)} = F^{(\gamma)} \sin 1' \, \Delta I^{(')} & \Delta I^{(')} = \dfrac{1}{F^{(\gamma)} \sin 1'} \Delta I^{(\gamma)} \end{array} \qquad (2)$$

In the following formulae, all quantities have to be inserted in gammas.

$$\Delta D^{(\gamma)} \left\{ \begin{array}{l} = \cot D \Delta H - \dfrac{1}{\sin D} \Delta X \\ = - \tan D \Delta H + \dfrac{1}{\cos D} \Delta Y \\ = - \sin D \Delta X + \cos D \Delta Y \end{array} \right. \qquad (3)$$

$$\Delta H \left\{ \begin{aligned} &= \frac{1}{\cos D}\Delta X + \tan D\,\Delta D^{(\gamma)} \\ &= \frac{1}{\sin D}\Delta Y + \cot D\,\Delta D^{(\gamma)} \\ &= \cos D\,\Delta X + \sin D\,\Delta Y \\ &= \cos I\,\Delta F - \sin I\,\Delta I^{(\gamma)} \\ &= \cot I\,\Delta Z - \frac{1}{\sin I}\Delta I^{(\gamma)} \\ &= \frac{1}{\cos I}\Delta F - \tan I\,\Delta Z \end{aligned} \right. \tag{4}$$

$$\Delta X \left\{ \begin{aligned} &= \cos D\,\Delta H - \sin D\,\Delta D^{(\gamma)} \\ &= \cot D\,\Delta Y - \frac{1}{\sin D}\Delta D^{(\gamma)} \\ &= \frac{1}{\cos D}\Delta H - \tan D\,\Delta Y \end{aligned} \right. \tag{5}$$

$$\Delta Y \left\{ \begin{aligned} &= \sin D\,\Delta H + \cos D\,\Delta D^{(\gamma)} \\ &= \tan D\,\Delta H + \frac{1}{\cos D}\Delta D^{(\gamma)} \\ &= \frac{1}{\sin D}\Delta H - \cot D\,\Delta X \end{aligned} \right. \tag{6}$$

$$\Delta I^{(\gamma)} \left\{ \begin{aligned} &= \frac{1}{\cos I}\Delta Z - \tan I\,\Delta F \\ &= -\frac{1}{\sin I}\Delta H - \cot I\,\Delta F \\ &= \cos I\,\Delta Z - \sin I\,\Delta H \end{aligned} \right. \tag{7}$$

$$\Delta Z \left\{ \begin{aligned} &= \sin I\,\Delta F + \cos I\,\Delta I^{(\gamma)} \\ &= \tan I\,\Delta H + \frac{1}{\cos I}\Delta I^{(\gamma)} \\ &= -\cot I\,\Delta H + \frac{1}{\sin I}\Delta F \end{aligned} \right. \tag{8}$$

$$\Delta F \left\{ \begin{aligned} &= \frac{1}{\sin I}\Delta Z - \cot I\,\Delta I^{(\gamma)} \\ &= \frac{1}{\cos I}\Delta H + \tan I\,\Delta I^{(\gamma)} \\ &= \cos I\,\Delta H + \sin I\,\Delta Z \end{aligned} \right. \tag{9}$$

The application of these formulae will be explained later. They may serve not only to reduce observed components to base-line but also for estimating errors when computing one element or component from two other components.

Time variations

51 The geomagnetic field is changing continuously under the influence of various factors. The most prominent variation is the diurnal (daily) variation which is caused by the solar electromagnetic radiation. The radiation sets up a current system in the ionosphere at a height of about 100 kilometres above the Earth's surface, which is more or less stationary with respect to the line connecting the sun's and Earth's centres, and extends into the night hemisphere of the Earth. The ionospheric current system is accompanied by a magnetic field which strengthens or weakens the Earth's permanent field, depending on the position of the place of observation with respect to the current system or, what is the same, on local time and latitude.

52 The amplitude of the diurnal variation is dependent on the latitude of the place of observation (Fig. 11) and on the sun's declination. At the geomagnetic equator, there is an anomaly of H-variation caused by a strong current system flowing from west to east on the sunlit side of the Earth, which is called the electrojet. Under the centre-line of the electrojet, the amplitude of the H-variation may amount to 200 gammas. The variation anomaly extends about 200 kilometres on both sides of the geomagnetic equator.

53 Furthermore, the amplitude of the diurnal variation is influenced by the sun's activity, of which one measure is the relative sun-spot number. At times of high sun-spot numbers (during the sun-spot maximum) the amplitude of the diurnal variation is considerably larger than at low sun-spot numbers (sun-spot minimum). The sun-spot cycle has a period of 11 years or, more accurately, 22 years because periods of opposite sun-spot polarity follow each other.

54 At times, the diurnal variation of the geomagnetic field is disturbed by increased particle radiation originating from active areas of the sun. The particles penetrate into the ionosphere and upset the current system maintained by the sun's electromagnetic radiation. The disturbances, called magnetic storms, are felt most strongly in the aurora belts and least at the geomagnetic equator, but start practically simultaneously all over the globe. During a magnetic storm the general level of H will be appreciably lowered. The recovery will take several days.

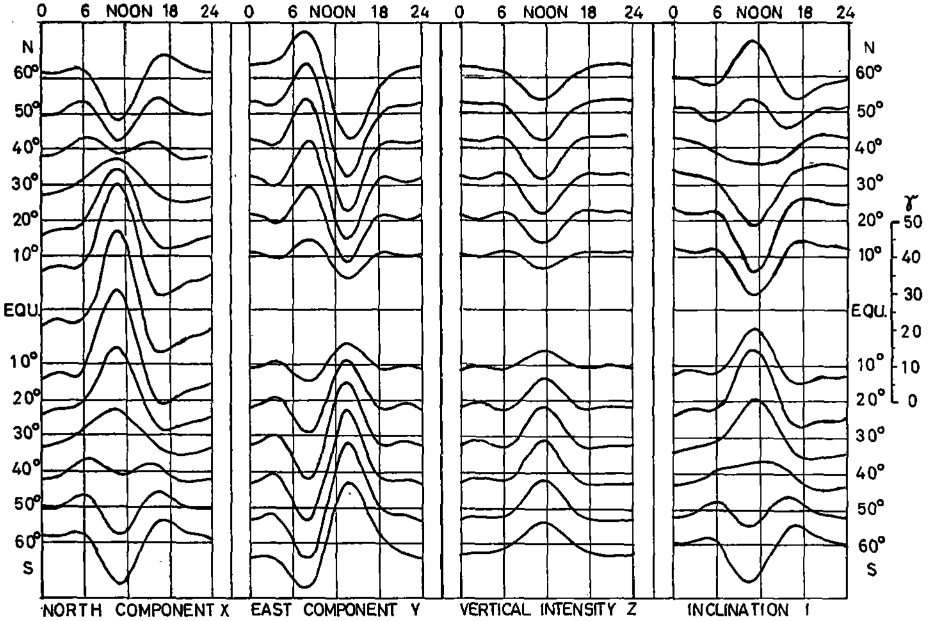

FIG. 11. Diurnal variation of X ,Y, Z, and I in a sun-spot minimum in relation to latitude. After Chapman (1919). For small values of D:

$$\Delta X^{(\gamma)} \sim \Delta H^{(\gamma)}; \qquad \Delta Y^{(\gamma)} \sim \Delta D^{(\gamma)} \qquad \text{or} \qquad \Delta D^{(')} \sim \frac{1}{H^{(\gamma)} \sin 1'} \, \Delta Y^{(\gamma)}.$$

This change is attributed to the ring current, a current flowing around the globe from east to west at a distance of several earth radii. Magnetic storms are most frequent and violent during the maximum of the sun-spot cycle.

55 The permanent part of the geomagnetic field also changes slowly in the course of time. This type of variation is called secular variation and differs from place to place, wide areas of continental size showing more or less uniform changes. In certain areas of the globe, the secular variation of one or other element changes more than in others. These areas of rapid change are called foci of rapid variation. The foci drift westward approximately 0.25° per year. The secular change is measured in gammas per year. It can be easily observed at permanent observatories. At other places, it is derived from repeat observations at secular variation stations.

Technical preliminaries

Demagnetization of the observer and the observing position

56 Many observations are marred by magnetic objects the observer is carrying on him while observing. Before you approach an instrument for observation remove from your pockets everything which is likely to be magnetic, such as purse, fountain pen, ball pen, penknife, keys, pipe cleaner and wirebound pocketbook. Inspect your dress for magnetic buckles, zippers and buttons. Sometimes cuff links may be magnetic. Remove braces, if you wear any, and belt. Some types of shoes contain steel plates in their soles which may cause considerable disturbances. Occasionally dentures are magnetic. Do not forget to remove your watch. Spectacles also need some attention. If the lenses are of low power you may observe without spectacles and correct your defective eyesight by adjusting the telescopes and microscopes. In this case spectacles are required for writing only and can be kept at some distance from the instrument. If you are compelled to use them for observation as well, the frame should be tested for magnetic material. Your optician will be able to provide you with a non-magnetic frame. When in the field, it is advisable to have a pair of spare glasses so that you are not disabled when you loose or break your usual pair.

57 Next inspect the area around your observing position up to a distance of 15 metres. Keep all instrument boxes and magnets at that distance from the instrument. Motor-cars should be at least 75 metres from the observing position. In the field, walk around the tent and see whether anything objectionable has been left near the instrument. If magnetic parts, such as galvanometers and magnets, are indispensable for observations, keep them always in exactly the same position.

Care of instruments

58 Geomagnetic instruments are made of soft metals such as copper, brass, aluminium or bronze. Therefore they have to be handled with great care. Dropping of an instrument or one of its vital parts can be calamitous. A component may be deformed and the instrument rendered useless. It is wise to have only one thing in one's hands at a time, so that your attention is focused on this one piece of equipment.

59 Always keep your instruments clean. Parts which are fitted together should be cleaned before assembly so that they join properly and do not jam. This applies especially to the surfaces where the turn magnet and the compensating magnet of the BMZ meet the body of the instrument, and where the deflection magnet of a magnetic theodolite meets its bearing. Lenses should be cleaned with a soft brush, clean linen or special lens-cleaning tissue paper. Take care that you do not damage the anti-reflection coating, i.e. do not rub with pressure.

60 Screws should be tightened with mild pressure. Always make sure that the male part enters its female counterpart easily. Never apply force in the initial phase of the threading-in procedure. The thread of the adjustable compensating magnet of the BMZ requires special care, since the accuracy of the instrument depends on the maintenance of the thread in its original shape. When attaching the turn magnet assembly, do not use the disc as a lever. It is advisable to keep one hand below the assembly to catch it in case the thread fails to engage. The same applies to dismantling the turn magnet.

61 The threads of tangent screws and levelling screws require a drop of oil from time to time so as to reduce wear. Sometimes the vernier drive of the BMZ turn magnet will fail to turn the disc. In this case, oil the bearings. Take care that oil does not flow into the drive mechanism because oil there will reduce friction and may result in a failure of the drive.

62 Careless clamping and unclamping of instruments may damage suspension fibres, pivots and agate cups of declinometers and compasses, and bearings and knife edges of balance-type instruments. Ribbon-suspended Fanselau balances require the same care, because rapid unclamping may stretch the suspension and result in undue scatter of the observations. While unclamping or clamping, observe the movement of the magnet through the telescope or, if possible, from outside so that you can see when the critical phase of the clamping procedure has come to an end. Then you may move the clamping mechanism more rapidly to its stop. Slow unclamping will prevent wild oscillations and the annoying pendulum motion of fibre-suspended magnets in QHMs and declinometers.

63 If in exceptional circumstances and for some very special reason an instrument has to be dismantled, study it carefully before you start and plan the work properly. Use exactly fitting screwdrivers for slotted screw heads (length of edge = diameter of screw head) and adjusting pins for capstan screws; pliers should not be used. You should keep a complete set of screwdrivers and a generous supply of adjusting pins in your tool kit. When the edge of a screwdriver is damaged it should be reconditioned at your earliest convenience. For the variometer room, one may keep a set of non-magnetic tools made from bronze or beryllium-copper. For extensive work, put the instrument near the centre of the table so that small parts cannot roll off and fall on the floor where they may be lost. Put the screws you remove in the same order on the table as they are arranged in the instrument so that every screw can be put back into its original position when the instrument is reassembled. This precaution is necessary because geomagnetic instruments are made by hand and a screw will in some cases fit only into its original thread. Sometimes it will be necessary to mark parts with pencil so as to make sure that the instrument is properly assembled. In the field a table may not be available. A sheet of canvas put on the ground will prevent small parts from being lost.

64 Magnets should not be dropped and should not touch each other because this may affect their magnetic moment. The compensating magnet of the BMZ should be kept at some distance from QHMs for the same reason. Magnets of magnetic theodolites and auxiliary magnets of field balances are occasionally stored in soft iron tubes or in mutual binding for protection from outside fields while in transit. After being taken out of the tube or binding, a magnet requires at least an hour for recovery before it can be used.

65 Before you start intensity observations with classical instruments, make sure that the temperature of the instrument and the magnet or magnets is near the temperature of the surrounding air, i.e. is changing only slowly. When carrying a QHM, wrap a piece of cloth around the instrument so that it is not unduly warmed by your hand. Tubular magnets of a magnetic theodolite are treated in a similar manner. The allowance made for the temperature when computing the results will not hold under rapidly changing temperature conditions, because the temperature you read off the thermometer may differ considerably from the temperature of the magnet. While observations are in progress, the temperature of a QHM or a theodolite magnet should not change more than 0.2 degrees centigrade per minute. With the BMZ, a change of 0.1 degrees centigrade per minute is the utmost that may be tolerated at high Z-values. At values around ± 20 000 gammas, larger changes are permissible. In the field, large temperature changes cannot always be avoided. In this case, continue as best you can and, if possible, repeat the observations under better conditions.

66 When operating an instrument, especially on a tripod, do not allow your hand to rest with its full weight on the instrument while adjusting tangent screws or turning the alidade. A tripod, although it looks strong, is a very flimsy support for the precision required. The effect caused by a heavy hand will show up in astronomical azimuth determinations and declination measurements, when comparing azimuth mark readings taken before and after observations. Also keep away from the area around the feet of the tripod, because on soft ground the instrument may go off level or turn in azimuth under the weight of your body.

Damping of oscillations of a magnet

67 There are more observers in the world than one would believe who wait for a suspended magnet to come to rest by itself. A QHM magnet requires about 15 minutes to come to rest and a normal QHM set of observations will under these circumstances last one hour. Therefore, the most important technique an observer must master is the damping of magnet oscillations by means of a small auxiliary magnet. For a damping magnet drive a short length of nail into a piece of wood or cork. Mark one end, preferably the north-seeking pole, by painting it red or giving it a special shape. Usually the natural magnetization of the nail will suffice. If not, increase the magnetization by means of a magnet (not one of your instrument magnets). The magnetic moment of the damping magnet is largely a matter of taste. Some observers prefer to use a screwdriver for this purpose. For finding the damping magnet on the floor, or when out in the field, on the ground, paint the magnet white. You may fasten the magnet to a cord of suitable length whose other end is tied to the top of the pier or tripod. When you drop the magnet it will hang vertically below the instrument and exert no influence when one of the horizontal components is being measured. Watch carefully that you do not get entangled in the cord.

68 Observe the oscillating magnet through the telescope. Suppose the reflected image of the diaphragm scale is moving to your right: approach the magnet chamber with one end of the damping magnet from the right. If the movement of the suspended magnet is decelerated you are holding the magnet properly; if the movement is accelerated use the other end of the damping magnet. When the oscillating magnet arrives at its extreme right-hand position, turn the damping magnet rapidly so that its other end is pointing to the oscillating magnet. When the oscillating magnet arrives at its extreme left-hand position, turn the damping magnet again, and so on, until the oscillating magnet has come to rest. At the beginning of the damping procedure, you may hold the magnet quite near to the instrument magnet, say at a distance of 10 centimetres. As the arc of oscillation gets smaller, withdraw the damping magnet slowly. Once the suspended magnet has stopped moving, drop the damping magnet. After some practice you will damp a magnet in 20 to 30 seconds.

69 When observing oscillations of the deflection magnet with a travel theodolite, the reverse procedure, namely, bringing the magnet to a certain arc of oscillation, will be required. In this case the damping magnet will have to be kept at a fair distance from the oscillating magnet so that a pendulum motion of the magnet is not excited; this will appear as a short-period superposition on the main oscillation of the magnet and lower the accuracy of the measurement.

70 The BMZ balance magnet is damped by turning the turn magnet through a small angle to and fro, counteracting the oscillations of the balance magnet.

71 It goes without saying that the labour of damping can be much reduced by unclamping the magnet slowly and by judicious use of the clamping mechanism. The magnet housings of some travel theodolites allow a large arc of oscillation of the magnet, which is annoying when observing deflections. From a soft piece of wood, carve a block which fits into the magnet housing in such a manner that it limits the arc of oscillation of the suspended magnet without touching the magnet when it has come to rest.

Thermometers

72 It will be seen later that the indications of most classical instruments vary with temperature. Some instruments may call for a very accurate measurement of the temperature because an error of 0.1 degree centigrade may cause a change of more than one gamma in the final result. For this reason, thermometers have to be calibrated before they can be used in geomagnetic measurements. Usually the makers provide thermometers with a table of corrections. When a thermometer of unknown origin is purchased locally, its corrections must be determined by comparison with a standard at a physics or chemistry laboratory.

73 When a thermometer warms up beyond its range, a drop of mercury may remain in the uppermost part of the capillary, or the mercury column may separate after contraction of the mercury. Sometimes the cause of the defect may be rough transport. A thermometer should be checked for these faults before being used in observations. Usually the mercury column will reunite when the thermometer bulb is tapped against the palm of the hand. Another expedient is to sling the thermometer. If these simple measures do not help, the thermometer may be warmed up until a fairly large quantity of mercury has entered the upper wide part of the capillary, and then cooled. In most cases the mercury column will reunite. Heating must not be overdone because the thermometer may break under the pressure of the expanding mercury. If warming up is of no avail, cooling in a mixture of ice and salt will usually be successful.

Occasionally a thermometer scale will break loose. Such an instrument has to be discarded.

Recording of observations

74 Observations should be recorded in such a manner that not only the observer can compute the results but also any other person, perhaps after many years. For this reason, legible writing is a necessity. The pencil should give a legible trace under moderate pressure. Notes made with soft pencil will be smeared. The methods of recording observations range from continuous notes in a copybook of squared paper, through printed forms on loose sheets, to well-bound books containing 50 or 100 forms. Any method of recording can be a success when it is applied properly.

75 For field work, a note book of 15 by 10 centimetres offers some advantages. It can be carried in the pocket of the observer's jacket and is therefore always at hand. The notes are arranged in chronological order so that errors in full hours or dates can be corrected when computing results. Noting the observations in a book requires some discipline. The notes should always be arranged in the same order, for example, time, temperature of instrument, angle readings, etc. Note on the first page of every book whether you use the standard time of your country or Greenwich Mean Time (GMT), and explain the relation between standard time and GMT by the equation GMT = standard time + n hours, if

necessary. Begin a day's work by entering the date and the day of the week (which is always better known than the date). Check whether the date you enter is compatible with the date noted on the previous day. Always record the types and serial numbers of instruments and thermometers you use. The notebook should have stiff covers and be well bound so that it does not disintegrate while in use. Note your address in printed letters on the inner side of the cover and offer a reward to the honest finder.

76 A notebook is also suitable for recording observations at an observatory. The it may be 20 by 15 centimetres in dimensions. However, the well-designed printed form, 30 by 20 centimetres in size, deserves preference because it ensures that no important detail is forgotten. In designing such forms, the examples in the text may be helpful. It is advisable to design a form in pencil and to try it several times in observations and computations. Sometimes alterations may be necessary before it can be given to the printers' office or cyclostyled. When using loose sheets, they should be clipped to a smooth board by means of elastic, a frame or non-magnetic leaf springs at the corners for comfortable writing. After the form is completed, it is punched and stored in a file, one for each type of observation. Forms may also be bound in books containing 50 or 100 forms. The paper used for the forms should be of good quality.

77 When forms are being used in the field it may be advisable to produce copies by means of carbon paper. This is only useful when the copies are kept apart from the originals in another box. Copies should be sent to headquarters every week or month.

78 How far computations should be carried out on a form is difficult to say. When small field books are being used, there will be no space for computations. On observatory forms, computations may be carried out to a certain extent. However, for complex computations it is better to use separate tables for the computations, so as to be in a position to compare results of observations taken at different dates. This offers a good opportunity for detecting errors.

79 If you have entered wrong figures while work is in progress, cross out those figures but maintain legibility and enter the correct figures. If you find discrepancies in the office, cross out the wrong figures, maintaining legibility in all circumstances, and enter the correct figures or what you believe to be the correct figures in coloured pencil or ball pen so that everybody can see that those entries have been made in the office. In no circumstances erase anything in your field books or observatory forms because you may be sorry for it later.

Adjustment of instruments

Levels

80 Instruments are usually delivered by the makers in a perfect state of adjustment. However, it may happen that after many years of use or rough transport an instrument will require at least a control of its adjustment. The observer should know how to adjust levels. For the more complicated adjustments he may, if he lacks confidence, contact the workshop of the geodetic survey department, where he also may get minor repairs done. Many modern geodetic theodolites as used for azimuth observations are entirely encapsuled. Only the levels are accessible. Instruments of this type can be adjusted at the factory, the workshop of an authorized dealer, or at the workshop of a geodetic survey department. The user should not try making adjustments except for those described in the directions.

81 Any theodolite consists of a base fitted with three levelling screws. On the base rests the alidade which can be revolved around a vertical axis. The alidade often carries a low-sensitivity circular level for rough levelling and at least one sensitive tube level for precise adjustment. Occasionally two tube levels are provided, arranged at right angles to each other. Instruments with telescopes, especially those of the older type, are often equipped with a striding level instead of a fixed tube level. For levelling, the striding level, which can be removed for transport of the instrument, is set with its legs on the stubs of the (horizontal) telescope axis.

82 Put the instrument on the pier or tripod so that its levelling screws rest in the grooves of the pier's top plate or the tripod head. After having adjusted the levelling screws until the bubble of the circular level is at the centre of the vial, which is marked by a circle, turn the alidade until the tube level or the striding level is parallel to the line joining two levelling screws. Bring the bubble of the tube level or striding level to the centre of its vial by adjusting the two levelling screws, turning one to the right and the other to the left in order to speed up the adjustment. Then turn the alidade 90° in azimuth and adjust the bubble of the tube level to the centre of the vial by means of the third levelling screw without touching the other two screws. Turn the alidade back to the first position and, if necessary, correct the adjustment by bringing the bubble back to the centre of the vial. Then turn the alidade 180°. Usually the bubble will now be off centre by a few divisions of the vial scale. Adjust the bubble half way between the new and previous position. Do the same for the third levelling screw. If you have achieved perfect adjustment the vertical axis of the theodolite is vertical and you may set the alidade to any azimuth with the bubble remaining in the same position within a quarter of a vial division. While levelling the theodolite, it is advisable for the beginner to move around the instrument so that he sees the level always from the same side. A common mistake is that, after levelling by means of the first two levelling screws, the alidade is turned only 120° instead of 180°, that is, the level is put parallel to the next two levelling screws, and so on. This process will never end in a perfect levelling of the instrument unless the level is in good adjustment to start with.

83 After adjusting the bubble to the centre of the vial and turning the alidade 180°, one end of the bubble may disappear under the metal cap covering the end of the vial. This indicates that the level requires adjustment by means of the screw or screws, usually capstan screws, at one of its ends. If only one screw is provided, counteraction is provided by a spring. With two screws, the adjustment is made by opening one screw and tightening the other. For this purpose use an adjusting pin. Single screws are sometimes provided with a slot for screwdriver adjustment. Bring the bubble towards the centre of the vial by means of the adjusting screws. Then adjust the bubble to the centre of the vial by using the levelling screws. Turn the alidade 180°, that is, back to its original position. Now the full length of the bubble may be visible, but not yet quite in the centre of the vial. Adjust half of the defect by means of the adjusting screws at the end of the level and the other half by means of the levelling screws. The process of adjustment will usually require several reversals of the alidade and successive adjustments of the level's adjusting screws and the levelling screws.

84 When the alidade is equipped with two tube levels at right angles to each other start with one level parallel to the line joining two levelling screws and adjust the bubble of this level to the centre of its vial by means of these levelling screws. Adjust the second level by means of the third levelling screw. Turn the alidade 180° in azimuth and continue with levelling and, if necessary, with adjustment of both levels as described before.

85 In old levels, the bubble may not move uniformly across the vial when turning the levelling screws. The bubble may stick for a while in one position and then jump by several vial divisions or, in the worst case, to the end of the vial. This defect is caused by crystallization on the inner surface of the vial and may be overcome by tapping gently with one finger on the alidade while adjusting the levelling screws. If this does not help, a new level is necessary.

86 The horizontal axis around which the telescope's optical axis or the axis of rotation of the earth inductor coil is moved in a vertical plane must be at right angles to the vertical axis of the theodolite; if the vertical axis of the theodolite is adjusted to vertical, the telescope's axis must be horizontal. This can be controlled by means of a striding level. The adjustment starts by levelling the theodolite carefully as described before. Suppose the bubble of the striding level is in the centre of its vial. Lift the striding level from the telescope's axle stubs and turn it 180°. If the telescope's axis is horizontal the bubble will remain in the centre of the vial. If not, remove half of the defect by raising or lowering the adjustable bearing of the telescope's axis and the other half by adjusting the level. If the maladjustment of the axis is considerable, several successive adjustments of the bearing and the level will be necessary. If no striding level is available, hang a long cord in front of a whitewashed wall, fixing the upper end on top of the gable or any other high point of the house. The collimation error of the telescope should previously be removed (see paragraph **89**). Tie the lower end of the cord to a plumb or stone which you let hang in a bucket of water for damping the pendulum motion. Set up the theodolite at some distance so that the telescope can be focused on the thread. Level the theodolite. Point the telescope exactly on the lowest part of the cord. Move the telescope upward to the top end of the cord. If the vertical cross-wire of the diaphragm no longer coincides with the cord, the telescope's axis requires adjustment. Remove the defect by raising or lowering the adjustable bearing of the telescope's axis. Check the result of your endeavours by pointing again at the bottom and top of the cord. The larger the difference in elevation angle of the telescope, the more accurate will be the adjustment.

The adjustment of the telescope's axis is not so very important because the magnetic theodolite is used for sightings on objects near the plane of horizon, where the tilt of the telescope's axis has a negligibly small influence on the horizontal angle. Sun observations are designed in such a manner that the tilt of the axis is eliminated by the observational procedure, namely, by observing a set in one position, turning the alidade 180°, reversing the telescope and observing a second set. The mean of the azimuths obtained from the two sets of observations will be free from errors caused by the tilt of the telescope's axis and other maladjustments.

Adjustment of the telescope

87 Direct the telescope against the sky. Adjust the eyepiece lens by moving it in or out until the diaphragm scale or the cross-wires can be distinctly seen. Sometimes eyepieces are clamped by a screw which has to be opened before and tightened after the adjustment. Point the telescope at some distant object which stands out well. Focus the telescope on the object by means of the rack-and-pinion drive or, in modern telescopes, by the ring which shifts a lens inside the telescope. Adjust the vertical cross-wire exactly on the object and move the eye from side to side in front of the eyepiece. The adjustment is perfect when no apparent movement between the vertical cross-wire and the object is observed. If movement (parallax) is present, change the focus until the parallax has disappeared. Optically poor telescopes may be troublesome in this respect and frequently one will have to be content with a compromise between the sharpness with which the object can be seen and the smallest parallax. The influence of parallax may be reduced by looking into the eyepiece from some distance. When adjusting the eyepieces of QHM and BMZ telescopes, watch that the prism illuminating the diaphragm remains in the rectangular notch of the telescope tube. The focusing of these telescopes is effected by loosening a screw near the objective end of the telescope and moving the objective lens in or out.

88 For adjustment of the cross-wires, point the lower end of the vertical cross-wire on a well-defined mark. Move the telescope vertically by means of the tangent screw until the upper end of the cross-wire is shifted to the mark. If the cross-wire no longer coincides with the mark, it is not vertical. Turn the diaphragm until the cross-wire is vertical, after having loosened the appropriate screws. Then the horizontal cross-wire will automatically be horizontal.

89 The optical axis of the telescope should be at right angles to the axis on which the telescope revolves in the vertical plane. Point at a distant object and read the horizontal circle. Turn the alidade 180° in azimuth, reverse the telescope, point again at the object and read the circle a second time. The telescope is in good adjustment when the two circle readings differ by exactly 180°. If this is not the case, adjust the circle to ½ (reading I + 180 + reading II) and shift the diaphragm laterally by means of the capstan screws until the vertical wire points on the object. If the telescope is mounted on one side of the theodolite, choose an object at a distance of ten kilometres. If no suitable object is available draw two marks on a piece of paper twice as far from each other as the optical axis of the telescope is from the theodolite's centre, and use them for the adjustment of the cross-wires. As long as the theodolite is used for pointing on objects near the plane of horizon, the collimation error has practically no influence on the horizontal angle. For sightings on celestial objects, the error is eliminated by using the instrument in both telescope positions as will be explained later.

Adjustment of vernier lenses and scale microscopes

90 Vernier lenses are adjusted by moving the eyepiece in its holder until the circle and the vernier can be seen properly. The eyepieces of scale microscopes are moved in or out until the scale and the circle are equally well visible and no parallax is present. Moreover, it is worth while checking whether the end marks of the scale exactly cover two adjacent circle divisions or not. Hard-and-fast rules cannot be given for this adjustment because there exists a large variety of microscope constructions. The general principle is to move the whole microscope in its support up or down, while continually adjusting the eyepiece, until the desired result has been obtained.

Instruments, methods of observation and computation

Measurement of time and time-keeping

91 The most convenient timepiece at an observatory is a clock with a seconds pendulum and with contacts for the second, the minute and the hour. The clock should be mounted on a solid wall in a room with fairly stable temperature. Adjust the clock by tilting it to one side or the other so that the second clicks produced by the escapement are equidistant in time. This requirement is usually fulfilled when the pendulum at rest is in front of the central division of the scale near the low end of the pendulum.

92 The rate (gain or loss in 24 hours) is adjusted by shifting the heavy pendulum lens up or down along the pendulum rod by means of a screw below the lens. Most pendulums are equipped with a small platform at about one-third of the way from the upper end of the pendulum rod. If not provided by the makers, a platform can be easily attached to the rod. By putting small weights on the platform the centre of gravity of the pendulum, which is within the lens, will be raised and the clock will be faster than before. When weights are removed the clock will slow down. With the weights, a very precise adjustment of the clock rate is possible. Cut from a copper wire a good supply of weights of different length. A weight can be added or removed with tweezers without stopping or disturbing the pendulum motion. Usually it will not be possible to adjust the clock to zero error. Allow the clock to accrue an error of a few seconds. Then reverse the rate by adding or removing a weight. After the clock has accrued an error of a few seconds in the opposite sense, reverse the rate again.

93 Control the clock every day by means of a radio time signal and note the results of the comparisons in a clock journal as in the following example:

Date	*Standard (GMT)*	*Clock (GMT)*	*Temperature*
5 January 1966	08h00m00s	07h59m58.5s	+ 16.8° C

This entry leaves no doubt as to the algebraic sign of the error or correction.

If only the error or correction is noted, the algebraic sign may be wrongly entered.

94 Of the contacts, the hour contact will certainly be used for marking the hours on the magnetogram. If the clock is at some distance from the variometer house, or the contact is not adapted to carrying a heavy current, a relay may be used for switching on the time-mark lamp. Place the relay so that it does not disturb the variometers, either by mounting it at some distance from the instruments or by turning it until no trace of disturbance is found on the magnetogram. Check that the hour contact, which holds for a few seconds, makes and breaks exactly at the full hour or, if it lasts longer, is symmetrical with respect to the full hour. When using the pendulum clock of the La Cour magnetograph, the full minute occurs when the contact falls from the high part of the cam, that is, when the minute contact is made. With this clock, attention has to be paid to the position of the spokes of the wheel which moves with the minute hand. The wheel should be adjusted so as to switch on the time-mark lamp only every fifth minute and at the 59th, 60th and 1st minute of every hour. The setting of the spokes requires checking from time to time because, when the wheel is not properly adjusted, the 'make' may occur one minute too early or too late, or two time signals may be given. If desired, the clock may be converted to giving time signals only at the full hour, by filing down all spokes except for the one giving the 60th minute. A less radical cure is to paste strips of paper over the end of the spokes which are not wanted.

95 The minute contact will be required for producing time marks on records of rapid variations and will not last longer than a second. The minute mark at the full hour is inhibited by the hour contact so as to make identification of the full hours easy. The second contact, for which a relay is always required, is used for the strip-chart chronograph. The second mark at the full minute is inhibited by the minute contact. Instead of the pendulum clock, a crystal clock or a contact chronometer may be used.

96 For observations with absolute magnetic instruments it is sufficient to record the time to the nearest minute. This accuracy can be easily maintained with a wrist watch that from time to time is compared with the pendulum clock or the time signal of a broadcasting station. Two measurements require better accuracy in time: for the determination of sun azimuths the time should be known to the nearest half-second; when observing oscillations of a magnet, an accuracy of one-tenth of a second or better is desirable. When the observer has an assistant who is recording his readings, timing of an event is easy. A few seconds before the event the observer will call, 'Ready', so that the assistant can concentrate his attention on the timepiece. At the event the observer will call, 'Up'. The assistant will record the time to the nearest half-second when an azimuth is observed, or to the nearest tenth-second when the event is the passage of an oscillating magnet.

97 When the inexperienced observer is working alone, recording of time is difficult. For the application of the eye/ear method, a half-second beating chronometer is indispensable. The chronometer must be placed near the instrument so that the observer can hear the chronometer beats while observing. By a glance at the dial he picks up the seconds and, guided by the beats, he counts while looking through the telescope, estimating the time of the event to one-half or one-tenth of a second and recording the result. This procedure requires much practice, especially when oscillations of a magnet have to be timed. In the field, strong wind often makes it impossible to hear the beats of the chronometer. A better solution to the problem of timing events is the chronograph, a stop-watch with two second hands of which one can be stopped by pressing a button while the other continues moving. After having read the watch and recorded the time, the button is pressed again and the arrested second hand will fall in step with the moving hand, thus making the watch ready for another observation. Chronographs allow either one-fifth or one-tenth of a second to be read, the latter being necessary for the observation of magnet oscillations. If time signals are available every full hour, the chronograph may be started exactly at the full hour and controlled at the next hour. Usually the error will not exceed a few tenths of a second per hour and has to be allowed for when computing the final times of the events. If time signals are infrequent, the chronograph is started at any full minute shown by the clock or chronometer and stopped after observations, again at a full minute. When using this procedure, the rate of the chronometer or clock as well as that of the chronograph will have to be allowed for.

98 If only astronomical observations are to be made, an ordinary stop-watch may be used. The stop-watch is started at the event and stopped at any five or ten seconds of the chronometer. Instead of subtracting mentally the time shown by the stop-watch from the time of the chronometer, it is better to write down both readings and to do the subtraction in the office. This method is not good enough for timing magnet oscillations.

99 The most perfect time recording is obtained by means of a strip-chart chronograph in conjunction with a contact clock or chronometer. One stylus of the chronograph records the seconds, while the second stylus, actuated by a hand key, records the events. Instead of a hand key, a photocell and an amplifier may be used for actuating the stylus when observing passages of an oscillating magnet at the observatory. For field work, a strip-chart chronograph is less suitable because it takes some time to set up.

100 At the observatory, time-keeping is a simple task; with a good radio receiver and a high antenna, numerous time signals will be available. On survey journeys, it is simple if a portable receiver with a sensitive short-wave section is at the disposal of the observer. There are numerous time signals to be heard on variou frequencies, of which the best known are those broadcast by WWV on 2.5, 5, 10, 15, 20, 25 and 30 Mc/s. Numerous broadcasting stations transmit time signals consisting of six pips of which the last one is the full or half hour. Most of these time signals are controlled by time standards of high precision. Time signals on medium waves may be received with a cheap midget radio, the range of which is several thousand kilometres during night hours. In daylight hours, the range of a midget radio may be boosted by using a long wire antenna. If the radio has no jack for the external antenna, coupling to the receiver can be arranged by wrapping a few turns of insulated wire around the radio so that the turns are parallel to the turns of the internal ferrite antenna. One end of this coil is connected to the long wire suspended a few metres above the ground, while the other end is connected to the ground or, in very dry country, to a length of wire resting on the ground. At the beginning of the field season, the observer should scan the frequency bands he can hear with his receiver for time signals and prepare a table of broadcasting stations with frequencies, dial settings of the receiver and times of time signals. If possible, a time signal should be obtained at every field station. With a good timepiece, a time signal in the morning and evening of a field day may be sufficient.

101 For field work, precise timepieces are available in several versions. Most common are half-second-beating marine chronometers, which are suspended in a gimbal. While in transit, the gimbal has to be clamped. Box chronometers are smaller in size and without gimbal. Both types of chronometers should be transported in upholstered boxes resting on a folded blanket and the dials should be kept horizontal. When exposed to heavy shocks, the escapement may snap and the chronometer may gain several seconds. Half-second-beating pocket chronometers are best carried in the breast pocket of the observer's jacket or shirt. One-fifth-second-beating precision watches are less susceptible to the hardships of transport. Those of box chronometer size, occasionally equipped with a second contact, have to be transported with the same care as a half-second-beating chronometer. Although precision chronometers and watches are temperature-compensated, they should be kept at a fairly uniform temperature. One should avoid exposing them to the sun.

Use of the magnetogram in absolute measurements

102 The purpose of a geomagnetic measurement at an observatory is to determine the base-line values D_0, H_0 and Z_0 on the magnetogram, so that the values of the three recorded elements can be determined for any other time (Fig. 12). The base-lines are recorded by the fixed mirrors of the respective variometers. If the temperature of the variometer room is variable and the variometers are not completely temperature-compensated, the base-line value T_0 of the thermograph has also to be determined. The base-line value of an element is the value which it will assume when the trace recorded by the magnet mirror of the variometer is exactly on the base-line (in Figure 12 the trace of the D-variometer is at 10.00h GMT). If at this time an absolute measurement of the declination had been made, the observed value would have been the base-line value of D. When an absolute measurement is made at any other time, say of H at 10.30 h, the base-line value can be computed by measuring the ordinate in millimetres, converting it to gammas by multiplication by the known scale value of the H-variometer S_H, and subtracting the result from the observed value of H:

$$\Delta H^{(\gamma)} = \Delta H_{mm} \,.\, S_H \quad \text{and} \quad H_0 = H_{obs} - \Delta H_{mm} \,.\, S_H. \tag{10}$$

This procedure is called the determination of the base-line value or alternatively the reduction of an observation to base-line. The arrows on the left-hand side

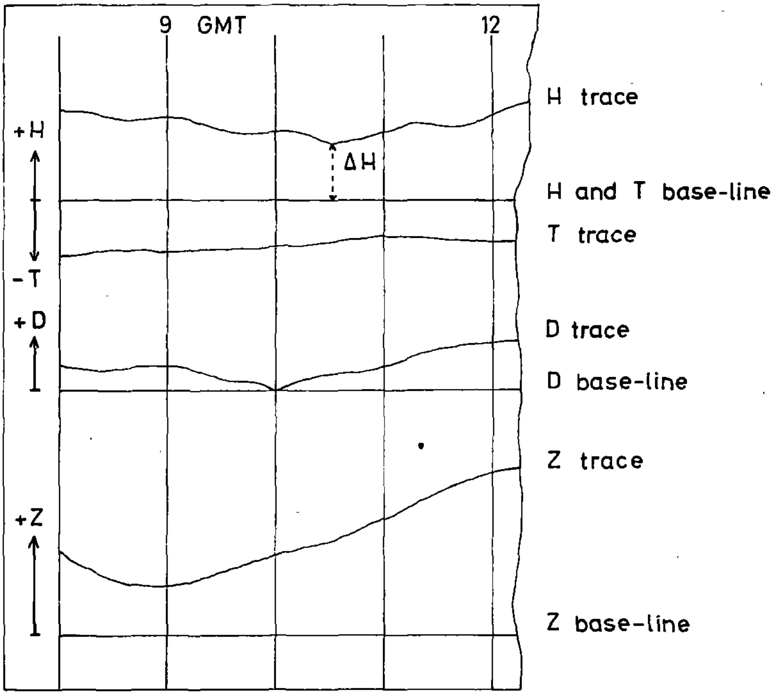

FIG. 12. The normal magnetogram.

of Figure 12 indicate the algebraic sign of the change of D, H, Z and T. The following symbols will be used:

Base-line values	Ordinates in millimetres	Scale values
D_0	ΔD_{mm} or n_D	S_D in minutes of arc/mm
H_0	ΔH_{mm} or n_H	S_H in gammas/mm
Z_0	ΔZ_{mm} or n_Z	S_Z in gammas/mm
T_0	ΔT_{mm} or n_T	S_T in °C/mm

One may also obtain base-line values for the total intensity F and the inclination I by reducing the observed values by means of the formulae for small changes. F_0 and I_0 are then based on the base-lines of H and Z because ΔF and ΔI are composed of ΔH and ΔZ. The base-line values must obey the relations

$$F_0^2 = H_0^2 + Z_0^2 \quad \text{and} \quad Z_0 = H_0 \tan I_0.$$

At some observatories, only one base-line is recorded at the bottom of the magnetogram. In this case it is advisable, when reducing F and I, not to use the whole ordinates n_D, n_H, n_Z and n_T, but to subtract multiples of 10 millimetres from them, in order to obtain smaller values and to remain within the limits of validity of the formulae for small changes. Thus, fictitious base-lines are introduced which run parallel to the recorded base-line. If, for instance, an amount of 100 millimetres is subtracted from n_H, we shall write the base-line value H_{100}. In this case the fictitious base-line is 100 millimetres above the recorded base-line.

Determination of the magnetic declination

103 In principle, the determination of the magnetic declination consists of two parts, namely, the determination of the magnetic meridian and the determination of the true north meridian. The task has been performed when both values are available on the same instrument circle. Figure 13 illustrates the situation. The magnetic declination is the angle between the true north meridian and the magnetic meridian. Az is the azimuth of the azimuth mark and is always reckoned positive from true north through east, south and west to north. It may assume values between zero and 360°. Then

$$D = A - (B - Az) \tag{11}$$

where: D = magnetic declination; A = circle reading of the magnetic meridian; B = circle reading of the azimuth mark; Az = azimuth of azimuth mark; B − Az = circle reading of true north meridian.

We recall that D is positive or east when the magnetic meridian is east of the true meridian.

104 The magnetic declination is measured by means of a magnetic travel theodolite or station theodolite, often called theodolite magnetometer because the instrument is also used for the determination of the horizontal intensity. It consists

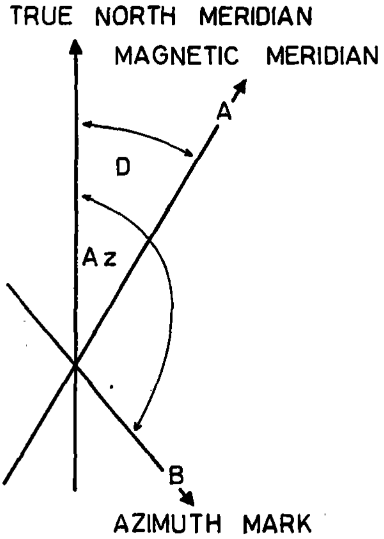

FIG. 13. True north meridian, magnetic meridian, and azimuth mark.

of a theodolite base with three levelling screws and a horizontal circle. On top of the base is mounted the magnet housing with the suspension tube. The suspension tube, with the torsion head at its upper and the clamping mechanism at its lower end, contains the suspension fibre of phosphor-bronze or tungsten wire of 0.02 to 0.04 millimetres diameter, depending on the weight of the magnet and stirrup. Sometimes phosphor-bronze ribbon is used with a width-to-thickness ratio of 10 to 1. Ribbon has the advantage that its rigidity compared with the rigidity of wire of equal cross-section is much smaller. Furthermore, the ribbon is easier to replace because it does not curl up when one end becomes loose. In some older types of theodolite magnetometers, especially those with short suspension tube, silk fibres are used. The upper end of the suspension fibre is clamped to the central part of the torsion head and can be raised or lowered by means of a screw and nut or a rack and pinion. This device allows adjustment of the height of the magnet in the magnet housing. The lower end of the suspension fibre is clamped to the stirrup, to which the magnet can be coupled by means of its hooks. The telescope, whose elevation angle can be adjusted by means of a tangent screw, is usually equipped with a diaphragm scale for facilitating declination observations. Some magnetic travel theodolites have bearings for an azimuth mirror.

105 Magnets of declinometers carry mirrors on both ends, the normals of the mirrors being approximately aligned with the magnetic axis of the magnets. Occasionally, magnetic theodolites are equipped with tubular magnets which have a lens at one end and a transparent scale at the other. The magnet has to be suspended with the lens pointing towards the telescope of the theodolite. The magnet can be connected to the stirrup in the 'erect' position (marked side up), and after rotating it around its axis 180°, in the 'inverted' position (marked side down), by means of two hooks which are fixed diametrically in the middle of the magnet, thus allowing correction for any small angle between the magnetic axis of the magnet and the normal to the mirror.

106 Often the windows of the magnet housing are not plane-parallel. Correct results will be obtained when the azimuth mark is observed through the window between the telescope and the magnet, keeping the window at the other end of the magnet housing open. If the windows are circular, this source of error may be removed by turning the glass in its frame and comparing the sighting through the glass at an azimuth mark with the sighting made without any glass. There will be one position at which no horizontal displacement of the azimuth mark occurs.

107 The eyepiece scale of the telescope extends 30 to 40 divisions on both sides of the vertical cross-wire. Its scale value is either one minute of arc or an arbitrary unit of about one minute. The scale value is checked or determined by means of the horizontal circle of the theodolite. Direct one end of the scale to a distinctly visible mark and read the circle. Direct the other end of the scale to the same mark and take another circle reading. The scale value of one division is:

$$\frac{\text{circle reading I} - \text{circle reading II}}{2\,.\ \text{number of scale divisions}}$$

In the denominator, twice the number of scale divisions of the whole scale has to be taken because the angular sensitivity of the scale is doubled by reflection on the magnet mirror. Here is an example:

Mark at division:	− 30	258°37.2′	mean of five sightings
Mark at division:	+ 30	257°05.9′	
Difference:	60	1°31.3′ or 91.3′	

$$\text{Scale value} = \frac{91.3'}{2\,.\,60} = 0.76'.$$

If the scale is divided in arbitrary units, as in the above case, compute a table for the conversion of scale divisions to minutes of arc.

108 The suspension fibre has to be adjusted with the torsion head so that it does not deflect the magnet from the magnetic meridian. For this purpose hang the non-magnetic torsion weight from the stirrup. There exist various forms of torsion weights, ranging from a disc graduated in degrees of arc on its rim, through bars, to weights in the shape of a declination magnet with mirrors at both ends. The line of no-torsion of the suspension fibre coincides with zero of the disc graduation or the axis of the bar. The weights have to be adjusted by means of the torsion head so that the line of no-torsion coincides with the direction of the telescope's optical axis. With discs and bars the adjustment is made by sight. When torsion weights with mirrors are used, the adjustment can be made with great accuracy by means of the telescope. For adjustment of the fibre, unclamp the declinometer and let the torsion weight come to rest. The initial arc of oscillation may be reduced by using the clamping mechanism. Even so, it may take hours before the torsion weight comes to rest or before its arc of oscillation has been reduced sufficiently for the reading to be taken by estimating the position of the weight from the extremes of the arc of oscillation. Adjust the torsion head until the zero of the graduated disc or the axis of the bar points toward the telescope. When the torsion weight has mirrors, adjust the torsion head until the diaphragm scale and its reflected image are in coincidence. This adjustment is not critical because a maladjustment of the line of no-torsion by one degree will cause a deflection of the declination magnet from the magnetic meridian of less than 0.1′. At an observatory, the line of no-torsion can be kept under control by inserting the torsion weight after having completed the observation of declination. Before starting a new observation a week later, the line of no-torsion is checked and, if necessary, corrected by using the fine drive of the torsion head. It will be noticed that a new fibre will change its line of no-torsion from observation to observation by a substantial amount but after some months the changes will become smaller and after a year the line will come to rest. When after some years the line of no-torsion starts to change again, the fibre will usually break soon afterwards.

109 If, for the measurement of the declination, only one magnet is available, the instrument is ready for use. A faulty adjustment of the line of no-torsion can be allowed for by using two magnets of different magnetic moments, the ratio

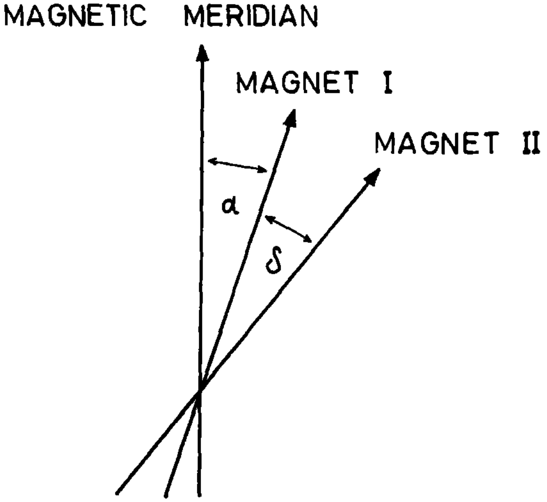

FIG. 14. Absolute measurement of magnetic declination with two magnets.

of the moments being between 2 : 1 and 3 : 1. If the line of no-torsion deviates from the telescope's optical axis, the weaker of the two magnets (Magnet II) will be forced away from the magnetic meridian by a larger angle than the stronger magnet (Magnet I; see Fig. 14). The circle readings obtained with Magnet I and Magnet II are known from the observations. For the computation of α, which is the correction of the circle reading obtained with Magnet I to the magnetic meridian, the ratio of the magnetic moments of the two declination magnets has to be known. The ratio of the magnetic moments is found by twisting the torsion fibre through a substantial angle, say, 90°. Magnet I may be deflected through ε_1 scale divisions of the diaphragm scale while Magnet II is deflected through ε_2 scale divisions. It can be shown that

$$\alpha = \delta \frac{\varepsilon_1}{\varepsilon_2 - \varepsilon_1} \tag{12}$$

where: δ = circle reading of Magnet I minus circle reading of Magnet II; $\varepsilon_1/\varepsilon_2 - \varepsilon_1$ is called the torsion factor TF. For the determination of ε, hang Magnet II (weak magnet) on the stirrup. Adjust the alidade of the theodolite in azimuth until you read zero on the diaphragm scale. Note the position of the torsion head. Twist the fibre until the magnet is deflected 20 to 30 divisions of the scale. Increase or decrease the angle of twist until you are at a round value, say, 90°, and read the diaphragm scale. Twist the fibre − 90° and read the diaphragm scale again. Repeat the procedure several times. Repeat the whole procedure again with Magnet I. The table explains the operations. The figures are obtained from the means of five observations.

Magnet	Twist of fibre	Reading of torsion head	Reading of diaphragm scale	Difference of scale readings
II	0°	79°30′	0.0	
	+ 90°	169°30′	+ 18.8	37.3
	− 90°	349°30′	− 18.5	
	0°	79°30′	− 0.1	
I	0°	79°30′	0.0	
	+ 90°	169°30′	+ 6.3	12.5
	− 90°	349°30′	− 6.2	
	0°	79°30′	− 0.2	

Using an approximation, the torsion factor is

$$\mathrm{TF} = \frac{\varepsilon_1}{\varepsilon_2 - \varepsilon_1} = \frac{12.5}{37.3 - 12.5} = 0.50.$$

If the telescope has no eyepiece scale, the first setting is made as before. Read the horizontal circle of the theodolite. After having twisted the fibre + 90°, adjust the alidade until the vertical cross-wire coincides with its reflected image. Read the circle again. Twist the fibre − 90°, adjust the alidade and read the circle, etc., until a sufficient number of readings has been obtained. Instead of using scale divisions of the diaphragm scale, use the differences of the circle readings for + 90° and − 90° fibre twist and treat the results as before. The torsion factor depends only on the ratio of the magnetic moment of the two magnets. Therefore, no new determination is required when the fibre is replaced. However, the torsion factor will have to be checked from time to time as long as the instrument is new, when the magnetic moment of the magnets may change through ageing.

110 The table opposite explains the observation and computation of the magnetic declination. The observations were made with an Askania travel theodolite whose circle is read by means of scale microscopes giving degrees and double-minutes. Minutes of arc are obtained by adding the double-minute readings of microscope A and B. For instance, the first circle reading of the example pertaining to the azimuth mark is 337°04.9′ for microscope A, and 157°05.0′ for microscope B. The minutes of the circle reading will be 04.9 + 05.0 = 09.9′. After having levelled the theodolite, a sighting on the azimuth mark is made. Then the alidade is turned in azimuth so that the telescope is south of the instrument (the observer when looking into the telescope is facing north). Hang Magnet I from the stirrup in the inverted position. Adjust the alidade to zero of the diaphragm scale. Up-turn the magnet to the erect position and read the diaphragm scale. If the reading be − 22, then the approximate magnetic meridian will be at − 11 of the diaphragm scale. Adjust the reflected image of the central line to this value by turning the alidade. Now adjust the alidade, by looking into the microscopes, to the nearest full double minute, which in our example is 26.0. From now on, do not touch the tangent screw of the circle. Read only the diaphragm scale. Damp the magnet, read the diaphragm scale and the time, and record the readings. Read the diaphragm scale again and record the reading. Invert the magnet and take two scale

Declination measurement with a fibre declinometer

1966, November 6, Sunday
Fürstenfeldbruck Observatory, calibration pier
Fibre declinometer Askania No. 661057

			A	*B*	*Mean*
Azimuth mark:	Concrete pole	Beginning	337°04.9′	157°05.0′	337°09.9′
	Concrete pole	Ending	337°04.9′	157°05.1′	337°10.0′
		MEAN			337°09.95′

Telescope south

Time (GMT)	Circle reading	Magnet position	Scale	Circle (192° +)	n_D (40)	$\Delta D^{(\prime)}$	Circle reduced to base-line	Mean
h m								
				Magnet I				
08 30	A: 192°26.0′	e	− 10.6	41.40′	39.5	+ 0.24′	192°41.16′	192°52.04′
	B: 12°26.0′	e	− 10.6					
31	192°52.0′	i	+ 11.1	63.10′	39.6	+ 0.19′	62.91′	
		i	+ 11.1					
33		e	− 11.0	41.00′	39.6	+ 0.19′	40.81′	51.83′
		e	− 11.0					
35		i	+ 11.0	63.00′	39.7	+ 0.15′	62.85′	
		i	+ 11.0					
MEAN				52.12′		+ 0.19′		192°51.94′
				Magnet II				
08 37		e	+ 9.3	61.30′	40.2	− 0.10′	192°61.40′	192°52.00′
		e	+ 9.3					
38		i	− 9.5	42.50′	40.2	− 0.10′	42.60′	
		i	− 9.5					
40		e	+ 9.4	61.40′	40.4	− 0.19′	61.59′	52.04′
		e	+ 9.4					
41		i	− 9.7	42.30′	40.4	− 0.19′	42.49′	
		i	− 9.7					
MEAN				51.88′		− 0.14′		192°52.02′

Azimuth mark (mean): 337°09.95′
Azimuth of mark: 142°19.00′
True north meridian: 194°50.95′

Magnet I: 192°51.94′
Magnet II: 192°52.02′
δ (= I − II): − 0.08′
α (= TF × (I − II)): − 0.04′
Magnetic meridian: 192°51.90′
True north meridian: 194°50.95′
D_{40} − 1°59.05′

TF: 0.50

S_D = 0.484′/mm negative n_D = positive $\Delta D^{(\prime)}$

readings as before. After having obtained enough readings with Magnet I, insert Magnet II in the erect position without touching the tangent screw of the circle. Continue as before. Finally, check the circle reading, remove the magnet and point the telescope on the azimuth mark. When the telescope has no diaphragm scale, the settings are made by bringing to coincidence the vertical cross-wire and its reflected image, and reading the circle for each setting.

111 The computation starts with adding the scale readings to the circle reading. The scale value of the diaphragm scale was exactly 1.0′/scale division. To reduce the individual observations to base-line, the ordinates have to be measured on the magnetogram. Since the base-line is at the bottom of the magnetogram, 40 millimetres are subtracted from the ordinates before they are converted to minutes of arc by means of the scale value S_D, which in this case is 0.484′/mm. On the magnetogram, D is decreasing when the ordinate increases. Therefore, positive n_D results in negative $\Delta D^{(\prime)}$. If $\Delta D^{(\prime)}$ is positive, the base-line is west of the trace and since the circle readings increase from north through east, $\Delta D^{(\prime)}$ has to be subtracted from the circle readings as has been done in the first line of the example for Magnet I. Below the columns 'Circle' and '$\Delta D^{(\prime)}$', the means of the whole set of observation have been inscribed, for controlling the final result (for Magnet I: 192°52.12′ − 0.19′ = 192°51.93′ instead of 192°51.94′ below the last column). The computation of the true meridian and the magnetic meridian can be inferred from the example. Finally we obtain

$$D_{40} = \text{magnetic meridian} - \text{true meridian}.$$

In the example, the magnetic meridian is west of the true meridian. Therefore, the declination is negative or west. Measurements with a single magnet are reduced in the same way, the magnetic meridian being given by the mean of all magnet readings. In the example, the difference between the two methods would have been 0.04′ when using Magnet I. With a station theodolite the error of a measurement will be 0.1′, while with a travel theodolite the error will be 0.2′ or higher.

112 Although the method described above is called the 'absolute measurement of declination', perfect results can only be expected from a station theodolite with a precise circle and made of carefully selected non-magnetic material. A reliable check of the theodolite consists in observing the declination at 'telescope south', which is the normal position, and at 'telescope north'. If the results obtained in the two positions are not in close agreement, it can be assumed that some part near the magnet is permanently magnetized. The mean of the values observed in the two alidade positions will be free from the error caused by permanent magnetization. This error is frequently found in declination attachments of travel theodolites with a narrow magnet housing. The seat of the magnetization is usually in the damper plates and the screws which hold the plates in position. The damper plates can be removed without impairing the performance of the instrument, for they are ineffective because of the slow movement of the magnet. Another error may be caused by magnetization induced by the declination magnet in parts of the magnet housing which are not perfectly non-magnetic. This error can only be found by comparing the instrument with a standard. With a magnet housing made of wood or fibre, in an extremely dry climate, errors may arise from electrostatic attraction. When the instrument is cleaned before starting observations, electric charges may be generated. A few spots of radioactive paint, as used by watchmakers for renewing luminous dials, may be put on the glass windows and other parts of the magnet housing in order to dissipate electric charges.

113 In the field, the fibre declinometer can be an uncomfortable piece of equipment, especially when being used with one magnet, because the frequent time-consuming adjustment of the line of no-torsion taxes the observer's patience. For this reason, some makers of geomagnetic instruments equip their travel theodolites with a pivot declinometer which not only works rapidly but is also unaffected by wind. The magnet comes to rest quickly owing to friction between the pivot and the agate cup of the magnet, without being helped by a damping magnet. This type of declinometer is especially suited for areas with high values of horizontal intensity. The magnet is equipped with mirrors at its ends. In the middle of the magnet, a double agate cup can slide up and down in a shaft so that the centre of gravity of the magnet remains below the point of support when the magnet is inverted. When the instrument is used for the first time, the magnet should be balanced. Set up the instrument and level the base. Turn the alidade so that the telescope is south of the instrument. Clean the pivot with pith and see that the agate cup slides up and down in the shaft by its own weight. If it does not, push the cup to and fro by means of a matchstick (not with a screwdriver!) until it moves easily. Turn the clamping lever to the position 'clamped' and insert the magnet carefully, so that the pivot and the cup are not damaged. For this purpose, special tweezers are sometimes provided. Unclamp gently and check the horizontality of the magnet. If the magnet is not horizontal, shift the balancing weight (which in the northern hemisphere is usually at the south-seeking pole) either towards the end or centre as required, until the magnet is horizontal. The magnet may have to be rebalanced when moved large distances in a north-south direction. Check the quality of the pivot and the agate cup by deflecting the magnet from the magnetic meridian by means of the damping magnet or a screwdriver. When both parts are in good condition, the magnet will oscillate smoothly and come to rest after 10 to 15 seconds near the same scale division as before. If the movement is jerky, the magnet will come to rest quickly, and repeated deflections will result in greatly differing settings. In this case, the pivot will have to be replaced. If this does not improve matters, the cup is probably damaged. Pivots are either specially made for the instrument or (frequently) are the sharp ends of high-quality needles. The height of the pivot is adjusted by means of a gauge.

114 Observations with the pivot declinometer differ only slightly from those with the fibre declinometer. After having set up the instrument, cleaned the pivot and the magnet housing with pith and checked the mobility of the agate cup, point on the azimuth marks. Turn the telescope to the south of the instrument. Insert the magnet in the erect position (marked side up). Unclamp the magnet and adjust to a division of the diaphragm scale so that the magnet, when inverted, will come to rest on approximately the same scale division on the other side of the central division. Read the circle after having adjusted it to the nearest full minute of arc. After having unclamped the magnet, tap gently with one finger on the theodolite so that the pivot settles properly in the agate cup. While the magnet is oscillating, scratch with a fingernail the rough rim of one of the levelling screws. This will help overcome friction between the agate cup and the pivot. When the magnet has come to rest read the diaphragm scale and record the value. Clamp and unclamp the magnet slowly and take another reading. Continue until you have obtained six or eight readings with a scatter of not more than one minute of arc. After having clamped the magnet, invert it and take another six or eight readings. Finally, take another round of azimuth observations. Since the magnet readings follow each other in rapid succession, times are noted only for the beginning and end of a set of observations. The accompanying example is self-explanatory. The reduction of the observations to base-line is simplified if, instead of measuring the ordinate of the declination trace for each setting, the mean ordinate for the span of time covered by one set (in the example, for 10h14m—10h17m and 10h18m—10h20m) is measured.

115 The magnet housing of a pivot declinometer is usually very narrow and errors caused by magnetic parts are therefore more prominent than with fibre declinometers; the worst offenders are again the damper plates; these can be removed, since enough damping is provided by friction. Even after having removed the damper plates an appreciable difference between telescope north and telescope south may be observed. In this case it is always necessary to observe the instrument in both telescope positions because the difference may be variable. The pivot declinometer is a relative instrument and has therefore to be compared frequently with an observatory standard when being used on a field survey.

116 It may happen that a mirror is loose in its frame. Then the difference between the readings in the erect and inverted magnet position will vary. If the frame consists of a nut the defect can be removed by tightening the nut. However, if the nut is too tight the mirror will bend and the reflected diaphragm scale will have a crooked appearance. The correct position of the nut is found by trial. With a fixed frame, a drop of sealing wax or picein (obtainable from any physics laboratory) applied to the frame and the rim of the mirror will cure a loose mirror.

117 Whereas the fibre declinometer, and to some extent the pivot declinometer, are suitable for observatory observations, the instruments described in the following paragraphs are good only for field work. Their characteristic is that the magnet cannot be inverted. An appreciable correction will therefore usually be necessary and has to be determined by comparison with an observatory standard.

118 A useful instrument for field surveying is the tube compass which is supplied as an accessory with various types of geodetic theodolites. The compass is usually put on a shoe on one of the theodolite standards. Observations are made in the same way as with the pivot declinometer. The instrument will give the declination within one or two minutes of arc.

119 Compass theodolites are instruments in which either a graduated circle is connected with the magnet or the compass needle oscillates over a graduated

Declination measurement with a pivot declinometer

1965, February 2, Tuesday
Fürstenfeldbruck Observatory, calibration pier
Pivot declinometer Askania No. 580141

		A	*B*	*Mean*
Azimuth mark: Alling church	Beginning	78°18.7′	258°18.8′	78°37.5′
	Ending	78°18.6′	258°18.7′	78°37.3′
	MEAN			78°37.40′

Telescope south

Time (GMT)	Circle reading	Magnet position	Scale	Circle (291° +)	n_D (40)	ΔD(′)	Circle reduced to base-line	Mean
h m								
10 14	A: 291°09.8′	e	+ 10.6′					
	B: 111°10.2′	e	+ 11.0′					
	291°20.0′	e	+ 10.8′					
		e	+ 11.0′					
		e	+ 10.8′					
		e	+ 11.0′					
		e	+ 11.0′					
10 17		e	+ 11.1′					
MEAN	291°20.0′		+ 10.91′	30.91′	46.3	– 3.05′	291°33.96′	
10 18		i	– 8.0′					
		i	– 8.0′					
		i	– 7.8′					
		i	– 7.8′					
		i	– 8.0′					
		i	– 8.0′					
		i	– 7.8′					
10 20		i	– 8.2′					
MEAN	291°20.0′		– 7.95′	12.05′	46.4	– 3.10′	291°15.15′	291°24.56′

Azimuth mark (mean):	78°37.40′	Magnet I:	291°24.56′	TF –
Azimuth of mark:	145°08.40′	Magnet II:		
True north meridian:	293°29.00′	δ (= I – II):		
		α (= TF × (I – II)):		
		Magnet meridian:	291°24.56′	
		True north meridian:	293°29.00′	
		D_{40}	– 2°04.44′	

S_D = 0.484′/mm   positive n_D = negative ΔD(′)

circle. To the first category belongs the theodolite type TO of Wild, which is made of carefully selected non-magnetic material. The telescope is first directed to the azimuth mark. Then the magnet is unclamped and, after it has been brought to rest with scratching at one of the levelling screws, the circle is read by means of a micrometer. Clamping and unclamping may be repeated several times so as to obtain a mean value accurate to the nearest minute of arc. In old-fashioned theodolites, the position of the magnet needle over the circle is read with either a prism or a lens.

120 Likewise, declination observations may be made with a good prismatic compass. However, the result will have an accuracy of only one-tenth or one-twentieth of a degree. Although the accuracy is low, results obtained with a prismatic compass are better than no results at all. Naturally, repeated clamping, unclamping and reading will improve the accuracy of the result. Some observers believe that with a simple instrument any desired accuracy can be obtained by increasing the number of observations. Unfortunately this is not true. There is a theorem which says that the result cannot be better than half of the smallest interval which can be read. When, for instance, the smallest interval to which a circle can be read is one minute, the best accuracy that can be obtained by numerous repetitions is 0.5 minute.

121 In recent years the QHM has been used successfully for declination measurements. The declination is derived as a by-product of the H measurement. With some precautions, the accuracy of the results will come near those obtained with a proper declinometer. The method will be described when treating the QHM and its use (paragraph **159**).

Determination of the horizontal intensity

MEASUREMENT OF H WITH THE MAGNETIC THEODOLITE

122 The magnetic theodolite or theodolite magnetometer has held a prominent position as almost the only standard of geomagnetic intensity since it has been given its present shape by Lamont. The method of observation is well developed and an instrument with aged magnets will exhibit a high degree of stability of its constants. The method described here entails the maintenance of the physical shape of the instrument and its magnets. The deflection distances, normally two, the moment of inertia of the deflection magnets, and the distribution of the magnetization of the magnets are combined in the instrumental constant C, which is obtained by comparing the instrument with a standard.

123 The basic instrument is the same as that used for the measurement of the magnetic declination. The station theodolite is equipped with a fixed deflection bar and a separate oscillation box. The deflection bar, sometimes divided in two separate pieces for comfortable transport, is an accessory to the travel theodolite which is attached to the theodolite base when required. The deflection bar carries the bearings for the deflection magnet, two at each end. The distances from the middle of the magnet bearings to the centre of the theodolite (the deflection distances) are usually 40 and 30 centimetres. Sometimes distances of 30 and 22.5 centimetres are used. On some types of deflection bars, which are graduated in centimetres, the magnet bearing can be shifted and set to the desired distance. The deflection bar must be at right angles to the optical axis of the telescope. For the observation of deflections, a short magnet is suspended in the magnet housing instead of the long declination magnet. The suspended magnet and the deflection magnet must be at the same level. Another accessory, the oscillation box, takes the place of the declination attachment when oscillations of the deflection magnet are being observed. The oscillation box is usually made of non-metallic material in order to keep the damping of the oscillating magnet small. When using the oscillation box, a lens may have to be attached to the objective of the telescope so that focusing on the external scale of the oscillation box is possible. Some types of magnetic theodolites have a wide declination housing made of fibre or wood, which can be used for the observation of magnet oscillations. For correct results, the magnet must always be at the same level in the oscillation box.

The method

124 The horizontal intensity is computed from

$$H_0 = \frac{C}{T_0 \sqrt{\sin \varphi_0}} \quad \text{or} \quad \log H_0 = \log C - \tfrac{1}{2} \log \sin \varphi_0 - \log T_0 \qquad (13)$$

where: H_0 = horizontal intensity reduced to base-line; C = instrumental constant; φ_0 = deflection angle corrected for asymmetry of deflections, temperature, and variation of D and H; T_0 = half-period of oscillation of the deflection magnet corrected for rigidity of suspension fibre, arc of oscillation, temperature, and variation of H.

When the instrument is used in the field, sometimes only deflections are observed. Then

$$H_0 = \frac{C_d}{\sin \varphi_0} \quad \text{or} \quad \log H_0 = \log C_d - \log \sin \varphi_0 \qquad (14)$$

where C_d is the deflection constant, which is either obtained by comparison with an observatory standard or, when the same instrument is used in the field and at the observatory, derived from complete observations of φ_0 and T_0 before and after a survey journey. Whereas C is constant over long periods of time, C_d varies with the magnetic moment of the deflection magnet. A valuable check on the computations is obtained by computing the magnetic moment of the deflection magnet. We have

$$M = C' \frac{\sqrt{\sin \varphi_0}}{T_0} \qquad (15)$$

where: M = magnetic moment of deflection magnet; C′ = constant involving the deflection distance, the moment of inertia of the deflection magnet, and the distribution coefficients of magnetization of the deflection magnet and the suspended magnet.

An approximate value of C′ may be obtained by using the nominal deflection distance, an approximate value of the moment of inertia of the deflection magnet and the distribution coefficients derived from the dimensions of the magnets. However, since $\sqrt{\sin\varphi'_0}/T_0$ is directly proportional to M, the changes of M can be followed by computing $1/2 \log \sin \varphi_0 - \log T_0$ and plotting this quantity against time; $1/2 \log \sin \varphi_0 - \log T_0$ should slowly decrease linearly with time, and exceptional values obtained from one or the other observation may indicate mistakes in the computation.

Deflections

125 The suspension fibre is adjusted to zero torsion as described in paragraph **108**, the instrument is well levelled and the telescope is at the southern side of the instrument. Moreover, the short magnet is suspended in the magnet housing. Observe with the suspended magnet the setting v_0, read the time and the circle, and record the readings. Read the eyepiece scale without touching the tangent screw and record the reading. Now insert the deflection magnet, which has been kept at a distance of 10 to 15 metres from the theodolite, in the magnet bearing at the eastern end of the deflection bar, in the erect position (marked side up) with its north-seeking pole towards east. Insert the thermometer so that its bulb is within the tubular magnet or, if the magnet is solid, touches the magnet. Watch that the magnet is resting properly in its bearing and is not disturbed by the thermometer. Follow the suspended magnet with the telescope and observe its setting, which is called v_1. Continue as indicated in the following schedule:

v_0		
v_1	deflection magnet E, north-seeking pole E	deflection magnet erect
v_2	deflection magnet W, north-seeking pole E	
v_3	deflection magnet W, north-seeking pole W	
v_4	deflection magnet E, north-seeking pole W	
v_4	deflection magnet E, north-seeking pole W	deflection magnet inverted
v_3	deflection magnet W, north-seeking pole W	
v_2	deflection magnet W, north-seeking pole E	
v_1	deflection magnet E, north-seeking pole E	
v_0		

The two readings v_0 serve as a check. They will be nearly equal after correction for D-variation if the theodolite has not turned in azimuth while observations were in progress.

126 Correct all circle readings for variation of declination (see example). The reductions are made to a fictitious base near the level of n_D, which in the example is $n_D = 11.6$ millimetres. Compute the deflection angle separately for magnet erect and magnet inverted from

$$\varphi' = \frac{1}{2}\left(\frac{v_1 + v_2}{2} - \frac{v_3 + v_4}{2}\right). \qquad (16)$$

With a perfectly levelled instrument, a symmetrical deflection bar and a symmetrically magnetized magnet one expects that

$$\nu_1 = \nu_2 \quad \text{and} \quad \nu_3 = \nu_4.$$

With most instruments these angles will show differences which sometimes are substantial, especially at the small deflection distance, resulting in too large a deflection angle. The correction, in radians, is:

$$\Delta\varphi = (\frac{1}{8} \tan \varphi + \frac{1}{6} \cot \varphi) \frac{\Delta_1^2 + \Delta_2^2}{2}, \tag{17}$$

where: $\Delta_1 = |\nu_1 - \nu_2|$ and $\Delta_2 = |\nu_3 - \nu_4|$.

When the differences of the angles are expressed in decimal fractions of degrees, the correction of the deflection angle in minutes of arc is

$$\Delta\varphi^{(')} = A\Delta_1^2 + A\Delta_2^2$$

where: $A = 0.523\,65\,(\frac{1}{8} \tan \varphi + \frac{1}{6} \cot \varphi)$.

In Table 1, $A\Delta^2$ is tabulated for Δ from 5′ to 90′ and for deflection angles from 5° to 80°. Moreover, the factor A is tabulated so that corrections can be computed in case Δ is beyond the range of the table. The deflection angle corrected for asymmetry of deflections is always

$$\varphi = \varphi' - \Delta\varphi.$$

Δ_1 and Δ_2 vary within narrow limits and afford a good check on the mechanical stability of the theodolite.

In the example the following values are found for Magnet II, erect: $\varphi' = 13°47.29'$; $\Delta_1 = 15.75'$; $\Delta_2 = 7.70'$. In the table we find: $A\Delta_1^2 = 0.02'$; $A\Delta_2^2 = 0.01'$. Hence, $\Delta\varphi = 0.02' + 0.01' = 0.03'$ and $\varphi = 13°47.29' - 0.03' = 13°47.26'$.

127 In the following, the reduction of log sin φ is treated because it offers considerable advantages over the numerical computation.

The temperature influences the magnetic moment of the deflection magnet and the length of the deflection bar, a rising temperature resulting in a decrease of the deflection angle. Both influences are combined in the temperature coefficient for deflections, q_d, which is usually contained in the certificate supplied by the makers or which may be determined experimentally by heating and cooling the instrument through a difference of 30 to 40 degrees centigrade and observing deflection angles (see paragraph **140**). For this experiment the deflection magnet can remain in the same position. The correction of the logarithm of the deflection angle is

$$\Delta\,(\log \sin \varphi) = \text{modulus}\,.\,q_d\,(t - t_0) = 0.4343\,q_d\,(t - t_0) \tag{18}$$

where: q_d = temperature coefficient for deflections; t = observed temperature corrected for thermometer errors; t_0 = reference temperature or standard temperature for which the deflection constant C is valid, t_0 may be 0, 5, 10 . . . 25, 30 degrees centigrade.

TABLE 1. Correction of deflection angle for asymmetry of deflections

φ(°)	A	Δ																	
		5′	10′	15′	20′	25′	30′	35′	40′	45′	50′	55′	60′	65′	70′	75′	80′	85′	90′
5	1.0031	0.01	.02	.06	.11	.17	.25	.34	.45	.56	.70	.84	1.00	1.18	1.36	1.57	1.78	2.01	2.26
6	0.8371	01	02	05	09	15	21	28	37	47	58	70	0.84	0.98	1.14	1.31	1.49	1.68	1.88
7	7187	00	02	04	08	12	18	24	32	40	50	60	72	84	0.98	1.12	1.28	1.44	1.62
8	6302	00	02	04	07	11	16	21	28	35	44	53	63	74	86	0.98	1.12	1.27	1.42
9	5613	00	02	04	06	10	14	19	25	32	39	47	56	66	76	88	1.00	1.13	1.26
10	5064	00	01	03	06	09	13	17	23	28	35	43	51	59	69	79	0.90	1.02	1.14
11	4616	00	01	03	05	08	12	16	21	26	32	39	46	54	63	72	82	0.93	1.04
12	4245	00	01	03	05	07	11	14	19	24	29	36	42	50	58	66	75	85	0.96
13	3931	00	01	02	04	07	10	13	17	22	27	33	39	46	53	61	70	79	88
14	3663	00	01	02	04	06	09	12	16	21	25	31	37	43	50	57	65	74	82
16	3230	00	01	02	04	06	08	11	14	18	22	27	32	38	44	50	57	65	73
18	2898	00	01	02	03	05	07	10	13	16	20	24	29	34	39	45	51	58	65
20	2636	00	01	02	03	05	07	09	12	15	18	22	26	31	36	41	47	53	59
25	2176	00	01	01	02	04	05	07	10	12	15	18	22	26	30	34	39	44	49
30	1890	00	01	01	02	03	05	06	08	11	13	16	19	22	26	30	34	38	43
35	1704	00	00	01	02	03	04	06	08	10	12	14	17	20	23	27	30	34	38
40	1589	00	00	01	02	03	04	05	07	09	11	13	16	19	22	25	28	32	36
50	1512	00	00	01	02	03	04	05	07	09	10	13	15	18	21	24	27	30	34
60	1637	00	00	01	02	03	04	06	07	09	11	14	16	19	22	26	29	33	37
70	2116	00	01	01	02	04	05	07	09	12	15	18	21	25	29	33	38	42	48
75	2583	00	01	02	03	04	06	09	12	15	18	22	26	30	35	40	46	52	58
80	3865	00	01	02	04	07	10	13	17	22	27	33	39	45	52	60	69	78	87

$\varphi = \varphi' - \Delta\varphi$

$\Delta\varphi = A\Delta_1^2 + A\Delta_2^2$

$A = 0.523\,56\left(\frac{1}{8}\tan\varphi + \frac{1}{6}\cot\varphi\right).$

φ = deflection angle corrected for asymmetry of deflections.

φ' = observed deflection angle.

$\Delta_1 = |\nu_1 - \nu_2|$; $\Delta_2 = |\nu_3 - \nu_4|$

Table values = $A\Delta^2$ in minutes of arc.

For the theodolite and Magnet II which were used in the example we have

$$q_d = 0.000\,2282 \text{ and } t_0 = 15.0 \text{ degrees centigrade}$$
$$\text{modulus} \,.\, q_d = 0.4343 \,.\, 0.000\,2282 = 0.000\,0991.$$

The mean of the temperatures read for Magnet II, erect, corrected for thermometer errors, is + 5.78 degrees centigrade and the correction to be applied to log sin φ is 0.000 0991 (+ 5.78 − 15) = 0.000 0991 (− 9.22) = − 0.000 914. Hence, $\Delta(\log \sin \varphi) = -0.000\,914$. Note that the reduction factor, modulus . q_d, will be valid at any place on the globe and for both deflection distances.

128 If H is increasing the deflection angle will decrease. The correction is

$$\Delta\,(\log \sin \varphi) = \frac{\text{modulus}}{H^{(\Gamma)}}\,\Delta H^{(\Gamma)} = \frac{0.4343}{H^{(\Gamma)}}\,\Delta H^{(\Gamma)} \tag{19}$$

In our example H = 0.204 and the reduction factor 0.4343/0.204 = 2.129. For Magnet II erect we find the mean ordinate n_H = + 11.4 mm. With the scale value of the H-variometer S_H = 2.81 gamma/mm we obtain ΔH = 32.0 gammas or 0.000 320 gauss. The base-line of the H-variometer was below the trace by this amount when the observations were made. Since the aim of the reduction is to find log sin φ for the base-line value, we have to add to the observed log sin φ:

$$\Delta\,(\log \sin \varphi) = 2.129 \,.\, 0.000\,320 = 0.000\,681.$$

The reduction factor modulus/H is constant at an observatory but has to be recomputed when H has changed appreciably by secular variation. It is valid for both deflection distances. Naturally, the reduction factor has to be recomputed for a place with a different H.

129 Summing up the corrections of the logarithm of the deflection angle to the standard temperature of the theodolite and to the base-line of the magnetograph, we obtain for the theodolite and Magnet II used in the example:

$$\log \sin \varphi_0 = \log \sin (\varphi - \Delta\varphi) + 0.000\,0991\,(t - 15) + 2.129\,\Delta H^{(\Gamma)}.$$

It is worth while to compute tables of the multiples of the correction factors for the required ranges of values in order to facilitate the reduction and to avoid errors.

Oscillations

130 Before starting observations, the suspension fibre of the oscillation box has to be adjusted to zero torsion by means of the non-magnetic torsion weight as described in paragraph **108**. Moreover, the deflection magnets, which are usually covered with a light coat of oil or grease in order to prevent corrosion, have to be cleaned inside and outside. Magnets of the Askania travel theodolite have to be freed of their plastic jackets. The stirrup, which may be a complex structure, has to be treated with great care so as to ensure that it is not distorted. Bending will change the moment of inertia of the stirrup-and-magnet assembly and hence the instrumental constant C. The same applies to the hooks or pins by which deflection magnets are coupled to the stirrup in some types of theodolites.

131 The torsion factor of the suspension fibre is determined as explained in paragraph **109**. Usually the eyepiece scale of the telescope can be used for this purpose. With some theodolites it may be necessary to use the external scale of the oscillation box. For the theodolite and Magnet II used in the example, the fibre was twisted + 90° and − 90°. This resulted in deflections, read on the eyepiece scale, of − 17.5 and + 17.5 (mean of three deflections). The torsion factor is

$$\eta = \frac{\varepsilon}{\zeta - \varepsilon} \tag{20}$$

where: η = torsion factor (not to be confused with the torsion factor TF used in declination); ε = difference of eyepiece scale readings in decimal fractions of a degree of arc caused by δ = difference of torsion head settings.

In the example the following figures were found: $\varepsilon = 17.5 + 17.5 = 0.584°$, and $\delta = 180°$. Then:

$$\eta = \frac{0.584}{180 - 0.584} = 0.003\,26.$$

132 When observing oscillations, the external scale of the oscillation box is used instead of the eyepiece scale, which for that purpose is too short. To focus the telescope on the external scale, some types of theodolite require a lens in front of the telescope's objective lens. Sometimes the tubular deflection magnets are fitted with a lens at one end and a transparent scale at the other end of the magnet. The scale value of the external scale or the magnet scale is determined by inserting the magnet in the oscillation box and setting the telescope to the 20th or 30th scale division on either side of the central division. For both settings the horizontal circle of the theodolite is read. The scale value of one scale division is

$$p = \frac{\alpha}{n\,(1 + \eta)} \tag{21}$$

where: p = scale value of external scale or magnet scale in degrees; α = difference between the two circle readings expressed in degrees and decimal fractions; n = number of scale divisions of external or magnet scale between the two circle readings; η = torsion factor, as explained in paragraph **131**.

For the theodolite of our example, the following figures were observed:

	Division of external scale	Circle reading	Mean of four observations
	− 20.0	298°16.4′	
	+ 20.0	285°07.5′	
Difference	40.0	13°08.9′	13.15°

$\eta = 0.003\,26$, as determined in paragraph **131**.
$p = 13.15/40 \,.\, 1.003\,26 = 0.327°$/scale division.

When a scale of unknown scale value has to be used for the determination of the torsion factor η, compute an approximation for the scale value; in our example this would be

$$p = \frac{13.15}{40} = 0.329°/\text{scale division.}$$

Compute the torsion factor η with this value. Then use η for the correction of the scale value. Finally compute η with the improved scale value. From this example it can be seen that the approximate scale value is in fact good enough for our purposes. However, with a weak magnet and a stiff suspension fibre the correction may be appreciable.

133 For the observation of oscillations, the magnet is damped and the telescope is adjusted to the central division of the external scale. Then oscillations are excited by means of the damping magnet (see paragraph **69**). The arc of oscillation should be sufficiently large, so that at the end of 160 or 200 oscillations the movement of the magnet is still sufficient for the accurate timing of passages. The observer will find the most convenient arc of oscillation after a few trials.

When the magnet passages through the central division of the scale are timed by an assistant or a stop-watch chronograph, every third or fifth passage is timed so that there is a sufficient interval for noting the timepiece readings. When a strip-chart chronograph is used, every passage is timed. The following table lists the passages which have to be timed in the three procedures.

Numbers of passages					
Strip-chart chronograph		Stop-watch chronograph		Assistant	
First set	Second set	First set	Second set	First set	Second set
0	100	0	100	0	100
1	101	3	103	5	105
2	102	6	106	10	110
3	103	9	109	15	115
..	...	..	...	..	...
..	...	..	...	..	...
18	118	54	154	90	190
19	119	57	157	95	195
20	—	60	—	—	—

Before beginning the observations proper, determine the time of ten half-periods with a stop-watch, in order to know how often to expect passages. At any one observatory this is practically a constant. In the field, the determination will have to be repeated at every station. Excite the magnet to the proper arc of oscillation. Read the thermometer and the extremes of the arc of oscillation. If you use a strip-chart chronograph, start the paper movement and time about 25 passages, which is more than you need. Stop the paper movement for economy in chart consumption. At passage No. 0 you have also started the stop-watch. From the time of ten half-periods, predict the 100th passage. Start the paper movement

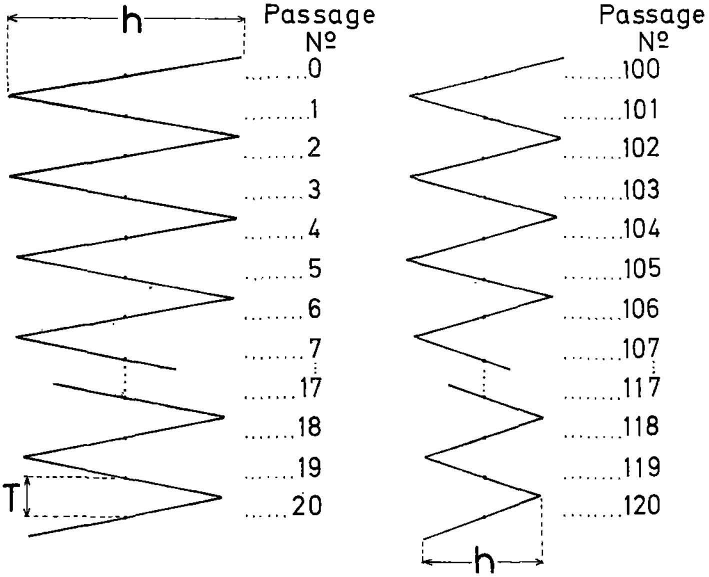

FIG. 15. Observation of oscillations of a magnet. h = arc of oscillation; T = half-period of oscillation.

in time to record a passage near passage No. 95. Record about 30 passages and stop the paper movement of the chronograph. The times of the passages are measured to the nearest hundredth of a second (in the office). From the time difference of passage No. 0 and No. 20, a precise prediction of passage No. 100 is made. You will find passage No. 100 near the predicted time on the strip chart (see example, below passage No. 20). If the half-period is more than 4.5 seconds and you have an assistant or use a stop-watch chronograph, every third passage is timed. Time passage No. 0. Predict passage No. 3 from the time of ten half-periods. If passage No. 0 came from the right hand, passage No. 3 will come from the left hand. A few seconds before the predicted time, look into the telescope and wait for passage No. 3, which you record. Continue until you have arrived at passage No. 60. Predict passage No. 100 from passages No. 0 and No. 60. A few seconds before passage No. 100 is due, look into the telescope and time passage No. 100. If passage No. 0 came from the right hand, passage No. 100 must also come from the right hand. Continue up to passage No. 157. If the half-period of oscillation is less than 4.5 seconds, time every fifth passage. Time passage No. 0 to passage No. 195. After having completed timing of passages, read again the extremes of the arc of oscillation and the thermometer.

When observing deflections, the thermometer is in close contact with the magnet. When oscillations are observed, the thermometer indicates the air temperature in the oscillation box. This requires that the temperature of the air be equal to the temperature of the magnet. After insertion of the magnet and the thermometer into the oscillation box, one must wait until thermal equilibrium has been reached inside the box. This may take a long time. For this reason, some observers prefer to measure the temperature of the clamped magnet, which takes only a few minutes. The same procedure is repeated at the end of oscillation observations.

134 Compute the time of 100 half-periods of oscillation from the time differences of passage No. 100 and passage No. 0, No. 101 and No. 1, up to No. 119 and No. 19.

Thus 20 values for 100 T are obtained. The mean, divided by 100, is the required half-period T. The half-period is computed in a similar manner when every third or every fifth passage has been timed.

The half-period T has to be corrected for the clock rate Δs, which is the change in clock correction expressed in seconds per day. Since a day has 86,400 seconds the correction is

$$\Delta T = \frac{\Delta s}{86\,400} T$$

where Δs = change of clock correction in 24 hours. The correction of log T is then:

$$\Delta(\log T) = \frac{\text{modulus}}{86\,400} \Delta s = \frac{0.4343}{86\,400} \Delta s = 0.000\,005\,\Delta s. \tag{22}$$

Δs is positive for a losing clock, negative for a gaining clock.

Since the half-period T is observed with a substantial arc of oscillation, it has to be reduced to infinitesimal arc, the corrected value being always smaller than the observed value. The well-known correction is

$$\Delta T = \frac{1}{64} \sin^2 1^\circ\, h^2\, T$$

or, in logarithmic form

$$\Delta(\log T) = \text{modulus} \,.\, \frac{1}{64} \sin^2 1^\circ\, h^2 = 0.000\,002\,07\, h^2 \tag{23}$$

where h = arc of oscillation expressed in degrees of arc and decimal fractions. The correction for arcs of oscillation from 1° to 10° is found in Table 2. The following figures are taken from the example.

	Readings of extremes of external scale of oscillation box in scale divisions	
Arc at beginning of observation	+ 9.8	− 9.9
Arc at end of observation	+ 5.9	− 5.8
MEAN	+ 7.85	− 7.85

Arc of oscillation $h = 15.7\,p$ or, with the scale value of the external scale of the oscillation box, $p = 0.327^\circ$ (see paragraph **132**), $h = 0.327^\circ \,.\, 15.7 = 5.13^\circ$.

From Table 2 we find $\Delta(\log T) = 0.000\,055$.

Those who like the utmost in computational comfort may derive a table for scale divisions of the oscillation box by dividing the values of *h* by the scale value *p* of the oscillation box.

TABLE 2. Correction of half-period of oscillation of a magnet to infinitesimal arc

h (°)	Correction	h (°)	Correction	h (°)	Correction
1.0	0.000 002	4.6	0.000 044	7.4	0.000 113
1.5	005	4.8	048	7.6	119
2.0	008	5.0	052	7.8	126
2.25	011	5.2	056	8.0	132
2.5	013	5.4	060	8.2	139
2.75	016	5.6	065	8.4	146
3.0	019	5.8	069	8.6	153
3.2	021	6.0	074	8.8	160
3.4	024	6.2	079	9.0	167
3.6	027	6.4	084	9.2	175
3.8	030	6.6	090	9.4	183
4.0	033	6.8	096	9.6	190
4.2	036	7.0	101	9.8	198
4.4	040	7.2	107	10.0	207

log T = log T' − correction.
T = half-period of oscillation corrected to infinitesimal arc of oscillation.
T' = half-period of oscillation observed at the arc of oscillation *h*.
h = arc of oscillation in degrees and decimal fractions observed between the two extremes of the arc.

Table values: correction = modulus . $\frac{1}{64}$ $\sin^2 1°$. h^2.

135 The rigidity of the suspension fibre accelerates the angular velocity of the oscillating magnet. For this reason the observed half-period will be too small. The correction which always has to be added to log T is

$$\Delta(\log T) = \frac{1}{2} \text{ modulus } \eta = 0.2171\ \eta. \qquad (24)$$

For our example, with $\eta = 0.003\,26$, we find $\Delta(\log T) = 0.000\,708$ (η is dependent on the horizontal intensity, the magnetic moment of the magnet and the torsion constant of the suspension fibre). For the accuracy required, the torsion constant of the fibre and the magnetic moment of the magnet can be considered constant so long as the same fibre is used. Then it can be shown that, when η_0 and T_0 have been determined at one place, say the observatory, η_1 at another place, for instance a field station, can be computed using T_1 observed at the field station from

$$\eta_1 = \frac{\eta_0}{T_0^2} T_1^2 \qquad (25)$$

where: T_0 = half-period of oscillation observed at the observatory; η_0 = torsion factor observed at the observatory; T_1 = half-period of oscillation observed at the field station; η_1 = torsion factor computed for the field station.

For T_1 the raw value as obtained from 100 T may be used; η has to be redetermined after replacement of the suspension fibre.

136 When the temperature of the oscillating magnet rises, the half-period of oscillation T will increase the correction to be applied to log T being

$$\Delta(\log T) = -\frac{1}{2}\,\text{modulus}\;q_{os}\,(t - t_0) = -\,0.2171\;q_{os}\,(t - t_0) \qquad (26)$$

where: q_{os} = temperature coefficient of magnet for oscillations; t = mean of temperatures observed at the beginning and end of a set of oscillations, corrected for errors of the thermometer; t_0 = standard temperature for which the constant of the theodolite has been determined.

In our example, $q_{os} = 0.000\,1922$.

Reduction factor $0.2171 \,.\, 0.000\,1922 = 0.000\,0417$.

In this case the reduction factor has to be increased by $65 \,.\, 10^{-7}$ in order to allow for the special shape of the stirrup. Thus the final reduction factor for our example will be 0.000 0482. For the observed set of oscillations the mean temperature of the set, corrected for thermometer errors, is + 4.10 degrees centigrade. With the standard temperature $t_0 = +\,15.0$ degrees centigrade, we obtain

$$\Delta(\log T) = -\,0.000\,0482\,(4.14 - 15.0) = +\,0.000\,525.$$

137 When H is increasing, the half-period T will decrease. The correction to be applied to log T is

$$\Delta(\log T) = +\frac{1}{2}\,\text{modulus}\,\frac{1}{H^{(\Gamma)}}\,\Delta H^{(\Gamma)} = +\,\frac{0.2171}{H^{(\Gamma)}}\,\Delta H^{(\Gamma)}. \qquad (27)$$

In our example, H = 0.204 gauss. Then:

$$\Delta(\log T) = +\,\frac{0.2171}{0.204}\,\Delta H^{(\Gamma)} = +\,1.064\;\Delta H^{(\Gamma)}.$$

Furthermore, $n_H = 11.8$ mm. With the scale value of the H-variometer $S_H = 2.81$ gammas/mm, we obtain $\Delta H = 33.2$ gammas = 0.000 332 gauss

and $\Delta(\log T) = +\,1.064 \,.\, 0.000\,332 = +\,0.000\,353$.

138 For the theodolite used in our example, the reduction of the logarithm of the half-period to standard temperature and base-line may be summarized in the following expression:

$$\log T_0 = \log T + 0.000\,005\;\Delta s - 0.000\,002\,07\;h^2 + 0.2171\;\eta - \\ -\,0.000\,0482\,(t - 15.0) + 1.064\;\Delta H^{(\Gamma)}$$

The properties of the correction terms may be summarized as follows:

The value of Δs is valid for any instrument and at any place of observation.

Δs is positive for a losing clock, negative for a gaining clock.

The value of h^2 is valid for any instrument and any place of observation and is always negative.

The value of η is valid for any instrument and place of observation and is always positive.

The value of $(t - t_0)$ is valid for a magnet at any place of observation.

The value of ΔH is determined by the magnitude of H and is therefore a constant for a place of observation.

Observation of deflections with a magnetic theodolite

1965, January 24, Sunday
Fürstenfeldbruck Observatory, calibration pier

Travel theodolite Askania No. 580 141, Thermometer No. 12 578
Deflection distance: 30 centimetres

Time (GMT)	Magnet position	Temperature	Circle reading A	Circle reading B	Circle reading Mean	n_D	$\Delta D^{(\prime)}$	Circle reduced (′)	Δ	n_H		
h m		°C										
						Magnet II, erect						
12 55	ν_0		291°03.2′	03.6	06.90′	+ 11.6	0	06.90′			$1/2(\nu_1 + \nu_2)$	304°54.28′
				+ 0.2							$1/2(\nu_3 + \nu_4)$	277°19.70′
57	ν_1	+ 5.6	304°23.2′	23.2	46.40′	11.6	0	46.40′		+ 11.3		
				0					15.75′		$2\varphi'$	27°34.58′
59	ν_2	5.7	305°01.1′	01.0	02.10′	11.7	− 0.05	02.15′		11.3	φ'	13°47.29′
				0							$\Delta\varphi$	− 0.03′
13 02	ν_3	5.8	277°07.7′	08.0	15.70′	11.9	− 0.15	15.85′		11.4		
				0					07.70′		φ	13°47.26′
05	ν_4	6.0	277°11.5′	11.8	23.40′	11.9	− 0.15	23.55′		11.6	φ	13°47′16″
				+ 0.2								
MEAN		+ 5.78								+ 11.40		
CORRECTED		+ 5.78							$\Delta H^{(\gamma)}$	+ 32.0		
						Magnet II, inverted						
13 07	ν_4	+ 6.2	277°11.6′	11.9	23.50′	+ 12.0	− 0.19	23.69′		+ 11.6	$1/2(\nu_1 + \nu_2)$	304°54.19′
				0					07.70′		$1/2(\nu_3 + \nu_4)$	277°19.84′
09	ν_3	6.4	277°07.8′	08.0	15.80′	12.0	− 0.19	15.99′		11.6		
				0							$2\varphi'$	27°34.35′
11	ν_2	6.5	305°01.0′	01.0	02.00′	12.0	− 0.19	02.19′		11.9	φ'	13°47.18′
				0					16.00′		$\Delta\varphi$	− 0.03′
14	ν_1	6.5	304°23.0′	23.0	46.00′	12.0	− 0.19	46.19′		11.9		
				0							φ	13°47.15′
16	ν_0		291°03.2′	03.5	06.80′	12.0	− 0.19	06.99′			φ	13°47′09″
				+ 0.2								
MEAN		+ 6.40								+ 11.75		
CORRECTED		+ 6.40							$\Delta H^{(\gamma)}$	+ 33.0		

$S_D = 0.484'/\text{mm}$ positive n_D = negative $\Delta D^{(\prime)}$ $S_H = 2.81$ gammas/mm positive n_H = positive $\Delta H^{(\gamma)}$

A second set of deflections was observed with the same magnet at a deflection distance of 20 centimetres, from 13h20 to 13h41. The results were:

	φ	Temperature	n_H	$\Delta H^{(\gamma)}$
Magnet II, erect	54°38′42″	+ 6.20	+ 12.05	+ 33.9
Magnet II, inverted	54°38′11″	+ 6.30	+ 12.45	+ 35.0

Observation of oscillations with a magnetic theodolite

1965, January 24, Sunday
Fürstenfeldbruck Observatory, calibration pier
Travel theodolite Askania No. 580 141, Thermometer No. 12 578
$p = 0.327°$/scale division.

Magnet II, erect

	Beginning	*End*	*Mean*	*Corrected*
Temperature (°C)	+ 4.0	+ 4.2	+ 4.10	+ 4.10
Arc of oscillation	+ 9.8 − 9.8	+ 5.9 − 5.9	15.7	$p = 5.13°$

Passage number	Time of passage (GMT)	Passage number	Time of passage (GMT)	100 T	n_H	$\Delta H^{(\gamma)}$
	h m s		h m s	m s		
0	12 34 13.55	100	12 41 21.00	7 07.45		
1	17.85	101	25.31	46		
2	22.22	102	29.70	48		
3	26.53	103	33.91	38		
4	30.78	104	38.24	46		
5	35.05	105	42.45	40		
6	39.32	106	46.78	46		
7	43.62	107	51.04	42		
8	47.89	108	55.38	49		
9	52.16	109	59.61	45		
10	56.38	110	42 03.85	47	+ 11.8	+ 33.2
11	35 00.67	111	08.07	40		
12	04.94	112	12.35	41		
13	09.24	113	12.64	40		
14	13.55	114	16.96	41		
15	17.84	115	21.28	44		
16	22.14	116	25.57	43		
17	26.32	117	29.79	47		
18	30.64	118	34.02	38		
19	35.00	119	38.38	38		
20	35 39.24					
0	− 34 13.55		MEAN	7 07.432		
			T	4.274 23		
20 T	1 25.69					
20 T	85.69					
100 T	4 28.45					
100 T	7 08.45					
0	12 34 13.55					
100th passage	12 41 22.00 (predicted)					

$S_H = 2.81$ gamma/mm. positive n_H = positive $\Delta H^{(\gamma)}$. $\eta = 0.003\ 26$.

A second set of oscillations was observed with Magnet II, inverted, after two sets of observations of deflections, from 14.55h to 15.03h. The results were: $T = 4.274\ 40$s; $h = 16.50$ $p = 5.40°$; $t = +\ 6.20°$ C; $n_H = +\ 15.5$; $\Delta H^{(\gamma)} = +\ 43.6$.

Summary of H observations

Reduction of deflection angle

$\log \sin \varphi_0 = \log \sin \varphi + 0.000\,0991\,(t - 15) + 2.129\,\Delta H^{(\Gamma)}$

Date	Magnet and distance	Time (GMT)	φ	log sin φ	Temperature (°C)	Correction to 15° C	$\Delta H^{(\Gamma)}$	Correction to base-line	log sin φ_0	Mean
		h m	° ′ ″							
24.I.1965	II e 30	12 59	13 47 16	9.377 172	+5.78	−0.000 914	+0.000 320	+0.000 681	9.376 939	9.376 950
	II i 30	13 11	47 09	7 111	6.40	852	330	703	6 962	
	II e 20	13 27	54 38 42	911 468	6.20	872	339	722	911 318	911 312
	II i 20	13 36	38 11	1 422	6.30	862	350	745	1 305	

Reduction of half-period of oscillation

$\log T_0 = \log T + 0.000\,005\,\Delta s - 0.000\,002\,07\,h^2 + 0.2171\,\eta - 0.000\,0482\,(t - 15) + 1.064\,\Delta H^{(\gamma)}$

Date	Magnet	Time (GMT)	T	log T	Δs 24 h	Correction	$h^{(\circ)}$	Correction	0.2171 η	Temperature (°C)	Correction to 15° C	$\Delta H^{(\Gamma)}$	Correction to base-line	log T_0	Mean
		h m	s		s										
24.I.1965	II e	12 38	4.27 423	0.630 858	− 0.5	− 0.000 002	5.13	− 0.000 055	+ 0.000 708	+ 4.10	+ 0.000 525	+0.000 332	+0.000 353	0.632 387	0.632 398
	II i	14 59	440	875	− 0.5	002	5.40	060	708	6.20	424	436	464	2 409	

Computation of H_0

$\log H_0 = \log C - 1/2 \log \sin \varphi_0 - \log T_0$

Date	Magnet	Deflection distance (cm)	log C	1/2 log sin φ_0	log T_0	log H_0	H_0	Mean
24.I.1965	II	30	9.632 400	9.688 475	0.632 398	9.311 527	20 489.3	20 490.2
	II	20	899 620	955 656	2 398	1 566	491.2	

139 The observations in the accompanying example, from which details have been used for explaining the various reductions in the preceding paragraphs, were made with a travel theodolite which allows double-minutes to be read, as explained in paragraph **110**. It is sufficient for all practical purposes to carry out computations of the angles to the nearest tenth of a minute of arc and to use five-place tables of logarithms. Under the column 'Circle reduced', the full degrees (to be found under A) have not been repeated. The final computation has been made using a list which helps to find mistakes in computation by making comparisons with previous results.

Temperature coefficients

140 When dealing with the reduction of the deflection angle and the half-period of oscillation, we used the temperature coefficient for deflections q_d and the temperature coefficient for oscillations q_{os}. Both quantities may be found in certificates of theodolites. If not available, the temperature coefficients may be determined from observations of deflection angles and oscillations, while varying the temperature over a wide range, say 25 to 40 degrees centigrade. The experiment is usually carried out in a small room heated by an electric fire. If a kerosene stove is used, provide for sufficient ventilation so that no poisonous gases can accumulate. First the room is cooled to the outside temperature. Then heat the room slowly in order to ensure that no temperature difference builds up between the magnet and the deflection bar. Finally cool the room again to the outside temperature. Before the observations can be used for the computations, they have to be corrected for time variations and the other variables. Sometimes another quantity, namely, the temperature coefficient of the magnetic moment, q, may be known. Then q_d and q_{os} can be derived from q, using the coefficient of expansion of brass q_{brass}, and the coefficient of expansion of steel q_{steel}. In the following, only the absolute values of the coefficients have been considered. This gives rise to fewer errors in algebraic signs. We have

$$q_d = q + 3q_{\text{brass}} = q + 0.000\,0570 \qquad (28)$$
$$q_{os} = q + 2q_{\text{steel}} = q + 0.000\,0210 \qquad (29)$$

and furthermore

$$q_{os} = q_d - 0.000\,036. \qquad (30)$$

The last equation is commonly used for deriving q_{os} from q_d, because q_d can be easily observed. For the travel theodolite used in the example, q_d was derived for Magnet II from deflection observations with the magnet at position v_1 (paragraph **125**), with a small deflection distance of 20 centimetres, between temperatures of − 5 and + 42 degrees centigrade. The result was

$$q_d = 0.000\,2282.$$

The temperature coefficient for oscillations was therefore

$$q_{os} = 0.000\,2282 - 0.000\,0360 = 0.000\,1922.$$

A different method for the determination of the temperature coefficient can be found in McComb's manual.

The induction coefficient

141 The magnetic moment of a magnet varies slightly according to the field component along its axis. When the magnet is freely suspended, this component is the horizontal intensity. For deflection observations, the field component along the axis of the deflection magnet is $-$ H sin φ, i.e. the magnetic moment of the deflection magnet is weakened. However, since H sin φ can be considered constant unless the magnetic moment of the deflection magnet changes drastically, it is not necessary to correct the deflection angle for induction. The correction for the influence of induction on log T is computed from

$$\Delta\,(\log \mathrm{T}) = +\frac{1}{2}\ \text{modulus}\ \mu \mathrm{H} \tag{31}$$

where μ = induction coefficient. It can be shown that, if at the place of calibration, where the horizontal intensity is H_1, the half-period of oscillation is not corrected for induction, at another place of observation, where the intensity is H_2, the correction to be applied to log C is

$$\Delta\,(\log \mathrm{C}) = -\frac{1}{2}\ \text{modulus}\ \mu\,(\mathrm{H}_1 - \mathrm{H}_2) = -\,0.2171\ \mu\,(\mathrm{H}_1^{(\Gamma)} - \mathrm{H}_2^{(\Gamma)}) \tag{32}$$

For the theodolite used in the example we have

$$\mu = 0.002\,51; \qquad \mathrm{H}_1 = 0.204\ \text{gauss.}$$

Observations are made at a place with $H_2 = 0.300$ gauss. Then

$$\Delta\,(\log \mathrm{C}) = -\,0.2171\,.\,0.002\,51\,(0.204 - 0.300) = 0.000\,052.$$

If this correction is not applied, the observed horizontal intensity would in this case be 3.5 gammas below the correct value.

The influence of errors of observation on the result

142 The differentiation of the basic formula for the horizontal intensity (13) results in

$$\Delta \mathrm{H}^{(\gamma)} = -\,\frac{1}{2}\,\mathrm{H}^{(\gamma)} \cot\varphi \sin 1' \Delta\varphi^{(')} - \frac{\mathrm{H}^{(\gamma)}}{\mathrm{T}^{(s)}}\,.\,\Delta \mathrm{T}^{(s)}. \tag{33}$$

The following table contains the errors of H in gammas caused by an error in deflection angle of 0.1′ and an error of the half-period of 0.0001 second of time:

	Error in H in gammas caused by $\Delta\varphi = 0.1'$						Error in H in gammas caused by $\Delta T = 0.0001$ seconds						
$H^{(\Gamma)}$	$\varphi = 5°$	10°	20°	30°	40°	50°	T = 2s	3s	4s	5s	6s	7s	8s
0.1	1.5	0.8	0.4	0.3	0.2	0.1	0.5	0.3	0.2	0.2	0.2	0.1	0.1
0.2	3.0	1.5	0.8	0.5	0.4	0.2	1.0	0.6	0.5	0.4	0.3	0.3	0.2
0.3	4.5	2.2	1.2	0.8	0.5	0.3	1.5	0.9	0.8	0.6	0.5	0.4	0.4
0.4	6.0	3.0	1.6	1.0	0.7	0.5	2.0	1.2	1.0	0.8	0.7	0.6	0.5

If only deflection angles are observed, as may be done in survey work, and the horizontal intensity is computed from equation (14), the errors shown in the left-hand section of the table will be doubled.

The errors tabulated above are what may be achieved in the most favourable circumstances. With increasing deflection angle, the resultant force holding the suspended magnet decreases. Therefore, the settings of the suspended magnet become uncertain and the errors will be considerably exceeded at large deflection angles. Unfortunately the errors committed in measuring deflection angles and half-periods of oscillations are not the only ones which contribute to reducing the accuracy of an H measurement. Of decisive importance is the precision with which the deflection magnet can be placed on the bearings of the deflection bar, especially when using the small deflection distance, or in the stirrup of the oscillation box. In oscillation observations, the most prominent source of error is the difference between the temperature indicated by the thermometer and the actual temperature of the magnet. The best results will be obtained with a station theodolite, when the error of an observation may be between one and two gammas. With a travel theodolite a good observer may achieve an average error of ± 3 gammas. At middle and low latitudes, a magnetic theodolite is still a good intensity standard and it should not be light-heartedly abandoned unless it can be replaced by a proton magnetometer. At high latitudes the combination of a magnetic theodolite with a proton magnetometer will be of great advantage (see paragraph **206**).

MEASUREMENT OF H AND D WITH THE QHM

143 The QHM is one of the most simple instruments for the precise determination of the horizontal intensity. It was constructed by D. La Cour mainly in order to overcome the difficulties in measuring the half-period of oscillations. In contrast to the magnetic theodolite, the observation and the computation of results takes little time and a moderately skilled observer will obtain good results provided the deflection angle is not too small.

144 The tube-like body of the instrument contains the suspension fibre with the magnet-and-mirror assembly and the clamping mechanism which is moved from outside by a screw. The telescope is fitted to one of the windows by means of a nut. A counterweight is attached to the opposite side of the instrument. Above the telescope window the instrument carries the thermometer.

145 For observation the QHM may be mounted on a special base provided by the Danish Meteorological Institute. The circle can be read to 0.5′ by means of verniers. The instrument may equally well be mounted on the base of a travel theodolite, provided a sufficiently large horizontal surface is available in the middle of the base. Put three small pieces of plasticine on the flat part of the theodolite base. Press the QHM down and turn it slightly to and fro so that the plasticine is spread and thinned out. If the plasticine has been warmed in the hand and kneaded before application, the connexion between the base and the QHM will be fairly firm. A more durable solution is to make a socket of aluminium or brass which fits the base in the place of one of its accessories. The QHM is connected to the socket by means of two screws. Upon request, Askania will supply a socket as an accessory to the travel theodolite. Usually the QHM is observed by means of its small telescope, which must not be touched while observations are in progress. However, if the socket is high enough, the theodolite telescope may be placed opposite the telescope window of the QHM, and the QHM may then be observed with the telescope of the theodolite base. This offers considerable advantages, especially when the declination is observed with the QHM, because the telescope of the theodolite base can be adjusted in elevation angle for pointing on the azimuth marks. Moreover, light can be directed to the diaphragm scale of the telescope from almost any angle. When the QHM is used in this way, it is preferable to leave the socket permanently connected to the QHM, after adjustment has been made to zero torsion by turning the QHM in azimuth on the socket, *not by removing the cap on top of the instrument and turning the rod which carries the upper end of the suspension fibre!* Any such attempt will result in a broken fibre. When using the telescope of the theodolite base, the counterweight is not required. When the QHM telescope is used, tighten the screws on both sides of the telescope holder, which represent the telescope's horizontal axis, so that the telescope does not shake in its holder. In spite of this precaution *it is not permissible to touch the telescope or to adjust its angle of elevation while observations are being made, azimuth sightings included.* The hazards introduced by touching the telescope may be avoided by finding the elevation angle of the telescope at which the reflected image of the diaphragm scale is visible. Put wedges of soft wood between the telescope and its holder with mild pressure and wrap Scotch tape around the assembly, thus providing a solid connexion of all parts.

146 The prism illuminating the diaphragm scale requires light from above. When observing in a room, some observers use aluminium foil as found in cigarette packs for directing light to the prism. A hole of the same diameter as the telescope is pierced through the foil, which is then put on the eyepiece end of the telescope. The foil is bent until the prism receives enough light. A better solution is a small lamp constructed at the Danish Meteorological Institute. A very soft cable hanging down from the ceiling of the room is attached to the QHM body and from there brought to a micro lamp which is clipped to the telescope above the prism. In order to exclude any influence on the magnet settings, the lamp is fed with AC obtained from a step-down transformer. Where no AC is available, a transistor inverter may be used to change DC to AC from a battery. When the QHM is directed against a bright object, especially when observing in the field, it is necessary to cover the rear window of the QHM with a handkerchief, a match box or a specially made cover.

147 When putting the QHM on the base, see that the instrument sits properly on its platform. If the instrument is tilted, the clamping mechanism may not grip the conical stem of the magnet-and-mirror assembly and the result may be a broken fibre. After levelling the theodolite base and turning the telescope towards the south, unclamp the QHM by turning the clamping screw anticlockwise as far as it will go. While unclamping, observe the magnet mirror from the rear window and check that the magnet-and-mirror assembly separates smoothly from the clamp. If the suspended system has stuck to one half of the clamp, which becomes obvious after the clamping screw has been turned a few revolutions, tap gently with one finger on the base until the magnet system is free. If the magnet assumes a pendulum motion, approach the assembly again with the clamp. This will usually result in smooth oscillations of the magnet. *If the instrument is new, the clamping screw is secured by a transport clamp. Open the slotted screw several turns.* Try to find the reflected image of the diaphragm scale, which at first will appear as a bright spot passing through the telescope's field of view. If nothing can be seen, look into the window opposite to the telescope and turn the alidade in azimuth until you see your eye reflected by the magnet mirror in the middle of the window. Look again into the telescope. If still nothing can be seen, adjust the telescope in elevation angle until you see a bright spot passing through the field of view. It is advisable to conduct the first experiments with a QHM out of doors so that enough light is available.

148 Once the reflected image of the diaphragm scale has been found, damp the oscillations of the magnet. This is the last chance to adjust the telescope and the light to the prism when you are using the QHM telescope without the precautions described in paragraph **145**. Point on the reflected diaphragm line. Read the thermometer (if necessary using a lens), the watch, and the circle, and record the readings (pointing I). Turn the alidade slowly clockwise more than 360°, find the diaphragm line (if necessary, by looking again into the rear window) and point on it. Read and note the values as before (pointing II). Now turn the alidade anticlockwise twice 360° and continue until you find again the reflected diaphragm line, and point on it (pointing III). The last pointing will be obtained by turning the alidade more than 360° clockwise (pointing IV). This pointing will give the same reading as the first, within a minute of arc. You may find the circle setting rapidly by adjusting the circle to the first circle reading. Thus four observations are obtained.

149 Figure 16 shows the relevant angles (La Cour, Comm. Mag. No. 15). N indicates the magnetic meridian while *m* is the position of the magnet at pointings I and IV. The magnet deviates from the magnetic meridian by an angle α, due to maladjustment of the line of no-torsion of the suspension fibre, by an angle β. The optical axis of the telescope is aligned with the normal to the mirror T, which makes an angle *c* (for collimation) with the magnetic axis of the magnet *m*.

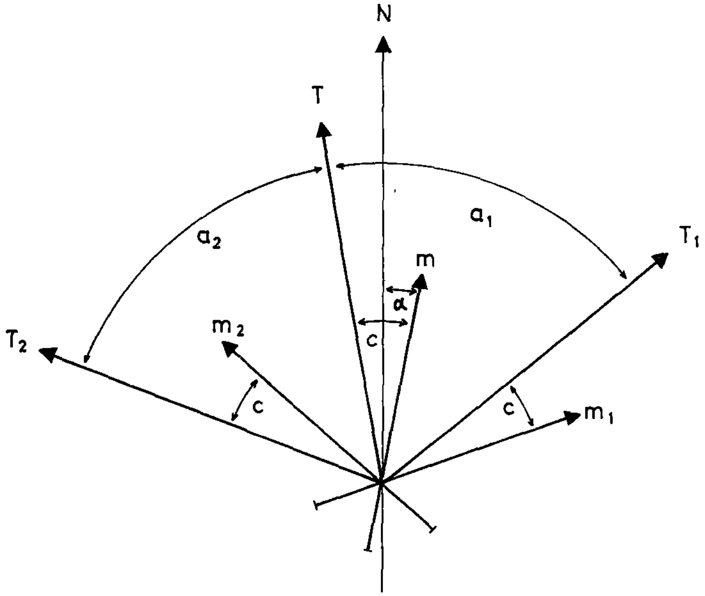

FIG. 16. Angles in QHM observations.

For pointing II the magnet will be at m_1 and the optical axis of the telescope at T_1, the fibre being twisted by $\beta + 2\pi$. For pointing III the magnet occupies the position m_2 while the normal to the mirror and the optical axis of the telescope are at T_2; the fibre is twisted by $\beta - 2\pi$. The angles a_1 and a_2 are computed from the observed angles I to IV. We have

$$\begin{aligned} a_1 &= T_1 - T = \text{II} - \text{I}; \\ a_2 &= T - T_2 = \text{IV} - \text{III}. \end{aligned} \tag{34}$$

For the three positions of the magnet, the following equations of equilibrium are valid:

$$\begin{aligned} M\,H \sin \alpha &= \Theta\beta; \\ M\,H \sin (\alpha + a_1) &= \Theta\,(\beta + 2\pi); \\ M\,H \sin (\alpha - a_2) &= \Theta\,(\beta - 2\pi). \end{aligned}$$

where: M = magnetic moment of magnet m; H = horizontal intensity; α = deviation of the magnetic axis of the magnet from the magnetic meridian; β = residual torsion of the suspension fibre (maladjustment of the line of no-torsion); Θ = torsion constant of the suspension fibre.

By adding the second and third equations and reducing by means of the first equation, we obtain

$$\tan \alpha = \frac{\sin a_1 - \sin a_2}{2 - (\cos a_1 + \cos a_2)} \tag{35}$$

TABLE 3. Magnetic declination from QHM observations

φ (°)	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
35	2.265	250	236	221	206	192	177	162	147	133
36	2.118	104	091	078	064	050	037	024	010	.996
37	1.983	971	958	946	933	921	909	896	884	871
38	1.859	848	836	824	813	802	790	778	767	756
39	1.744	733	723	712	701	690	680	669	658	648
40	1.637	627	617	607	597	588	578	568	558	548
41	1.538	529	520	510	501	492	483	474	464	455
42	1.446	438	429	420	412	404	395	386	378	370
43	1.361	353	345	337	329	322	314	306	298	290
44	1.282	275	267	260	252	245	238	230	223	215
45	1.208	201	194	187	180	173	166	159	152	145
46	1.138	131	125	118	112	105	098	092	085	079
47	1.072	066	060	054	048	042	035	029	023	017
48	1.011	005	000	.994	.988	.982	.977	.971	.965	.960
49	0.954	949	943	938	932	927	922	916	911	905
50	0.900	895	890	885	880	874	869	864	859	854
51	0.849	844	839	835	830	825	820	815	811	806
52	0.801	796	792	788	783	778	774	770	765	760
53	0.756	752	747	743	739	734	730	726	722	717
54	0.713	709	705	701	697	692	688	684	680	676
55	0.672	668	664	661	657	653	649	645	642	638
56	0.634	630	627	623	620	616	612	609	605	602
57	0.598	595	591	588	584	581	578	574	571	567
58	0.564	561	557	554	551	548	544	541	538	534
59	0.531	528	525	522	519	516	512	509	506	503
60	0.500	497	494	491	488	485	482	479	476	473
61	0.470	467	464	462	459	456	453	450	448	445
62	0.442	439	437	434	431	428	426	423	420	418
63	0.415	412	410	408	405	402	400	398	395	392
64	0.390	388	385	383	380	378	376	373	371	368
65	0.366	364	361	359	357	354	352	350	348	345
66	0.343	341	339	336	334	332	330	328	325	323
67	0.321	319	317	315	313	310	308	306	304	302
68	0.300	298	296	294	292	290	288	286	284	282
69	0.280	278	276	274	272	270	268	266	264	262
70	0.260	258	256	254	252	250	249	247	245	243
71	0.241	239	238	236	234	232	231	229	227	226
72	0.224	222	221	219	217	216	214	212	210	209
73	0.207	205	204	202	201	199	197	196	194	193
74	0.191	189	188	186	185	183	181	180	178	177
75	0.175	174	172	170	169	168	166	164	163	162
76	0.160	158	157	156	154	152	151	150	148	146
77	0.145	144	142	141	139	138	137	135	134	132
78	0.131	130	128	127	126	124	123	122	121	119
79	0.118	117	115	114	113	112	110	109	108	106

$\alpha^{(\prime)} = \frac{\cos\varphi}{2(1-\cos\varphi)}(a_1 - a_2)^{(\prime)}$ Table values of $\frac{\cos\varphi}{2(1-\cos\varphi)}$

or, with $\varphi = \frac{a_1 + a_2}{2}$ and small α,

$$\alpha^{(')} = \frac{\cos \varphi}{2\,(1 - \cos \varphi)}\,(a_1 - a_2)^{(')}. \tag{36}$$

For the determination of α the factor $\cos \varphi / 2(1 - \cos \varphi)$ is tabulated in Table 3. Furthermore, by subtracting the third equation from the second equation we obtain

$$H = \frac{4\,\pi\Theta}{M} \times \frac{1}{\sin(\alpha + a_1) - \sin(\alpha - a_2)}. \tag{37}$$

Usually α is small, so that the denominator of the second fraction can be replaced by $\sin a_1 + \sin a_2$, which for practical purposes equals $2 \sin (\frac{1}{2}a_1 + \frac{1}{2}a_2)$ or $2 \sin \varphi$. This simplification results in

$$H = \frac{2\,\pi\Theta}{M} \cdot \frac{1}{\sin \varphi}$$

or in logarithmic form, with $\log 2\pi\Theta/M = C$,

$$\log H = C - \log \sin \varphi. \tag{38}$$

The constant C is determined by comparing the instrument with an observatory standard.

150 If the difference between a_1 and a_2 is large, a correction to H can be introduced instead of using equation (37) (Howe, 1938). Let $\varepsilon = \frac{1}{2}(a_1 - a_2)$ and moreover $H = H' + \Delta H$ where: H' = horizontal intensity computed with $\varphi = \frac{1}{2}(a_1 + a_2)$; H = horizontal intensity corrected for residual torsion. Then

$$\Delta H = \frac{H\,.\,\varepsilon^2}{2\,(1 - \cos \varphi)^2} = \frac{H \sin^2 1' \varepsilon^{(')2}}{2\,(1 - \cos \varphi)^2}$$

When an approximate value of H is introduced in gauss and ε in minutes of arc we obtain:

$$\Delta H^{(\gamma)} = \frac{0.004\,24\,H^{(\Gamma)}\,\varepsilon^{(')2}}{(1 - \cos \varphi)^2} \tag{39}$$

ΔH is always positive, that is, the horizontal intensity H' determined by means of the simple formula (38) is too small when a_1 and a_2 differ. The following table computed by Wiese (Fanselau, 1960) contains the upper limit of the angle ε when a maximum error in H of one gamma is tolerated:

φ	H = 0.1	0.2	0.3	0.4 gauss
20°	2.9′	2.1′	1.7′	1.5′
40°	11.4′	8.0′	6.6′	5.7′
60°	24.3′	17.2′	14.0′	12.1′
80°	40.3′	28.4′	23.2′	20.1′

From this table it may be inferred that the line of no-torsion has to be well adjusted for high values of H and small deflection angles; if not, the correction has to be computed. The following example illustrates the computation of the correction. QHM No. 82 was observed on 16 May 1966 at Fürstenfeldbruck observatory. The following values were found:

$a_1 = 64°07.3'$

$a_2 = 64°39.9'$

$\mathrm{H}' = 20\,556.5$ gammas

$\varphi = 64.4°$

$(1 - \cos\varphi)^2 = 0.323$

$\varepsilon = -16.3'$

$\varepsilon^2 = 266$

$$\Delta\mathrm{H} = \frac{0.00424\,.\,0.206\,.\,266}{0.323} = 0.7 \text{ gamma}$$

$$\begin{aligned} \mathrm{H}' &\doteq 20\,556.5 \text{ gammas} \\ \Delta\mathrm{H} &= 0.7 \\ \hline \mathrm{H} &= 20\,557.2 \text{ gammas} \end{aligned}$$

The same results will be obtained when the complete formula (37) is used. However, some care is required with respect to the algebraic signs.

151 The effect of temperature on the suspension fibre and the magnetic moment of the magnet can be combined in a factor which, in the following, will be designated c_1. The factor c_1 is determined experimentally by running the instrument through a large temperature range; c_1 is usually around 0.000 16.

152 The magnetic moment of the magnet is slightly influenced by the induction caused by the component of the horizontal intensity in the direction of the magnetic axis of the magnet. This effect is allowed for by the constant c_2 which differs from instrument to instrument and may assume values between 0.0002 and 0.0008.

153 The complete formula for the QHM is

$$\log \mathrm{H} = \mathrm{C} - \log \sin\varphi + c_1\,t - c_2\,\mathrm{H}\cos\varphi \tag{40}$$

where: H = horizontal intensity; C = constant of the QHM for a torsion angle of 2π; φ = deflection angle; c_1 = temperature coefficient; c_2 = induction coefficient; t = thermometer reading corrected for thermometer errors.

The constants C, c_1 and c_2 are contained in the calibration certificate which is supplied with the instrument; c_1 and c_2 can be considered constant for ten years or longer while C varies on the average 0.000 04 per year. Therefore, the QHM has to be compared with a standard every two years. For this purpose IAGA has acquired several sets of QHMs which are in the custody of the Reporter on the Comparison of Observatory Standards, Dr. V. Laursen, Danish Meteorological Institute, Charlottenlund, Denmark. A set of three instruments will be supplied upon request.

154 The sensitivity of the QHM can be found by differentiating the basic formula, which gives

$$\Delta\mathrm{H} = -\,\mathrm{H}\cot\varphi\,\Delta\varphi$$

or, when $\Delta\varphi$ is introduced in minutes of arc,

$$\Delta\mathrm{H}^{(\gamma)} = -\,\mathrm{H}^{(\gamma)}\cot\varphi\,\sin 1'\Delta\varphi^{(')} = -\,29.1\,\mathrm{H}^{(\Gamma)}\cot\varphi\,\Delta\varphi^{(')} \tag{41}$$

The table below gives ΔH in gammas for a change of deflection angle of one minute of arc, at various values of H and φ.

φ	H = 0.1	0.2	0.3	0.4 gauss
20°	8.0γ	16.0γ	24.0γ	32.0γ
25	7.6	15.2	22.8	24.9
30	5.0	10.0	15.1	20.1
40	3.5	6.9	10.4	13.9
50	2.4	4.9	7.3	9.8
60	1.7	3.4	5.0	6.7
70	1.0	2.1	3.2	4.2
80	0.5	1.0	1.5	2.0
85	0.25	0.5	0.8	1.0

The table shows that best results will be obtained at large deflection angles and low values of H. However, at deflection angles above 75°, the magnet will become sluggish and difficult to damp. Moderately skilled observers will obtain best results at deflection angles between 55° and 70°. In survey work, smaller deflection angles may be tolerated.

155 When, on a survey journey for instance, the observer moves to lower latitudes the deflection angle will decrease owing to higher values of H. The sensitivity of the instrument can be increased by changing the torsion angle from 2π to 3π. Instead of turning the alidade 360° + φ after the first pointing at zero torsion, turn the alidade 540° and continue until you find the reflected diaphragm. Now the telescope will be north-east of the instrument and the rear face of the mirror is observed. The deflection to the other side will be observed similarly. For the computation of a_1 and a_2, the circle readings obtained in the deflected state of the magnet have to be decreased by 180°. The torsion angle can be increased from 2π to 3π when the deflection angle at 2π is less than 41°. At 3π the deflection angle will then be approximately 78°.

When the observer moves to higher latitudes (i.e. to places with smaller horizontal intensity), and the deflection angle becomes uncomfortably large, the fibre may be twisted by π only, by turning the alidade 180° in azimuth and then continuing until the reflected diaphragm is found. Again, the rear face of the mirror is observed and the circle readings in the deflected states of the magnet have to be decreased 180° for the computation of a_1 and a_2. When, at a torsion angle of 2π, the deflection angle is nearly 90°, the deflection angle at π will be about 30°.

In extreme cases, e.g. for comparisons at other observatories, it may be necessary to increase the torsion angle to 4π in order to arrive at a reasonably large deflection angle.

156 The constant C of a QHM is always given for a torsion angle of 2π. The modified formulae for the four cases of practical interest are:

Torsion angle

$$\left.\begin{aligned}
\pi&:\ \log H = C + \log 1/2 - \log \sin \varphi + c_1 t - c_2 H \cos \varphi \\
2\pi&:\ \log H = C - \log \sin \varphi + c_1 t - c_2 H \cos \varphi \\
3\pi&:\ \log H = C + \log 3/2 - \log \sin \varphi + c_1 t - c_2 H \cos \varphi \\
4\pi&:\ \log H = C + \log 2 - \log \sin \varphi + c_1 t - c_2 H \cos \varphi
\end{aligned}\right\} \qquad (42)$$

157 It has been explained in paragraph **148** that a complete observation with the QHM consists of four readings, namely:

Pointing I, torsion angle 0
Pointing II, torsion angle $+ 2\pi$
Pointing III, torsion angle $- 2\pi$
Pointing IV, torsion angle 0

This is the most simple schedule of observation. For more accurate work, such as the intercomparison of observatory standards, another schedule is used, which consists of six readings as follows:

Pointing I, torsion angle 0
Pointing II, torsion angle $+ 2\pi$
Pointing III, torsion angle $- 2\pi$
Pointing IV, torsion angle $- 2\pi$
Pointing V, torsion angle $+ 2\pi$
Pointing VI, torsion angle 0

This schedule is called the international schedule for observing declination with the QHM. Van Wijk and Gotsman (1951) added the reversed international schedule. Another schedule, described by Thiessen (1953) is very useful when the magnetic declination is derived from QHM measurements, because it contains three observations at zero torsion. The readings are:

Pointing I, torsion angle 0
Pointing II, torsion angle $+ 2\pi$
Pointing III, torsion angle $- 2\pi$
Pointing IV, torsion angle 0
Pointing V, torsion angle $- 2\pi$
Pointing VI, torsion angle $+ 2\pi$
Pointing VII, torsion angle 0

158 As an example, an observation made according to Thiessen's schedule has been selected. As in deflection observations with the magnetic theodolite, the circle readings are corrected for D variation, preferably to the time of the first pointing, before the deflection angle is computed (paragraphs **102** and **126**). In the accompanying example, the deflection angle is computed from the means of $+ 2\pi$ and $- 2\pi$ torsion. The deflection angle may be computed separately from the pointings II and III and the pointings V and VI. The thermometer readings are corrected for thermometer errors (in the example: 0) before they are used for the computation of the temperature correction. Finally, the base-line value of the H-variometer is computed by subtracting the mean of the ordinates n_H found for the circle readings II, III, V, and VI, converted to gammas (paragraph **102**).

Instead of doing the computation on the observation form one may prepare a table for the logarithmic reduction of the deflection angle as was done for the deflection angle observed with the magnetic theodolite (paragraph **139**). Note that the algebraic sign of the temperature correction will have to be reversed when correcting the deflection angle. The logarithmic reduction of the deflection angle to the base-line is the same as described in paragraph **128**.

In routine work at an observatory or for the survey of a limited area, the constant C may be modified by the correction for induction, which for the required accuracy can be considered constant. For the computation of the correction, use average values of H and φ. This will save the subtraction of the correction for every observation and will thus remove a source of error. The modified constant may be designated C′ or C*.

Observation of H and D with the QHM

1956, March 17, Wednesday
Fürstenfeldbruck Observatory, calibration pier
Theodolite Tesdorpf No. 2679; QHM No. 81

		A	*B*	*Mean*
Azimuth mark:	Beginning	276°21.0′	21.3′	42.30′
Alling church	Ending	276°21.0′	21.4′	42.40′
	MEAN			276°42.35′

	Time (GMT)	Torsion	Temperature	Circle reading A	Circle reading B	Circle reading Mean	n_D	$\Delta D^{(\prime)}$	Circle reduced	n_H			Temperature corrected (°C)
	h m		°C										
I	13 08	0	+ 17.2	131°22.1′	22.3′	44.4′	+ 15.8	0	44.40′		1/2(II + VI)	184°34.45′	+ 17.35
II	10	+ 2π	17.3	184 17.0	17.3	34.3′	15.9	− 0.05	34.35′		1/2(III + V)	78°49.85′	+ 17.55
III	12	− 2π	17.4	78 24.7	25.5	50.2′	16.0	+ 0.10	50.10′	+ 16.7			
IV	14	0	17.4	131 22.0	22.3	44.3′	15.8	0	44.30′		2φ	105°44.60′	Mean
V	16	− 2π	17.5	78 24.4	25.2	49.6′	15.8	0	49.60′		φ	52°52.30′	temperature
VI	18	+ 2π	17.6	184 17.1	17.5	34.6′	15.7	+ 0.05	34.55′	16.6	φ	52°52′18″	+ 17.45
VII	13 20	0	17.6	131 22.0	22.3	44.3′	15.6	+ 0.10	44.20′				

Computation of H

C	9.210 840
$c_1 t$	0.002 844
	9.213 684
log sin φ	9.901 614
c_2H cos φ	0.000 025
log H	9.312 045
H	20 513.8
n_H + 16.65 mm	
$\Delta H^{(\gamma)}$	+ 46.8
H_0	20 467.0

Computation of D

1/2(II + VI)	184°34.45′
1/3(I + IV + VII)	131°44.30′
a_1	52°50.15′
1/3(I + IV + VII)	131°44.30′
1/2(III + V)	78°49.85′
a_2	52°54.45′
$a_1 - a_2$	− 4.30′
$\dfrac{\cos\varphi}{2(1-\cos\varphi)}$ 0.762	
	− 3.29′
c	− 2°25.60′
c − α	− 2°22.31′
(A) 1/3(I + IV + VII)	131°44.30′
Magnetic meridian:	129°31.99′

(B) Mean, azimuth mark		276°42.35′
(Az) Azimuth of azimuth mark		145°08.40′
(B − Az) True north meridian		131°33.95′
Magnetic meridian		129°21.99′
D at 13h08		− 2°11.96′
n_D	+ 15.8 mm	
$\Delta D^{(\prime)}$		− 7.65′
D_0		− 2°04.31′

Note that $\varphi = 1/2(a_1 + a_2)$. Therefore, when H and D are computed from the same observation, the separate computation of φ is not required.

$\log H = 9.210\,840 - \log\sin\varphi + 0.000\,163\,t - 0.0002H\cos\varphi$

$D = A + c - \alpha - (B - Az)$ $c = -2°25.6'$; Az = 145°08.4′

$S_D = 0.484'$/mm positive n_D = negative $\Delta D^{(\prime)}$ $S_H = 2.81$ gammas/mm positive n_H = positive $\Delta H^{(\gamma)}$

159 When it is intended to derive the magnetic declination from H observations with the QHM, two different procedures have to be considered. When the QHM is used with its telescope, unclamp the magnet and adjust the telescope in elevation angle so that the reflected diaphragm can be seen. Turn the alidade in azimuth until the plane of the magnet mirror is parallel to the optical axis of the telescope, and clamp the magnet. From now on, the telescope should neither be touched nor adjusted in elevation angle. Point on the azimuth marks. If no azimuth mark is visible at the elevation angle of the telescope, point on any prominent object or set up a surveyor's beacon at a distance of 100 to 200 metres from the instrument, so that it can be seen through the telescope, and adjust the beacon to vertical by means of a plumb-line. After having observed the azimuth marks, turn the alidade so that the telescope is south of the instrument. When the magnet is unclamped, it will swing back to its normal position with the plane of the mirror at right angles to the optical axis of the telescope. Observe H, using one of the schedules described in paragraph **157**. Clamp the magnet again with the plane of the mirror parallel to the telescope's optical axis and observe another round of azimuth marks. Finally, unclamp the magnet, bring it back to its normal position (mirror plane at right angles to the optical axis of the telescope) and clamp again. Take care that the magnet is not clamped with its north-seeking pole towards the telescope, because this may affect the adjustment to zero torsion. If an auxiliary azimuth mark has been used, one should not forget to relate this azimuth mark to the principal azimuth marks by means of theodolite observations.

When the telescope of the theodolite base is used, observe first the azimuth marks without the QHM. Then put the QHM on the base and observe H. Remove the QHM from the base and point again on the azimuth marks. When the objective lens of the base telescope is far from the QHM window, stray light may be a nuisance. In order to exclude stray light, slip a piece of cardboard tube over the objective end of the telescope and the QHM window.

160 In deriving the magnetic declination from QHM observations, the mean of the circle readings obtained at zero torsion (in the accompanying example, the readings I, IV, and VII) have to be corrected for the collimation c and the angle α. The circle reading of the magnetic meridian is:

$$\text{magnetic meridian} = \mathrm{A} + c - \alpha \text{ (see Fig. 16)}$$

where A is the mean of the circle readings obtained at zero torsion. Moreover, the circle reading of the true north meridian is

$$\text{true north meridian} = \mathrm{B} - \mathrm{Az} \text{ (see Fig. 13)}$$

where B is the circle reading of the azimuth mark and Az the azimuth of the azimuth mark. Since the magnetic declination is

$$\mathrm{D} = \text{magnetic meridian} - \text{true north meridian}$$

the total formula is

$$\mathrm{D} = \mathrm{A} + c - \alpha - (\mathrm{B} - \mathrm{Az}) \qquad (43)$$

where: D = magnetic declination; A = mean of circle readings at zero torsion corrected for variation of D; c = angle between the magnetic axis of the magnet and the normal of the mirror; α = departure of the magnetic axis of the magnet from the magnetic meridian due to the residual torsion of the suspension fibre; B = circle reading of the azimuth mark; Az = azimuth of azimuth mark.

The quantities c and α are found in the calibration certificate provided with the QHM. However, c must be checked from time to time by comparison of the QHM with a declinometer, while α should be computed for every observation. The computation of α is facilitated by Table 3, which contains the expression $\cos \varphi/2(1 - \cos \varphi)$ for deflection angles from 35° to 80° (see paragraph **149**).

In the accompanying example, the computations have been made more accurately than required in order to make it easy for the reader to follow the various operations. For practical purposes it will be sufficient to compute angles to 0.1′. Five-place logarithms are accurate enough for the nearest full gamma at high, and the nearest half gamma at low values of H, although occasionally rounding-off may be responsible for higher departures from the true result.

161 Since the suspension fibre of the QHM is subject to elastic after-effects, the accuracy of the results is to some extent influenced by the uniformity of the observational procedure. The time required for twisting the fibre, damping the magnet and adjusting the telescope to the reflected image of the diaphragm line should always be the same. Furthermore, the fibre should not be left in a twisted state longer than necessary. If, at large deflection angles, the magnet has turned over, clamp the instrument and start again from the beginning.

162 When three QHMs are at hand, all instruments should always be used although the results obtained with the individual instruments may differ from each other. It is better to use the mean of three instruments than to rely on a single QHM, unless one of the instruments is far away from the mean. Much insight into the behaviour of an individual instrument may be obtained by plotting not only the mean of the base-line values obtained with the three instruments, but also the base-line values of the individual instruments.

163 While the constant C of older instruments has a tendency to decrease, C of QHMs produced more recently increases on the average by 0.000 04 per year. However, there are some instruments in which C has been steady for many years, while the constants of others have changed by up to 0.0001 per year. Occasionally C may remain constant for several years and then start to change. Thus it seems that the behaviour of this constant is not predictable. The collimation c seems to vary at random. It will remain fairly constant for a few months and then jump to another value. Normally, c will scatter over a range of two minutes of arc from peak to peak. The odd instrument will show a wide range of scatter of up to ten minutes of arc, although it may give reliable values of H.

164 *A QHM should never be exposed to the sun either in its box or directly.* The magnet-and-mirror assembly is cemented together. At high temperatures the cement will soften and the magnet mirror will change its position, so that it cannot be observed any longer. The Danish Meteorological Institute has received several instruments for repair in recent years, for this very reason.

MEASUREMENT OF H WITH THE FIELD BALANCE

165 Whereas the calibration of a magnetic theodolite or a QHM will remain valid for years, the calibration of a field balance can be relied on for only over a brief period of time. For this reason the field balance is not suitable for the checking of the base-line value of an H-variometer. For successful application of the field balance in a magnetic survey, a special technique has to be used. The advantage of the field balance is that an observation can be made in a few minutes, the operation of the instrument and the computation of results is extremely simple, and the instrument is temperature-compensated, thus avoiding tedious reduction work. The results of observations may be computed and plotted in the field.

166 In principle, any field balance for the measurement of the horizontal intensity consists of a magnet moving in the (vertical) plane of the magnetic meridian, either on knife edges or suspended by means of a taut suspension, the magnetic axis of the magnet being vertical. The change of the horizontal intensity from one place to another is measured by the change of the angle between the vertical and the magnetic axis of the magnet, using the telescope's diaphragm scale and its image reflected by the magnet mirror. Thus the line of reference is the optical axis of the telescope, which must therefore always occupy the same position with respect to the vertical. This is ensured by precise levelling of the instrument. The balance is calibrated in gammas per scale division, by means of a Helmholtz-Gaugain coil and a precision milliammeter. The scale value may vary between 10 and 30 gammas per scale division and can be made to order (except for Fanselau balances). Since the balance magnet stands vertical, the scale value will vary slightly with the vertical intensity. Therefore, on a north-south traverse, occasional recalibration is necessary.

167 For observation, the tripod of the balance is set up with one of its legs north (preferably always the same) in order to facilitate levelling. The tripod head is levelled by means of the three levelling screws and the circular level. Then the compass is put on the tripod, following the instructions given by the makers, and the tripod head is turned in azimuth until the compass gives the prescribed reading, usually 0°. This adjustment has to be made with care so as to make sure that the balance magnet will move in the plane of the magnetic meridian. When the magnet moves in any other vertical plane the instrument will measure only a component of the horizontal intensity. After this adjustment, clamp the tripod head, remove the compass and put the balance on the tripod. See that the studs on the bottom plate of the balance enter the proper holes in the tripod head, and that their lower ends are caught by the clamping ring, which when turned

FIG. 17. Eyepiece scale of field balance.

20° or 30° connects the balance firmly to the tripod. The instrument is precisely levelled by means of the two tube levels arranged at right angles to each other on top of the balance. Make sure that the upper part of the balance, which can be turned independently around the vertical axis of the tripod head, has been turned against the prescribed stop, and that the proper side of the instrument is directed towards north. Now unclamp the magnet slowly and read the scale division with which the reflected diaphragm line coincides. Figure 17 shows what the observer will see when looking into the telescope. There are three reflected lines, the position of the central line being read as long as it is within the scale (in Fig. 17, 33.5 scale divisions). When, on a survey journey, the observer is moving south, i.e. to higher values of H, the central reflected line will sooner or later go beyond 65. Then the position of the line marked + on the left-hand side is read, and 30 added to the reading. The line marked − on the right-hand side of the central line is used when the central line goes beyond − 5. In this case, 30 has to be subtracted from the reading. When none of the reflected lines is visible, the range of the balance has to be reset by inserting an auxiliary magnet (balance with knife edges) in a holder below the tripod head, or by changing the torsion angle of the suspension fibre.

In recent years, torsion balances have appeared on the market, in which a different system is used. The diaphragm consists of a double line while the reflected line is single. The reading is made by adjusting the torsion head of the suspension until the single line appears between the double line. The divided circle of the torsion head appears in the telescope's field of view beside the diaphragm, and is read by means of a micrometer. In this case the magnet always occupies the same position with respect to the vertical. The balance is calibrated in gammas per degree twist of the suspension fibre, by means of a Helmholtz-Gaugain coil. Instruments of this type have a very large range and offer more comfort to the observer than any other type of balance. In order to obtain a better value, several readings may be made by clamping and unclamping the magnet in between.

168 All types of balances have to be clamped and unclamped with great care unless the magnet system is very small. Knife-edge balances and Fanselau balances will certainly be damaged if transported without being clamped. It is advisable not to expose balances to shocks while transporting them.

169 When a balance is used for the first time, it is worth while to check whether the magnet is really moving in the plane of the magnetic meridian, by opening the tripod clamp and turning the head in azimuth. The azimuth adjustment given by the compass must yield the highest value of the horizontal intensity.

170 The simplicity of operation of a balance is somewhat deceptive. The performance of balances may vary from instrument to instrument over a wide range, without the makers being to blame. Naturally, the experienced observer who takes the trouble to study the peculiarities of an instrument will get better results than the beginner who just manages to operate the balance according to the makers' instructions. For an example of observations see paragraph **195**.

Determination of the inclination

171 The earth inductor has scarcely changed its form since its introduction by H. Wild at the end of the last century. It consists of a heavy ring of about 25 centimetres diameter with three levelling screws. In the centre of the ring rests the alidade, which carries the bearings of the horizontal axis. The horizontal axis carries a frame in which the inductor coil is mounted. The latter can be rotated on two bearings of high precision. At one end of the coil's axis the commutator is mounted, while the other end is extended for fitting a flexible shaft which connects the inductor coil to a gear. Recent types of station earth inductors are fitted with a gear at one end of the horizontal axis. The other end of the horizontal axis carries the vertical circle. For levelling, a U-shaped frame with a sensitive tube level on top is set on the stubs of the horizontal axis. The inductor coil is adjusted to the plane of the magnetic meridian by means of a box compass which takes the place of the tube level.

172 The earth inductor resembles in every respect a geodetic theodolite, the *axis of the inductor coil being the pendant to the telescope. While the horizontal* axis of the earth inductor is adjusted as described in paragraph **86**, the level in the coil is used for the adjustment of the coil's axis. Level the inductor carefully, bring the axis of the inductor coil to the vertical and turn its plane at right angles to the horizontal axis. Use the level in the coil for the final adjustment and, if necessary, adjust this level. Turn the coil 90° in azimuth so that its plane is parallel to the horizontal axis of the inductor. Check by means of the coil level whether the coil's axis is still vertical and hence at right angles to the horizontal axis. If not, use the four (or two) capstan screws at one of the coil bearings and adjust the coil's axis exactly to vertical. The adjustment of a station earth inductor will hold for a long time. The precision of the inclination measurement is primarily dependent on the adjustment of the coil bearings, which must not have any play. Usually the bearing at the commutator end is adjustable.

173 For routine observations, level the inductor. Replace the tube level by the box compass and turn the alidade until the north-seeking pole of the compass needle is exactly on the mark. Remove the level frame and move the box compass to a distance of ten metres from the instrument. Read the horizontal circle of the earth inductor and turn the alidade 90° in azimuth so that the vertical circle is east of the instrument. The axis of the inductor coil will now move in the (vertical) plane of the magnetic meridian when the coil frame is turned about the horizontal axis of the inductor. Bring the coil axis to vertical with the commutator below ('commutator down') and turn the inductor coil so that its plane is parallel to the magnetic meridian. Adjust the coil axis to vertical, using the coil level. Read the vertical circle. Turn the inductor coil 180° around its axis and adjust the bubble of the coil level again to the centre of the vial. Read again the vertical circle. For higher precision, the two operations may be repeated as has been done in the accompanying example. The mean of the readings is the zenith point on the vertical circle. Now set the vertical circle to the co-inclination. The axis of the inductor coil will now be aligned with the geomagnetic field vector (or the lines of force).

174 Next adjust the astatic galvanometer, which should be placed two to three metres from the inductor. When the magnet system of the galvanometer is highly astatic, i.e. when the resultant magnetic moment is zero, the directive force on the magnet system will be provided by the suspension fibre only, and the galvanometer may be adjusted to any direction. Normally a small resultant will be present and the galvanometer will drift with the resultant's magnetic moment towards the magnetic meridian. Once the direction of preference has been found, the galvanometer should always be set up in that direction. Connect the twin cable to the galvanometer and check the sensitivity by taking the cable tags to be connected to the earth inductor between thumb and forefinger, one in each hand. The galvanometer should be deflected by a few scale divisions, unless your skin is very dry.

Usually the galvanometer is read by means of a telescope and an external scale. This may be done by the observer himself or by an assistant. Some observers prefer to project the filament of a bright low-voltage lamp, via the galvanometer mirror, on to a scale conveniently placed near the observer's position, using a long optical lever, the room being dark or semi-dark.

When the axis of the inductor coil is adjusted to the correct inclination, i.e. parallel to the lines of force, no line of force will cut the coil windings and no electromotive force (e.m.f.) will be induced in the rotating coil by the earth's field. The galvanometer will remain at rest.

175 The inclination is found by means of a trial-and-error method. Usually, an approximate value of the inclination is known. Set the vertical circle to that value, which may be designated I_1. Rotate the coil slowly in the positive direction. The galvanometer may be deflected to the right. Increase I_1 by 10′ to $I_2 = I_1 + 10'$. For this purpose the drum of the tangent screw may be used instead of the vertical circle. Wait until the galvo has come to rest. Rotate the coil again slowly in the positive direction. The galvo may be thrown violently to the right. This indicates that the inclination was changed in the wrong sense. Try a setting: $I_3 = I_1 - 10'$. Now the galvo may be deflected to the left. This means that the galvo will indicate no current somewhere between I_1 and I_3. Set the vertical circle to $I_4 = \frac{1}{2}(I_1 + I_3) = I_1 - 5'$. The galvo may be deflected to the left, from which we conclude that the galvo will indicate zero current somewhere between I_4 and I_1, etc., as outlined below:

Vertical circle or drum of tangent screw	Galvanometer deflection	Vertical circle or drum of tangent screw	Galvanometer deflection
I_1	Right	$I_6 = I_1 - 3.8'$	Right
$I_2 = I_1 + 10'$	Right	$I_7 = I_1 - 4.4'$	Left
$I_3 = I_1 - 10'$	Left	$I_8 = I_1 - 4.1'$	Left
$I_4 = I_1 - 5'$	Left	$I_9 = I_1 - 4.0'$	Zero
$I_5 = I_1 - 2.5'$	Right	Read vertical circle.	

The reader will notice that, from I_4 onwards, each successive setting of the vertical circle lies always between two of the previous settings. The procedure is shown

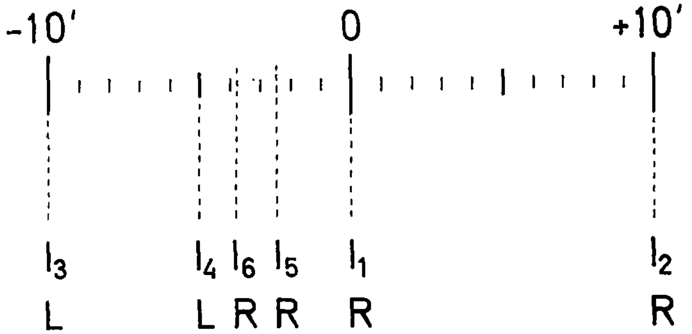

FIG. 18. Determination of inclination.

in a diagram (Fig. 18) up to I_6. The nearer the correct inclination is approached the faster the rotation of the coil must be, in order to obtain a reasonable galvanometer deflection.

The procedure has to be repeated for rotation of the inductor coil in the negative direction. Naturally, one will start somewhere near the previous setting of the vertical circle in order to make sure that the galvanometer has not meanwhile gone dead. Find the setting of the vertical circle for zero current as before. With the two circle readings, one with rotation of the inductor coil in the positive direction, and the other with rotation in the negative direction, we have one set of readings. One should observe at least two sets, but better three to five sets. While observing, watch that the inductor coil comes to rest at a point where the coil is connected across the galvo. When the coil stops with the brushes at the breaks of the commutator, the galvo will be undamped and certain types of galvos may require a long time for coming to rest. Finally, repeat the determination of the zenith point of the circle.

Turn the commutator up and determine the zenith point again. This is possible because the vial of the tube level is curved on both sides. Determine the inclination and repeat the zenith point readings.

After having completed the observations with the vertical circle east, turn the alidade 180° in azimuth, i.e. with vertical circle west, and take observations with positive and negative directions of coil rotation and with commutator up and commutator down, including readings of the zenith point. The observational procedure is summarized below:

Vertical circle east		*Vertical circle west*	
Commutator down		*Commutator up*	
Zenith point		Zenith point	
+ Rotation − Rotation	2 to 5 sets	+ Rotation − Rotation	2 to 5 sets
Zenith point		Zenith point	
Commutator up		*Commutator down*	
Zenith point		Zenith point	
+ Rotation − Rotation	2 to 5 sets	+ Rotation − Rotation	2 to 5 sets
Zenith point		Zenith point	

176 Most of the trouble encountered in earth inductor operation originates from a dirty collector. For cleaning, it is recommended to wash the commutator and the brushes with alcohol, using a piece of linen and rubbing dry with another cloth. Some observers use pith or brass polish. Every few years it is necessary to polish the collector and the brushes, using the finest grade sandpaper. A very common fault is to use high pressure on the brushes. This not only wears out the collector but also entails generation of disturbing thermoelectric currents. One should use as little pressure on the brushes as is compatible with a reasonable behaviour of the galvanometer. In an extremely dry climate, it may be necessary to apply a drop of sperm oil or kerosene to the commutator in order to reduce friction and minimize the generation of thermoelectric currents.

If the axis of rotation of the inductor coil is not exactly in the plane of the magnetic meridian, different values of inclination will be found for positive and negative rotations. The azimuth may be changed until either direction of rotation yields the same inclination; the amount of correction to be applied to the box compass setting may be determined as explained in detail by Egedal (1937). A correct azimuth will also reduce the error caused by a faulty position of the plane of commutation, which in most inductors cannot be adjusted. Users of astatic galvanometers complain about the low sensitivity of this type of instrument. This applies especially to galvanometers which are observed with telescope and external scale from a short distance. A long optical lever will increase the sensitivity, although this will not overcome the basic shortcoming of the astatic galvanometer, which as supplied by most makers of earth inductors no longer represents the best state of the art.

177 The cumbersome procedure outlined above for finding the inclination is dictated by the unfavourable characteristics of the astatic galvanometer, its long period being the main obstacle. Great advantages are offered by the string galvanometer, whose period is less than 0.1 second. It will follow any change of current instantaneously, thus enabling the observer to adjust the axis of the inductor coil to zero current within a few seconds, instead of the minutes required when using the astatic galvanometer. Furthermore, the string galvo will indicate a maladjustment of the coil's axis in azimuth by flutter of the string. Upon correction of the azimuth, the flutter will disappear. For observatory use, the microscope of the string galvo does not provide enough magnification. This difficulty can be overcome by projecting an image of the string to a distance of four to five metres. For that purpose a condenser and a lamp are placed behind the string, and the eyepiece of the microscope is removed.

Askania has equipped numerous earth inductor attachments of travel theodolites with Edelmann string galvos. Users of these galvanometers are notified that repairs cannot be carried out any longer, and that production of the instrument has been discontinued.

178 At some observatories moving-coil galvanometers, usually spares of short-period seismographs, have been used with success. The resistance of an inductor coil under rotation, measured at the brushes, is about 80 ohms. A galvanometer with a coil resistance and a resistance for critical damping of the same magnitude

Observation of inclination with the earth inductor

1963, May 4, Saturday
Fürstenfeldbruck Observatory, inclination pier

Station earth inductor Askania No. 111 775
String galvanometer Edelmann No. 1358

Vertical circle east, commutator down

	Circle reading A	Circle reading B	Circle reading Mean
Zenith	359°58.8′	60.3′	59.55′
	60.0′	61.5′	60.75′
	58.8′	60.4′	59.60′
	60.0′	61.5′	60.75′
MEAN			0°00.16′

Time (GMT)	Rotation				n_H	n_Z	$\Delta H^{(\gamma)}$	$\Delta Z^{(\gamma)}$
08h30	+	25°54.6′	56.0′	55.30′				
	−	54.5′	55.9′	55.20′				
	+	54.6′	56.0′	55.30′				
	−	54.5′	55.9′	55.20′				
	+	54.7′	56.1′	55.40′	+ 0.3	+ 3.4	+ 0.8	+ 9.1
	−	54.6′	56.0′	55.30′				
	+	54.6′	56.0′	55.30′				
	−	54.7′	56.1′	55.40′				
	+	54.5′	55.9′	55.20′				
08h36	−	54.6′	56.0′	55.30′				
MEAN				25°55.29′				

Zenith	359°58.8′	60.3′	59.55′	Mean zenith	0°00.18′
	60.2′	61.5′	60.85′	Mean circle reading	25°55.29′
	58.8′	60.4′	59.60′		
	60.0′	61.5′	60.75′	Co-inclination	25°55.11′
				Inclination	64°04.89′
MEAN			0°00.19′		

The results obtained in the three other inductor positions were:

	I_{obs}	n_H	n_Z	$\Delta H^{(\gamma)}$	$\Delta Z^{(\gamma)}$
Vertical circle east, commutator up	64°04.64′	+ 2.7	+ 3.4	+ 7.6	+ 9.1
Vertical circle west, commutator up	03.96′	5.5	2.5	15.4	6.7
Vertical circle west, commutator down	04.26′	4.1	2.7	11.5	7.2

Reduction of observations to base-line $\Delta I^{(')} = -0.0661\,\Delta H^{(\gamma)} + 0.0322\,\Delta Z^{(\gamma)}$

Time (GMT)	I_{obs}	$\Delta H^{(\gamma)}$	$\Delta Z^{(\gamma)}$	$\Delta H^{(')}$	$\Delta Z^{(')}$	$\Delta I^{(')}$	I_0
08h30-36	64°04.89′	+ 0.8	+ 9.1	− 0.05	+ 0.29	+ 0.24	64°04.65′
53-58	04.64′	+ 7.6	+ 9.1	− 0.50	+ 0.29	+ 0.21	04.85′
09h32-38	03.96′	+ 15.4	+ 6.7	− 1.02	+ 0.22	− 0.80	04.76′
51-56	04.26′	+ 11.5	+ 7.2	− 0.76	+ 0.23	− 0.53	04.79′
						MEAN	64°04.76′

S_H = 2.80 gammas/mm   positive n_H = positive $\Delta H^{(\gamma)}$ S_Z = 2.68 gammas/mm   positive n_Z = positive $\Delta Z^{(\gamma)}$

will be perfectly matched and will therefore give optimum performance. The market offers numerous types of low-priced galvanometers in this range, with periods between 1.5 and 2.0 seconds and a scale value of 20 . 10^{-9} A/mm/m. When using such a galvanometer it is possible to adjust the axis of the inductor coil, by continuous rotation, within a few seconds. Again it will be advantageous to use a long optical lever.

179 The string galvo or the moving-coil galvo must be connected to the earth inductor either by a pair of wires twisted throughout their length and mounted far from any AC power line, or by a shielded cable. Loose wires are not suitable because, if they move relative to each other, the earth's field will induce an e.m.f. which may give rise to faulty indications.

180 Some makers of geomagnetic instruments supply earth inductor attachments for magnetic travel theodolites or small earth inductors. The instruments are equipped with verniers reading to 0.5′. The patient observer will obtain good results with such an instrument.

181 Unlike the earth inductor, the Japanese GSI magnetometer which appeared on the market in the early fifties is modern in concept and execution. The instrument was developed by I. Tsubokawa (1951) of the Japanese Geographical Survey Institute. It is in principle an earth inductor with a horizontal and vertical circle. Both circles can be read to 0.1′ by means of scale microscopes. Instead of the customary DC detection with a sensitive galvanometer, AC is taken from the inductor coil by means of slip rings and amplified by a narrow-band amplifier, whose output is fed either to a 'magic eye' or a robust milliammeter. The most recent version uses a small transistorized amplifier and earphone detector. The detection works rapidly and the alignment of the axis of the rotating coil with the geomagnetic field vector is therefore a matter of seconds. The magnetic meridian and the inclination are read off the horizontal and vertical circles respectively.

182 Although a station earth inductor looks very sturdy, it is in fact a delicate device. While the coil is being rotated, considerable forces act on the frame of the rotating coil, causing distortions which can be made visible with a fast-reacting string galvanometer. It will be observed that in the initial phase of rotation, i.e. when force is applied, the galvanometer is considerably deflected. Once the coil has picked up speed, the forces are small and the deflection will disappear. Like any other geomagnetic instrument, the earth inductor should therefore be treated gently.

183 The enclosed example explains the procedure for an inclination measurement and the computation of angles. For the reduction of the inclination to the base-lines of the H- and Z-variometers, we use the last of the equations (7), which is:

$$\Delta I^{(\gamma)} = -\sin I \Delta H^{(\gamma)} + \cos I \Delta Z^{(\gamma)}$$

and

$$\Delta I^{(')} = -\frac{\sin I}{F \sin 1'} \Delta H^{(\gamma)} + \frac{\cos I}{F \sin 1'} \Delta Z^{(\gamma)} \quad \text{(insert F in gammas)}$$

For F = 46 800 gammas and I = 64° we obtain

$$\Delta I^{(')} = -0.0661\ \Delta H^{(\gamma)} + 0.0322\ \Delta Z^{(\gamma)}$$

$$\text{and} \qquad I_0 = I_{obs} - \Delta I^{(')},$$

which is the base-line value of I. From the base-line values of I and H the base-line value of Z is computed by means of $Z_0 = H_0 \tan I_0$ (see also paragraph **102**). The computation of H_0 and Z_0 from I_0 and F_0 will be explained in paragraph **205**.

Determination of the vertical intensity

MEASUREMENT OF Z WITH THE BMZ

184 The BMZ (Balance Magnétométrique Zéro) was designed by D. La Cour (1942). Unlike other balance-type instruments, it has excellent long-term stability thanks to its unique balance system, in which the magnet, knife edges and mirror are made of a single piece of steel. The BMZ is a null instrument. The balance magnet indicates the degree of compensation of the vertical component of the earth's magnetic field by a fixed magnet above the balance magnet, called the compensating magnet, and an adjustable magnet mounted on a graduated disc below the balance magnet, called the turn magnet. The range of the instrument, which is about 2200 gammas, can be extended by screwing small supplementary magnets to the lower end of the turn magnet holder. For covering a wide range, the BMZ may be ordered with an adjustable compensating magnet. The distance between the balance magnet and the compensating magnet is varied by means of a precise thread and a nut. The position of the nut is indicated by a scale.

185 The temperature coefficient of the instrument is a combination of the temperature coefficients of the magnetic moments of the compensating magnet, the turn magnet and the supplementary magnet, and the temperature coefficients of the metal parts carrying the magnets. The temperature coefficient of the balance magnet has no influence on the result because it is supported slightly above its centre of gravity and in the state of compensation no magnetic force acts on it at right angles to its magnetic axis.

186 The formula for the BMZ is

$$Z = Z_C + Z_S + Z_T - \alpha t - 2\alpha\Delta t \tag{44}$$

where: Z = vertical intensity of the Earth's magnetic field; Z_C = field of the compensating magnet at the centre of the balance magnet at 0 °C; Z_S = field of the supplementary magnet or magnets at the centre of the balance magnet at 0 °C; Z_T = field of the turn magnet at the centre of the balance magnet at 0 °C (positive for disc readings from 90° to 0° and from 270° to 360°; negative for disc readings from 90° to 180° and 270° to 180°); α = temperature coefficient; t = temperature in degrees centigrade (thermometer reading corrected for thermometer errors); Δt = change of temperature per minute.

For a BMZ with fixed compensating magnet, the calibration certificate of the Danish Meteorological Institute contains the complete formulae for:

Z_C and the sums and differences of Z_C and Z_S for the three supplementary magnets with figures up (*chiffres en haut*) and figures down (*chiffres en bas*);

α for values of $Z_C + Z_S + Z_T$, i.e. for the applied compensating field at 0 °C;
Z_T for disc readings from 0° to 180°;
the correction to be applied to the disc readings for maladjustment of the turn magnet;
a table of corrections for the three thermometers.

For a BMZ with adjustable compensating magnet the calibration certificate includes:

Z_C and α for every scale division of the adjustable compensating magnet;
corrections to be applied to α for the various settings of the turn magnet;
Z_T and thermometer corrections as supplied for the BMZ with fixed compensating magnet.

For a BMZ with adjustable compensating magnet the supplementary magnets are only required for extreme cases.

187 For the proper functioning of the instrument, it is necessary to keep the knife edges of the balance magnet and the agate bearings dry. In order to make the magnet housing airtight, all joints are covered with vacuum grease. On one side of the magnet housing, two glass vessels are attached which contain silica gel. As long as the silica gel is blue, it is able to extract water from the air. When it turns pink, it has to be replaced because it is saturated with water. For this purpose, unscrew the glass vessels, remove the cotton stoppers which prevent the silica gel from entering the magnet housing, and replace the material. Take care that the washers of wax paper are not lost. Pink silica gel is reconditioned by heating it gently until it turns blue. Heating above 125 degrees centigrade will disintegrate the dye which indicates the state of the silica gel.

188 For observation, set up the tripod preferably with one of its legs pointing towards north, the notch in the tripod head pointing towards south, and the tripod head level. Give the legs a generous spread and press the shoes of the legs firmly into the ground. Tighten all thumb screws of the tripod. Before assembling the BMZ, wipe with a dry clean cloth all parts which meet each other. Put the BMZ on the tripod, with the zero of the horizontal circle below the clamping ring south. When taking the compensating magnet from the box, see that the inner part does not slip out of the outer tube. Pull the inner part slightly out and attach the assembly to the thread on top of the BMZ. Tighten with mild pressure. Pull the outer tube down and insert a thermometer of suitable range in the upper end of the compensating magnet assembly. Screw the turn magnet assembly to the thread below the instrument. Avoid using the disc as a lever when tightening. Rather, hold the cylindrical part with the whole hand and tighten. When threading in (and also when taking the turn magnet assembly off), hold the left hand below the assembly in order to prevent the latter falling to the ground in the event of the thread not engaging immediately. When using an adjustable compensating magnet, check the scale adjustment. See that the upper side of the nut is at the correct scale division and that the mark on the rim of the nut coincides with the graduated side of the scale. When adjusting the magnet to another division, first loosen the nut. Pull up the outer tube. Next, set the nut to the desired division.

Finally, turn the magnet tube against the nut with mild pressure. Never force the assembly to a higher scale division by turning the nut only. The precise thread, which consists of soft material, may be deformed and the calibration will not be valid any longer. Mount the telescope with the prism up and check the focusing.

189 In contrast to the QHM, the BMZ requires careful levelling. Upon completion of levelling, turn the alidade in azimuth until the telescope is approximately south of the instrument. This position is called 'telescope south'. To turn the alidade, use the handles on both sides of the magnet housing, not the telescope. Open the clamp by lifting with a thumb-nail the circular spring on the clamping ring, and turn the ring slightly to the right. Now look into the telescope and continue to turn the clamping ring slowly until the magnet is free. Move the clamping ring to the stop. The latter part of the movement may be faster. Damp the oscillations of the magnet by counteraction with the vernier drive of the turn magnet. If, upon unclamping, the reflected diaphragm line disappears, turn the turn magnet until the line reappears in the telescope's field of view. If this fails to give the required result, the compensating field is either too small (when unclamping, the reflected diaphragm line moves upward) or too large (the reflected diaphragm line moves downward). When a fixed compensating magnet is used, add a supplementary magnet. With an adjustable compensating magnet, set the compensating magnet to another scale division.

190 When the balance magnet has come to rest, adjust the reflected diaphragm line to the neutral division ND by turning the vernier drive of the turn magnet. The approximate value of ND may be known from previous observations or from the calibration certificate. If nothing is known about ND, start with a setting to scale division 20 of the diaphragm scale. Then turn the alidade slowly 180°. This position is called 'telescope north'. Do not touch the vernier drive but wait until the magnet has come to rest. Then read the position of the magnet on the diaphragm scale. If the magnetic axis of the magnet is horizontal, the reading of the eyepiece scale should again be 20. If not, read the eyepiece scale, turn the alidade back to telescope south and adjust the reflected diaphragm line to the reading found at telescope north by means of the vernier drive. Turn again to telescope north and check whether you have the same reading on the diaphragm scale. If a different value is read, turn the telescope south, adjust the reflected line to that value, etc. After two or three repetitions of the procedure you will have the same reading of the eyepiece scale at both telescope positions and with it the neutral division ND. When adjusted to ND, the magnetic axis of the balance magnet is exactly horizontal, i.e. the vertical component of the magnetic field at the balance magnet is zero, the vertical component of the Earth's magnetic field having been compensated by the sum of the fields of the compensating magnet, the turn magnet, and the supplementary magnet (if used). The precision with which ND is determined is decisive for the accuracy of the Z measurement. ND is almost constant but has to be determined for every measurement, because it may vary slightly, either with temperature or for other reasons. Occasionally, observers do not determine ND themselves but use the value given in the calibration certificate. If the actual ND is off by several scale divisions, the results

Observation of Z with the BMZ

$$Z = Z_C + Z_S + Z_T - \alpha t - 2\alpha\Delta t$$

1966, December 30, Friday
Pendeli Observatory, absolute pier
BMZ No. 286, compensating magnet No. 286 B at division 15
ND: 18.8 $Z_C = 36\,312.0$; $\alpha = 10.08$; $2\alpha = 20.2$
Thermometer No. 1608

$S_Z = 3.50$ gammas/mm
positive n_Z = positive $\Delta Z^{(\gamma)}$

1 Turn magnet	2 Time (GMT)	3 Thermometer (°C)	4 Thermometer corrected (+ 0.10)	5 Disc	6 Disc corrected (+ 0.35)	7 Supplements	8 Z_T	9 αt	10 $2\alpha\Delta t$	11 Sum	12 Mean	13 Z
Erect	15h10m00s	+ 7.84	+ 7.94	93.4°	93.75°		− 74.0	− 80.0	− 1.1	− 155.1	− 154.2	36 157.8
	11 30	7.92	8.02	93.3	93.65		72.0	80.8	1.1	153.9		
	12 25	8.00	8.10	93.2	93.55		70.0	81.6	1.7	153.3		
	13 15	8.08	8.18	93.2	93.55		70.0	82.5	2.0	154.5		
Inverted	15 15	8.20	8.30	266.1	266.45	93.55°	70.0	83.7	1.2	154.9	− 154.9	36 157.1
	16 25	8.30	8.40	266.2	266.55	93.45	68.0	84.7	1.7	154.4		
	17 45	8.40	8.50	266.2	266.55	93.45	68.0	85.7	1.5	155.2		
	18 45	8.44	8.54	266.2	266.55	93.45	68.0	86.1	0.8	154.9		

Z, turn magnet erect:		36 157.8 gammas	Z, turn magnet inverted:		36 157.1 gammas
n_Z	+ 10.1 mm		n_Z	+ 10.1 mm	
$\Delta Z^{(\gamma)}$		+ 35.4	$\Delta Z^{(\gamma)}$		+ 35.4
Z_0		36 122.4			36 121.7

MEAN Z_0 36 122.0 gammas

Observation of Z with the BMZ, method of interpolation

$Z = Z_C + Z_S + Z_T - \alpha t - 2\alpha\Delta t$

1967, January 26, Thursday
Quetta Observatory, absolute house, BMZ tripod
BMZ No. 286, compensating magnet No. 286 B at division 20
ND: 18.8; Thermometer No. 1608 $Z_C = 33\,701.0$; $\alpha = 9.36$; $2\alpha = 18.7$

Position and scale division		Time (GMT)	Thermometer (°C)	Thermometer corrected (+ 0.10)	Disc	Disc corrected (+ 0.35)	Supplements	Z_T	αt	$2\alpha\Delta t$	Sum	Mean	Z_C + mean	$\Delta Z^{(\gamma)}$	Z' reduced to base-line
Z_S	25	6h31m00s	+ 6.24	+ 6.34	90.4°	90.75°		− 15.0							
Erect	15	32 10	6.30	6.40	86.15	86.50		+ 69.0							
	19	33 15	6.36	6.46	88.3	88.65		+ 27.0	− 60.5	− 1.1	− 34.5	− 34.6	33 666.4	− 13.0	33 679.4
	19	33 55	6.40	6.50	88.3	88.65		+ 27.0	− 60.8	− 1.1	− 34.9				
	19	34 45	6.42	6.52	88.3	88.65		+ 27.0	− 61.0	− 0.4	− 34.4				
Inverted	19	36 20	6.50	6.60	271.2	271.55	88.45°	+ 31.0	− 61.8	− 0.9	− 31.7	− 31.9	669.1	− 14.0	683.1
	19	37 15	6.56	6.66	271.2	271.55	88.45	+ 31.0	− 62.3	− 1.2	− 32.5				
	19	38 15	6.60	6.70	271.25	271.60	88.40	+ 32.0	− 62.7	− 0.7	− 31.4				
Z_N	19	40 15	6.68	6.78	269.85	270.20	89.80	+ 4.0	− 63.5	− 0.7	− 60.2	− 60.0	641.0	− 15.0	656.0
Inverted	19	41 05	6.72	6.82	269.9	270.25	89.75	+ 5.0	− 63.8	− 0.9	− 59.7				
Erect	19	42 10	6.76	6.86	89.4	89.75		+ 5.0	− 64.2	− 0.7	− 59.9	− 59.6	641.4	− 15.0	656.4
	19	43 10	6.80	6.90	89.35	89.70		+ 6.0	− 64.6	− 0.7	− 59.3				
	25	44 15	6.84	6.94	113.2			− 454.9							
	15	45 15	6.88	6.98	65.35			+ 469.4							

S_S = 8.4 gammas/scale division

S_N = 92.4 gammas/scale division

$Z_0 = Z'_S + \frac{S_S}{S_N - S_S}(Z'_S - Z'_N)$ $Z'_S = 33\,681.2$ gammas $Z'_N = 33\,656.2$ gammas

$Z_0 = 33\,681.2 + \frac{8.4}{92.4 - 8.4}(33\,681.2 - 33\,656.2)$

$Z_0 = 33\,681.2 + (0.10\ .\ 25.0) = 33\,683.7$ gammas obtained will naturally not be correct. If ND is far off from a full scale division or from the centre of the eyepiece scale, adjust it by means of the screw which turns the prism above the magnet mirror. Access to this screw is obtained by removing the cap on the magnet housing opposite the telescope. When removing the cap, the instrument must be clamped. Adjust the screw in small increments and check after each adjustment whether the desired result has been obtained.

191 After having found ND, turn the telescope south. Start observations by damping the magnet and adjusting it to ND by means of the vernier drive of the turn magnet. Clamp and unclamp. Take care that you do not knock against the tripod legs: you may dislocate the magnet and damage the knife edges. The beginner may clamp the magnet after every setting and unclamp after having taken the readings. Read the time to the nearest five seconds, the thermometer to 1/50 of a degree centigrade using a lens, and the graduated disc to 1/20 of a degree of arc. The time and the thermometer reading belong together, as will be seen later. Note that at low values of the vertical intensity it will suffice to read the thermometer to the nearest tenth of a degree centigrade because the temperature coefficient is small. While you record the readings the magnet will almost come to rest. Damp the magnet, adjust the reflected diaphragm line to ND and read as before. Continue until you have four or five sets of readings. Turn the disc of the turn magnet to its supplement and take four or five readings again. When the disc readings are between 0° and 180°, the position is called 'turn magnet erect', when between 180° and 360°, 'turn magnet inverted'. *Do not forget to clamp the instrument upon completion of the observations.* It is advisable to observe the thermometer a few minutes before starting observations. When the temperature change per minute is more than 0.1 degree centigrade wait until the rate of change has become smaller than this.

192 In the example, the figures recorded while observing are contained in columns 2, 3, and 5. Fill in column 4 by adding the thermometer correction to the thermometer readings. Next correct the disc readings for the maladjustment of the turn magnet. This correction has to be added to all disc readings. Quite a common mistake is to compute the supplement of the disc readings which are higher than 180° and then to add the correction. This will aggravate the error. The correction has been applied in the right sense when approximately the same value is obtained for both turn magnet positions. The application of the correction to the disc readings is not absolutely necessary when observations are made in both turn magnet positions. The mean of the two positions will be the correct value of the vertical intensity. Compute the supplements for disc readings higher than 180° (in column 7) and convert the disc readings to gammas by means of the conversion table given in the calibration certificate.

For the next step in computation, the temperature coefficient α is required. All fields participating in the compensation of Z are added up. In the example, the adjustable compensating magnet was set to division 15, for which $Z_C = 36\,312$ gammas according to the certificate. The mean of the turn magnet readings as obtained from column 8 is $-$ 70 gammas. Hence the temperature coefficient has to be interpolated from the certificate for $36\,312 - 70 = 36\,242$ gammas, and is

10.08 (2α is rounded to 20.2). Note that for interpolating the temperature coefficient the sum of the compensating fields is not corrected for temperature. At an observatory, one will find α for an average value of Z_T and compute results with a constant α. If, because of large temperature variations in the course of the year, Z_T varies over a wide range, it may be necessary to compute two temperature coefficients, one for the lower part of the range and another for the higher part.

Δt is determined from two adjacent thermometer readings. For the first two observations in the example, the temperatures were + 7.94 and + 8.02. The time lapsed between the two readings was 90 seconds. The change of temperature per minute was therefore $0.08/90 \times 60 = 0.053$ or $\simeq 0.05$, which has to be multiplied by 2α. Some observers derive $2\alpha\Delta t$ once for the whole group of observations. In the example, the time difference between the first and last observation is 3m15s and the temperature difference is 0.24 degrees centigrade, from which we find $2\alpha\Delta t = 1.5$ gammas, but the values have nevertheless been computed separately for each difference. The reader will notice that both procedures yield the same result. Complete the computations as indicated in the example. Add the mean (column 12) to Z_C and reduce the two parts of the measurement to base-line by subtracting $\Delta Z^{(Y)}$.

193 In BMZ observations, the determination of the neutral division is an element of considerable uncertainty, especially when ND is far off a full scale division. Kring Lauridsen developed a method which avoids this difficulty. When at $H > 0$ the balance magnet is set to the same full scale division of the diaphragm scale at two azimuths, unsymmetrical with respect to the magnetic meridian, we have

$$Z_1' + x\,S_1 = Z_2' + x\,S_2$$

where: Z_1' = nominal Z-value at full scale division, as computed from the BMZ formula with the balance magnet in azimuth 1; Z_2' = nominal Z-value at full scale division, with the magnet in azimuth 2; S_1 = scale value of the telescope's eyepiece scale in gammas per scale division, in azimuth 1; S_2 = scale value of telescope's eyepiece scale in gammas per scale division, in azimuth 2; x = difference between ND and the full scale division to which the balance magnet was set at both azimuths, expressed in scale divisions of the eyepiece scale.
Further,

$$x = \frac{Z_1' - Z_2'}{S_2 - S_1}$$

and the vertical intensity which would have been obtained if the magnet had been set to the neutral division

$$Z = Z_1' + \frac{S_1}{S_2 - S_1}(Z_1' - Z_2') = Z_2' + \frac{S_2}{S_2 - S_1}(Z_1' - Z_2').$$

It can be seen that the term containing the scale values will be smallest when azimuth 1 and azimuth 2 are the positions telescope south and telescope north, respectively. Furthermore, at these positions S_1 and S_2 will vary least with azimuth. Therefore, it suffices to determine the scale values once only, when observations are made at an observatory. In the field, a new determination of the scale values has to be made when H has changed appreciably. For practical work we use

$$Z = Z'_S + \frac{S_S}{S_N - S_S}(Z'_S - Z'_N). \tag{45}$$

The scale values S_S and S_N of the diaphragm scale at telescope south and telescope north, respectively, are determined by setting the reflected diaphragm line to scale divisions 15 and 25, and reading the disc of the turn magnet. The scale values are

$$S_S = \frac{Z_{T_{15}S} - Z_{T_{25}S}}{10} \quad \text{and} \quad S_N = \frac{Z_{T_{15}N} - Z_{T_{25}N}}{10} \tag{46}$$

where: S_S = scale value of diaphragm scale in gammas per scale division at telescope south; S_N = scale value of diaphragm scale in gammas per scale division at telescope north; $Z_{T_{15}S}$, $Z_{T_{25}S}$ = reading of turn magnet disc converted to gammas at scale division 15, 25 and telescope south; $Z_{T_{15}N}$, $Z_{T_{25}N}$ = reading of turn magnet disc converted to gammas at scale division 15, 25 and telescope north.

It is not necessary to correct the disc readings for maladjustment of the turn magnet, variation of Z or temperature. If the balance magnet cannot be adjusted to one or the other scale division because the disc reading is near 0° or 180°, use another pair of scale divisions, for instance 10 and 20, or 20 and 30, or a smaller number of scale divisions in between.

The example illustrates the schedule of observation and the computation of the result. Determine ND. In contrast to the previously described method of BMZ observation, no great care is required. In the example, ND was found at 18.8 and the magnet was therefore set to 19.0. Start with the two observations at scale division 15 and 25 for the determination of the scale value at telescope south. Observe the magnet at division 19.0 and with the turn magnet erect and inverted. Turn the alidade to position telescope north. Observe the magnet at division 19.0 with turn magnet erect and inverted. Since the influence of Z'_N on the result is small, only two observations are made at the two turn magnet positions. Next, take the readings at the settings of the magnet to scale division 15 and 25, for the determination of S_N. The observations are computed as explained before. Finally the individual groups of observations are reduced to base-line and the result is the base-line value of the vertical intensity, Z_0. Note that the term $(Z'_S - Z'_N)$ will be positive when the neutral division is below, negative when the neutral division is above the scale division at which the observations were taken.

MEASUREMENT OF Z WITH THE FIELD BALANCE

194 Like the field balance for the measurement of the horizontal intensity (see paragraphs **165-170**), the field balance for the measurement of the vertical intensity, or briefly the Z-balance, is a relative instrument and not suitable for the checking of base-line values at an observatory. In the past it has been used much in prospecting and is therefore technically well developed. For the Z-balance, much of what has been said about the H-balance is valid.

In principle, the field balance for the measurement of the vertical intensity consists of a horizontal magnet resting on knife edges or supported by a taut suspension. In most Z-balances, the magnet moves in the magnetic prime vertical. Therefore, the horizontal intensity has no influence on the scale value. If the magnet moves in the magnetic meridian, as in the Askania torsion balance and the Fanselau balance for measuring H and Z with the same instrument, this dependence is present and has to be allowed for. The advantage of the Z-balance with the magnet in the magnetic prime vertical is that small errors in levelling and azimuth setting are eliminated by observing the instrument in two positions, namely, with the north-seeking pole east and west. Details about calibration and observations can be found in paragraphs **165-170**.

195 The field balance is an instrument for measuring differences of H and Z. If the absolute value of a component is known at one station, the absolute values of the component at the other stations can be computed. The following example explains the simple procedure. With a Z-balance of a scale value of 15.0 gammas/scale division, observations were made at an observatory where the absolute value of Z was known, and at a field station. The following values were found:

	Reading of eyepiece scale	Absolute value of Z
Observatory	20.6	42 165 gammas
Field station	28.6	
Difference	8.1	
Difference in gammas	8.1 × 15.0 =	121.5
Absolute value at field station		42 286.5 gammas

Since the long-term stability of a field balance is low, it is advisable to make a comparison at the observatory at the beginning and end of a series of field measurements.

The proton magnetometer

196 More than any other development, the invention of the proton magnetometer has revolutionized geomagnetic measurements. Its high degree of stability is due to the fact that the instrumental constant, which in classical instruments includes numerous factors, depends on the gyromagnetic ratio of the proton γ_p and some other parameters which can be easily kept under control. For γ_p IAGA has, after careful inspection of the results of determinations at various national bureaux of standards, adopted the value 26 751.3 s^{-1} Γ^{-1}. Thus, after the electronics of the instrument have been designed, the constant can be computed without tedious determination of basic quantities or reference to any geomagnetic standard, provided that the sensor of the instrument is free from magnetic impurities. Furthermore, the results are of high accuracy and can be obtained in seconds instead of hours.

THE PRINCIPLE OF THE PROTON MAGNETOMETER

197 The sensor of the proton magnetometer consists of a bottle of 100 to 500 cc proton-rich liquid, for instance pure water, alcohol, kerosene or hexane, around which are wound 800 to 1000 turns of copper wire. With its axis at right angles to the geomagnetic field vector, the sensor is connected to a current source by a polarizing unit. A current of one to ten amperes passes through a coaxial cable and the sensor coil and sets up a field of 100 to 1000 oersteds in the bottle containing the proton-rich liquid. Within three seconds, about 70 per cent of the maximum possible polarization will be achieved. While the polarizing field is on, the protons will align themselves in greater numbers parallel (state $+\ 1/2$) and in smaller numbers antiparallel (state $-\ 1/2$) to the polarizing field. The result is a small magnetic moment along the coil's axis, proportional to the polarizing field. The sensor is then switched from the current source to an amplifier. The ensemble of protons will now start a precessional movement around the geomagnetic field vector, inducing a potential difference of one to two microvolts in the sensor coil. The frequency of precession is proportional to the scalar magnitude of the field vector. The signal, whose amplitude decays exponentially and falls to the noise level within five to ten seconds, is amplified to a square wave of five to ten volts, peak-to-peak, and passes through an electronic gate to a binary counter. The counter suppresses a discrete number of cycles, usually 128 or 256, in order to prevent switching transients from influencing the result. Then a second gate, the RF gate, is opened and the RF signal of the time base flows into a decade counter. After another 512, 1024, 2048 or 4096 precession cycles have passed the binary counter, both gates are closed. The decade counter stops and displays the duration of 512, 1024 . . . 4096 precession periods in units of the time base ($1/f_{\text{time base}}$). The gyromagnetic ratio of the proton γ_p, the precession frequency f and the geomagnetic field vector F are connected by the equation

$$\omega = 2\pi\, f = \gamma_p \mathrm{F}$$

$$\mathrm{F} = \frac{2\pi}{\gamma_p} f \qquad (47)$$

where: f = frequency of precession in hertz; F = scalar magnitude of the vector to be measured in gauss; and $2\pi/\gamma_p$ = 0.000 234 874 gauss/hertz = 23.4874 gammas/hertz.

From the frequency of the time base ($f_{\text{time base}}$), the number of precession periods for which the RF gate was open (N) and the number of time units (n) counted by the decade counter during N precession periods, we obtain

$$\mathrm{F} = \frac{f_{\text{time base}}\, \mathrm{N}\, 2\pi}{n\, \gamma_p} \text{ gauss.} \qquad (48)$$

Except for n, all quantities on the right-hand side of the equation are constants and can be combined into one constant, C. For example, in a device having a time-base frequency of 100 000 hertz and counting 1024 precession periods, the constant c is 24 051.1. For counting N, a decade counter may be used instead of the binary counter. As in any counting device, the count n will be uncertain by $\pm$ 1 unit. This defect can be overcome by repeating the observation several times and taking the mean of the counts. From equation (48) it can be seen that the resolution can be increased by increasing $f_{\text{time base}}$ and N. However, this cannot be carried far, because the signal-to-noise ratio of the precession signal will ultimately determine how far the resolution can be raised without increasing the scatter of n.

198 The method outlined above is a measurement of the period of the precession signal. The count n is inversely proportional to the total intensity F. A conversion table is therefore useful. Moreover, the resolution decreases, for a given time base frequency and given N, towards higher values of F. In order to overcome this difficulty, Serson (1962) designed a circuit that measures the multiplied precession frequency over a predetermined period of time and displays the result in gammas or one-tenth gammas. The circuit offers high noise rejection.

199 The most serious difficulty encountered in the application of the proton magnetometer at an observatory arises from the noise emanating from the AC power line. The noise shows peaks at the harmonics of 50 or 60 hz, of which some may be strong. Furthermore, random noise is radiated by the power line when collector motors, neon lights, or sometimes even television receivers are operated in the vicinity of the absolute house. It is always useful to make a noise survey in order to find the least noisy position for the sensor. The noise is strongest near the power line and the ground. Usually, reasonable conditions are found at a height of two metres above the ground. In the field, the vicinity of high-voltage power lines should be avoided. Other sources of noise may be near-by broadcasting stations, ionosondes and UHF relay stations. The noise may be observed by connecting an oscilloscope across the terminals of the precession signal amplifier (some observers have a CRT permanently connected to the amplifier), or by making observations at various places and comparing the scatter of the readings. In order to overcome these difficulties, noise-cancelling sensors, as provided by Barringer and Varian, may be used. The toroid falls into the same class of devices. However, sensors of this type are voluminous and are therefore not so suitable for use in a vector magnetometer. A closed metal shield must be very large in order to avoid damping of the proton spin. *For this reason it is not permissible to place the sensor on metal of appreciable area*, for instance, on a theodolite base or a tripod head. A block of wood, ten centimetres high, fitting the theodolite base or the tripod head should be used below the sensor. Occasionally, it may be found helpful to turn the sensor until it picks up least noise. Another solution to the problem is to observe at hours of low noise.

200 Another point which requires attention is the homogeneity of the magnetic field across the sensor, because in an inhomogeneous field the precession signal will decay rapidly. The gradient across the sensor should not exceed 0.1 gamma/cm. Normally the homogeneity in an absolute house will be sufficient.

201 At the time of writing at least five different types of proton magnetometer are commercially available, varying in precision, observational convenience and price over a wide range. So long as only the total intensity is being measured, all instruments are satisfactory. However, when it comes to vector applications, observational convenience must be sacrificed, because it is difficult to construct a highly sensitive narrow-band amplifier which covers a frequency range from 650 to 3500 hz (15 000 to 82 000 gammas). For this reason some magnetometers are designed for a limited range, e.g. 25 000 to 75 000 gammas, in order to permit simple range switching. Other makers of proton magnetometers take resort in exchanging amplifiers or filters. A geomagnetician with reasonable experience in assembling electronic equipment may construct a proton magnetometer himself, as has been done at several observatories. Most of the electronics can be assembled from logic elements offered commercially at low prices. If the geomagnetician is not good enough in electronics, he may approach the physics department of a university. The construction of a magnetometer including some innovations may be a suitable exercise for an M.Sc. student.

202 A proton magnetometer will give correct results when the time-base oscillator is adjusted to its nominal frequency, usually 100, 200 or 1000 khz. Moreover, when the crystal is kept in an oven it must have the correct operating temperature. In Europe, North Africa and the Near East, a 100 or 200 khz oscillator may be compared in the early morning or late evening, by means of a portable transistor radio, with the frequency of the Droitwich broadcasting station, which emits exactly on 200 khz. The strength of the oscillator signal may be adjusted by placing the receiver at a suitable distance from the magnetometer. Direct coupling is in most cases not necessary because the leakage of the magnetometer will be sufficient. After some trials, a suitable adjustment will be found so that the beat signal between the time-base oscillator and Droitwich can be heard. When both signals are in phase their amplitudes will be added and the automatic volume control of the receiver will decrease the amplification. As a consequence, little or no receiver noise will be heard. When the two signals are 180° out of phase, practically no signal will be present, and the automatic volume control will increase the amplification so that the receiver noise will be prominent. If the two signals differ in frequency by a small amount the noise of the receiver will periodically increase and decrease, and the beat frequency (which will usually not exceed a few tenths of a hertz) can be measured by means of a stop-watch. For instance, one beat per second means that the broadcasting station and the oscillator differ by one part in 200 000. This difference is small enough for all practical purposes. If the time-base oscillator has a trimmer, its frequency can be adjusted easily to one part in a million or better (one beat every five seconds). In other parts of the world, the comparison may be made with normal frequencies radiated by WWV or some other station. A communications receiver or a radio receiver with a sensitive short-wave section will be necessary for the comparison. On high frequencies, e.g. 15 mhz, the harmonic of the time-base oscillator may be too weak for a comparison. In this case, a tighter coupling may be obtained by connecting a wire to the time-base oscillator and wrapping the insulated end of the wire around the antenna binding post of the receiver. Sometimes, distortion of the oscillator signal by means of a diode may be necessary. If the crystal of the time-base oscillator has an odd frequency, as, for instance, in some timers with the Serson circuit, sophisticated equipment will be needed. This may be available either at a physics department of a university or at a national bureau of standards.

When the instrument allows the count N to vary, the consistency of the results obtained may be tested by measuring the total intensity at different counts. Reference to the variometers is not necessary when the comparison is made on a magnetically quiet day.

203 Further tests concern the sensor. Usually the sensor will have a small heading error, i.e. the result will change with the azimuth (or heading) of the axis of the sensor coil. The heading error may be caused by a leakage current passing through the sensor coil because of low insulating resistance of the polarizing relay. The leakage current will set up a field along the axis of the sensor coil which will be added vectorially to the field to be measured. The disturbing field will reverse with the reversal of the polarity of the polarizing source. A leakage current of one microampere will generate a disturbing field of ten gammas. A similar effect on the result can be expected from magnetically soft impurities which will also change polarity with the reversal of the polarizing source. A leakage current and magnetically soft ferromagnetic impurities will have no effect on the results of observations when the (horizontal) axis of the sensor is set up at right angles to the magnetic meridian or, if the polarity of the polarizing source can be reversed, one takes the mean of observations at both directions of the polarizing current. The influence of permanently magnetized parts, which may be contained in the plug connecting the sensor to the cable, will depend on the direction of their axis of magnetization. All three sources of disturbance may, if they are appreciable, cause the precession signal to decay rapidly.

A test commences with an investigation of the sensor assembly for permanently magnetized parts by means of a declinometer or QHM. The leakage current may be measured at the plug to which the sensor cable is connected, by means of a sensitive moving-coil galvanometer with the polarizing relay in the off position. It is advisable to make a measurement with an avometer before connecting the galvanometer, in order to make sure that the relay is off. The complete sensor assembly is tested by measuring the total intensity at various azimuths of the sensor axis, provided that the inclination is between 30° and 70°. If the inclination is near 90°, any leakage current or magnetically soft impurities will cause no heading error, because the horizontal sensor axis is always at right angles to the geomagnetic field vector. With an inclination of 30°, the precession signal may be weak when the axis of the sensor approaches the magnetic meridian. The table shows the results of a sensor test made with the proton magnetometer Elsec No. 592/128 at Fürstenfeldbruck, where the inclination is 64°. The resolution of the magnetometer was 0.9 gammas/count. At every sensor heading, six readings were taken in rapid succession. Every second observation was made with the sensor axis east-west, mark east. The observations made at other headings are referred to this heading. The results in detail were:

Sensor axis	Mark		Mean at mark east	Heading error
East-west	East	46 887.8		
North-south	North	888.5	46 888.0	+ 0.5
East-west	East	888.2		
North-south	South	888.0	888.3	− 0.3
East-west	East	888.4		
East-west	West	888.6	888.6	0
East-west	East	888.7		
(The sensor was rolled around its axis 180°.)				
East-west	East	888.6		
North-south	North	888.8	888.6	+ 0.2
East-west	East	888.6		
North-south	South	888.2	888.7	− 0.5
East-west	East	888.8		
East-west	West	888.4	888.6	− 0.2
East-west	East	888.4		

Since the heading error of this particular instrument does not exceed the resolution, no further investigations were made. For further tests see Schmidt (1964).

204 An observation of the total intensity is reduced to the base-lines of the H and Z variometers by means of

$$\Delta F = \Delta H \cos I + \Delta Z \sin I. \qquad (9)$$

For Fürstenfeldbruck with I = 64° we obtain

$$\Delta F^{(\gamma)} = 0.438\ \Delta H^{(\gamma)} + 0.899\ \Delta Z^{(\gamma)}.$$

The scale values of the variometers are

$$S_H = 2.74 \text{ gammas/mm} \quad \text{and} \quad S_Z = 2.66 \text{ gammas/mm}$$
$$\text{positive } n_H = \text{positive } \Delta H^{(\gamma)} \quad \text{and} \quad \text{positive } n_Z = \text{positive } \Delta Z^{(\gamma)}.$$

In routine work when many reductions have to be made, much labour can be saved by multiplying cos I and sin I by S_H and S_Z, respectively. Then

$$\Delta F = 1.20\, n_H + 2.39\, n_Z.$$

The following table contains some examples of reductions of F to the base-lines of H and Z.

Date	Time (GMT)	F_{obs}	n_H	n_Z	1.20 n_H	2.39 n_Z	$\Delta F^{(\gamma)}$	F_0
22 December 1965	07h23	46 911.0	+ 17.8	+ 11.0	+ 21.4	+ 26.3	+ 47.7	46 863.3
	34	909.6	16.4	11.2	19.7	26.8	46.5	863.1
	35	909.2	15.7	11.3	18.8	27.0	45.8	863.4

USE OF THE PROTON MAGNETOMETER WITH CLASSICAL INSTRUMENTS

205 It has been pointed out in paragraph **197** that with the proton magnetometer only the scalar magnitude of the geomagnetic field vector can be measured. For the determination of the components, further information is required. The most usual combination is a proton magnetometer with an earth inductor, in which case

$$H = F \cos I \qquad \text{and} \qquad Z = F \sin I. \tag{1}$$

The error can be estimated by means of the equations:

$$\Delta H^{(\gamma)} = \Delta F^{(\gamma)} \cos I - F^{(\gamma)} \sin I .\ \sin 1' \ \Delta I^{(')} \tag{4}$$

$$\Delta Z^{(\gamma)} = \sin I \Delta F^{(\gamma)} + F^{(\gamma)} \cos I .\ \sin 1' \ \Delta I^{(')}. \tag{8}$$

For the evaluation of errors under the various conditions, we assume that the standard deviation is

$$\Delta F = 0.5 \text{ gammas} \qquad \text{and} \qquad \Delta I = 0.1',$$

which is within the reach of a good observer. If double standard deviations are inserted in the above error equations (i.e. $\Delta F = 1.0$ gamma and $\Delta I = 0.2'$), then, according to the laws of error statistics, 94 per cent of all observations will fall within the specified limits of error. Moreover, we take the worst case, namely, that the two error components are additive. We obtain for the dip equator where $I = 0°$ and $F = 0.40$ gauss

$$\Delta H = \pm 1 \text{ gamma} \qquad \text{and} \qquad \Delta Z = \pm 2.4 \text{ gammas},$$

at $I = 45°$ and $F = 0.45$ gauss

$$\Delta H = \pm 2.5 \text{ gammas} \qquad \text{and} \qquad \Delta Z = \pm 2.5 \text{ gammas},$$

and, at the poles, where $I = 90°$ and $F = 0.70$ gauss

$$\Delta H = \pm 4.0 \text{ gammas} \qquad \text{and} \qquad \Delta Z = \pm 1 \text{ gamma}.$$

The above errors compare well with the errors obtained with classical equipment. Moreover, each observation is a true absolute measurement. Since observation and computation do not require much time, it is recommended that observations should be made every three or four days. Alternatively, take two full sets of observations on the day on which absolute observations are habitually made each week. The following example is taken from observations made at Fürstenfeldbruck; each line contains a full set of observations consisting of six F measurements and one full inclination measurement, reduced to the base-lines of the two intensity variometers as explained in paragraphs **183** and **204**:

Date	Time (GMT)	I_0	F_0	sin I_0	cos I_0	Z_0	H_0
19 July 1967	06h55-07h16	64°01′50″	46 860.0	0.899 028	0.437 892	42 128.4	20 519.6
	09h29-09h54	01′43″	860.0	9 013	7 922	127.7	521.0

The computation was carried out by means of a table-top computer, but logarithms may be used equally well.

This method is in use at several observatories. The errors are usually smaller than those given above. At Fürstenfeldbruck, for instance, with F = 46 900 gammas and I = 64°, the maximum errors in 1965 were 1.9 gammas in H and 1.0 gamma in Z. The standard deviations were 1.0 gamma and 0.5 gamma in H and Z respectively. Although the method is absolute, it is advisable to make a comparison with a standard of the smaller of the two components because its departure from absolute level is mainly determined by the index correction of the earth inductor. With reasonable care no drift of absolute level will occur, because all instrumental constants can be kept under control.

206 At some observatories the vertical intensity is derived from the total intensity and the horizontal intensity. This method is suitable for places with $I \geqslant 45°$ as can be seen from

$$\Delta Z = \Delta F \operatorname{cosec} I - \Delta H \cot I. \tag{8}$$

The fact that the factor ΔF is always > 1 is no disadvantage, because F can be measured with sufficient precision. The factor ΔH can in the worst case be 1. It will be seen later that the method can be used with great advantage in field surveys. After having reduced F and H to base-line, we obtain

$$Z_0 = \sqrt{F_0^2 - H_0^2}. \tag{49}$$

207 Likewise, in areas where $I \leqslant 45°$, F and Z may be observed, and H computed from

$$H_0 = \sqrt{F_0^2 - Z_0^2}. \tag{50}$$

Near the magnetic equator, even a substantial error in Z will have a negligibly small influence on H, as can be seen from

$$\Delta H = \Delta F \sec I - \Delta H \tan I. \tag{4}$$

At higher values of Z, the method is not however so advantageous as the computation of Z from H and F, because the only means of measuring Z directly is the BMZ, which at the present time cannot be easily compared with a standard. This situation may change in the near future because tests made with a standard BMZ at the Danish Meteorological Institute are very encouraging and indicate that comparisons in Z may soon become possible. Naturally, the method is also applicable to geomagnetic surveys.

208 Although the methods described in the previous paragraphs do not exploit the full capabilities of the proton magnetometer, they are more reliable than classical methods alone. It is worth while to introduce one or the other of these new methods as a first step towards the modernization of an observatory.

Vector magnetometers

209 Vector magnetometers serve to derive intensity components and directions of the geomagnetic field vector, by applying bias fields of known direction and defined magnitude. What is observed is the resultant of the geomagnetic field vector and the bias field vector. The resultant should not be smaller than 18 000 gammas (for simple magnetometers not below 25 000 gammas). The ideal vector magnetometer would have a bias coil mounted like the detector coil of an earth inductor, with the magnetometer sensor in its centre, a horizontal circle, a vertical circle and, over and above, a circle indicating the direction of the bias coil's magnetic axis with respect to the vertical plane passing through the instrument at right angles to the horizontal axis. Such an instrument could be called the Bacon-Alldredge theodolite and would allow measurement of all components of the geomagnetic field vector under ideal conditions. Since the technical requirements for such an instrument are onerous, special coil positions are chosen which offer the possibility of determining the basic quantities by means of a horizontal circle, precise levels and a stable power supply. The theodolite base must allow adjustment of its vertical axis with a high degree of precision.

NELSON'S METHOD

210 Well known and much used is Nelson's method (Hurwitz and Nelson, 1960) which however fails at high latitudes in H and at low latitudes in Z. The bias coils, when used with a small sensor, may be of the Helmholtz-Gaugain or square configuration, with maximum dimensions of 100 centimetres. The power supply feeding the bias coils should have a stability of one part in 1 000.

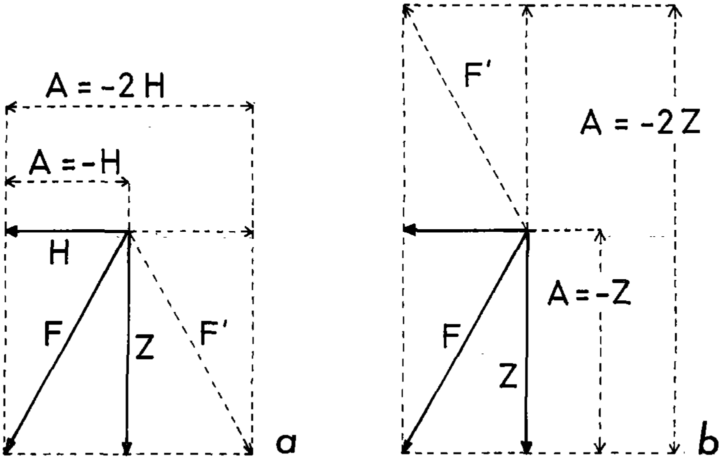

FIG. 19. Nelson's vector method. (*a*) Determination of the bias field and Z. (*b*) Determination of the bias field and H.

211 With Nelson's method, each intensity component is measured by compensating the other intensity component, thus turning the resultant of the geomagnetic field vector and the bias field vector into the direction of the component to be measured (Fig. 19). The required bias field A is determined by increasing it to $-2H$ ($-2Z$), i.e. to a value where the proton magnetometer indicates $F' = F$. Then the bias field is reduced to half this value, that is to $A = -H$ ($A = -Z$) by halving the current in the bias coil by means of a potentiometer or the digital voltmeter of the power supply. In the application of the method, nothing need be known about the magnitude of the bias field. However, in order to curtail the trial-and-error search for $A = -2H$ ($A = -2Z$), it is useful to know the approximate constant of the bias coil, so that the search for the bias field can be started somewhere near the correct value.

212 If no potentiometer or digital voltmeter is available one may determine the compensating field of the bias coil in a different manner, which is explained in Figure 20. Measure F. Compensate H (Z) approximately by computing the required bias field from the approximate coil constant derived from the dimensions of the bias coil, and the current measured with an avometer. Observe the approximate value of Z (H) by means of the proton magnetometer. Now reverse the current in the bias coil. The bias field will add to the component to be compensated. Adjust the coil current until you observe the resultant F_+ which, from simple geometrical considerations, is

$$F_{+Z} = \sqrt{4F^2 - 3Z^2}, \text{ for measuring Z} \quad \text{and} \quad F_{+H} = \sqrt{4F^2 - 3H^2}, \text{ for measuring H.} \qquad (51)$$

Compute tables of F_{+Z} and F_{+H} for values of F, H, and Z occurring at your observatory and convert them to magnetometer counts. The complete theory

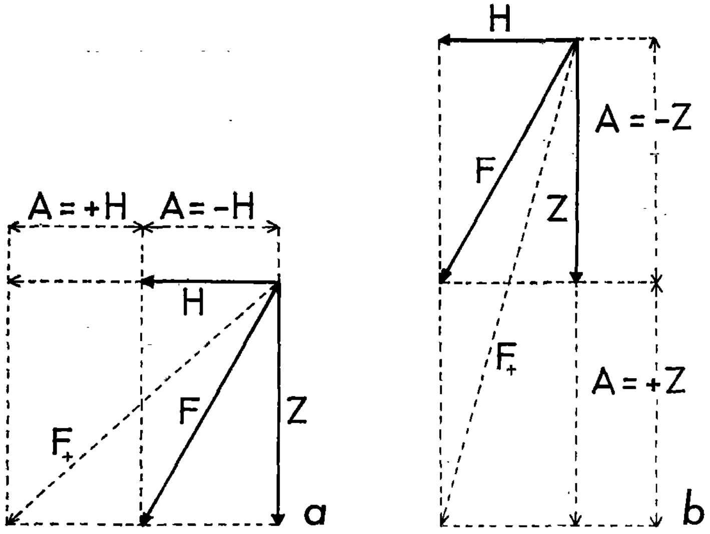

FIG. 20. Simplified method of bias-field determination for Nelson's vector method.

of the Nelson vector magnetometer has been treated by Hurwitz and Nelson (1960). We assume that all spurious errors, which can be kept easily under control, do not exceed 0.1 gamma and restrict our considerations to errors of practical importance.

Measurement of Z

213 The theodolite base, on which the bias coil rests with its magnetic axis horizontal, is levelled by means of a sensitive level (scale value 2 to 10 seconds of arc per vial division) so that the vertical axis is vertical to within 2 seconds. The error caused by a maladjustment (i) of the vertical axis in the plane of the magnetic meridian is

$$\Delta Z^{(\gamma)} = H^{(\gamma)} \sin 1' \, i^{(')} \tag{52}$$

At a point of observation where H = 20 000 gammas, the error caused by a maladjustment of 1′ would be ΔZ = 20 000 . 0.000 291 = 5.8 gammas, and for 2″ about 0.2 gamma. Note that this error will not be eliminated by the reversal of the alidade. Precise levelling of the theodolite base is therefore a necessity. The error caused by the inclination of the (horizontal) axis of the bias coil can be eliminated by observing in two azimuths, 180° apart, and taking the mean of the two observed Z-values.

214 In order to adjust the bias coil to the magnetic meridian, turn the coil so that its axis is approximately in the magnetic prime vertical. Apply the bias field in one direction and observe the resultant F_+. Reverse the bias field and observe the resultant F_-. Adjust the alidade in azimuth until $F_+ = F_-$. Then the coil axis will be in the magnetic prime vertical. Turn the alidade + 90° or − 90° so that the coil axis comes into the direction of the magnetic meridian, with the mark on the bias coil pointing north. Determine the bias field for compensating H by one of the methods described in paragraphs **211** and **212**.

Measure Z_N (mark on the bias coil pointing north). Turn the alidade 180° in azimuth. Measure Z_S (mark on the bias coil pointing south). Compute Z from

$$Z_0 = \frac{(Z_N - \Delta Z^{(\gamma)}) + (Z_S - \Delta Z^{(\gamma)})}{2} \tag{53}$$

where $\Delta Z^{(\gamma)}$ is the ordinate measured in the magnetogram and converted to gammas. When the difference between Z_N and Z_S is appreciable, adjust the inclination of the axis of the bias coil until the two values are approximately equal.

215 It may be of interest to know the error caused in Z by a maladjustment of the coil axis in azimuth, ε, or by a maladjustment of the bias field, H′ − H. Figure 21 illustrates the situation. H and Z are the true components while Z′ is the value measured due to a faulty compensating field H′. The vectorial difference between H and H′ is approximately

$$r^{(\gamma)} = \sqrt{\varepsilon^{(\gamma)2} + (H' - H)^2} \tag{54}$$

and moreover,

$$r^{(\gamma)} = \sqrt{2Z\,(Z' - Z)}. \tag{55}$$

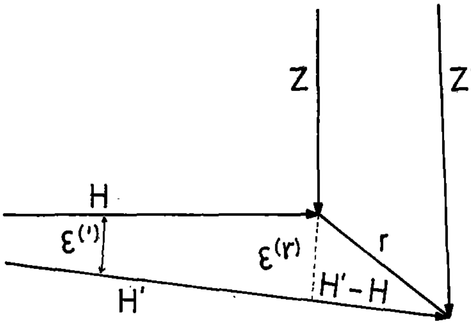

FIG. 21. Influence of a maladjustment of the bias field on the determination of Nelson's Z.

Example : Z = 42 000 gammas. The error tolerated in the determination of Z may be 0.1 gamma. Then from (55)

$$r = \sqrt{84\,000\,.\,0.1} = \sqrt{8400} = 92 \text{ gammas.}$$

For practical work one will allot half of the permissible error to ε and the other half to (H′ − H) which in this case gives

$$\varepsilon^{(\gamma)} = H' - H = \sqrt{4200} = 65 \text{ gammas.}$$

Then, for H = 20 000 gammas, the permissible departure of the coil axis from the magnetic meridian is, from equation (2)

$$\varepsilon^{(\prime)} = \frac{65}{20\,000\,.\,0.000\,291} = \pm\, 11'.$$

Thus, at a point of observation with Z = 42 000 gammas and H = 20 000 gammas, the bias field may depart from the magnetic meridian 11′, and from H 65 gammas, before an error of 0.1 gamma is incurred in Z. The axis of the bias coil may therefore be adjusted to the mean magnetic meridian of the point of observation once and for all. The permissible swing of the magnetic meridian to either side of the coil axis will be exceeded only during periods of magnetic storms. One may arrange stops on the theodolite base so that the bias coil can be set to the two azimuths (coil mark north and coil mark south) rapidly without reading the horizontal circle of the theodolite base. Naturally, one will have to check the azimuth setting from time to time and allow for the secular change in declination.

216 With suitable equipment, the observation of Z will take about ten minutes. The computation of the base-line value is simple, as can be seen from the following example.

1967, December 29, Friday
Fürstenfeldbruck Observatory, Pier 2 — S_Z = 2.66 gammas/mm
Vector magnetometer — positive n_Z = positive $\Delta Z^{(\gamma)}$

Time (GMT)		Z_{obs}	n_Z	$\Delta Z^{(\gamma)}$	Z_0	Mean
Z_N	12h52	42 160.7	+ 11.9	+ 31.7	42 129.0	42 128.5
Z_S	54	159.9	12.0	31.9	128.0	

Measurement of H

217 For the measurement of H, the axis of the bias coil must be vertical. As in the measurement of Z, the vertical axis of the theodolite base carrying the bias coil must be adjusted to vertical within 2″. The error caused in H by a maladjustment, *i*, of the vertical axis of the theodolite base is

$$\Delta H^{(\gamma)} = Z^{(\gamma)} \sin 1' \, i^{(')}. \tag{56}$$

At a place where Z = 42 000 gammas the error in H caused by a maladjustment of 1′ will be H = 42 000 . 0.000 291 = 12.2 gammas, and for 2″ about 0.4 gammas. This error will not be eliminated by observing at different azimuth settings of the alidade. The error caused by the inclination of the (vertical) axis of the bias coil may be eliminated by observing the horizontal intensity at four different azimuth settings, 90° apart. The observational procedure is as follows:

After careful levelling of the theodolite base, adjust the bias field by one of the methods described in paragraphs **211** and **212**. Measure H_N (mark on coil pointing north). Turn the alidade exactly 180° in azimuth. Measure H_S (mark on coil pointing south). Turn the alidade 90° in azimuth. Measure H_E (mark on coil pointing east). Turn the alidade 180° in azimuth. Measure H_W (mark on coil pointing west). Compute the horizontal intensity (base-line value) from

$$H_0 = \frac{1}{4}\left\{(H_N - \Delta H^{(\gamma)}) + (H_S - \Delta H^{(\gamma)}) + (H_E - \Delta H^{(\gamma)}) + (H_W - \Delta H^{(\gamma)})\right\} \tag{57}$$

where: $\Delta H^{(\gamma)}$ = ordinate in gammas measured on the magnetogram.

The bias coil for the compensation of Z rests, on the theodolite base, on three adjusting screws which are used for setting the axis of the coil to vertical (parallel to the vertical axis of the theodolite base). One of the adjusting screws points in the direction of the mark on the coil. This screw is used for adjusting the axis of the bias coil so that H_N and H_S become nearly equal. The other two adjusting screws are used for making H_E and H_W almost equal.

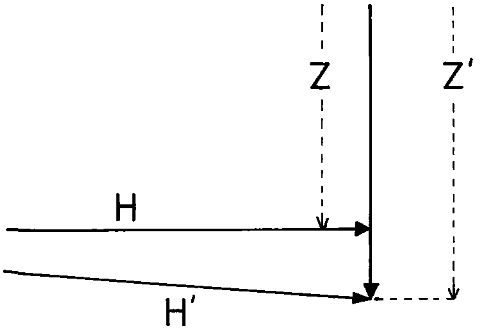

FIG. 22. Influence of a maladjustment of the bias field on the determination of Nelson's H.

218 The effect of a small departure of the axis of the bias coil from the vertical is eliminated by the observational procedure. A maladjustment of the bias field in magnitude, Z′ − Z, causes the measured value H′ (Fig. 22) to be larger than the true H, the relations between the quantities being

$$(Z' - Z) = \sqrt{2H\,(H' - H)}. \tag{58}$$

With H = 20 000 gammas and a permissible H′ − H = 0.1 gamma, we obtain

$$Z' - Z = \sqrt{40\,000\,.\,0.1} = \sqrt{4000} = 63 \text{ gammas.}$$

SERSON'S METHOD

219 When one of the intensity components is so small (below 18 000 gammas) that it cannot be measured because of practical difficulties, mainly the high noise level, Serson's method may be used instead of Nelson's method. Serson's method requires a precise power supply which is constant to one part in 100 000 or better. A bias coil with a horizontal axis is needed for measuring H and a coil with a vertical axis for measuring Z. For this reason Serson's method is admirably suited for supplementing Nelson's method. Only one bias coil is required for measuring both intensity components, namely, a coil with a horizontal axis for (large) Nelson's Z and (small) Serson's H (I > 45°), and a coil with a vertical axis for measuring (large) Nelson's H and (small) Serson's Z (I < 45°). While Nelson's method is difficult to apply to the measurement of small components,

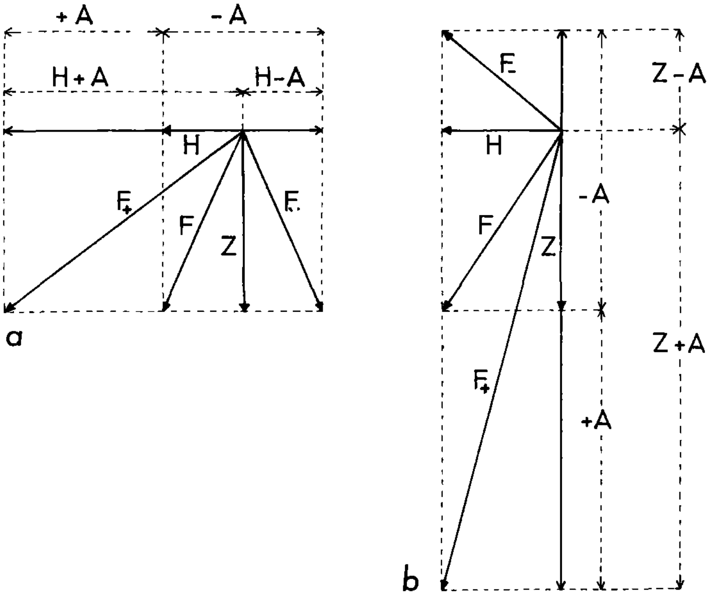

Fig. 23. Serson's vector method : (*a*) Determination of H. (*b*) Determination of Z.

with Serson's method difficulties will be encountered in measuring large components. In both cases the inhomogeneity of the bias fields limits the duration of the precession signal and hence, the accuracy of the measurement of the resultants.

220 From Figure 23 it follows that

$$H = Z = \frac{F_+^2 - F_-^2}{4A} \quad \text{and the bias field} \quad A = \sqrt{\frac{F_+^2 + F_-^2}{2} - F^2}$$

or

$$H = Z = \frac{F_+^2 - F_-^2}{4\sqrt{\dfrac{F_+^2 + F_-^2}{2} - F^2}} \tag{59}$$

From differentiation of equation (59) it follows that

$$\left.\begin{aligned} \Delta H &= \frac{F_+}{2A}\left(1 - \frac{H}{A}\right)\Delta F_+ - \frac{F_-}{2A}\left(1 + \frac{H}{A}\right)\Delta F_- + \frac{F}{A}\,\frac{H}{A}\,\Delta F \\ \Delta Z &= \frac{F_+}{2A}\left(1 - \frac{Z}{A}\right)\Delta F_+ - \frac{F_-}{2A}\left(1 + \frac{Z}{A}\right)\Delta F_- + \frac{F}{A}\,\frac{Z}{A}\,\Delta F \end{aligned}\right\} \tag{60}$$

Equations (60) allow estimation of the errors ΔH and ΔZ for given values of F, H and A, and F, Z and A, respectively. It can be seen that, when $A = H$ or $A = Z$, the method becomes the same as Nelson's method for the other component. The coefficient of F_+ becomes zero, and F_- is Z or H, respectively. The first equation of (60) changes to

$$\Delta H = -\Delta F \sec I - \Delta Z \tan I. \tag{4}$$

i.e. the error is the same as if H were computed from F and Z. The second equation (60) changes to

$$\Delta Z = -\Delta F \operatorname{cosec} I - \Delta H \cot I. \tag{8}$$

that is, the error is the same as if Z were computed from F and H. Hence the cases $A = H$ and $A = Z$ have no merit except for finding the bias fields for Nelson's cases as described in paragraph **212**. If reasonably small coefficients of F_+, F_- and F are expected, the bias fields should be at least $\frac{3}{2}H$ and $\frac{3}{2}Z$, and not below $\frac{1}{2}F$.

Example: It is intended to measure H with Serson's method at Fürstenfeldbruck. A is made equal to $\frac{3}{2}H - 30\,800$ gammas. Then the other values are: $F_+ - 66\,300$ gammas, $F_- - 43\,300$ gammas. F and H are about 46 900 and 20 500 gammas respectively. The following coefficients are obtained by inserting the values (in gammas) in the first of equations (60):

$$\Delta H = 0.36\,\Delta F_+ - 1.2\,\Delta F_- + 1.0\,\Delta F.$$

Since the errors committed in measuring F_+, F_- and F are below ± 0.5 gamma, the chosen bias field seems large enough. Subsequent series of observations confirmed that the error in H was less than ± 1.0 gamma.

221 Equations (60) are not only useful for the estimation of errors but also for the routine computation of H and Z, because (59) is rather unwieldy. Since the observation of Serson's H and Z takes some time, it is necessary to reduce F_+, F_- and F to the base-lines of the intensity variometers, as will be shown in paragraphs **224** and **229**. When inserting the reduced values F_{+0}, F_{-0} and F_0 in equation (59), H_0 or Z_0 is found. Further observations are computed by means of equation (60) in the following manner. The values just found are designated F'_{+0}, F'_{-0}, F'_0, and H'_0 or Z'_0. By means of F'_{+0}, F'_{-0}, F'_0 and the values F_{+0}, F_{-0}, F_0 of a new observation, we find $\Delta F'_+ = F_{+0} - F'_{+0}$, $\Delta F'_- = F_{-0} - F'_{-0}$, and $\Delta F' = F_0 - F'_0$, and insert these values in equation (60). The result will be $\Delta H'$ or $\Delta Z'$, from which we find the base-line values

$$H_0 = H'_0 + \Delta H' \quad \text{and} \quad Z_0 = Z'_0 + \Delta Z'.$$

When applying this method of computation, it is desirable to keep A near the same level so that $\Delta F'_+$ and $\Delta F'_-$ remain small. This is done by adjusting F_+ always to more or less the same value before beginning observations. The application of the method will be shown in paragraph **230**.

Measurement of Z

222 Level the theodolite carefully. Adjust the bias field by regulating the current of the power supply until the magnetometer reading for F_+ is near the average value found from previous observations, with the mark on the bias coil pointing north. Measure F. Measure F_{+N}. Reverse the bias field. Measure F_{-N}. Turn the alidade 180° in azimuth (mark on bias coil pointing south). Measure F_{+S}. Reverse the bias field and measure F_{-S}. Measure F. Turn the alidade 90° (mark on bias coil pointing east). Measure F_{+E}. Reverse the bias field and measure F_{-E}. Turn the alidade 180° (mark on bias coil pointing west). Measure F_{+W}. Reverse the bias field and measure F_{-W}. Measure F.

Since Serson's Z is measured together with Nelson's H, the axis of the bias coil is adjusted as explained in paragraph **217**. Any remaining error in coil adjustment is eliminated by observing the four different azimuths.

223 As in Nelson's Z, the error ΔZ caused by an inclination of the vertical axis of the theodolite base, *i*, is

$$\Delta Z^{(\gamma)} = H^{(\gamma)} \sin 1' \, i^{(')}. \tag{52}$$

The error is not eliminated by the observational procedure.

224 The influence of the variation in H and Z on F_+, F_- and F is given by the following expressions (De Vuyst and Hus, 1966):

$$\Delta F_+^{(\gamma)} = \frac{H}{F_+} \Delta H^{(\gamma)} + \frac{Z + A}{F_+} \Delta Z^{(\gamma)}. \tag{61}$$

$$\Delta F_-^{(\gamma)} = \frac{H}{F_-}\,\Delta H^{(\gamma)} + \frac{Z - A}{F_-}\,\Delta Z^{(\gamma)};\ \text{note that } Z - A \text{ is negative for } A > Z.$$

$$\Delta F^{(\gamma)} = \Delta H^{(\gamma)}\cos I + \Delta Z^{(\gamma)}\sin I.$$

where $\Delta H^{(\gamma)}$ and $\Delta Z^{(\gamma)}$ are the ordinates measured in the magnetogram, at the times of observation, converted to gammas.

Measurement of H

225 Level the theodolite base carefully. Determine the azimuth setting of the axis of the bias coil as explained in paragraph **214**. According to paragraph **215** it will suffice to set the coil axis to the mean magnetic meridian. Turn the alidade in azimuth so that the mark on the bias coil is pointing north. Adjust the bias field by regulating the current of the power supply until the magnetometer reading for F_+ is near the average value found from previous observations. Measure F. Measure F_{+N}. Reverse the bias field and measure F_{-N}. Turn the alidade 180° in azimuth (mark on bias coil pointing south). Measure F_{+S}. Reverse the bias field and observe F_{-S}. Measure F.

226 As for Nelson's H, the error ΔH caused by an inclination *i* of the vertical axis of the theodolite base is

$$\Delta H^{(\gamma)} = Z^{(\gamma)} \sin 1'\, i^{(')}. \tag{56}$$

The error is not eliminated by the observational procedure. The inclination of the axis of the bias coil is eliminated by observing in two azimuths, 180° apart.

227 When the axis of the bias coil departs from the magnetic meridian by the small angle ε, only the component of H along the axis of the bias coil will be measured. The error will be

$$\Delta H^{(\gamma)} = -\frac{H^{(\gamma)} \sin^2 1'\, \varepsilon^{(')2}}{2}$$

or

$$\Delta H^{(\gamma)} = -\,0.004\,23\, H^{(\Gamma)}\, \varepsilon^{(')2}. \tag{62}$$

At $H = 20\,000$ gammas and $\varepsilon = 10'$, the observed horizontal intensity will be 0.1 gamma too small.

228 This method of measuring the horizontal component of the geomagnetic field along the axis of the bias coil may be utilized for measuring the geomagnetic north component X and the geomagnetic east component Y, by adjusting the axis of the bias coil to the true meridian and the prime vertical, respectively (Serson, Canada Patent No. 654 552).

Computation of Serson's H

1968, February 14, Wednesday
Fürstenfeldbruck Observatory, Pier 2
Vector magnetometer

$S_H = 2.74$ gammas/mm
positive n_H = positive $\Delta H^{(\gamma)}$

$S_Z = 2.66$ gammas/mm
positive n_Z = positive $\Delta Z^{(\gamma)}$

Time (GMT)	Observed values	n_H	n_Z	1.20 × n_H	2.39 × n_Z	$\Delta F^{(\gamma)}$	2.09 × n_H	1.71 × n_Z	$\Delta F_+^{(\gamma)}$	− 0.569 × n_H	2.60 × n_Z	$\Delta F_-^{(\gamma)}$	Values reduced to base-lines
F 07h22	46 919.4	+ 22.0	+ 14.3	+ 26.4	+ 34.2	+ 60.6							46 858.8 F_0
F_{-N} 27	43 095.1	21.9	14.3							− 12.5	+ 37.2	+ 24.7	43 070.4 F_{-0N}
F_{+N} 28	65 459.9	21.9	14.3				+ 45.8	+ 24.5	+ 70.3				65 389.6 F_{+0N}
F_{-N} 30	43 094.1	21.9	14.3							12.5	37.2	24.7	43 069.4 F_{-0N}
F_{-S} 33	43 095.9	22.0	14.2							12.5	36.9	24.4	43 071.5 F_{-0S}
F_{+S} 34	65 450.1	21.9	14.2				45.8	24.3	70.1				65 380.0 F_{+0S}
F_{-S} 36	43 095.4	21.9	14.2							12.5	36.9	24.4	43 071.0 F_{-0S}
F 38	46 919.4	21.9	14.2	26.3	33.9	60.2							46 859.2 F_0

		Coil mark north				*Coil mark south*	
F_{+0N}	65 389.6	F^2_{+0N}	0.427 5800	F_{+0S}	65 380.0	F^2_{+0S}	0.427 4544
F_{-0N}	43 069.9	F^2_{-0N}	185 5016	F_{-0S}	43 071.2	F^2_{-0S}	185 5128
Numerator:		$F^2_{+0N} - F^2_{-0N}$	242 0784			$F^2_{+0S} - F^2_{-0S}$	241 9416
		$F^2_{+0N} + F_{-0N}$	613 0816			$F^2_{+0S} + F^2_{-0S}$	612 9672
		$1/2(F^2_{+0N} + F_{-0N})$	306 5408			$1/2(F^2_{+0S} + F^2_{-0S})$	306 4836
F_0	46 859.0	F^2_0	219 5766	F_0	46 859.0	F^2_0	219 5766
		$1/2(F^2_{+0N} + F^2_{-0N}) - F^2_0$	086 9642			$1/2(F^2_{+0S} + F^2_{-0S}) - F^2$	086 9070
		A_N	294 897			A_S	294 800
Denominator		$4A_N$	1.179 588			$4A_S$	1.179 200
		H_{0N}	20 522.2			H_{0S}	20 517.4
		MEAN			20 519.8 gammas		

229 The observed quantities F_+, F_- and F are reduced to the base lines of the H and Z variometers by means of the expressions

$$\Delta F_+^{(Y)} = \frac{H + A}{F_+} \Delta H^{(Y)} + \frac{Z}{F_+} \Delta Z^{(Y)}$$
$$\Delta F_-^{(Y)} = \frac{H - A}{F_-} \Delta H^{(Y)} + \frac{Z}{F_-} \Delta Z^{(Y)} \qquad (63)$$

$$\Delta F^{(Y)} = \Delta H^{(Y)} \cos I + \Delta Z^{(Y)} \sin I \qquad (9)$$

where $\Delta H^{(Y)}$ and $\Delta H^{(Y)}$ are the ordinates measured in the magnetogram at the times of observations.

The accompanying example illustrates the computation of Serson's H. It will be noticed that F_- was observed twice in each coil position because that quantity has the greatest influence on the result. Furthermore, in this way any slight drift of the bias supply is allowed for. All observed values are reduced to the base-lines of the intensity variometers by means of equations (9) and (63). The following values have been used for the computation of the coefficients:

F = 46 900 gammas
F_+ = 65 400 gammas
F_- = 43 100 gammas
A = 29 400 gammas
Z = 42 130 gammas
H = 20 550 gammas
I = 64°

The reduction to base-line of F has been explained in paragraph **204**. The coefficients of equations (63) are computed in a similar manner, i.e. they contain the scale values S_H = 2.74 gammas/mm and S_Z = 2.66 gammas/mm. Thus, for example, the coefficient of ΔH for reducing F_+ to base-line is $\frac{H + A}{F} S_H = \frac{49\,950 \,.\, 2.74}{65\,400} = 2.09$. Note that H − A is negative. The reduced values F_+, and the means of F, F_{+N} and F_{-N}, are inserted in equation (59). H_N and H_S have to be computed separately. It is not permissible to take the means of all F_+ and F_- values and to compute H only once: owing to the non-linear relation among the quantities, even small differences of the values between the two coil positions cause considerable errors in the result. The computations were carried out by means of tables of squares and a desk-top computer.

230 In contrast to equation (59), equation (60) is easy to solve, as indicated in paragraph **221**. For the computation the following round values, which are near the base-line values, were chosen: F'_{+0} = 65 380.0 gammas, F'_{-0} = 43 070.0 gammas, F'_0 = 46 860.0 gammas. By inserting these values in equation (59) we obtain H'_0 = 20 520.0 gammas and A'_0 = 29 478 gammas. The coefficients of equation (60) are computed on the basis of these values. The result is

$$\Delta H' = 0.337\ \Delta F'_+ - 1.239\ \Delta F'_- + 1.107\ \Delta F'.$$

From the preceding example of computation, we take the following values (reduced to base-line):

Coil mark north	*Coil mark south*
$F_{+0N} = 65\,389.6$ gammas	$F_{+0S} = 65\,380.0$ gammas
$F_{-0N} = 43\,069.9$	$F_{-0S} = 43\,071.2$
$F_0 \;= 46\,859.0$	$F_0 \;= 46\,859.0$

Furthermore we compute

$\Delta F'_{+N}$	$+ 9.6\gamma$	$+ 0.337\ \Delta F'_{+N}$	$+ 3.2\gamma$	$\Delta F'_{+S}$	0γ	$+ 0.337\ \Delta F'_{+S}$	0γ
$\Delta F'_{-N}$	$- 0.1$	$- 1.239\ \Delta F'_{-N}$	$+ 0.1$	$\Delta F'_{-S}$	$+ 1.2$	$- 1.239\ \Delta F'_{-S}$	$- 1.5$
$\Delta F'$	$- 1.0$	$+ 1.107\ \Delta F'$	$- 1.1$	$\Delta F'$	$- 1.0$	$+ 1.107\ \Delta F'$	$- 1.1$
$\Delta H'$		$\Delta H'$	$+ 2.2$			$\Delta H'$	$- 2.6$
H_0		H_0	20 522.2			H_0	20 517.4
MEAN				MEAN	20 519.8 γ		

which is in agreement with the result obtained by means of equation (59). This method has been used at Fürstenfeldbruck with good success. When for one reason or another the base-line values change and the differences become large, new values F'_{+0}, F'_{-0} and F'_0 are chosen and H'_0 and A'_0 are computed. The coefficients of equation (60) have to be recomputed if the changes are appreciable. Since equation (60) is linear, it is permissible to take the means of the values obtained at coil mark north and coil mark south and to do the computation only once.

INSTRUMENTAL REQUIREMENTS

231 It has been pointed out before that for a vector magnetometer a stable non-magnetic theodolite base with a highly precise vertical axis is a necessity. The load on the theodolite base may be reduced by mounting the support for the magnetometer sensor in the ceiling of the room (Fig. 24), thus avoiding the disturbing drag of the sensor cable. Bases of station theodolites and station earth inductors are suitable for this purpose. Occasionally, bases of magnetic travel theodolites have been used with success. It is also important that the base have a level of precision not less than 2″ to 10″ per vial division.

232 The homogeneity of the bias field is of great importance for the successful application of vector methods. It has been mentioned in paragraph **200** that the gradient of the magnetic field across the sensor should not exceed 0.1 gamma per centimetre, because in an unhomogeneous field the proton precession signal decays rapidly. The signal useful for measurement will be of short duration and the resolution will be low, because the measurement has to be carried out with a small number of precession cycles. In addition to highly homogeneous bias coil systems it is advantageous to use a small magnetometer sensor. To some extent, the required homogeneity of the bias field will depend on the noise level at the magnetometer position and the noise rejection of the magnetometer. A sophisticated type of proton magnetometer will require a lower degree of homogeneity of the bias field than a simple instrument.

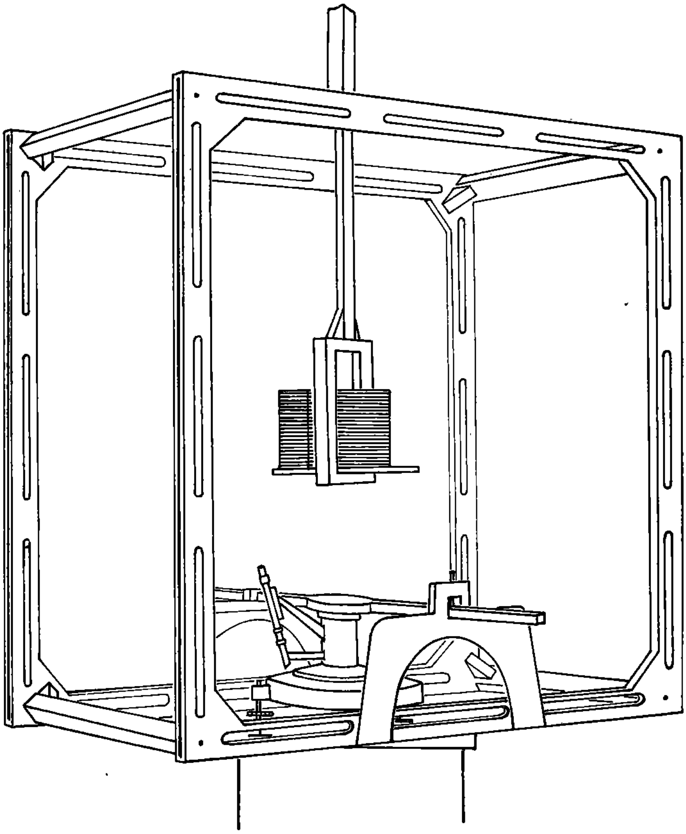

FIG. 24. Vector magnetometer of Fürstenfeldbruck observatory for measuring Nelson's Z and Serson's H.

233 For bias fields up to 40 000 gammas, simple coils of sufficient size will give an adequately homogeneous magnetic field. A well-known coil system is the Helmholtz-Gaugain coil, which is made of two similar coils arranged on a common axis, the spacing being equal to the radius of either coil. The windings of the coils are connected in series. The magnetic field along the axis of a Helmholtz-Gaugain coil is

$$\mathrm{A} = \frac{89.92\,\mathrm{N}}{r}\, i \text{ (gammas)} \tag{64}$$

where A = magnetic field along the axis of the coil in gammas; r = radius = spacing of coils in centimetres; N = number of turns in each coil; i = coil current in milliamperes.

Coils of a diameter of 80 to 100 centimetres have been used successfully with vector magnetometers up to fields of 43 000 gammas. In order to obtain the necessary bias field at a low current and voltage, 30 to 50 turns of enamelled copper wire of a diameter of 0.4 to 0.7 millimetres will be required.

234 Helmholtz-Gaugain coils of the desired size are difficult to make. The square coil described by Fanselau (1956) offers a mechanically simple solution. This type of coil produces a magnetic field that is less homogeneous than that of a Helmholtz-Gaugain coil of comparable dimensions (Fig. 24). The two coils are wound on square frames which are mounted on a common axis with a spacing of $d = 0.5445 \times$ side length. Such a coil can be made by a joiner from slats of wood, with an accuracy of ± 0.5 millimetres. When varnished and painted, the coil will not be susceptible to humidity and will therefore be fairly stable. A more rigid coil may be made from T-shaped aluminium rods. The magnetic field along the axis of a square coil is

$$A = \frac{88.68\ N}{d}\ i \text{ (gammas)} \tag{65}$$

where: A = magnetic field along the axis of the coil in gammas; d = spacing of the coils in centimetres = 0.5445 × side length of coil; N = number of turns in each coil; i = current in milliamperes.

235 When a coil with a highly homogeneous magnetic field is needed, or small coil dimensions are required, more complicated coil systems have to be used. A coil which is still comparatively simple to make is the square Fanselau coil (Fanselau, 1958). It has several times the homogeneity of a simple square coil of equal cross-section but is much longer. Serson (Canada Patent No. 654 552) describes a coil which occupies a space of 30 × 30 × 30 centimetres and has the homogeneity of a Helmholtz-Gaugain coil of 150 centimetres diameter. The circular Fanselau coil (Fanselau, 1929) and the Braunbeck coil (Braunbeck, 1934) require a high degree of precision in construction, in order to obtain the theoretically predicted homogeneity of the magnetic field. Recently Everett has designed a spherical coil which produces a highly homogeneous magnetic field of small dimensions (Thesis, Department of Geodesy and Geophysics, University of Cambridge).

236 Several vector magnetometers have been described recently. Nelson's vector magnetometer (Hurwitz and Nelson, 1960) carries two Helmholtz-Gaugain coils, one of 83 centimetres diameter with its magnetic axis horizontal, the other of 97 centimetres diameter with its magnetic axis vertical. Serson's vector magnetometer is equipped with the afore-mentioned coil system, which is mounted like the telescope of a theodolite (Fig. 25). A telescope with its optical axis parallel to the magnetic axis of the coil allows sightings on azimuth marks and may thus be used in conjunction with a horizontal circle for absolute measurements of D, X and Y in addition to H and Z. The coil's magnetic axis can be adjusted to horizontal and vertical by means of sensitive levels. Figure 24 shows the vector magnetometer of the Fürstenfeldbruck magnetic observatory. The square-coil system is mounted on the deflection bar of a Bamberg station theodolite and allows observation of Nelson's Z and Serson's H. So far, only one type of instrument is commercially available, namely, the vector magnetometer of Askania.

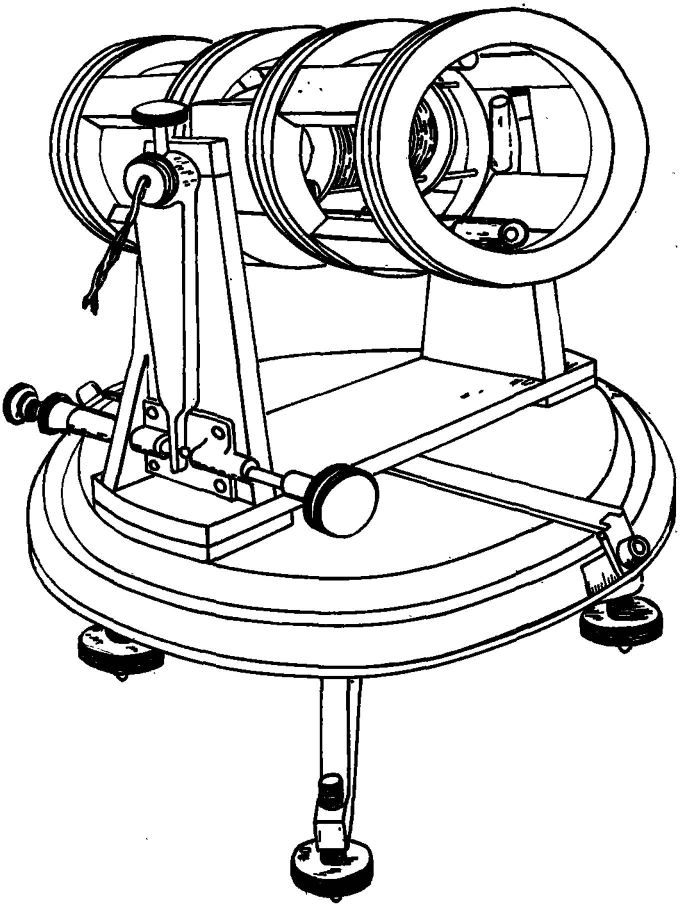

FIG. 25. Serson's vector magnetometer (after Canada Patent No. 654552). The coil is adjusted for the measurement of Nelson's Z and Serson's H.

The two Helmholtz-Gaugain coils, one with a horizontal and the other with a vertical axis, have diameters of 80 and 90 centimetres, respectively. The instrument may be used for the measurement of Nelson's and Serson's H and Z.

237 For first experiments with a vector magnetometer, storage batteries may be used. The required number of cells will depend on the largest field to be produced and the resistance of the bias coil, which in the coil systems described above will range from 20 to 30 ohms. Moreover, one will have to allow a few volts for the voltage regulation and the standard resistor when a potentiometer is being used for measuring the coil current. In most cases, a 12-volt motor-car starter battery will be sufficient. For Nelson's method a simple student's potentiometer is adequate. For Serson's method a precise potentiometer with short-term stability of one part in 100 000 is required, in order to achieve an accuracy of one gamma in the measurement of the intensity components. The absolute accuracy of the potentiometer is not of importance. In this case, attention has to be paid to good insulation of all parts carrying the bias current. When using batteries, switches and reversal switches should have negligibly small contact resistance, in order to reduce adjustment work. Before starting a measurement, the battery should be put under load for 30 minutes, in order to stabilize its voltage. Likewise, the battery should be kept under load during the off intervals of the measuring cycle.

238 Batteries are not only difficult to maintain but also require continuous checking and regulation of the current while observations are in progress. Recently, low-priced current-regulated power supplies (for instance, Hewlett-Packard) have appeared on the market, which can compete with batteries and potentiometers in price and performance. In this case, simple toggle switches of sufficient insulating resistance can be used in the bias circuit because the power supply will automatically allow for any variation in load resistance. Usually, the output current of a power supply will show little noise but occasionally an objectionably strong harmonic of the 50 or 60 cycles power line may appear near the frequency of the proton precession signal.

239 For correct results the sensor of the proton magnetometer has to be placed exactly in the centre of the bias coil. When in addition the sensor is free from magnetic impurities (paragraph **203**) and the time base of the proton magnetometer is correct, one may expect that the results are near IMS level of accuracy. However, before accepting a vector magnetometer as standard, it may be useful to make a comparison by means of a set of standard QHMs (paragraph **257**).

240 The difficulties caused by noise emanating from the 50 or 60 cycles power line, and the methods of avoiding them, have been discussed in paragraph **199**. When using vector magnetometers, further measures for reducing noise may be necessary, especially when large bias fields have to be applied and small resultants have to be measured. The signal-to-noise ratio of the proton precession signal may be appreciably improved by keeping the cable connecting the sensor to the electronics of the proton magnetometer as far as possible from all power lines, and suspending it several metres above the ground.

Determination of the true meridian

241 For the determination of the magnetic declination, the true meridian, also called geographic meridian, has to be known (paragraph **103**). The true meridian may be determined from observations of bearings on terrestrial objects whose coordinates are known. When using this method, the magnetic survey has to be planned in co-operation with the geodetic survey department, which will furnish the co-ordinates and the methods of computation. In this chapter, the determination of the true meridian from observations of the sun will be dealt with. The method yields good results throughout the day if the sun is not too high. An error in time and other errors will have the least influence on the result when the sun is near the horizon.

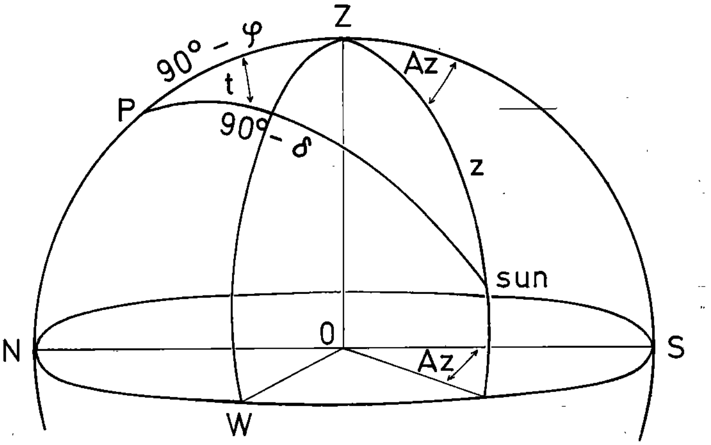

FIG. 26. Spherical triangle showing relations for the computation of the azimuth.

242 The true meridian of a place of observation is most conveniently derived from a measurement of the sun's bearing at the time of observation. The sun's azimuth is computed from the spherical triangle defined by the celestial pole P, the zenith Z, and the sun (see Fig. 26). From the spherical triangle we find the following relations:

$$\sin z \cos \mathrm{Az} = -\cos \varphi \sin \delta + \sin \varphi \cos \delta \cos t. \tag{66}$$

$$\sin z \sin \mathrm{Az} = \cos \delta \sin t. \tag{67}$$

Dividing (66) by (67) we obtain

$$\cot \mathrm{Az} = \frac{\sin \varphi \cos t - \cos \varphi \tan \delta}{\sin t}. \tag{68}$$

This equation is most convenient for the computation of the azimuth when using a desk computer. For logarithmic computation we introduce in equation (66)

$$n \sin \mathrm{M} = \sin \delta \tag{69}$$

$$n \cos \mathrm{M} = \cos \delta \cos t \tag{70}$$

and find

$$\cos \mathrm{Az} = \frac{n \sin (\varphi - \mathrm{M})}{\sin z} = \frac{\cos \delta \cos t \sin (\varphi - \mathrm{M})}{\sin z \cos \mathrm{M}}. \tag{71}$$

Dividing (71) by (67) yields

$$\tan \mathrm{Az} = \frac{\cos \mathrm{M} \tan t}{\sin (\varphi - \mathrm{M})}. \tag{72}$$

When dividing (69) by (67) we obtain the auxiliary angle M from

$$\tan M = \frac{\tan \delta}{\cos t}. \qquad (73)$$

The meanings of the symbols used in the above equations are :

Az = azimuth of the sun at the time of observation, reckoned positive from the true south meridian to the great circle passing through the zenith and the sun, from zero to 180° east and 180° west;

t = meridian angle, reckoned positive from the true south meridian to the plane of the great circle passing through the pole and the sun, from zero to 180° east and 180° west (t is determined from the time of observation);

z = zenith distance of the sun at the time of observation;

δ = sun's (apparent) declination varying between N.23°27′ or + 23°27′ and S.23°27′ or − 23°27′, given in the ephemeris of the sun;

φ = geographic latitude of the place of observation (derived from a large-scale map) reckoned positive in the northern hemisphere, negative in the southern hemisphere.

For the computation of the meridian angle t, the following are required:

λ = geographic longitude of the place of observation (derived from a large-scale map), ranging from zero to 180° east and 180° west;

GHA = Greenwich Hour Angle, to be interpolated from the *Nautical Almanac* for the time of observation, reckoned from the true south meridian through west, north and east to south, from zero to 360°, or

Ephemeris Transit = sun's meridian passage at the Ephemeris Meridian expressed in Ephemeris Time, which for our purposes are identical with Greenwich Meridian and Greenwich Mean Time (or Universal Time) respectively; Ephemeris Transit is interpolated from the ephemeris of the sun for the time of observation; at Ephemeris Transit, GHA is zero.

With the conventions given above, cot Az and tan Az will be positive for azimuths in the two south quadrants, negative for azimuths in the two north quadrants, in both hemispheres. Since it is known whether the observations were made before noon or in the afternoon, the azimuth obtained from the computations can be converted to true azimuth (or true bearing) which is reckoned from north through east, south and west to north from zero to 360°. The azimuth computed from the above formulae is valid for the sun's centre at the time of observation. Since sightings can be made only on the sun's limb, the readings of the horizontal circle of the theodolite have to be reduced to the sun's centre by adding to them or subtracting from them the sun's semidiameter reduced to the plane of the horizon, which is

$$\text{sun's semidiameter} \times \operatorname{cosec} z \quad \text{or} \quad \text{sun's semidiameter}/\sin z. \qquad (74)$$

For the computation of the zenith distance z we find from the spherical triangle

$$\cos z = \sin \varphi \sin \delta + \cos \varphi \cos \delta \cos t. \qquad (75)$$

The true meridian is found by subtracting the computed azimuth from the reading of the horizontal circle of the theodolite. In order to fix the direction of the true meridian, it is related to prominent terrestrial objects near the plane of horizon (azimuth marks).

243 For correct results, the theodolite must occupy exactly the same position as that occupied by the magnetic theodolite when the magnetic declination is observed. When observations are made over a bench mark, set up the tripod over the mark, giving the legs a generous spread with the head approximately level. Centre the theodolite over the mark, using the quick-centring device which allows one to shift the theodolite a few centimetres on the tripod head, or else change the position of the legs until the plumb is over the mark. Press the legs firmly into the ground by treading on them. Tighten the screws of the tripod head, thus providing a firm connexion between the legs and the head. This is often forgotten by beginners. If observations are made on flat ground and the tripod has to be changed afterwards, drive a peg into the ground exactly under the plumb. The accuracy required in centring is inversely proportional to the distance of the object whose bearing will be observed; if the object is one kilometre away, a transverse shift of the instrument of 30 centimetres will cause an error of one minute of arc in bearing. Finally, level the theodolite carefully.

244 In order to eliminate the collimation error and the error due to tilt of the axis of rotation of the telescope, observations have to be made in the two possible telescope positions which are distinguished by the position of the vertical circle of the theodolite with respect to the observer when he looks into the telescope. Thus we have the telescope positions 'Vertical circle left' (VCL) and 'Vertical circle right' (VCR).

245 Select several azimuth marks so that the bearings on them will give good intersections at the observing point. This is important for finding the station again when observations are not made over a bench-mark or the mark cannot be found. At least one azimuth mark should be very distinct, so that it can be seen clearly with the comparatively poor telescope of a magnetic travel theodolite, or the QHM telescope in case the latter is used for observing the magnetic declination. Take a round of sightings on the azimuth marks in both telescope positions. Then point the telescope on the sun, using the aiming device which is a sort of coarse gun-sight. The telescope can be adjusted by means of the shadow cast by the front part of the aiming device on the rear part. Adjust the telescope so that the sun is approximately in the centre of the field of view and the vertical cross-wire slightly ahead of the sun's leading limb. Time the contact of the leading limb with the vertical cross-wire. Read the horizontal circle and record the observations. Without touching the theodolite wait for the contact of the trailing limb. When the sun moves rapidly in elevation it may be necessary to adjust the telescope using the tangent screw of the vertical circle. Turn the alidade 180° in azimuth, reverse the telescope and observe the transit of the sun as before. Finally take another round of sightings on the azimuth marks in both telescope positions. The following example of field notes illustrates the procedure. For timing the contacts, a chronometer and a stop-watch were used as described in paragraph **98**.

1967, June 30, Friday
Fürstenfeldbruck Observatory   Time signal: BBC   13h00m00.0s GMT
Theodolite Wild T2, No. 10913   Chronometer: Schweitzer No. 62   12h59m59.5s

		Before sun observations	After sun observations
Azimuth mark:	VCL	103°16′16″	103°16′20″
Alling church, cross on tower	VCR	283°16′51″	283°16′56″
	Means	283°16′34″	283°16′38″
	MEAN	283°16′36″	

Limb	Chronometer	Stop-watch	Circle	Chronometer	Difference	Mean
VCR						
⊙|	14h15m20s	− 13.8s	28°47′47″	14h15m06.2s	3m08.4s	14h16m40.4s
|⊙	18 25	− 10.4		18 14.6		
VCL						
⊙|	14 20 45	− 4.9	210°09′12″	20 40.1	3 09.1	22 14.6
|⊙	24 00	− 10.8		23 49.2		

Note the limbs as you see them in the telescope. Do not try to allow for inversion in the telescope and the prismatic eyepiece. (In this case the theodolite had an inverting telescope which was used with a prismatic eyepiece. Therefore, the sun's apparent movement in azimuth was in the same direction as the actual movement.) Subtract the stop-watch readings from the chronometer readings and note the result after the circle readings. Compute the time difference between the leading and trailing limb. The time differences should be nearly equal for the two sets of observations. The observation has been successful if the azimuth mark readings before and after the sun observations are in agreement within a few tenths of a minute of arc.

246 This simple method is efficient at middle and high latitudes, and in clear weather. At low latitudes, many minutes may pass between the contacts of the leading and trailing limb. In cloudy weather, it may not be possible to observe the contact of the trailing limb. The following method is generally applicable. After having taken a round of azimuth sightings in both telescope positions, point twice on each limb of the sun. Reverse the telescope and take another four sun observations. Complete the observations by taking a round of azimuth mark sightings. The following example of field notes explains the procedure.

1966, March 18, Friday		
Bir El Hagg Hussein	Time signal: BBC	06h00m00s GMT
Askania Midget theodolite	Chronometer: Frodsham	05h59m59.0s

Azimuth marks				
Beginning		Ending		Mean
VCL	*VCR*	*VCL*	*VCR*	
1. Top of cairn, about one kilometre N. of station				
242°23.7′	62°24.5′	242°23.9′	62°24.7′	62°24.2′
2. Acacia tree, bottom, about 500 metres SSE. of station				
349°41.0′	169°42.0′	349°41.3′	169°42.1′	169°41.6′
3. Telephone pole at bend of road, bottom, 300 metres W. of station				
139°28.6′	319°29.4′	139°28.8′	319°29.6′	319°29.1′

VCR			*VCL*		
Limb	Chronometer	Circle	Limb	Chronometer	Circle
|⊙	06h20m23.5s	166°46.6′	⊙|	06h24m45.5s	348°03.3′
|⊙	21 11.0	166 54.0	⊙|	25 40.0	348 12.2
⊙|	22 15.0	167 40.0	|⊙	26 30.5	347 44.4
⊙|	23 10.5	167 49.1	|⊙	27 15.0	347 51.7

247 For the computation of the azimuth, the accuracy of the *Nautical Almanac* is adequate. It has the advantage that no fundamental mistake can be committed in the computation of the meridian angle. The *Nautical Almanac* contains GHA and the declination of the sun for every full hour of GMT, as in the following extract.

1967, June 30 Sun

GMT	GHA	Declination	GMT	GHA	Declination
14h	29°08.4′	N.23°11.9′	15h	44°08.3′	N.23°11.8′

The task consists of interpolating GHA and declination for the mean of the first and last times of observation expressed in GMT, and of converting GHA to Local Hour Angle (LHA). The computation is shown for the first observation in the example of field notes of 30 June 1967 (paragraph **245**).

Mean of times of first and last observation	14.3h
GHA for 14h00m00s GMT at 14.3h = 29°08.37′, or, rounded to the nearest tenth of a minute of arc	29°08.4′
Declination for 14.3h GMT = N.23°11.87′, or, rounded to the nearest tenth of a minute of arc	N.23°11.9′
Time of observation in chronometer time	14h16m40.4s
Chronometer correction as found from time signal	+ 0.5
Time of observation in GMT	14 16 40.9

GHA at 14h00m00s as interpolated above	29°08.4′
Add minutes and seconds of GMT of observation converted to angle (16m40.9s)	+ 4 10.2
Add longitude east, subtract longitude west	+ 11 16.6
Sum = LHA	44 35.2
Meridian angle *t*	44 35.2

Note. Meridian angle *t* = LHA for values of LHA between 0° and 180°; meridian angle *t* = 360° − LHA for values of LHA between 180° and 360°.

Instead of doing the step-by-step conversion for every time of observation, add up all constant quantities (convert chronometer correction to angle) and convert the times of observation in one step, as has been done in the example for the logarithmic computation of the azimuth.

248 In astronomical ephemerides such as the *American Ephemeris and Nautical Almanac* and *The Astronomical Ephemeris*, the apparent declination and the semidiameter of the sun are listed for (practically) 0h GMT each day. Ephemeris Transit is valid for the precise instant of culmination of the sun, *not for 0h GMT.* In the example of field notes of 18 March 1966 (paragraph **246**), the following values are extracted from *Efemérides Astronómicos, Año 1966.*

Sun, March 1966

Date	Apparent declination	Difference	Semidiameter	Ephemeris Transit	Difference
17				12h08m29.41s	− 17.35s
18	− 1°13′03.4″	+ 1423.7″	16′05.69″	12h08m12.06s	
19	− 0°49′19.7″		16′05.42″		

The errors caused by linear interpolation will usually affect the azimuth by much less than 0.1′. For the observations of 18 March 1966, the mean of the times of the first and last observation is 6.4h GMT. For this instant we find for declination − 1°06′43″. The sun's semidiameter is interpolated by sight. The seconds of arc are converted to hundredths of minutes of arc. Thus the sun's semidiameter for the time of observations is 16.09′. We interpolate for Ephemeris Transit 12h08m16.2s. This is the sun's meridian passage at the place of observation expressed in Local Mean Time, and the instant for which LHA is zero. The following example explains the computation of the meridian angle for the first observation of the field notes of 18 March 1966.

Chronometer time of observation	6h20m23.5s
Chronometer correction as found from time signal	+ 1.0
Time of observation in GMT	6 20 24.5
Convert longitude of place of observation to time Add longitude E., subtract longitude W. (27°12.7′ E.)	+ 1 48 50.8
Time of observation in Local Mean Time	8 09 15.5
Ephemeris Transit as interpolated above for 6.4h GMT	12 08 16.2
Meridian angle *t* (subtract the earlier from the later time)	3 59 00.7

All constant quantities may be added once and, instead of converting the times of observation to Local Mean Time, one may convert Ephemeris Transit to chronometer time. Note that the algebraic signs of longitude and the chronometer correction have then to be reversed. The modified procedure is used in the example for the numerical computation of the azimuth.

249 When in cloudy weather the observations have lasted longer than in the two examples given above, it may be necessary to interpolate the declination and the Ephemeris Transit or GHA for several groups of observations, especially in periods of the year when one or other quantity changes rapidly.

250 For the conversion of angles to time and vice versa, tables can be found in astronomical ephemerides, or in tables of logarithms and trigonometrical functions. For the numerical computation of the azimuth by means of equation (68), the six-place tables of Peters or Brandenburg are very suitable. Both tables contain the trigonometrical functions for every ten seconds of arc. In Chambers's tables, the trigonometrical functions are listed for every minute of arc. Although six-place tables are more accurate than required, time can be saved by interpolating by sight or by rounding the angles to the nearest five seconds of arc. The accompanying example of numerical computation of the observations of 18 March 1966 was computed by means of a small desk computer. A few hints will facilitate the computation. Feed cos t into the computer. Multiply by sin φ. Subtract the constant quantity cos φ tan δ which you find on top of the computation form. Watch that the decimal points are below each other. Divide by sin t. The result is cot Az. The whole computation can be done in one operation without shifting any figures in the registers or noting intermediate results. In case of doubt as to the position of the decimal point, a slide-rule estimate will help. Multiply in negative direction if positive sin φ cos t is smaller than negative cos φ tan δ, and add the latter term. The rules for converting azimuth to true azimuth have been given in paragraph **242**. In the example of computation, the true azimuth is written below the (observed) circle reading because true north meridian is found by subtracting true azimuth from the circle reading (paragraph **103**, Fig. 13). It will be noticed that the circle readings taken at VCL have been changed by 180°. The subtraction gives the reading of the horizontal circle of the theodolite for true north meridian. The beginner may finally check the accuracy of his observations by reducing the individual sightings to the sun's centre by means of equations (74) and (75), as has been done in the example.

Finally the true azimuth (or true bearing) of the azimuth marks is computed. Since in the azimuth computation the degrees of arc found for VCR have been used, the means of the azimuth marks are computed for the same telescope position.

251 This method of computation looks cumbersome but it is the only way of obtaining a complete check of all details of observation and computation. The observer who is sure of himself may curtail the computation by taking the means of the observed times and angles of observations Nos. 1, 2, 3, 4, and Nos. 5, 6, 7, 8, respectively, and do the computation twice instead of eight times as shown in another computation of the above example. The difference between the results

Numerical computation of the sun azimuth

1966, March 18, Friday

Bir El Hagg Hussein
Askania Midget theodolite

$\varphi = 31°02.3'$ N.
$\delta = -1\ 06'43''$
Sun's semidiameter = 16.09

Ephemeris Transit	12h08m16.2s
λ (27°12.7′ E)	− 1 48 50.8
Chronometer correction	− 1.0
Meridian passage in chronometer time	10 19 24.4

sin φ	0.51 5612
cos φ	.85 6823
sin δ	−.01 9406
cos δ	.99 9812
tan δ	−.01 9409

cos φ tan δ	− 0.01 6630
sin φ sin δ	− .01 0006
cos φ cos δ	.85 6662

$$\cot Az = \frac{\sin\varphi\cos t - \cos\varphi\tan\delta}{\sin t}$$

$$\cos z = \sin\varphi\sin\delta + \cos\varphi\cos\delta\cos t$$

Position of alidade	VCR				VCL			
Number of observation	1	2	3	4	5	6	7	8
Sun's limb	|⊙	|⊙	⊙|	⊙|	⊙|	⊙|	|⊙	|⊙
Chronometer time of observation	06h20m23.5s	06h21m11.0s	06h22m15.0s	06h23m10.5s	06h24m45.5s	06h25m40.0s	06h26m30.5s	06h27m15.0s
Meridian passage in chronometer time	10 19 24.4	10 19 24.4	10 19 24.4	10 19 24.4	10 19 24.4	10 19 24.4	10 19 24.4	10 19 24.4
Meridian angle *t* (E)	03 59 00.9	03 58 13.4	03 57 09.4	03 56 13.9	03 54 38.9	03 53 44.4	03 52 53.9	03 52 09.4
Meridian angle *t*	59°45′14″	59°33′21″	59°17′21″	59°03′28″	58°39′44″	58°26′06″	58°13′28″	58°02′21″
cos *t*	0.50 3715	0.50 6699	0.51 0706	0.51 4173	0.52 0083	0.52 3465	0.52 6593	0.52 9340
sin *t*	.86 3870	.86 2124	.85 9756	.85 7686	.85 4116	.85 2047	.85 0118	.84 8410
cot Az	.31 9899	.32 2332	.32 5623	.32 8493	.33 3434	.33 6290	.33 8950	.34 1302
Circle reading (VCR)	166°46′36″	166°54′00″	167°40′00″	167°49′06″	168°03′18″	168°12′12″	167°44′24″	167°51′42″
True Azimuth (N)	107 44 22	107 51 57	108 02 11	108 11 06	108 26 24	108 35 14	108 43 27	108 50 42
Circle reading of true north meridian	58 02 14	59 02 03	59 37 49	59 38 00	59 36 54	59 36 58	59 00 57	59 01 00
Means	59°02′08″		59°37′54″		59°36′56″		59°00′58″	
Means	59°20′01″				59°18′57″			
MEAN	59°19′29″							

Position of alidade	VCR				VCL			
Number of observation	1	2	3	4	5	6	7	8
Sun's limb	|☉	|☉	☉|	☉|	☉|	☉|	|☉	|☉
cos z	0.4215	0.4241	0.4275	0.4305	0.4355	0.4384	0.4411	0.4435
cosec z	1.1028	1.1042	1.1062	1.1072	1.1109	1.1126	1.1143	1.1158
semidiameter cosec z	17′45″	17′47″	17′49″	17′50″	17′53″	17′55″	17′56″	17′58″
True north meridian	59°19 59	59°19 50	59°20 00	59°20 10	59°19 01	59°19 03	59°18 53	59°18 58
MEAN	59°19′29″							

	cairn	tree	telephone pole
Azimuth marks, means (VCR) :	62°24.2′	169°41.6′	319°29.1′
True north meridian	59°19.5′	59°19.5′	59°19.5′
True azimuth of azimuth marks	3°04.7′	110°22.1′	210°09.6′

obtained with the full computation and the abbreviated method is small, provided the observations are fairly equidistant in time and the first and last observation are not too far apart.

252 At latitudes between 10° and 60° N., the true meridian may be derived with practically no computation from observations of Polaris (Pole Star) during the periods of twilight. Astronomical ephemerides, other than the Nautical Almanac, contain tables of the azimuth of Polaris whose use is sufficiently explained therein, so that no example need be given here. When observing in the evening, the sightings on the azimuth marks are made before the Polaris observations and, in the morning, after them. It suffices to know the time of observation to the nearest 20 seconds when Polaris is near the meridian; when it is at its eastern or western elongation, an accuracy of ± 1 minute is adequate.

The best instrument for azimuth observations is a modern theodolite which enables the observer to read the horizontal circle to 0.1′ or better from the observing position, i.e. without moving round the instrument. Most observers will have to depend on old-fashioned instruments which they may be able to obtain on loan from a geodetic survey department. As a substitute for a theodolite, one can use the QHM base which the Danish Meteorological Institute will equip with an astronomical telescope upon request. Many observers will have magnetic travel theodolites at their disposal. When the sun is near the horizon, direct observations may be made with the telescope, which can be tilted 10° to 15°. At higher sun altitudes, one will have to use the black mirror as explained in Figure 27. In either position, the mirror has to be used at the positions 'marked axle stub left' and 'marked axle stub right' in order to eliminate instrumental errors. The use of the travel theodolite for sun observations must be regarded as an emergency measure only, because the magnification of the telescope rarely exceeds four or five diameters, which means that the sun moves slowly through the telescope's field of view and the timing of contacts is not very accurate. However, good results will be obtained with the sun near the horizon.

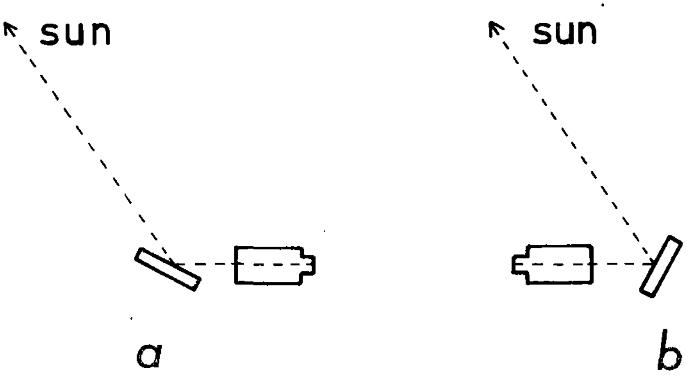

FIG. 27. Use of the black mirror of a magnetic travel theodolite for sun observations. (*a*) Sun in front of the observer. (*b*) Sun behind the observer.

It is essential for sun observations to have several coloured glasses which may be either screwed or clipped to the eyepiece of the telescope. It is also useful to reduce the aperture of the objective lens to five millimetres by means of a diaphragm, which can be made of a piece of cardboard if not supplied by the makers, in order to reduce heating of the glass plate carrying the diaphragm scale or the cross-wires. For sightings on the sun exceeding 25° in elevation angle, a prismatic eyepiece is required for the telescope and, when the micrometer moves with the telescope, for the micrometer as well.

253 Azimuth observations are easier to make than the reader might suspect. After a few practice runs, in the beginning with the sun near the horizon, he will have gained sufficient confidence and the scatter of the individual observations will be small enough for geomagnetic work. The computation of the azimuth requires a good deal of patience. When the computations seem to be correct a final check can be obtained by deriving the magnetic declination. Gross errors will show up immediately. However, the most rigorous check is afforded by two observations at widely differing meridian angles, preferably by one observation in the morning and a second in the evening.

Numerical computation of the sun azimuth from means of times and angles

1966, March 18, Friday	Ephemeris Transit	12h08m16.2s
Bir El Hagg Hussein	λ (27°12.7′ E.)	– 1 48 50.8
Askania Midget theodolite	Chronometer correction	– 1.0
φ = 31°02.3′ N.		
δ = – 1°06′43″	Meridian passage in chronometer time	10 19 24.4

sin φ 0.51 5612
cos φ 85 6823
tan δ – 01 9409

cos φ tan δ – 0.01 6630

$$\cot Az = \frac{\sin \varphi \cos t - \cos \varphi \tan \delta}{\sin t}$$

Position of alidade	VCR	VCL
Number of observation	1,2,3,4	5,6,7,8
Sun's limb	⦶	⦶
Chronometer time of observation	06h21m45.0s	06h26m02.8s
Meridian passage in chronometer time	10 19 24.4	10 19 24.4
Meridian angle t (E)	3 57 39.4	3 53 21.6
Meridian angle t	59°24′51″	58°20′24″
cos t	0.508 829	0.524 878
sin t	.860 868	.851 178
cot Az	.324 078	.337 489
Circle reading (VCR)	167°17′25″	167°57′54″
True azimuth (N)	107 57 23	108 38 56
Circle reading of true north meridian	59 20 02	59 18 58
MEAN	59°19′30″	

Logarithmic computation of the sun azimuth

1967, June 30, Friday	GHA (14h00m00s)	29°08.4
Fürstenfeldbruck Observatory	Add longitude E., subtract longitude W.	+ 11 16.6
Theodolite Wild T2	Chronometer correction (0.5s)	+ 0.1
$\varphi =$ 48°09.9′ N.		
$\delta = +$ 23°11.9′	LHA of full hour in chronometer time	40°25.1′

$$\tan M = \frac{\tan \delta}{\cos t}; \qquad \tan Az = \frac{\cos M \tan t}{\sin(\varphi - M)}$$

Position of alidade	VCR	VCL
Chronometer time of observation	14h16m40.4s	14h22m14.6s
Minutes and seconds of time in angle	4°10.1′	5°33.6′
LHA of full hour in chronometer time	40 25.1	40 25.1
LHA	44 35.2	45 58.7
Meridian angle t (W) (t_W = LHA)	44 35.2	45 58.7
log tan δ	9.632 01	9.632 01
log cos t	9.852 60	9.841 94
log tan M	9.779 41	9.790 07
φ	48°09.9′	48°09.9′
M	31 02.2	31 39.7
φ − M	17°07.7′	16°30.2′
log cos M	9.932 90	9.930 02
log tan t	9.993 73	0.014 84
log cos M tan t	9.926 63	9.944 86
log sin (φ − M)	9.469 11	9.453 43
log tan Az	0.457 52	0.491 43
Circle reading (VCR)	28°47.8′	30°09.2′
True azimuth (N)	250 46.9	252 07.4
Circle reading of true north meridian	138°01.3′	138°01.8′
MEAN	138°01.6′	
Azimuth mark: Alling church	283°16.6′	
True north meridian	138 01.6	
True azimuth of azimuth mark	145°15.0′	

Comparison of instruments

Comparison by means of travelling standards

254 Primary standards are not portable. Up to 1935, magnetic travel theodolites were therefore used for the comparison of observatory standards with primary standards. Later, Forbush and Johnson (1937) used a portable sine galvanometer as means of comparison. In 1934, La Cour made his first experiments with the QHM, which subsequently proved to be the most convenient instrument for the comparison of standards of horizontal intensity. In recent years, experiments have been made with a BMZ of wide range. Naturally, sooner or later the portable proton magnetometer will be a useful means of comparison in conjunction with QHMs or BMZs. In the literature the term 'International Magnetic Standard' (IMS) is frequently found. The term is used for instruments which are free from faults, that is to say, the intensities (F, Z, H) are measured in the correct unit and the angles given by the instruments do not deviate from the true values (D and H). For the measurement of the horizontal intensity the sine galvanometer of the Carnegie Institution of Washington, constructed by Barnett is considered to be such an ideal instrument. For the other components, no recognized standards exist. It is usually assumed that declinometers, especially those with wide or non-metallic magnet housings, and station earth inductors free from magnetic impurities, can be considered as ideal or almost ideal instruments. A proton magnetometer whose sensor has been tested as outlined in paragraph **203** and whose time base is correct can also be considered as a standard.

255 When comparing observatory standards with primary standards, it is sufficient to make a comparison for H and Z as well as for D, thus checking also F and I. This method is applicable anywhere in the world, irrespective of the type of equipment used at an observatory. At observatories where H and I are measured, a comparison for H may suffice for obtaining information on the absolute level of H, Z and F, on the assumption that the station earth inductor is correct. The results obtained for F and Z will be poor at places with I > 60°, adequate when 60° > I > 45°, and excellent when I < 45°. At high latitudes, it is advantageous to make the comparison of Z instead of H. A proton magnetometer requires no comparison with a magnetic standard, provided its time-base frequency is controlled as explained in paragraph **202** and its sensor is fairly free from magnetic impurities. When the proton magnetometer is used in conjunction with an earth inductor or some other classical instrument, it is useful to make the comparison for the smaller of the two intensity components.

The comparison of observatory standards of D and I received considerable attention between 1904 and 1925, when observers of the Carnegie Institution of Washington made comparisons at numerous observatories. More recently, comparisons of these two elements have been somewhat neglected, with some justification. Declinometers and earth inductors are compared with the standards of well-established observatories before they are delivered by the makers. Instruments made of carefully selected materials will show either small or no corrections. Moreover, the corrections vary with time only within narrow limits. However, it is advisable to make frequent comparisons for D if at an observatory the base-line values of the declination are derived from QHM observations (see paragraph **153**).

256 The frequency of comparisons will depend on the type of equipment used at an observatory. QHMs should be compared every two years. The constants of BMZs are on the average more stable than QHM constants but a comparison every three or four years is desirable (at the present time, by sending the instrument to the Danish Meteorological Institute). Station theodolites and magnetic travel theodolites may require a comparison for H every five to ten years.

257 At the time of writing, comparisons can be made easily for H. It has been mentioned in paragraph **153** that IAGA possesses several sets of QHMs which are in the custody of the Reporter on the Comparison of Observatory Standards (IAGA Commission I), Dr. V. Laursen of the Danish Meteorological Institute, Charlottenlund (Denmark). The instruments will be sent free of charge by air freight, upon request. The recipient will have to pay the return shipment. When ordering a set of QHMs, it should be indicated whether a calibration for D is required for checking the declination constant, *c*, of QHMs. In the near future, the wide-range BMZ may also be available for comparisons.

258 At the observatory whose standard is to be compared, observations are made alternately with the IAGA standard and the observatory standard, preferably on the same pier with the magnets at the same height above the pier, in cases when the observatory standard can be removed. If the observations have to be made on different piers, the pier difference should be accurately known. The absolute levels of the IAGA standard and the observatory standard are compared by means of the base-line values of the magnetograph obtained for the two instruments. The results of comparisons are written in form of the following equation

$$\text{IAGA standard} - \text{Observatory standard} = \text{Correction of observatory standard to IMS.} \quad (76)$$

259 If it is desired to avoid the comparison by means of the base-line values of a magnetograph, or if no magnetograph is available, the time variations are eliminated by observing *simultaneously* the IAGA standard at position A and the observatory standard at position B. The next observation is made after an exchange of the instruments. The procedure is repeated several times. For the computation of the difference we use the following notation: S_A and S_B are the values obtained with the IAGA standard, O_A and O_B are the values obtained with the observatory standard, at the positions A and B, respectively. The difference between the two positions is

$$\Delta p = \text{true value at position A} - \text{true value at position B}.$$

The observed differences between the standards are

$$\Delta_1 = S_A - O_B \quad \text{and} \quad \Delta_2 = S_B - O_A.$$

Then

$$\Delta p = \frac{\Delta_1 - \Delta_2}{2}. \tag{77}$$

and

$$\text{Correction of observatory standard to IMS} = \frac{\Delta_1 + \Delta_2}{2} \tag{78}$$

This method is frequently used when survey parties compare instruments at a field station.

260 It has been seen in paragraph **258** that the correction of an observatory standard (or any other instrument) is obtained by a subtraction. For H, the correction obtained in this way is valid only for values of H close to that at which the comparison was made. At an observatory or in a survey of a limited area, the correction derived from the comparison can be added to the result without adverse effect. However, when observations have to be made at places with widely differing values of H, the constant of the QHM or the magnetic theodolite has to be adjusted by means of the equation:

$$\Delta C = 0.4343 \, \frac{\text{Correction to IMS}^{(\Gamma)}}{H^{(\Gamma)}}$$

where ΔC = correction of C or log C of a QHM or magnetic theodolite, respectively.

For a BMZ with a fixed compensating magnet, the correction will be valid for the whole range of the instrument, because normally only the magnetic moment of the compensating magnet changes. When a BMZ with an adjustable compensating magnet is used, the correction can be determined for three or four adjacent scale divisions. The corrections so found may be used for another two or three scale divisions above and below the calibrated divisions. With the earth inductor and the declinometer, the range of validity of a correction is difficult to predict. In a declinometer, the correction may be due to permanently magnetized parts and/or soft magnetic impurities, in which case it may vary with the horizontal intensity.

261 At the present time, Working Groups 1 (Observatories) and 2 (Instruments) of Commission I of IAGA take the view that observatory standards should not be corrected to IMS if the observatory has been in operation for some time. However, the corrections should be published in a table of the observatory's magnetic yearbook. In geomagnetic survey work, either the observations should be based on the IMS level or the corrections to IMS should be applied to observations based on the level of the observatory standards.

Checks on stability of observatory standards by data exchange

262 In paragraph **351** it will be mentioned that the best time of day for determining the difference in geomagnetic components between an observatory and a field station is between midnight and 4 a.m. local time on magnetically quiet days. Naturally this period is also best for comparing the values obtained at two or more neighbouring observatories which are not too far apart. One may expect the difference in any component between two observatories to be constant, departures from a mean difference being caused by variations in the standards of one or of both observatories. If the values of three observatories are compared it may be possible to decide at which observatory the absolute level has changed. However, nothing can be said about the absolute level itself.

263 This method of intercomparison of observatory data has been used at seven Central European observatories since 1955. Comparisons are made of instantaneous values of D, H, Z and F at 02.00h GMT on ten magnetically quiet days each month. The ten quiet days of each month are selected by one of the observatories (Wingst), using three-hour-range indices. Waiting for the international ten quiet days would last too long. When the differences in any component between any pair of observatories are plotted against time, one obtains a straight line which is either horizontal or slightly inclined, depending on the difference of the secular change between the two observatories.

264 The scatter of the individual values indicated that, during the first few years of this data exchange, the instrumental accuracy was certainly below what most observers had believed. Subsequently, improved observational techniques removed most of the scatter. The intercomparison data should not be used for the correction of base-line values at any observatory, because phenomena which are not as yet known may be involved. The scheme may be varied by using hourly means instead of instantaneous values, or the means of two adjacent hours. One may restrict the comparison to the five quiet days of each month.

Recording of time variations

Basic considerations

265 At roughly 90 per cent of the existing geomagnetic observatories, declination, horizontal intensity and vertical intensity are recorded. The disadvantage of this combination of elements is that the variometers of the horizontal components have to be adjusted from time to time because the magnetic declination, and hence the line of reference, changes due to the secular variation. When, instead of D and H, the components X and Y are recorded (in this case the line of reference is the (invariable) true meridian), the variometers are in good adjustment as long as the traces remain at approximately the position to which they were initially adjusted. When the components change owing to secular variation and the traces move away from their original positions, it is only necessary to bring them back by twisting the suspension fibres or adjusting the compensating magnets. With variometers using multiple reflection, the fixed counter-mirrors should not be used for this purpose, because in this case only the light beams are adjusted and not the position of the recording magnets, which is what is required.

266 For the components D and H, the line of reference is the magnetic meridian of the absolute pier on which they are measured. In order to obtain complete agreement between the values observed on the absolute pier and the values recorded by the variometers, the same magnetic meridian has to be established in the variometer room before any adjustment of the variometers can be made. If the magnetic homogeneity of the observatory site is good and the variometer house is constructed of non-magnetic material, it suffices to determine the magnetic meridian in the variometer room by means of a declinometer or a long box compass. The magnetic meridian may be marked on the variometer pier with a note of the date of its determination. A similar note should be made in the observatory's log-book, in which all work is carefully recorded.

267 A more convenient method is described in McComb's *Magnetic Observatory Manual* (paragraphs 345-56). Fasten boards horizontally along the walls of the variometer room at a height of 180 to 200 centimetres above the floor, at a distance of three centimetres from the walls. Mark the magnetic meridian and the magnetic prime vertical on the boards. When using a declinometer, determine the magnetic meridian in the middle of the room. If you cannot tilt the telescope of the declinometer so that you can see the boards, let an assistant hang a plumb-line from the boards and direct him until the line is in coincidence with the vertical cross-wire of the telescope. In this way, mark the magnetic meridian and the magnetic prime vertical. Write the date of establishment of the marks, and their meaning, on the boards. By means of the marks, the magnetic meridian and prime vertical can be established at any place above the variometer pier by measuring equal distances off the marks and hanging a cord across the room over the new marks so determined. The directions of the cords are projected to the level of the variometers by hanging plumb-lines from the cords, about one metre apart, and using these lines for aiming when setting up the Helmholtz-Gaugain coils of the variometers.

268 When the observatory site is magnetically unhomogeneous, when you have doubts as to the magnetic properties of the variometer house or when variometers are installed in another variometer room near by, a different approach is necessary. The method to be applied requires two theodolites, of which one may be your magnetic theodolite. The essence of the method is to transfer the magnetic meridian from the absolute pier to the variometer room by means of a traverse. Determine the magnetic meridian at the absolute pier by means of the declinometer, preferably in the late afternoon when the magnetic declination is near the daily mean. If you have planned well, you may have a direct sight from the absolute pier to the variometer room. Direct the telescopes of the theodolites on to each other. The final adjustment is made by putting a light behind the eyepiece of one telescope and sighting the other telescope on the vertical cross-wire of the first telescope. Sight the first telescope in the same manner. Read the horizontal circles of both theodolites and compute the magnetic meridian for the circle of the theodolite in the variometer room. Mark the magnetic meridian and prime vertical on the boards as before. Instead of the magnetic meridian, a true bearing near the magnetic meridian may be transferred to the variometer room. If there is no direct line of sight from the absolute pier to the variometer room, use intermediate points and carry the magnetic meridian or the true bearing from one point to another until you arrive in the variometer room. Check all computations carefully. In order to be sure, the whole procedure should be repeated. When the results of the two traverses agree within five minutes of arc, you may be satisfied. When setting up a theodolite tripod on a concrete floor it is advisable to prepare small grooves in the floor in which the tripod legs may be set, so that they do not slip.

269 A magnetograph is expected to give a complete record of all variations of the geomagnetic field, large and small, without loss of trace. If the scale values of the variometers are small (the sensitivity high) it will be possible to follow all small variations. With spare traces, even small and moderate geomagnetic storms will be completely recorded. However, in periods of violent geomagnetic storms the traces, even the spares, may go off the magnetogram or, more frequently, move so fast in ordinate that they leave no legible trace on the magnetogram or get entangled so that it is difficult to find out by which variometer a particular trace was produced. If large scale values are used, the normal diurnal variation will produce only small amplitudes. When only one magnetograph is available at an observatory, the scale values of the variometers will have to be a compromise. With two magnetographs, one should be adjusted to small, the other to large scale values, so that all events are recorded properly.

270 We have seen in paragraph **52** that the amplitudes of diurnal variations and geomagnetic storms depend on the geomagnetic latitude of the place of observation. This fact will have to be considered when choosing scale values for the variometers. IAGA (formerly International Association of Terrestrial Magnetism and Electricity, abbreviated IATME) recommended certain scale values in 1950 *(IATME Bulletin No. 13)* which at that time seemed to satisfy all requirements. However, especially in the light of experience gathered during the International Geophysical Year, it was later felt that the scale values for declination were too large at low latitudes. The following table represents a slight modification of the IATME recommendation.

Geomagnetic latitude of observatory	Observatories with one magnetograph			Observatories with two magnetographs					
				Sensitive			Insensitive		
	D ('/mm)	H (γ/mm)	Z (γ/mm)	D ('/mm)	H (γ/mm)	Z (γ/mm)	D ('/mm)	H (γ/mm)	Z (γ/mm)
0°-30°	0.5	3.5	3	0.3	2.5	2.5	0.7	6	3.5
30 -50	0.8	4	3	0.5	2.8	2.5	1.3	8	4
50 -60	1.0	6	5	1	5	4	3	30	25
60 -90	5	25	25	1	7	7	9	45	45

Note that, with the recommended scale values, complete temperature compensation cannot be achieved for the La Cour H-variometer at low latitudes.

The magnetograph

271 A magnetograph consists of a photographic recorder and the variometers for declination or Y, horizontal intensity or X, and vertical intensity.

THE RECORDER

272 The housing of the recorder contains a drum driven uniformly by clockwork, making one revolution per day. The paper speed is 20 millimetres per hour. Some makes of recorders may be used at different paper speeds either by exchanging cog-wheels or by shifting other cog-wheels into the gear train by means of a lever. The width of the drum is 20 centimetres and its diameter is about 16 centimetres. The photographic paper which is clipped to the drum is either 19 cm by 52 cm or 20 cm by 52 cm in size. The recorder drum of the La Cour magnetograph has a width of 30 centimetres and a diameter of about 12 centimetres. Photographic paper of 30 by 40 centimetres such as can be found in any photographic shop will fit on this drum. For this reason the La Cour magnetograph is especially suitable for countries with currency problems. The paper speed of the La Cour recorder is 15 millimetres per hour.

273 A clockwork system, driven by a spring or chain and weight, rotates the drum so that the part facing the variometers moves downward. A perfectly balanced drum should move in its bearings with some friction, in order to prevent backlash. Unbalance of the drum can be cured by applying solder to the side which has the mass deficit. If backlash occurs, friction can be increased by a leaf spring pressing against the drum axle. The La Cour recorder is equipped with a chain and weight for preventing backlash. Sometimes the clockwork drive is not perfectly uniform. When inspecting the traces of the magnetogram with a lens, one may find that they vary in width or that gaps appear with a period of several tens of seconds. This defect is caused by irregularities in a cog-wheel of the gear train, resulting in periodically varying friction. Sometimes a watchmaker may be able to remove the defect but usually it is beyond remedy.

274 Most clockwork systems are equipped with a contact that turns on the time-mark lamp for a few seconds every full hour. The time marks appear as straight lines cutting across the magnetogram. There exist some older types of recorders in which a screen intercepts the light beams every full hour for 15 to 30 seconds. The time marks appear as gaps in the variometer traces and baselines. Recorder clocks are usually not reliable and require checking and adjustment practically every day. At most observatories, clocks or chronometers are therefore used for actuating the time marks as described in paragraph **94**. Sometimes the time-mark lamp is used for giving additional time marks when absolute observations are being made, in order to facilitate the measurement of ordinates. However, it is more practical to install for that purpose a second lamp which is shifted sideways with respect to the time-mark lamp so that the additional time marks are shifted in ordinate and can be distinguished from the hour marks.

275 In front of the drum is mounted a cylindrical lens of focal length between 5 and 25 millimetres. Best results are obtained with a short focal length. An adjustable slit between the lens and the drum allows the aperture of the cylindrical lens to be restricted in order to give sufficient depth of focus. In some recorders, a ground glass can be inserted in the plane of the photographic paper, after the drum has been removed, for focusing the variometers.

VARIOMETERS FOR RECORDING THE HORIZONTAL COMPONENTS

276 The variometers for recording the horizontal components D, H, X and Y, manufactured by Ruska, by Mattig & Wiesenberg and by Askania, are similar in design and are all based on concepts of Eschenhagen. These variometers are therefore often called Eschenhagen variometers. They consist of a base with three levelling screws. The alidade on which the magnet housing rests is adjustable in azimuth. The suspension tube on top of the magnet housing carries, on its upper end, the torsion head with a divided circle and a micrometer drive for the fine adjustment of the fibre torsion. The lower armature of the fibre, which is also called the stirrup or coupler, can be clamped by means of the clamping mechanism at the bottom of the suspension tube. In the clamped state, the variometer can be transported and the magnet-and-mirror assembly may be hung to the stirrup without danger of breaking the suspension fibre. The column below the magnet housing is provided with two collars which can be turned independently in azimuth, one of the collars carrying four arms for setting up the Helmholtz-Gaugain coil, the other collar being provided with four holes into which bars can be screwed. The latter are equipped with riders on which compensating magnets can be fitted in the horizontal plane of the recording magnet.

277 The magnet-and-mirror assembly has a hook at its upper end which fits into the stirrup at the lower end of the suspension fibre. In the single-reflection type variometers, mirrors can be adjusted by means of a fine screw or by bending the stem on which magnet and mirror are mounted. The magnet can be turned in azimuth with respect to the normal to the mirror. Variometers of the single-reflection type are without parallel in sharpness of trace but their adjustment requires patience.

278 In periods of storminess, the excursion of the light spot may go beyond the photographic paper. In order to avoid loss of trace, the mirror has three facets which are so arranged as to give three different light spots which appear about 20 centimetres apart on the recorder drum. When one spot leaves the drum at one end, the other spot appears at the opposite end of the drum. For a short while both traces will be on the photographic paper. Variometers of this type can be only used at the distance from the recorder prescribed by the makers, unless spare traces are provided by other means. If the mirror of the single-reflection type variometer has only one facet, spare traces may be provided by a second and third light source, left and right of the source producing the normal trace. This causes no difficulty when electricity is available from mains. If batteries are used, an additional prism or mirrors may provide the spare traces as in the La Cour magnetograph.

279 Variometers with a fixed counter-mirror offer greater ease of adjustment but the increased number of reflections causes loss of light and sharpness of the traces. It suffices to adjust approximately the normal of the magnet mirror with respect to the magnetic axis of the recording magnet. The final adjustment of the light beam is made by turning the counter-mirror by means of three or four capstan screws in azimuth and elevation angle, without touching the magnet-and-mirror assembly. Figure 28 (*a*) depicts the La Cour D-variometer, in which a prism is used instead of a mirror. The light beam can be adjusted by turning the prism in elevation (after having loosened two capstan screws in the prism-holder) and the alidade carrying the magnet chamber in azimuth. Figure 28 (*b*) shows a case which is theoretically possible but difficult to realize because a large projection lens is required. The arrangement shown in Figure 28 (*c*) uses double reflection in order to double the effective length of the optical lever. This case is

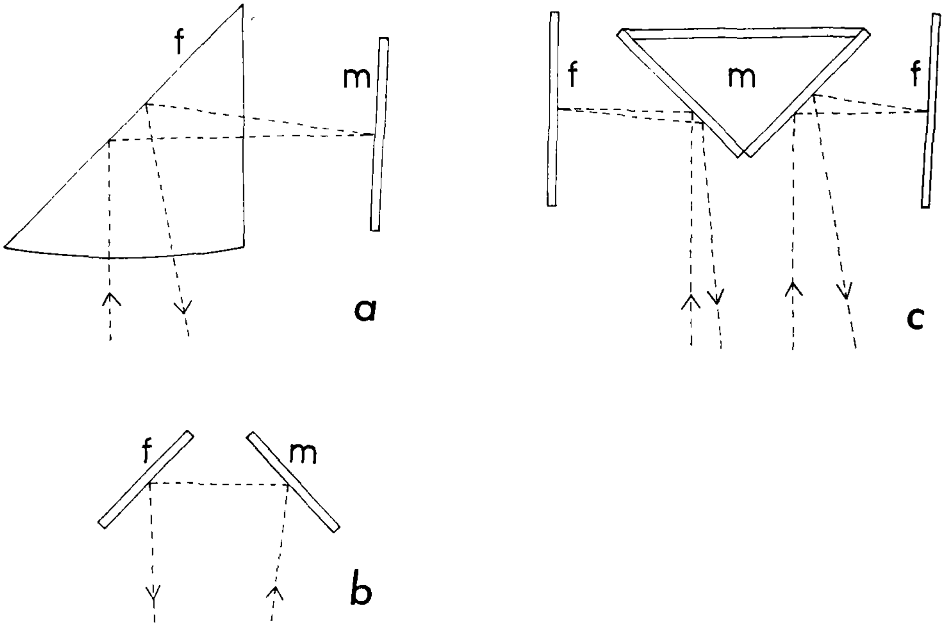

FIG. 28. Types of reflections in variometers for recording horizontal components. m = magnet mirrors; f = fixed counter-mirrors. (*a*) La Cour D-variometer. (*b*) Inversion of light-beam movement by means of a fixed mirror. (c) Double reflection for doubling the effective length of the optical lever.

of great practical importance for low latitudes because it enables the sensitivity of a D-variometer to be doubled without changing the distance between the variometer and the recorder. It is also frequently used in sensitive H-variometers, in order to obtain high sensitivity with small angular movements of the recording magnet. The number of reflections may be increased but every additional reflection causes loss of light and sharpness of the trace. In the Askania variograph, the number of reflections is carried to an extreme by using mirrors of high quality. Note that the configurations shown in Figure 28 (*a*) and (*b*) invert the direction of the light beam.

280 The Copenhagen H-variometer described by La Cour and Laursen (Comm. Mag. No. 11) belongs to the class of variometers shown in Figure 28 (*a*) and (*b*), but it does not invert the direction of movement of the light beam. The instrument is adjusted in azimuth by turning the whole variometer. The light beam of the magnet mirror can be adjusted by means of two prisms, of which one is suspended on a bimetallic strip in order to provide optical compensation of temperature changes. The suspension fibre has quartz drops at either end which prevent it from slipping in its holders (a defect quite common in Eschenhagen variometers). Purchasers of the Copenhagen H-variometer are provided with the above-mentioned publication, so that no further description is required here.

281 The suspension fibres of variometers are usually of quartz because quartz combines high strength with low rigidity and its elastic properties are superior to those of other materials. For the declination variometer, the suspension fibre is made as thin as is compatible with the weight of the magnet-and-mirror assembly. The recording magnets of the variometers for H, X and Y are brought to the prescribed azimuth, at least partly, by means of fibre twist. The fibres of these variometers are therefore larger in diameter and less fragile than the suspension fibre of a D-variometer. Makers of variometers supply fibres of suitable diameter and sufficient in number, either mounted in brass tubes in a clamped state or fitted with brass stems at both ends. Fibres of La Cour variometers have quartz drops at either end. In these circumstances the observer is rarely confronted with the problem of selecting and mounting a quartz fibre as described in McComb's *Manual* (paragraphs 179-95).

282 Suspension fibres mounted in brass tubes can be easily inserted and replaced. Lift the torsion head of the variometer from the suspension tube, after loosening the clamping screw of the micrometer drive. In some cases a second screw may have to be loosened. It will be noticed that the armature at the lower end of the suspension fibre is held by four rectangular pieces of the slotted part of the tube, which are pressed together by a short length of clamping tube. After having connected the stirrup to the lower end, and the torsion head to the upper end of the tube, hold the assembly vertically over the suspension tube of the variometer. Hold the clamping tube with one hand and push the fibre tube slowly downward with the other hand. When the fibre tube is pushed down, the clamping tube will slide upwards. The slotted part of the fibre tube will spread outward and the stirrup will become free. When the stirrup passes the clamping mechanism at the lower end of the suspension tube, it may get entangled in the clamp and the fibre may become slack. If this occurs, lift the tube assembly slowly and lower it again until the stirrup appears in the magnet chamber. The presence of an assistant to guide you in this operation is often helpful.

283 Fibres fitted with brass stems at both ends are supplied clamped in a case. Open the clamps at the ends of the fibre and make sure that the stems are not stuck to the velvet lining of the case. Lift the fibre from the box on to a piece of stiff cardboard 20 by 40 centimetres in size, using tweezers. Connect the stirrup to one end and the torsion head to the other end of the fibre. Press the torsion head on to the cardboard with one hand, and with the other hand lift the end of the cardboard near the torsion head slowly to the vertical position. After having removed the cardboard, move cautiously to the variometer and thread the fibre with the stirrup into the suspension tube, observing the precautions mentioned in the previous paragraph. Fibres of La Cour variometers may be treated the same way. Kring Lauridsen proposes a different approach in the instructions supplied by the makers with this magnetograph.

284 Prepare the threading-in of fibres by mentally repeating the procedure over again and again, in order to foresee and forestall all difficulties you may meet. Have the required tools handy and make the conditions for working (e.g. position of light, height of seat relative to the bench, etc.) as comfortable as practicable before starting the operation. If you do not succeed at the first attempt, interrupt the work with a walk in the fresh air, or put it off till next morning.

BALANCES FOR RECORDING THE VERTICAL INTENSITY

285 Conventional (Eschenhagen) balances made by Ruska, by Mattig & Wiesenberg and by Askania consist of a base resting on three levelling screws and the alidade carrying the magnet chamber. At the bottom of the chamber, a cam is arranged that can be turned from outside by means of a clamping lever which raises and lowers a platform, also called a cradle, with three spikes on its top side. Three grooves arranged radially on the lower side of the body of the magnet system engage the spikes of the platform when the magnet system is inserted. When inserting the magnet system, take care that the balance is in the clamped state (platform raised) and see that the knife edges do not touch the magnet chamber. Finally check whether the magnet system rides properly on the spikes.

286 The magnet system consists of two ellipsoidal magnets fitted to the opposite sides of a cubical body or frame of aluminium. The mirror is mounted on the upper side of the frame. On the sides of the frame, between the magnets, two spindles are arranged which carry the balancing poises. When the spindles are of the same material, both poises are used for balancing the magnet system. Some types of balance magnets are temperature-compensated mechanically; in this case, one spindle is of invar and carries the latitude or balancing poise (McComb, paragraph 271). For places with positive/negative Z, the invar spindle is on the side of the south-/north-seeking pole of the magnet system. The aluminium spindle carrying the temperature poise is on the opposite side of the frame. On the bottom side of the frame, a heavy screw with central locking screw, the sensitivity poise, enables adjustment of the sensitivity of the balance by turning the screw in or out, thus raising or lowering the centre of gravity of the magnet system.

The lid on top of the magnet chamber carries the prism for turning the incoming light beam from horizontal to vertical and the outgoing light beam from vertical to horizontal. The prism can be tilted by means of three or four capstan screws for adjustment of the outgoing light beam in azimuth and elevation angle. If the balance is temperature-compensated magnetically the lid may also carry the holder for the compensating magnet. Some makes of balances allow the lid to be placed in two directions, 180° apart, so that the north-seeking pole of the magnet may point either to the left or to the right of the light beam.

287 Balances of the type described are equipped with knife edges of agate, quartz or hard glass. They function well at a relative humidity below 90 per cent. At higher relative humidity they react with erratic changes of base-line values. In any climate, except a very dry one, fungus develops on the knife edges and bearings in the course of time, causing a slow rise in the scale value and also, at an advanced stage, erratic or continuous changes in the base-line values. This can be prevented by cleaning the knife edges and bearings with alcohol every six months, or whenever the scale value and/or the base-line value starts to change. Use a clean piece of linen for washing and another piece for rubbing dry. Apply only mild pressure, in order to prevent damage to the knife edges. It will be noticed that the scale value will return to normal after washing. However, for a week or two the base-line value may change continually by a few gammas in one or other direction. It may be useful to inspect the knife edges with a lens before inserting the magnet, and to direct the air stream of a small blower against the bearings and knife edges when lowering it, in order to prevent dust particles settling between the knife edges and the bearings.

288 A balance of perfect performance is the Godhavn balance described by La Cour (Comm. Mag. No. 8). The magnet system, including the knife edges and the mirror, is shaped from a single piece of tungsten steel. The weight of the magnet system is less than that of any conventional magnet system. The instrument consists of a heavy base equipped with three levelling screws, and is adjustable in azimuth by turning the whole base. The clamping mechanism and the bearings are mounted in the centre of the base. The magnet chamber consists of a plexiglass cylinder which rests on the base. The upper chamber, containing the optical temperature compensator, the base-line mirror, the temperature mirror and the projection lens, covers the plexiglass cylinder. The magnet chamber is made airtight by greasing the smooth circular part of the base, the rims of the plexiglass cylinder and the bottom of the upper chamber, using a special grease supplied by the makers. The air in the magnet chamber is dried once and for all by a small quantity of silica gel, so that the balance performs well even in an extremely humid variometer room. The first Godhavn balances were equipped with facilities for producing a vacuum in the magnet chamber. Later it was found that the magnet behaves well in air of atmospheric pressure. Some observers do not apply the grease because they fear difficulty in separating the parts. However, when the magnet chamber is not airtight, the balance cannot develop its full capabilities. The separation of the base and the cylinder is not so difficult when alcohol or petrol is applied to the joints. After a few minutes, twist the upper part of the balance against the base, which is held by an assistant. The parts will separate. The forceful method described by La Cour (i.e. separation by means of a lever) should be used only as a last resort for opening the balance.

289 The balance magnet, which is preadjusted by the makers, is adjusted to the horizontal by grinding its dipping end. If, in the operating position, the north-seeking pole of the magnet is not directed towards south, a better adjustment may be obtained by putting the base on a levelled glass plate with the magnet in the magnetic prime vertical. Adjust the magnet to the horizontal by grinding the dipping end. Turn the base slowly in azimuth with the north-seeking pole towards south until a dip becomes visible (because of the increased sensitivity caused by the destabilizing effect of H). Grind the dipping end of the magnet again and continue turning the base in azimuth and grinding the magnet until the north-seeking pole points towards south. If the scale value of the balance is small, the magnet may become unstable before its north-seeking pole points towards south. In this case, discontinue the adjustment when, upon slight grinding, the magnet dips to the other side. Detailed instructions concerning adjustment of the balance and grinding the magnet are given in the instructions accompanying the La Cour magnetograph.

290 In order to overcome the basic difficulties of knife-edge balances, which are mainly caused by humidity, various approaches have been made towards constructing balances with taut suspensions. Until recently, the performance of balances of this type was far from satisfactory. However, a few years ago Fanselau constructed a balance with good stability. Sokkisha Ltd. manufacture a balance of the taut-suspension type which performs well. Bobrov uses quartz fibres for suspending the very small magnet system.

291 Except in the La Cour variometers, recording magnets are damped by means of copper plates or pots. Ferromagnetic impurities contained in the copper often cause irregularities in the indications of the variometers. Usually the impurities originate from tools and may be removed by etching. If all traces of ferromagnetic material cannot be removed, the distance between the recording magnets and the damping plates may be increased or the plates may be taken out. Occasionally damping plates of pure aluminium or silver have been used with success.

TEMPERATURE COMPENSATION

292 Intensity variometers change their indications with temperature. It has been mentioned in paragraphs **10** and **11** that the best method of eliminating this source of error is to keep the variometer room at a constant temperature. If this is not feasible, one of the methods of temperature compensation may be employed in order to reduce the labour in data processing.

293 The most common method of temperature compensation involves the use of magnets which reduce the recorded component at the location of the recording magnet to approximately half its value. With changing temperature, the angular movement of the light beam caused by the changes in the magnetic moment of the recording magnet and in the torsion constant of the suspension fibre is offset by a change in the magnetic field of the compensating magnets. The exact compensation has to be found by heating and cooling the room. Detailed information on the temperature compensation of the different types of variometers can be found in McComb's *Manual.*

294 The change in the magnetic moment of the recording magnet under the influence of temperature may be compensated by shunting this magnet with material of opposite temperature coefficient, such as thermoperm or thermoflux. Exact compensation is achieved by varying the dimensions of the shunt.

295 The Godhavn balance and the Copenhagen H-variometer are optically compensated. In the light beam of the magnet mirror, a prism is suspended on a bimetallic strip. The strip consists of silver and platinum. Since silver has the larger coefficient of thermal expansion, with rising temperature the strip will bend towards the platinum side, thus turning the prism. If the strip is inserted properly, its effective length can be so adjusted as to offset the angular movement of the light beam caused by a change in the magnetic moment of the recording magnet. In the Copenhagen H-variometer, the strip has to be inserted so that the silver side (marked by a black dot) is at the left-hand side of the observer looking into the variometer lens, when the north-seeking pole of the recording magnet points east, at the right-hand side when the pole points west, irrespective of the direction of the light beam. The north-seeking pole of the recording magnet is marked by red paint. In the Godhavn balance, the black dot must be on the side of the south-seeking pole of the balance magnet when Z is positive, on the side of the north-seeking pole when Z is negative. The bimetallic strip can be inserted in the prism in either position. A final check of the position of the bimetallic strip is afforded by looking at the record. With rising temperature, the temperature trace should move towards increasing numerical values of the element in question.

296 The state of compensation of variometers is found by heating and cooling the variometer room to as high and as low a temperature as possible. When using a kerosene stove, make sure that there is sufficient ventilation. Heating and cooling should be done slowly, so that all parts of the instruments have the same temperature at all times. At the extremes, keep the temperature constant for one hour.

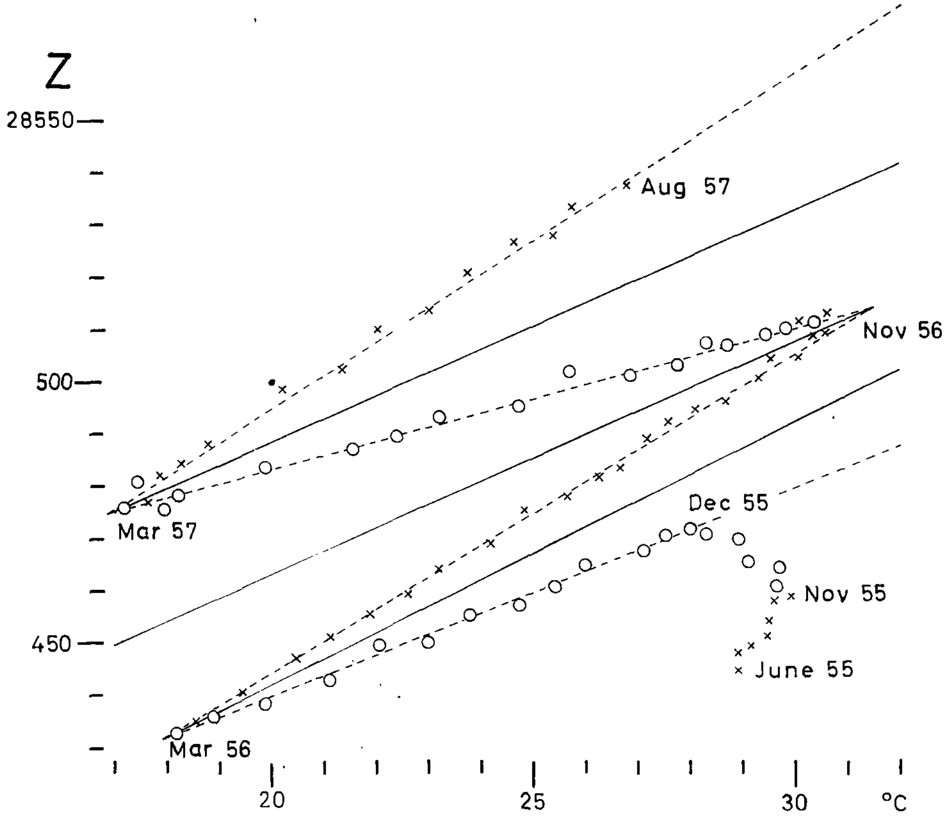

FIG. 29. Determination of the residual temperature coefficient of a Godhavn balance from base-line values.

Make parallel absolute observations with instruments of sufficient accuracy at least at the two extremes of the room temperature. Also read the thermometers of the variometers. From the ordinates of the variometer traces, the thermometer readings and the observed absolute values, the temperature coefficients of the variometers and (if La Cour variometers are used) the correct effective length of the bimetallic strips for complete compensation can be computed, as given in McComb's *Manual* and by La Cour (Comm. Mag. No. 8). Adjust the compensating magnets or the bimetallic strips to the values found from the computations, and heat and cool the room again in order to check the compensation. Frequently, another adjustment will be required. When the residual temperature coefficients do not exceed 1 gamma/°C, one may be satisfied.

297 A valuable check on the state of temperature compensation is obtained by following up the base-line values of the intensity variometers over a period of several years. When the temperature of the variometer room is not kept constant, residual temperature coefficients will be indicated by an annual fluctuation in the base-line values, unless the difference between summer and winter temperatures is small. Figure 29 shows, as an example, the determination of the residual temperature coefficient of a Godhavn balance at the observatory of Helwan. The magnetograph was installed in June 1955, on a recently constructed pier. The temperature variation in the variometer room followed a slightly distorted sine wave with a period of one year. The change of base-line values was irregular from June to December 1955. From then onwards, the base-line values followed a saw-tooth pattern which is brought about by superposition of the temperature effect and a loss of magnetic moment of the recording magnet. At that time the magnet was four years old. The residual temperature coefficient can be derived from straight lines through the clouds of points. During periods of decreasing temperature (indicated by circles), the temperature coefficient appears smaller than with rising temperature (indicated by crosses). The means of the apparent temperature coefficients obtained from adjacent branches of the graph are the true temperature coefficients.

BASE-LINE MIRRORS, DIAPHRAGMS AND FILTERS

298 Often it is difficult to obtain sharp traces from the magnet mirror and the base-line mirror, because of slight curvature of one or the other mirror. One may exchange the base-line mirrors among the variometers until the greatest sharpness is obtained. Occasionally, base-line mirrors (and also projection lenses) are deformed by pressing them in the frame. Tighten the retaining screws mildly so that the mirrors move at a slight touch.

299 Some makers provide variometers with screens which can be moved in front of the mirrors in order to reduce their effective height. If the effective width of a mirror is made smaller, the sharpness of the trace will suffer. When no screens are provided, the strength of the trace may be reduced by a circular diaphragm mounted in front of the projection lens. Sometimes it may be necessary to dim the traces of base-line mirrors by means of paper strips in front of the mirrors.

Alternatively, a blue filter may be installed in the path of the light beam between the light source and the variometer whose traces are to be dimmed. A filter will also enhance the sharpness of the traces and remove ghosts.

PROJECTION LENSES

300 When the recorder and the trace lamp are at the same distance from the variometer, the focal length of the projection lens must equal that distance if a sharp image of the filament of the incandescent lamp is to appear on the recorder drum, i.e. the lamp and the recorder drum must be in the focal plane of the projection lens. This condition is usually valid for the Eschenhagen magnetograph. If the lamp is between the projection lens and its focal plane, the image will be sharp behind the focal plane. This explains why in the La Cour magnetograph the distance of the variometers from the drum is larger than the focal length of the projection lenses specified in the data sheet.

301 Sometimes the focal length of a projection lens has to be changed. The price of a lens made to specifications at a factory would be prohibitive, not to speak of the time required for obtaining it. Inexpensive lenses of reasonable quality are available in the shape of spectacle lenses. The raw lenses have a diameter of 50 to 60 millimetres and will therefore usually fill the frame of a variometer. Any optician will grind the lens to shape so that it fits into the frame. The La Cour D-variometer has a lens ground to the surface of a prism. The focal length of the system can be changed by mounting a convex or concave lens in front of the prism. Opticians grade lenses according to diopter, defined by

$$d = \frac{1}{f} \tag{79}$$

where d = diopter; f = focal length of lens in metres.
If two lenses of diopter d_1 and d_2 are joined, the diopter of the resulting lens will be

$$d_x = d_1 + d_2 \quad \text{and} \quad f_x = \frac{1}{d_x}. \tag{80}$$

The lenses of interest to a geomagnetician, among the optician's usual stock, are of + 0.75, + 0.50, + 0.25 (convex) and – 0.25, – 0.50, – 0.75 (concave) diopter. When investigating a batch of lenses, one will find appreciable departures of individual lenses from their nominal values, so that almost any focal length is available in the range of interest.

Example. It is planned to change the focal length of the projection lens of a La Cour D-variometer from 170 to 250 centimetres. Then

$$d_x = \frac{1}{2.50} = 0.40 \text{ diopter.}$$

$$\text{Projection lens of variometer } d_1 = \frac{1}{1.70} = 0.59 \text{ diopter.}$$

$$\text{Further,}\quad 0.40 = 0.59 + d_2$$
$$\therefore\ d_2 = -\ 0.19.$$

The desired lens is concave. Take the prism to an optician's workshop and try a number of lenses of nominal diopter − 0.25 together with the prism until the desired focal length of 250 centimetres is obtained. The optician may perhaps lend you a batch of lenses so that you can try them *in situ*. Note that it may be difficult to obtain a lens of a diopter smaller than ± 0.25. One may try to stack two lenses of − 0.50 and + 0.25 diopter in order to obtain about − 0.19 diopter. When several lenses are stacked they must be centred accurately.

Example. It is planned to replace an Eschenhagen H-variometer (distance from variometer to recorder = 125 centimetres) by a Copenhagen H-variometer (focal length of projection lens = 170 centimetres). Select from a batch of lenses of + 0.75 diopter (nominal focal length = 133 centimetres) one of the required focal length and replace the original lens.

AGEING OF MAGNETS

302 Magnets supplied with La Cour variometers are properly aged; the loss of magnetic moment in the course of time is inappreciable. For that reason La Cour variometers will be stable almost from the beginning of operation. Occasionally, makers of variometers supply un-aged recording and compensating magnets. With un-aged magnets, the base-line values will change rapidly in the beginning. After several years the ageing process will slow down. Cobalt-steel magnets age faster than Alnico magnets.

303 In general, the observer will not know whether the manufacturer of his instruments has taken care to age the magnets. Correspondence will clear up that point. The ageing of cobalt-steel magnets starts with the reduction of their magnetic moment to 70 per cent of its original value in an alternating field (50 or 60 cycles per second). This may be produced by a choke from which the yoke of the E-shaped core has been removed, or by a coil wound on a cylinder of 2 to 3 centimetres diameter. Feed the choke or coil from a step-down transformer and use a rheostat for regulating the current. Start the demagnetization at low current, exposing the magnet one or two seconds to the demagnetizing field. Measure the magnetic moment. Continue in small steps until the magnetic moment is down to the required value. Take care that the magnet is not totally demagnetized by applying too much current or exposing the magnet to the AC field for too long periods. Alnico magnets should be demagnetized to about 95 per cent of their original magnetic moment. After demagnetization, heat treatment is applied as described by La Cour. Cobalt-steel magnets are boiled 24 hours in water, Alnico magnets in oil at 200° C. Then the magnets are cooled in dry ice (carbon-dioxide snow) and heated and cooled again through ten cycles, which may be done in rapid succession. Magnets treated in this manner will maintain an almost constant magnetic moment from the beginning.

Layout of an Eschenhagen magnetograph

304 In any magnetograph, the position of the variometers with respect to the recorder should be such that the light beams from the magnet mirrors meet the drum nearly at right angles. The angle between the incoming and outgoing light beam of a variometer should be small and should be bisected by the optical axis of the projection lens. Furthermore, the variometers should be sufficiently far apart for interaction between the (moving) recording magnets to be small. The fields of the Helmholtz-Gaugain coils should exert a negligibly small influence on the other variometers when scale value determinations are made. These requirements are best met by the Eschenhagen magnetograph, which also permits the use of compensating and sensitivity control magnets. Although the light beams of a magnetograph can be arranged in any direction, the magnetic meridian deserves preference because the balance magnet can be inserted with the north-seeking pole either east or west without the necessity of readjusting the scale value. Ruska specifies the magnetic prime vertical for the direction of the light beams. Figure 30 shows the layout of a magnetograph with the light beams near the magnetic meridian. The recorder may face either north or south.

305 The variometers are set up on the pier so that the light beams are not intercepted by the frames of the Helmholtz-Gaugain coils (whose contours are indicated in the drawing) or the compensating magnets. Difficulties can be avoided if the recorder pier is made large enough for the recorder to be shifted to one side or the other, or turned so that the axis of the drum departs from the magnetic meridian or the prime vertical.

306 If, at low latitudes, a higher sensitivity of the D-variometer of the single-reflection type is required, sensitivity control magnets may be introduced. However, if the variometer room is sufficiently long, the D-variometer may be moved to a distance of four metres from the recorder, after one has replaced the projection lens or modified its focal length as described in paragraph **301**, thus retaining a proper D-variometer. The arrangement is advantageous because the distance between the variometers is increased to one metre.

307 The adjustment of Eschenhagen variometers is described by McComb. His method of adjustment of the recording magnets to the prescribed direction, by means of a long magnet, has the advantage that the determination of the ex-orientation angles of the recording magnets can be made without touching the variometers, but it requires a room with special facilities (shelves along the walls). Helmholtz-Gaugain coils can be used for the orientation of recording magnets in any variometer room (Bock, 1942; Laursen, 1943), provided that the magnetic meridian has been established as described in paragraphs **266-68**. The method consists in setting up the axis of the Helmholtz-Gaugain coil of a variometer in the magnetic meridian (D-variometer) or magnetic prime vertical (H-variometer) and feeding a current through the coil. If the recording magnet departs from the direction of the coil's axis, it will move when a current is passed through the coil. The magnet is adjusted until there is no visible movement of the light spot produced by the magnet mirror on the recorder drum, i.e. when the

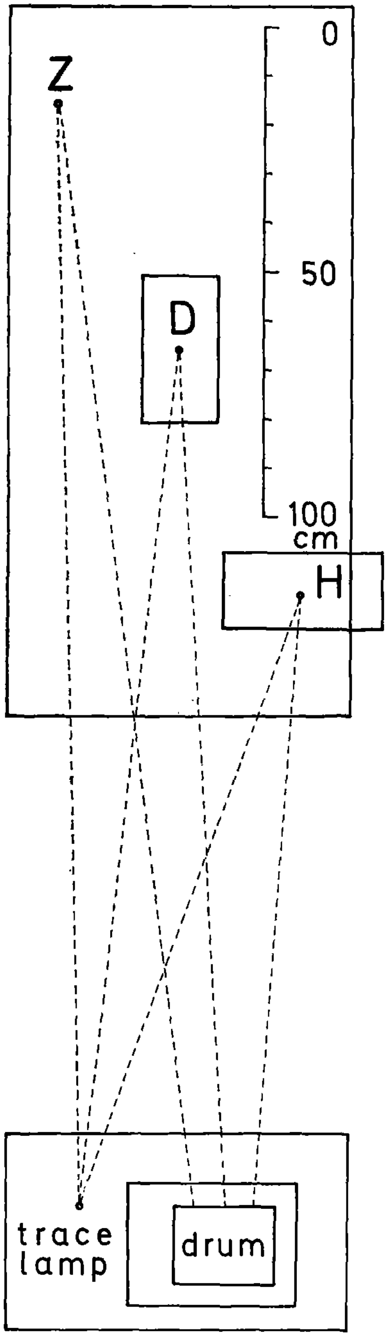

FIG. 30. Layout of an Eschenhagen magnetograph.

magnet is aligned with the axis of the Helmholtz-Gaugain coil. Start the adjustment by turning the axis of the Helmholtz-Gaugain coil and the recording magnet approximately to the required azimuth. Establish a magnetic meridian (or magnetic prime vertical) above one of the coil frames, using a cord hung over the boards on the walls of the room. Hang plumbs from the cord on either side of the variometer, about one metre apart. Turn the coil until its frame is aligned with the threads of the plumbs. Aiming may be improved by holding a ruler to the coil frame. If you have marked the magnetic meridian and prime vertical on the pier, draw a parallel below one of the coil frames and align the frame with the parallel. Limit the current in the Helmholtz-Gaugain coil to 0.5 or 1 ampere, depending on the diameter of the wire of the coil, by inserting a rheostat in the circuit and switch the current on only for one second in order to prevent burning of the coil. Upon completion of the adjustment of the recording magnets, the Helmholtz-Gaugain coils are turned 90° in azimuth for the determination of the scale values.

308 Makers of magnetographs specify the dimensions and directions of piers. The specifications should be obtained before designing the variometer house. It is recommended that very meagre concrete be used for the construction of the piers, so that it may be possible to modify or demolish them if desired. Before setting up any magnetograph in the variometer room, the operator should study all details of the adjustment of the variometers in the comfort of the laboratory. He may adjust the magnetograph on a bench or a couple of sturdy tables, in order to learn how the various adjustments are made and where difficulties have to be expected. The recording magnets may not be used if the variometers cannot be clamped (La Cour D and H). This preparatory work in the laboratory will give the operator confidence for the adjustment of the magnetograph in the usually narrow variometer room.

Layout of the La Cour magnetograph

309 The purchaser of a La Cour magnetograph is supplied with the following publications:

La Cour, D. *La balance de Godhavn.* Danish Meteorological Institute. (Comm. Mag. No. 8.)
——; V. Laursen. *Le variomètre de Copenhague.* Danish Meteorological Institute. (Comm. Mag. No. 11.)
Laursen, V. *Observations faites à Thule.* Part I: *Magnétisme terrestre.* Copenhagen, 1943.

Supplementary instructions concerning the installation of a La Cour magnetograph are given in a set of notes (in English) which are also supplied with the equipment. The three publications describe in detail and explain in numerous figures the construction of the variometers and their adjustment.

310 Figure 31 shows the position of the variometers with respect to the recorder. Usually the light beams are arranged near the magnetic meridian, for reasons mentioned in paragraph **304**, but the light beams may be arranged in any other direction without undue complications. The La Cour magnetograph was originally designed for high latitudes, where the amplitudes of variations are large. In order

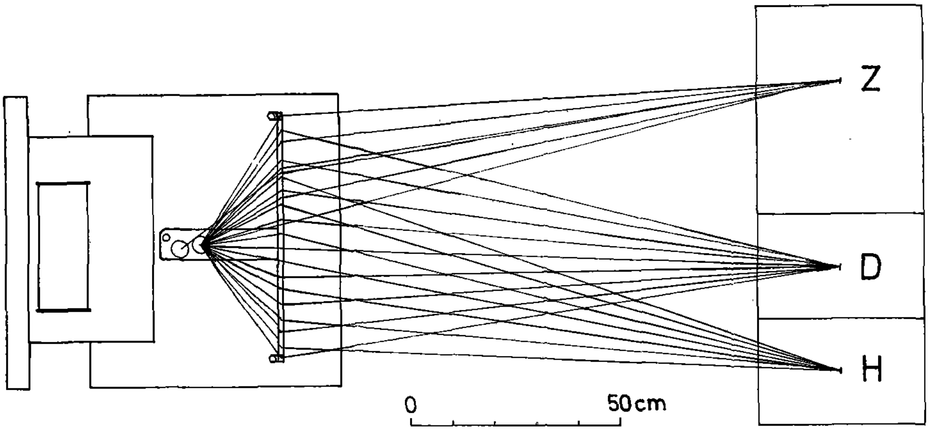

FIG. 31. Layout of a La Cour magnetograph (after Laursen, 1943).

to avoid confusion of the traces, the registration of each variometer is restricted to ten centimetres, which is one-third of the width of the recorder drum, by placing the variometers at different heights and using three cylindrical lenses of long focal length.

311 At low latitudes, where the amplitudes of variations are small, the restriction of the traces to one-third of the drum width may be removed. The three variometers may be set up at the same level and a long cylindrical lens of short focus may be mounted on the front wall of the recorder housing. Time marking can be provided by lines across the magnetogram as is done in the Eschenhagen magnetograph. The variometers may be adjusted to higher sensitivities by grinding the magnet of the Godhavn balance and using a fibre of smaller diameter in the H-variometer. If full temperature compensation is desired, the scale values of the intensity variometers should not be smaller than $S_H = (H^{(\gamma)}/6000)\gamma$/mm and $S_Z = (Z^{(\gamma)}/18\,000)\gamma$/mm. Hence one should either provide a variometer house of high temperature stability or introduce temperature control in order to arrive at a reasonable small scale value in H.

312 In the (close-spaced) La Cour installation, the sensitivity of the D-variometer cannot be raised by using sensitivity control magnets. By introducing a stiff suspension fibre, the north-seeking pole of the recording magnet can be forced towards south, thus providing destabilization by the horizontal component (Laursen, 1943). Assume that the magnetic meridian, to which the recording magnet was originally adjusted with its north-seeking pole towards south, is in the direction designated 'magnetic north' (Fig. 32). A change in the declination by ΔD towards east will turn the magnet through an angle $\Delta\theta$ towards west. The scale value of the variometer can be estimated from the equation above equation (119) in McComb's *Manual*, which is

$$S_D = \frac{3438}{2R}\left(\frac{-H + C + k'/M}{H}\right) \tag{81}$$

where S_D = scale value of D-variometer, in minutes of arc per millimetre; R = distance of variometer from recorder drum, in millimetres; H = horizontal intensity, in gauss; C = component of stray fields from other variometers in the direction of the recording magnet, in gauss; k' = torsion constant of suspension fibre, in dyne-cm per radian; M = magnetic moment of recording magnet, in gauss cm^3.

The precise scale value has to be determined by means of a Helmholtz-Gaugain coil and a milliammeter. Equation (81) is used for finding the torsion constant of the suspension fibre.

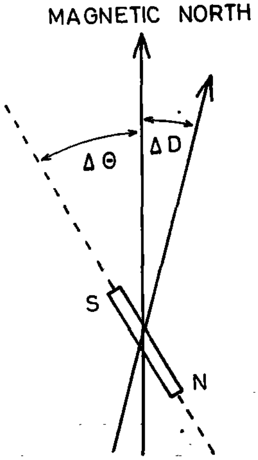

FIG. 32. D-variometer with inverted magnet (after Laursen, 1943).

Example. The torsion constant k' has to be determined for a D-variometer set up at a recording distance R = 1 719 millimetres, with the north-seeking pole of the recording magnet pointing towards south (with the recording magnet in the normal position this variometer would have a scale value S_D = 1′/mm). The other quantities required for the computation of k' are: desired scale value S_D = 0.5′/mm; H = 0.2 gauss; magnetic moment of the recording magnet M = 3 gauss cm^3; stray fields C = 0. Inserting the quantities in the above equation, we obtain

$$0.5 = \frac{3438}{3438}\left(\frac{-0.2 + k'/3}{0.2}\right) = -1 + \frac{k'}{0.6}$$

$$k' = 0.9 \text{ dyne-cm/radian.}$$

If D changes by 10′, the recording magnet of this variometer will move through the angle $\Delta\theta$ = 20′ in the opposite direction. Thus the difference in angle between the magnetic meridian and the direction of the recording magnet will be 30′. The D-variometer with inverted magnet should therefore be used only in areas where the (angular) variation of D is small, i.e. at low latitudes.

The sensitivity of the D-variometer may also be increased by shifting it behind the other two variometers to a distance of about 250 centimetres from the recorder, after adjustment of the focal length of the projection lens (paragraph **301**). This modification offers all the advantages of the normal Eschenhagen arrangement. It permits the introduction of sensitivity-control magnets. The optical temperature compensation may be supplemented by magnetic compensation when small scale values are used with the intensity variometers. Furthermore, a scale value determination may be made with all three variometers at the same time, if three Helmholtz-Gaugain coils are available. Note that the distance between the variometer and the recorder cannot be increased much beyond 250 centimetres, because it will be difficult to obtain a trace of sufficient strength from the magnet mirror.

313 La Cour variometers may also be used in the Eschenhagen arrangement, as has been done successfully by McComb (McComb's *Manual*, Fig. 13). It will however be of advantage to interchange the D-variometer and Z-balance, because the trace of the balance mirror will be weak at a distance of 225 centimetres from the recorder.

Distribution of traces on the magnetogram

314 The La Cour magnetograph restricts each element to a strip of ten centimetres width. It is practical to place the traces of D and Z approximately in the middle of their strips and H slightly to the positive side, so as to allow uninterrupted recording of the initial positive and subsequent negative phase of a mild magnetic storm, and also to allow the scale-value determinations to be recorded. The numerous spare traces on either side of the main trace will allow space for large excursions of the traces during a violent magnetic storm.

315 With an Eschenhagen magnetograph, one should place the trace of the Z-variometer, which usually has no spare traces, in the middle of the record. When D has lost its spare traces due to modifications, the D-trace should be adjusted to the middle of the magnetogram and the Z-trace slightly below, so that in magnetically quiet conditions the traces of D and Z do not intersect. When D has one spare trace (Fig. 28 (*c*)), place the Z-trace in the middle, the D-trace in the lower part, and the spare trace of D above the upper margin of the record, so that the distance between the main trace and the spare, measured on the drum, is about 180 millimetres. The main trace of H is always put near the positive margin of the record, while the spare trace is put above the positive margin so that it comes on to the record during deep negative phases of a strong magnetic storm. If D and H have two spare traces, there is practically full freedom in placing the traces but it will again be practical to place the main H-trace near the positive margin of the magnetogram.

316 The base-lines are placed 20 millimetres below the traces, (i.e. on the negative side) so that in magnetically quiet conditions the ordinates are positive. This has the advantage that the ordinates converted to gammas have to be added to the base-line values, which is easier than subtraction. If one or several traces are negative in upward direction, the base-lines may be arranged above the trace. For measuring, the magnetogram is turned lower margin up and hourly values are scaled, proceeding from right to left. With some types of magnetogram scaler, it may be advantageous to place base-lines one centimetre from either margin.

Observatory routine

Daily routine

317 Change the photographic paper of the recorder just before a full hour, which may be at the beginning of one of the three-hourly intervals covered by K-indices (0, 3, 6 . . . 21h GMT). If you prefer not to use Greenwich Mean Time, the full hour of the time you use must coincide with a full hour of Greenwich Mean Time or else you will cause the users of your data great inconvenience. Switch the trace lamp off a few minutes before the full hour. Remove the photographic paper from the recorder drum and put it immediately into a light-tight container. Read the temperature of the intensity variometer containing the thermograph to the nearest tenth or fiftieth of a degree centigrade. Wind the recorder clock and, if this clock produces the time marks, adjust it to the correct time. Take a new sheet of photographic paper from the light-tight box, stamp or write the date on the paper side and put the paper on the recorder drum, emulsion outside. When you use glossy paper, the smooth emulsion side can be felt with the finger tips. It may be difficult to feel the emulsion side of mat paper. Usually the paper will be slightly curled towards the emulsion side. For convenience of the operator, photographic paper may be reliably marked in the dark room. Before a new supply of paper (say, 50 sheets) is brought to the variometer room, pencil marks may be made on the paper side, or one corner may be cut, indicating for instance, that the observer faces the emulsion side when he holds the paper with the cut corner up and to the left-hand side. Some manufacturers of photographic paper will (upon request) cut one corner when packing the paper. Turn the trace lamp on when the hour contact makes. Contributors of microfilm copies to world data centres may improve the determination of the parallax by leaving the trace lamp on as long as the hour contact holds, and then switching the trace lamp off for one or two minutes. This more precise parallax test may be made weekly or monthly. Check the electrolyte level of the storage battery and add distilled water so that the plates are covered. Check the voltage of the trace lamp. A voltmeter connected permanently across the lamp at some distance from the variometers is useful for that purpose, because it is difficult to adjust the trace lamp by sight.

318 At some observatories it is considered part of the daily routine to press a gauge across the new sheet of photographic paper in the direction of the ordinates. The gauge carries two short spikes at its ends whose distance apart is somewhat less than the width of the paper. From the true distance between the spikes and the distance of the impressions on the processed paper, the shrinkage is determined for each magnetogram and allowed for when converting millimetres of ordinates to minutes of arc and gammas. At many observatories, the gauge is applied only for every new consignment of photographic paper and a change of shrinkage is allowed for by correcting the scale values of the variometers.

319 Observatories should maintain a magnetograph journal, in which are noted the times of switching the trace lamp on and off, the temperatures of one intensity variometer, and occasionally the relative humidity of the variometer room. Furthermore, adjustments and modifications to the variometer room are recorded. At some observatories the daily data are entered on the paper side of the magnetogram in pencil.

320 When performing the daily routine, take care that you do not disturb the thermal conditions in the variometer room. Close all doors behind you when entering the house and the room. Do not stay in the variometer room longer than absolutely necessary, because the narrow room is warmed up rapidly by the observer. At some observatories, the recorder is installed in the wall so that it can be serviced from outside, and the thermometer is read by means of a telescope in order to avoid changes of temperature in the variometer room.

321 When developing the photographic paper, follow the instructions of the manufacturers unless you have good experience with modified procedures. Warm the developer to the proper temperature. If the developer is too cold, it will work slowly and cause a grey fog on the magnetogram. A grey fog will also result when the lights of the variometer room and the dark room are not safe, if the paper is very sensitive. Use light filters recommended by the manufacturers of the photographic paper. If such filters cannot be obtained, dim the lights by wrapping red paper around the bulbs, or change and develop the paper in complete darkness (which is less difficult than it sounds). This requires that the developer be always warmed or cooled to the same temperature and that development be continued during a time found by trial and error. In some instances the grey fog on the magnetogram may be due to stray light from the trace lamp. Mount a diaphragm in front of the trace lamp so that only narrow strips of light fall on the variometers.

After developing, lift the paper from the bath and let the developer drip off. Wash the paper in water before putting it into the fixing bath, where you leave it until all light-sensitive material is removed (usually 30 minutes). Lift the paper out, let the fixer drip off, and put the paper into the water tank for washing, which should last one hour in standing water and 30 minutes in flowing water. Properly fixed and washed magnetograms will last longer than a century. Take care that the magnetogram is not distorted while processing it. After washing, hang the paper on a line by means of clips. When the paper is almost dry, i.e. when curling starts, roll it up with the emulsion outside and put it into a cardboard cylinder for further drying. At some observatories, curling of magnetograms is prevented by giving them a final wash in a bath of water and glycerine for a few minutes. The proper ratio of glycerine to water will have to be found by trial and error; too much glycerine will make the paper sticky. Photographic paper treated in this way will neither curl nor break at the edges. Whether the treatment has disadvantages, such as an increased variation of dimensions with relative humidity, is not known but may be suspected. Although the drying of magnetograms in a hot press gives them a perfect appearance, it cannot be recommended because the paper may be unduly distorted. Finally, the magnetograms of each current month are put between heavy boards in order to keep them flat for measuring. Magnetograms which are not required any longer may be stored between stiff cardboard covers tied together with string.

322 When the magnetogram is completely dry, write on the paper side the dates and times of switching the trace lamp on and off, and the temperatures. Enter also the clock correction, if any, whose algebraic sign you derive from the equation

$$\text{Recorded time} + \Delta \text{ seconds} = \text{GMT or local standard time.}$$

If you use local standard time, also indicate its meridian. At many observatories, a form is stamped on the paper and the data are filled in. If microfilm copies are contributed to a world data centre, the front side of the magnetogram should be labelled, as described in paragraph **344** and Figure 36. For local use, it is sufficient to inscribe in Indian ink or to stamp on, by means of rubber stamps, the name of the observatory and date in the upper left corner of the magnetogram, together with the times of every third or fourth (or of all) hour marks in either GMT or local standard time. Mark the traces of the recorded elements by D, H, Z and T (T for temperature). Mark the base-lines by D_0, H_0, Z_0, T_0. Indicate the direction of increasing ordinates by means of arrows on the first magnetogram of each month.

323 The comparison of the observatory clock with a time signal also belongs to the daily routine. Further routine work will depend on local custom. At some observatories the hourly means of ordinates are scaled and converted to minutes of arc and gammas each day for one of the previous days.

Weekly routine

324 Absolute observations for the determination of the base-line values are usually made once every week. Normally these observations will be made on the same day each week, unless a magnetic storm is in progress. In this case, the observations are postponed until the disturbance has abated. At some observatories, absolute observations are made every three or ten days. With a vector magnetometer, it is possible to measure the intensities every day without undue increase of labour. Compute the observations soon after making them, in order to ensure that you still remember every detail. Observations and computations should be done by one and the same person, so that the observer can study the defects of his observations. When the computations are made by a different person, the observer will not learn much from the results unless the former is a well-versed geomagnetician who can point out defects. The reduction of the observations to base-line is made two to three days later, when the magnetogram has assumed normal dimensions. The habits of making absolute observations vary from place to place. At most observatories, the best observer will do the routine observations. When he is on leave, the second best observer will take over. It is good practice, before and after the leave of the observer-in-charge, to make two parallel observations by both observers, in order to guard against systematic differences and to give the second observer a chance to improve his proficiency. At remote observatories where staff is relieved every week or month, observations must of course be made by several different observers who should be equally well trained. It is desirable that the observers should be scientists capable of continuous critical examination of their own work, but experienced technicians can produce excellent results under the supervision of a scientist.

325 Scale-value determinations are made once every week, not only for the calibration of the variometers but also to ensure the early detection of defects. With Helmholtz-Gaugain coils connected in series and a D-variometer, whose scale value has been derived from the length of the optical lever, no difficulties are encountered. The milliammeter only serves for setting the coil current to a value by which the traces of the magnet mirrors are shifted 30 to 40 millimetres. If the scale value of the D-variometer is derived from deflections as well, and if the scale values of the variometers are determined individually (as with the La Cour magnetograph), a precision milliammeter has to be used. This must be calibrated against a standard from time to time. An ordinary avometer will not be sufficient for this purpose. When observing scale-value deflections, the undamped recording magnets of the La Cour D- and H-variometer will oscillate with considerable amplitude and make it difficult to measure the displacement of the traces. The circuit shown in Figure 33 will reduce the amplitude of oscillations. Set R_1 to zero and close switch S. Advance R_1 slowly until the desired current

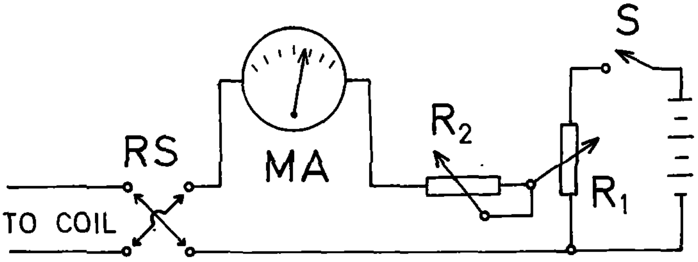

FIG. 33. Circuit for suppressing oscillations of the recording magnets when determining scale values with a La Cour magnetograph (R_1 = 200 ohms, R_2 = 50 ohms).

is indicated by the milliammeter. Use R_2 for fine adjustment of the current. After having recorded for five minutes, turn R_1 slowly back to zero. Throw the reversal switch RS and advance R_1 again slowly. After another five minutes of recording, turn R_1 back to zero and switch the battery off.

In some older types of magnetographs, scale-value deflections are obtained by means of a magnet which is put on the deflection bars of the variometers. In Eschenhagen assemblies, the magnet is calibrated by deflecting the recording magnet of the D-variometer, whose scale value is known from the length of the optical lever, and then the recording magnets of the intensity variometers. If the D-variometer has no provision for placing the deflection magnet (as, for instance, in the Kew magnetograph), the magnetic moment of the deflection magnet has to be determined from time to time, either on a magnetic theodolite or by other methods known to a physicist. The magnet should in this case be treated with great care and kept apart from other magnets. A better approach is to provide the D-variometer with a bearing similar to that of the H-variometer and to include deflections of the D-variometer in scale-value determinations. Before starting observations, let the magnet assume the temperature of the variometer room.

Monthly routine

326 After two or three absolute observations at the beginning of a month, the base-line values of the previous month can be drawn and stepped so that the monthly tables of hourly means can be completed, including computation of the means for 'All days'. The magnetograms are prepared for microfilming and microfilm copies of the tables of hourly means and the magnetograms are made (paragraph **344**).

Other routine work

327 Some servicing and readjustment of the variometers is required from time to time. In a new installation, the base-line value of the H-variometer will decrease, rapidly at first and later more slowly, because of relaxation of the suspension fibre. If the variometer is temperature-compensated magnetically, the compensating magnets may also contribute to lowering the base-line values when they are not well aged. Restore the H-trace from time to time, exclusively by fibre twist or by adjustment of the compensating magnets, *not* by adjustment of the counter-mirror of a multiple-reflection type variometer or the prism of the La Cour H-variometer, because adjustment of the fixed mirror or the prism will only turn the light beam. The recording magnet of the D-variometer will usually remain near the magnetic meridian, unless the suspension fibre is very twisted because of an unduly large artificial component in the magnetic prime vertical. A readjustment of the D-variometer will be necessary when the trace comes near the margin of the magnetogram, owing to secular variation. In this case, the fixed counter-mirror or prism of the La Cour D-variometer may be used. Any Z-balance will remain in a good state of adjustment as long as the trace is restored to its original position by rebalancing the magnet or adjusting the compensating magnet. If the prism is used for this adjustment, only the light beam is adjusted, not the magnet.

Eschenhagen balances require cleaning of the knife edges and bearings whenever the scale value begins to rise continually and/or the base-line value changes rapidly (paragraph **287**).

328 It is desirable to determine the ex-orientation angles of the recording magnets every two years. When facilities are available for the application of McComb's method, a long magnet may be used for this purpose. At latitudes higher than 45°, the ex-orientation angles can be computed from a series of determinations of the base-line values during stormy periods, as explained by La Cour and Sucksdorff (Comm. Mag. No. 16). The scale values can be checked by the same method. In declination, it suffices to insert the strong magnet in the fibre declinometer and to read the diaphragm scale from time to time. Allowance for the rigidity of the suspension fibre has to be made. The absolute values for H may be derived from QHM observations or deflection observations made with an absolute or travel theodolite.

329 In the course of time, dust accumulates on all optical parts of a magnetograph. The deterioration of the quality of records is imperceptible when comparing magnetograms of different months of a year. However, when making a comparison with records obtained several years apart, one will see the difference in quality. It is recommended that all optical parts of the magnetograph be cleaned every four or five years and the variometers readjusted. When dismantling the instruments, take care that you do not spoil the temperature compensation.

330 The frequency of comparisons of observatory standards with primary standards has been discussed in paragraph **256**.

Data processing

Preparation of the base-line value graph

331 It has been pointed out in paragraph **10** that the amount of labour involved in data processing is a minimum when the temperature of the variometer room is constant. Favourable conditions prevail as long as no diurnal variation of the temperature occurs or when the variometers are completely temperature compensated. The worst case is a variometer room with an appreciable diurnal variation of temperature and uncompensated or only partly compensated intensity variometers. In that case every ordinate of the intensities has to be reduced to the standard temperature of the magnetograph. It is convenient to choose for the standard temperature the annual mean temperature of the variometer room rounded to the nearest full degree centigrade.

332 In an earlier chapter ('Instruments, Methods of Observation and Computation'), it has been shown how the base-line values can be computed from the observed values. Temperature corrections of the ordinates were not mentioned because the variometers used in the examples were either temperature-compensated or the temperature of the variometer room was kept at a constant level. The reduction of ordinates obtained with uncompensated variometers to the standard temperature of the magnetograph will be explained in paragraph **337**.

333 If the variometers are kept at a constant temperature or if, in a room with variable temperature, they are either temperature-compensated or the absolute observations are reduced to base-line by means of temperature-corrected ordinates, the base-line values will show only small variations over the course of the year and can be drawn on a single sheet of graph paper together with the scale values. If the intensity variometers have small temperature coefficients, and if the temperature in the variometer room shows no diurnal variation and changes only slowly from day to day, the temperature correction of the ordinates may be omitted. The base-line values of the intensity variometers will probably show an annual variation. In this case it is practical to plot the base-line values of each variometer against time on a separate sheet of graph paper, at a scale of 0.1′ or

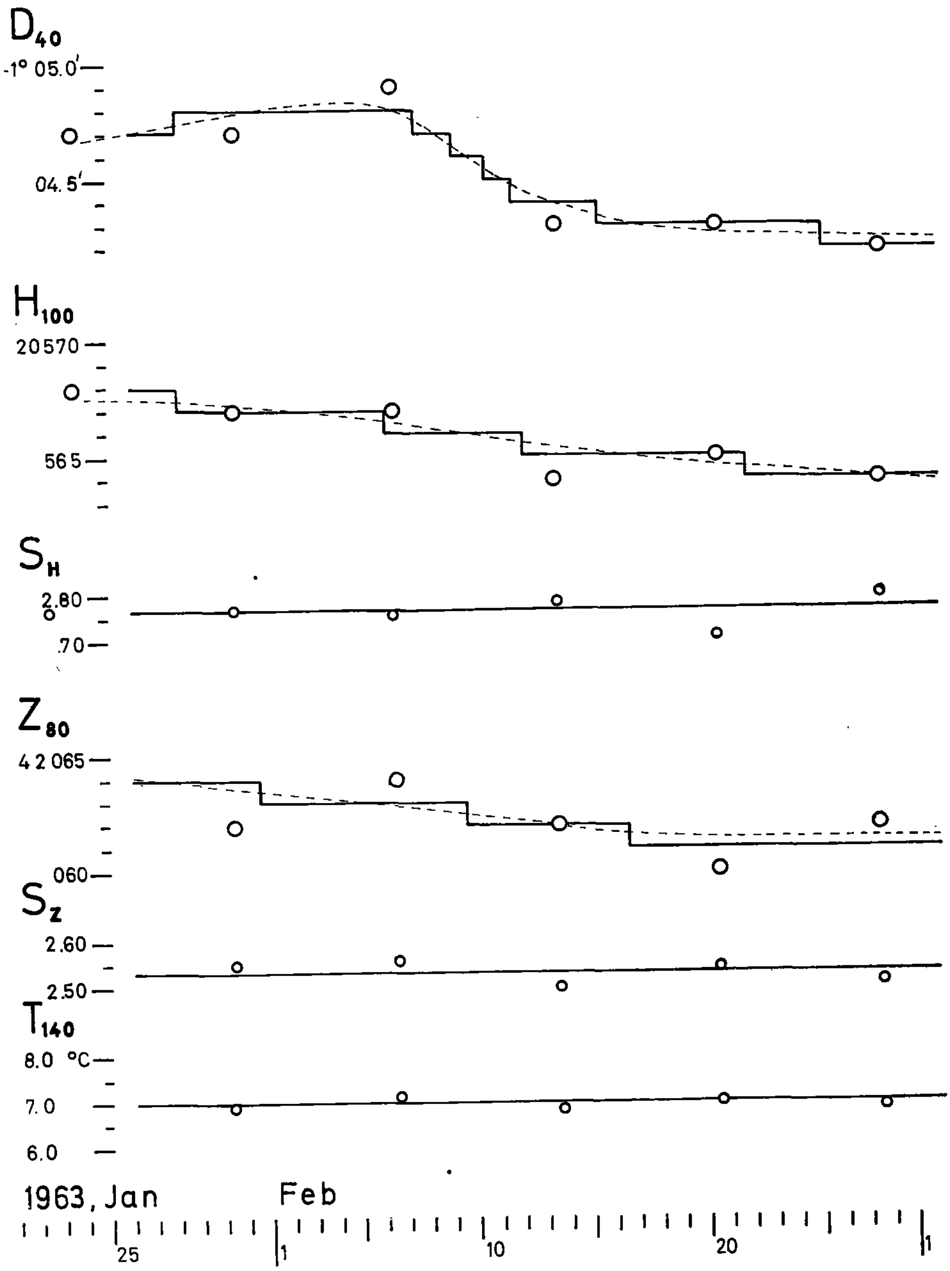

FIG. 34. Graph of base-line values.

1 gamma per millimetre in ordinate and one day per millimetre in abscissa, for instance. The base-line values will usually show scatter because of errors in absolute observations and instability of the variometers. It is therefore general practice to draw a smooth line through the cloud of points representing the base-line values (Fig. 34). At some observatories the well-known smoothing formulae $\frac{1}{4}(a + 2b + c)$ centred at b, or $\frac{1}{9}(a + 2b + 3c + 2d + e)$ centred at c, are used. However, since the eye is a good judge, visual smoothing is usually satisfactory. The smooth line is approximated by a step function using steps of 0.1′ in D and 1 gamma in the intensities, respectively. The base-line values obtained by stepping the smooth line are called adopted base-line values and are used for the computation of the hourly means. Figure 34, and the table on which the graph is based, explain the procedure. If the base-line value of any of the three components changes abruptly (as, in this case, the declination between 6 and 13 February), the change should be evenly distributed over the interval between the two measurements, unless the change has been caused by an adjustment of the variometer, in which case the precise time is known. If a single value departs much from the general level of values, it is ignored; as, for instance, the scale value of the H-variometer on 21 February. Figure 34 also shows the base-line values of the temperature, which are derived from the temperature readings taken when changing the photographic paper. They are used for converting the ordinates of the temperature trace to degrees centigrade.

Observed and adopted base-line and scale values of a magnetograph (fictitious) (see also Fig. 34)

	Date						
	23.I.1963	30.I.1963	6.II.1963	13.II.1963	20.II.1963	27.II.1963	6.III.1963
Observer	NN	NN	NN	NN	NN	NN	NN
D_{40}							
Observed	– 1°04.7	– 1°04.7	– 1°04.9	– 1°04.3	– 1°04.3	– 1°04.2	– 1°04.2
Adopted	– 1°04.7	– 1°04.8	– 1°04.8	– 1°04.4	– 1°04.4	– 1°04.3	– 1°04.3
H_{100} (γ)							
Observed	20 568	20 567	20 567	20 564	20 565	20 564	20 563
Adopted	20 568	20 567	20 566	20 565	20 564	20 563	20 563
Z_{80} (γ)							
Observed	42 065	42 062	42 064	42 062	42 060	42 062	42 061
Adopted	42 064	42 063	42 062	42 062	42 061	42 061	42 061
S_H (γ/mm)							
Observed	2.77	2.77	2.76	2.78	2.70	2.76	2.80
Adopted	2.77	2.77	2.77	2.77	2.77	2.77	2.77
S_Z (γ/mm)							
Observed	2.50	2.55	2.56	2.50	2.54	2.51	2.52
Adopted	2.53	2.53	2.53	2.53	2.53	2.53	2.53

Hourly means

334 The scaling of hourly means and their computation is usually regarded as the dullest job at a geomagnetic observatory. It can be mastered with some ease provided that arrears are not allowed to accrue. Magnetograms should, if possible, always be measured at approximately the same relative humidity and temperature, because these two quantities influence the dimensions of the paper. The stability of conditions in the office room will usually be adequate. The magnetogram should have been one or two days in the office before it is measured so that it has assumed 'normal dimensions'. Paper shrinkage may be determined for every magnetogram from the impressions of the gauge mentioned in paragraph **318**.

335 The most simple device for scaling instantaneous ordinates and ordinates of hourly means is a glass plate, as described in paragraph 431 of McComb's *Manual*. An alternative is shown in Figure 35. A scale of this kind can be engraved on plexiglass using the micrometer scales of a lathe. A plexiglass ruler whose zero division is some distance from one end is a possible substitute, though a poor one. Place the scale on the magnetogram, with the engraved side next to the paper and with the vertical scale on the hour mark. For scaling ordinates of hourly means, shift the scale in ordinate until the left- or right-hand edge of the horizontal line is set to the average ordinate of the trace between two adjacent hour marks, i.e. until the shaded areas above and below the horizontal line are equal. Read the position of the base-line from the vertical scale, to the nearest tenth of a millimetre (17.5 millimetres in Figure 35 (*a*)). For measuring the ordinate at a discrete time, shift the scale in abscissa until the minute (30 minutes in Figure 35 (*b*)) on the horizontal line coincides with the hour mark, and in ordinate until the zero of the vertical scale is at the centre of the trace. See that the vertical scale is parallel to the hour mark. Read the vertical scale at the base-line. Since the traces and base-lines have a finite width, use the centres of lines for setting and reading the scale. If the base-line is at the lower margin of the magnetogram, subtract mentally the multiples of ten millimetres at which the fictitious base-lines are situated (paragraph **102**). In the example (see table, 'Computation of Hourly Means (Fictitious)'), the base-line is at the lower margin of the magnetogram and the fictitious base-lines are at 40, 80, 100 and 140 millimetres for D, Z, H and T, respectively. Scale the hourly means of the ordinates and convert millimetres to minutes of arc, gammas and degrees centigrade by means of the respective scale values. Rather than doing the multiplications on a desk computer, compute tables of multiples of the scale values. If you have a book of multiplication tables, copy the tables that are used most and paste them on cardboard for routine multiplications, in order to prevent the book being ruined by too frequent use. Note that in our example of computation of hourly means

$$\text{positive } n_{\mathrm{D}} = \text{negative } \Delta\mathrm{D}^{(')}.$$
$$\text{positive } n_{\mathrm{H}} = \text{positive } \Delta\mathrm{H}^{(\gamma)}.$$
$$\text{positive } n_{\mathrm{Z}} = \text{positive } \Delta\mathrm{Z}^{(\gamma)}.$$

336 When adding ordinates to base-line values of D and Z, caution is required because in both elements positive and negative base-line values may occur. Furthermore, recall that $\Delta D^{(\prime)}$ is positive when the north-seeking pole of the recording magnet moves eastward at either positive or negative values of D, and $\Delta Z^{(\gamma)}$ is positive when the north-seeking pole moves downward at either positive or negative values of Z. Thus we find, for the first line of D in our example, – 1°04.3′ – 11.9′ = – 1°16.2′ or 1°16.2′ west.

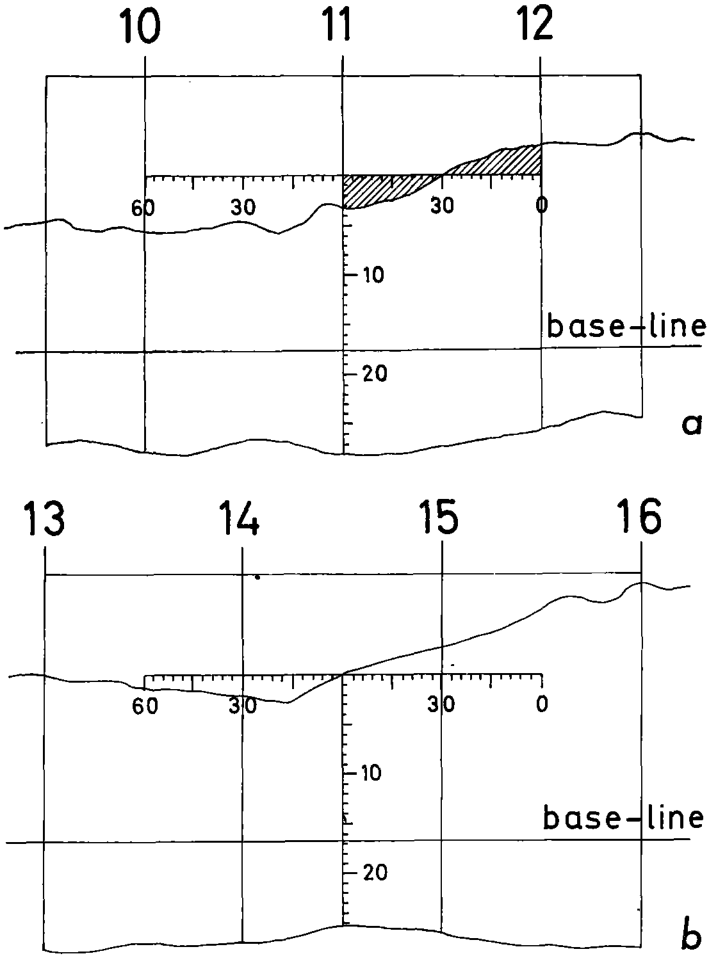

FIG. 35. Measurement of ordinates by means of a glass scale. (*a*) Scale adjusted for measuring the hourly mean (11-12 hours, 17.5 mm). (*b*) Scale adjusted for measuring the ordinate at a discrete time (14h30, 16.7 mm).

Computation of hourly means (fictitious)

1963, February 23

Adopted base-line values (from Fig. 34):
D_{40} = − 1°04.3′
H_{100} = 20 564 gammas
Z_{80} = 42 062 gammas
T_{140} = 7.00° C

Adopted scale values (from Fig. 34):
S_D = 0.50′/mm
S_H = 2.77 gammas/mm
S_Z = 2.53 gammas/mm
S_T = 0.50° C/mm

Temperature coefficients:
q_H = − 5.50 gammas/°C
q_Z = − 3.75 gammas/°C
Standard temperature of magnetograph:
T_s = + 10.0° C

Time (GMT)	n_D mm (40)	ΔD(′)	D	n_H mm (100)	2.77 × n_H (γ)	5.50 × (T − T_s) (γ)	ΔH (γ)	H (γ)	n_Z mm (80)	2.53 × n_Z (γ)	3.75 × (T − T_s) (γ)	ΔZ (γ)	Z (γ)	n_T mm (140)	0.50 × n_T (°C)	T (°C)
0-1	+ 23.8	− 11.9′	− 1°16.2′	+ 19.0	+ 52.5	− 8.5	+ 44	20 608	+ 17.7	+ 44.8	− 5.8	+ 39	42 101	+ 2.9	+ 1.45	+ 8.45
1-2	24.2	12.1	16.4	19.4	53.7	8.8	45	609	17.8	45.0	6.0	39	101	2.8	1.40	8.40
2-3	24.6	12.3	16.6	19.9	55.1	9.1	46	610	17.9	45.3	6.2	39	101	2.7	1.35	8.35
3-4	24.6	12.3	16.6	20.8	57.6	9.6	48	612	17.6	44.5	6.6	38	100	2.5	1.25	8.25
4-5	25.2	12.6	16.9	22.4	62.0	9.9	52	616	17.7	44.8	6.8	38	100	2.4	1.20	8.20
5-6	25.6	12.8	17.1	22.8	63.2	10.2	53	617	17.8	45.0	6.9	38	100	2.3	1.15	8.15
6-7	25.6	12.8	17.1	24.0	66.5	10.4	56	620	17.4	44.0	7.1	37	099	2.2	1.10	8.10
7-8	27.0	13.5	17.8	24.6	68.1	11.0	57	621	17.6	44.5	7.5	37	099	2.0	1.00	8.10
8-9	25.4	12.7	17.0	25.9	71.7	10.7	61	625	16.1	40.7	7.3	33	095	2.1	1.05	8.05
9-10	25.5	12.8	17.1	26.9	74.5	10.4	64	628	14.3	36.2	7.1	29	091	2.2	1.10	8.10
10-11	27.3	13.6	17.9	26.1	72.3	10.2	62	626	14.2	35.9	6.9	29	091	2.3	1.15	8.15
11-12	28.6	14.3	18.6	23.7	65.6	8.8	57	621	14.2	35.9	6.0	30	092	2.8	1.40	8.40
12-13	26.8	13.4	17.7	20.6	57.1	8.0	49	613	14.8	37.4	5.4	32	094	3.1	1.55	8.55
13-14	25.8	12.9	17.2	22.2	61.5	7.4	54	618	15.5	39.2	5.1	34	096	3.3	1.65	8.65
14-15	24.9	12.4	16.7	18.8	52.0	6.1	46	610	16.3	41.2	4.1	37	099	3.8	1.90	8.90
15-16	24.8	12.4	16.7	15.4	42.7	5.5	37	601	16.9	42.8	3.8	39	101	4.0	2.00	9.00
16-17	23.4	11.7	16.0	9.0	24.9	5.0	20	584	18.0	45.5	3.4	42	104	4.2	2.10	9.10
17-18	24.5	12.2	16.5	12.6	34.9	5.0	30	594	18.3	46.3	3.4	43	105	4.2	2.10	9.10
18-19	23.0	11.5	15.8	14.9	41.3	5.2	36	600	18.4	46.6	3.6	43	105	4.1	2.05	9.05
19-20	23.4	11.7	16.0	16.8	46.5	5.5	41	605	18.1	45.8	3.8	42	104	4.0	2.00	9.00
20-21	23.6	11.8	16.1	17.3	47.9	5.8	42	606	17.8	45.0	3.9	41	103	3.9	1.95	8.95
21-22	23.5	11.8	16.1	18.6	51.5	6.6	45	609	18.0	45.5	4.5	41	103	3.6	1.80	8.80
22-23	23.7	11.8	16.1	18.8	52.1	8.0	44	608	18.4	46.6	5.4	41	103	3.1	1.55	8.55
23-24	23.6	11.8	16.1	19.1	52.9	8.8	44	608	18.6	47.1	6.0	41	103	2.8	1.40	8.40

337 The ordinates of the intensities have to be reduced to the standard temperature of the magnetograph (in our example + 10.0° C) before they can be added to the base-line values. The temperature coefficient of a variometer indicates by how many gammas the ordinate changes when the temperature of the variometer increases by one degree centigrade. The temperature coefficient q_H of an uncompensated H-variometer is always negative, while the temperature coefficient q_Z of an uncompensated balance is negative at positive values of Z, positive at negative values of Z. The temperature coefficient will have the opposite algebraic sign when the variometer is overcompensated. For the computation of intensity ordinates, we have the following equations:

$$\Delta H^{(\gamma)} = S_H n_H - q_H (T - T_s) \quad \text{and} \quad \Delta Z^{(\gamma)} = S_Z n_Z - q_Z (T - T_s) \qquad (82)$$

where: q_H = temperature coefficient of the H-variometer in gammas/°C; q_Z = temperature coefficient of the Z-variometer in gammas/°C; T = temperatures of the variometers; T_s = standard temperature of the magnetograph. For the other symbols see paragraph **102**.

Summarizing the operations necessary for the computation of hourly means, we obtain the following equations:

$$\begin{aligned} D &= D_0 + S_D n_D & Z &= Z_0 + S_Z n_Z - q_Z (T - T_s) \\ H &= H_0 + S_H n_H - q_H (T - T_s) & T &= T_0 + S_T n_T \end{aligned} \qquad (83)$$

Inserting the values in our example of computation of hourly means for 23 February 1963 we have

$$\begin{aligned} D &= -1°04.3' - 0.50\, n_D & Z &= 42\,062 + 2.53\, n_Z + 3.75\, (T - 10) \\ H &= 20\,664 + 2.77\, n_H + 5.50\, (T - 10) & T &= 7.00 + 0.50\, n_T \end{aligned}$$

Since the base-line value of the thermograph is fairly stable over long periods of time, one can simplify the computation of the temperature correction of the H and Z ordinates by computing tables of corrections with n_T as argument, thus saving the computation of the temperature. In our example a small section of the table reads as follows:

n_T (mm)	$5.50\,(T - T_s)$ (gammas)	$3.75\,(T - T_s)$ (gammas)
2.0	− 11.0	− 7.5
2.1	10.7	7.3
2.2	10.4	7.1
2.3	10.2	6.9
etc.		

The example of computation of the hourly means of 23 February 1963 represents the worst case. When the temperature of the variometer room changes slowly, or the residual temperature coefficients of the intensity variometers are small, a change of temperature correction by one gamma may occur only every five or ten hours, or even less frequently. In that case, it is of advantage to add the temperature correction to the base-line value instead of correcting the ordinates, thus saving a substantial amount of labour. The temperature corrections can be omitted when they change by one gamma only every few days (see also paragraph **333**); this is the ideal case, which requires about 50 per cent less labour than the worst case.

338 Upon completion of a month's daily data sheets, carry the hourly means over to monthly tables, as has been done for June *1967 in the accompanying* example ('Monthly Table of Hourly Means, Horizontal Intensity, Fürstenfeldbruck, June 1967'). Compute the sums of lines and columns, the grand totals, the daily means and the hourly means for 'All days'. Mark the five quiet (Q) and five disturbed (D) days after they have been published in the *Journal of Geophysical Research* under 'Geomagnetic and Solar Data', usually with a delay of five months. If you want to know the five quiet and disturbed days earlier, make an arrangement with the Permanent Service for Geomagnetic Indices, Royal Netherlands Meteorological Institute, De Bilt (Netherlands), from whom you may receive the data by airmail with a delay of about six weeks.

The adding of lines and columns is done best on an accountant's calculator with strip-chart control. Label the columns on the strip chart by pencil notes such as '3 May' or 'May, 12-13h' so that you can find your way through the data when searching for mistakes. If the grand totals of lines and columns do not agree, the figures recorded on the strip chart may be compared with the values in the monthly table, instead of doing the computation again as one has to do if an ordinary computer is used. Correct all wrongly entered figures, the sums of lines and columns containing faulty values, and compute the grand totals again. The strip-chart saves many hours of frustrating searching for errors. Even a slow operator will complete the adding of one monthly table, including corrections, in about two and a half hours.

339 The scalers described in paragraph **335** are inconvenient to use. McFarland described a scaler that glides along the upper edge of a board. The magnetogram is adjusted on the board until the base-line gives a zero reading for the whole length of the magnetogram. At Fürstenfeldbruck, a device has been used that requires a base-line at the lower margin of the magnetogram. The base-line is clamped under the upper edge of a ruler along which the scaler glides. The index, whose position is read on a vertical scale by means of a vernier, is engraved on a glass plate. Both these scalers are less tiresome than an ordinary hand scale, because the operator need not pay attention to the position of the scale with respect to the hour marks. More advanced scalers are equipped with scales divided in intervals of minutes of arc and of five gammas, and allow measurement of hourly means in absolute values that can be entered immediately in monthly tables. With such devices, the magnetogram is so adjusted that the base-line value is read when the index line is set to the base-line. When the scale values of the variometers have changed more than 2 per cent, new scales have to be made or else scales with different scale values have to be kept in stock. Simple direct scalers which can be made locally have been described by McFarland (1926) (see also Fleming, 1939) and Weingärtner (1960). Commercially available scalers coupled with an electric typewriter or a tape punch may also be used. Semi-automatic and automatic scalers have been described by Caner and Witham (1962), Lenners (1965), and Nelson (1967).

Monthly table of hourly means, horizontal intensity, Fürstenfeldbruck, [1] *June 1967*

	GMT Date	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Mean	Total
Q	1	537	535	535	540	541	539	533	524	516	514	523	531	526	529	533	538	546	552	552	551	550	549	546	546	537	12 886
	2	547	547	550	549	550	550	546	545	539	537	542	548	546	548	545	545	544	556	562	570	559	555	555	551	549	13 186
	3	554	556	551	553	546	549	546	538	530	531	541	545	550	550	555	556	561	570	571	569	567	564	562	561	553	13 276
	4	560	567	564	562	561	557	554	546	542	545	555	566	565	561	562	569	569	565	556	547	542	554	576	561	559	13 406
D	5	551	548	551	556	557	556	548	548	551	551	553	560	554	553	546	551	569	562	569	647	620	591	585	560	564	13 527
D	6	507	520	528	496	496	488	481	479	474	480	493	510	526	535	538	535	529	537	554	554	547	553	539	536	518	12 435
	7	545	544	551	545	549	535	512	491	494	501	508	520	529	530	529	535	535	536	542	545	546	549	551	552	532	12 774
	8	551	552	552	554	559	557	546	544	536	528	510	524	536	550	534	549	546	556	558	560	595	585	559	556	550	13 197
	9	559	556	552	553	562	555	544	537	530	535	535	537	540	550	554	557	557	555	561	564	565	561	575	581	553	13 275
	10	559	551	562	564	561	553	540	529	523	531	537	543	550	556	560	564	565	567	569	568	568	567	567	565	555	13 319
	11	560	560	565	567	570	566	560	546	539	541	546	549	551	557	568	572	571	581	580	569	560	563	561	562	561	13 464
	12	560	560	561	565	565	559	558	553	550	551	555	549	543	537	548	564	568	563	566	575	577	576	578	574	561	13 455
	13	571	570	576	582	584	578	569	565	555	551	544	544	544	546	552	557	563	571	577	576	576	584	581	580	566	13 596
	14	579	579	580	585	585	579	568	559	560	551	538	538	538	541	559	562	556	565	572	575	569	566	575	575	565	13 554
	15	576	595	565	565	557	560	555	547	541	536	540	549	553	562	569	571	570	568	572	574	574	572	571	570	563	13 512
	16	570	569	571	573	575	571	565	561	551	549	546	557	555	559	564	574	569	578	576	576	577	579	581	578	568	13 624
	17	575	576	574	571	571	572	571	568	569	562	551	551	553	559	567	567	572	565	570	571	575	575	575	576	568	13 636
Q	18	571	560	561	560	560	557	557	559	561	569	571	568	561	560	561	566	574	574	575	575	575	576	577	576	567	13 604
	19	574	573	575	575	575	575	572	570	561	561	570	577	577	577	585	583	570	565	570	578	580	580	580	580	574	13 783
Q	20	580	580	580	581	578	569	559	550	546	553	565	571	574	571	573	573	571	573	575	576	575	576	579	580	571	13 708
	21	580	580	579	580	580	575	567	563	559	556	569	576	580	582	585	580	582	581	577	579	577	575	574	574	575	13 810
	22	574	575	577	579	578	572	561	559	552	557	566	570	568	565	569	566	571	579	581	586	586	583	583	583	572	13 740
Q	23	583	581	582	585	588	584	573	561	556	554	557	568	575	576	574	575	580	583	588	589	589	589	578	575	577	13 843
Q	24	574	579	582	585	582	575	570	569	559	554	556	565	569	568	568	574	579	585	590	590	588	588	590	591	576	13 830
D	25	585	581	594	607	605	593	582	585	585	580	570	565	570	565	566	589	594	609	600	586	557	542	534	540	578	13 884
D	26	561	557	555	557	548	547	551	544	526	518	528	541	549	560	564	591	586	566	578	586	583	579	567	564	559	13 406
D	27	570	591	591	591	589	565	557	540	523	509	500	511	536	546	547	546	552	561	569	561	562	566	570	575	555	13 328
	28	576	571	566	570	575	570	561	550	540	529	523	524	535	546	552	563	567	562	570	575	568	564	565	565	558	13 387
	29	565	565	565	571	575	566	544	547	551	552	551	547	542	542	545	558	576	558	561	571	574	574	572	578	560	13 450
	30	584	575	569	570	569	562	551	541	559	563	555	561	561	563	560	569	570	573	579	585	580	579	581	591	569	13 650
Mean :																											
All days		565	565	565	566	566	561	553	547	543	542	543	549	552	555	558	563	565	567	571	574	572	570	570	569	560	
5 days Q		569	567	568	570	570	565	558	553	548	549	554	561	561	561	562	563	570	573	576	576	575	576	574	574	566	
5 days D		555	559	564	561	559	550	544	539	532	528	529	537	547	552	552	562	564	567	574	587	574	566	559	555	555	
Total All days		16 938	16 953	16 964	16 991	16 991	16 834	16 601	16 418	16 278	16 249	16 298	16 465	16 556	16 644	16 732	16 899	16 952	17 016	17 120	17 228	17 161	17 114	17 087	17 056	Grand total 403 545	

[1] Horizontal intensity = 20 000 plus tabular values, in gammas.

340 If the hourly means of ordinates are scaled in millimetres, computer processing will be of advantage. The hourly means of ordinates are punched on cards. Special cards are prepared for base-line values and scale values. With hourly temperature corrections, the programme will be fairly long. For details, contact your computing centre. With direct scaling of hourly means in absolute values, computer processing scarcely offers any advantage because, long before the cards have been punched and checked, a technician will have computed the sums of a monthly table on an accountant's calculator.

341 Finally, the monthly tables are typed for reproduction on microfilm and in the yearbook. Use a typewriter with clear type and a new silk ribbon. If it is intended to print the yearbook in offset, which saves proof-reading, consult your publishers with regard to details.

342 The observatory yearbook should contain the following information:

A brief description of the observatory and its equipment, an account of the work done at the observatory and figures indicating the reliability of data.

Geographic coordinates of the observatory and altitude above sea level.

Geomagnetic coordinates.

Corrections of the piers on which observations are made, to the observatory's main pier.

Mean ex-orientation angles of the recording magnets of variometers.

Paper speed of recorder.

A table of observed and adopted base-line values and scale values, as discussed in paragraph **333**, and/or a graph of base-line values and scale values as shown in Figure 34.

Monthly tables of hourly means, as discussed in paragraph **338**, for D, H and Z, or X, Y and Z. The sums of lines and columns should be included (see example of monthly table of H for June 1967).

A table of monthly means of the actually observed elements, the computed values of the other elements or components, and the annual means.

A table of all annual means of all components for the present site, and also for previous sites if the observatory has been shifted since its creation.

A magnetic yearbook containing the above information is a minimum yearbook. The user is able to derive all other data from the information provided. Observatories with adequate staff may prepare further tables.

In an appendix, brief technical papers that are too specialized for publication in a scientific journal may be published. Unfortunately the flow of technical information has almost completely ceased since the *Journal of Terrestrial Magnetism and Electricity* was changed to *Journal of Geophysical Research.* It is certainly desirable that observers make their achievements known to the geomagnetic community: in an appendix to a magnetic yearbook, such information is accessible to most observatory workers.

Before preparing the first magnetic yearbook and making decisions with regard to its final form, it is useful to study yearbooks of other observatories, copies of which may be obtained on request.

Microfilming of magnetograms and monthly tables

343 At the present pace of scientific research, information on new results is needed quickly at numerous institutions. For such purposes the observatory yearbook will come out much too late. Moreover, the magnetograms are often required as well. World data centres were therefore created for the International Geophysical Year and have been continued to the present day. The world data centres collect microfilm copies of monthly tables of hourly means, of magnetograms and of published articles. Any scientist can obtain copies from a centre for a small fee.

344 Microfilm copies of magnetograms will be useful only if they conform to certain specifications (see also *IQSY Instruction Manual No. 6*). Figure 36 shows part of a magnetogram prepared for microfilming. The following required information may be inscribed in Indian ink or stamped on by means of rubber stamps:

Name of observatory on a free space in the upper left-hand corner of the magnetogram.

Date and time (in GMT) of beginning and end of record. It may suffice to give the date of beginning of the record near the first hour mark. Also inscribe the times of every second, third or fourth hour mark or all hour marks. When you use the standard time of your country, whose full hour must coincide with a full hour of GMT, state its meridian, for example, 60th MT (60th Meridian Time).

Clock correction, if any, given in the form:

Recorded time + Δ seconds = GMT or . . .th Meridian Time.

Mark at one end of the record, by the letters D, H, Z, T (T for temperature), the corresponding traces, and by the letters D_0, H_0, Z_0, T_0, the corresponding base-lines.

Temperature of the variometer room.

Arrows which indicate in which direction of trace movement the recorded elements increase. An alternative is to give this information on the data sheet, which will be discussed later.

When photographing a magnetogram, place a centimetre or millimetre scale in the direction of the ordinates (parallel to the hour marks) as indicated in Figure 36.

Inscribe the required information on a free space of the magnetogram. Best results will be obtained from magnetograms whose traces are perfectly black and sharp. Weak or grey traces, which sometimes cannot be avoided, may be strengthened by soft pencil (not ink). Do not try to draw traces where there are none as, for instance, during phases of rapid change during a geomagnetic storm. Parallax tests as described in paragraph **317** should be made every week or month. You may try to remove parallax if there is any.

345 The microfilming of a month's data should be started by photographing a sheet containing all data concerning the observatory and the magnetograph. The following details are required:

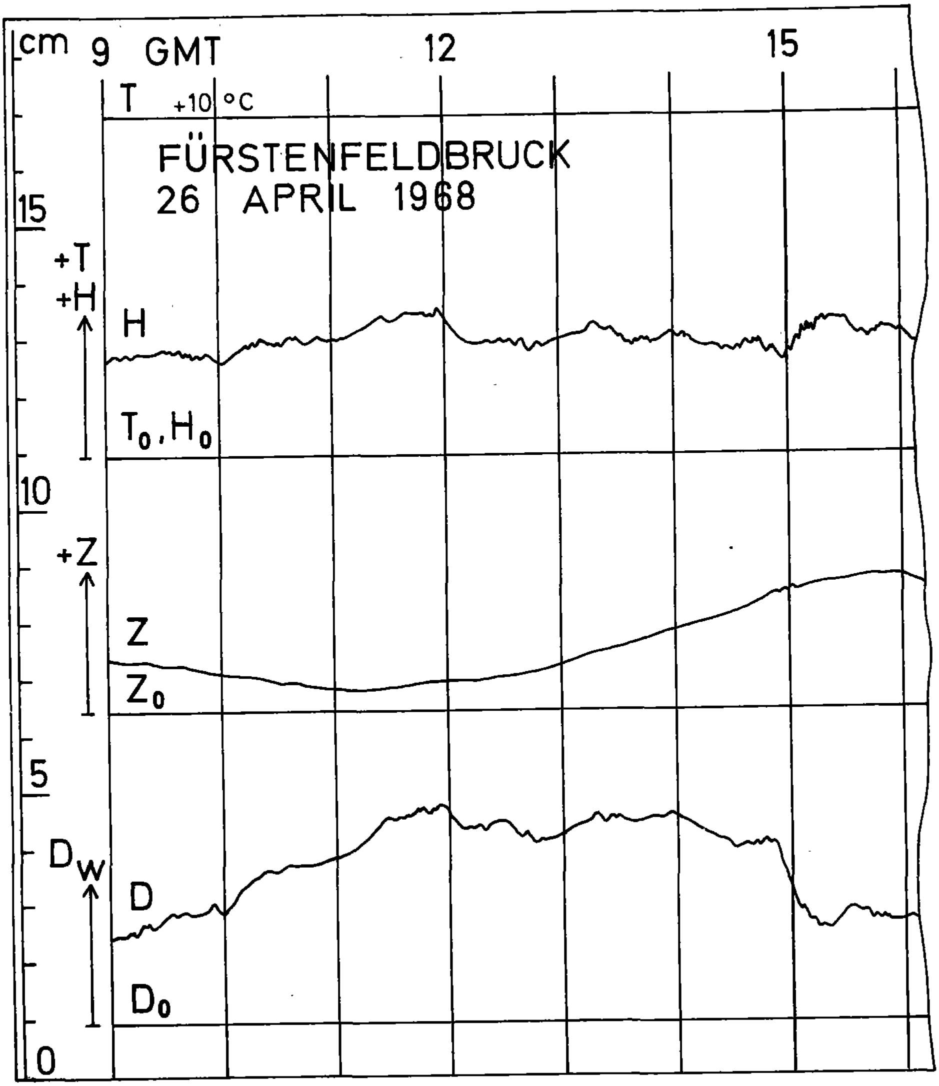

FIG. 36. Magnetogram prepared for microfilming.

Name of observatory. The letters should be large so that they can be read on the 24 by 36 millimetres negative without a lens.

Geographic and geomagnetic coordinates, altitude above sea level.

Type of data, for example, 20 mm/hour, D, H, Z.

The year and month in letters which are legible on the negative without a lens. This information may be inscribed on a small piece of paper which is changed every month.

Scale values in ′/mm, γ/mm and °C/mm.

Direction of ordinates, if not given on the magnetograms (for Figure 36: increasing D: downward; increasing H: upward; increasing Z: upward; increasing T: upward).

Temperature coefficients, if any.

Scale values, directions of ordinates, and temperature coefficients, which may be given in the form of equations, as indicated in paragraph **337**.

Adopted base-line values and the periods of time for which they are valid. Indicate whether the base-line values are preliminary or final.

Dates of missing or incomplete magnetograms.

Next, photograph the tables of hourly means of the three components and then the magnetograms. In order to make the magnetograms lie flat, it may be necessary to put a glass plate on top of them or to strap them to a board by means of elastic. Put a centimetre scale, drawn on paper, as near as possible to one end of the magnetogram. Adjust the lamps so that no highlight due to reflection from the glass plate or from a glossy surface of the magnetogram is visible in the camera's viewfinder. Check that the magnetogram is evenly illuminated. Magnetograms of paper speed 20 millimetres per hour should fill the whole length of the frame, as should magnetograms of the La Cour magnetograph. Take care that the tables and magnetograms are properly inserted, i.e. that they appear on the film so that one end of a magnetogram is followed by the beginning of the next one or, in other words, when looking at the film the information can be read from left to right.

After having copied the magnetograms of the main magnetograph, photograph the data sheet of the second (usually less sensitive) magnetograph and its magnetograms for those days for which the magnetograms of the main magnetograph are missing or incomplete.

346 Microfilming is done best at a documentation centre or at a library where a high-quality reproduction camera and suitable equipment for illumination is available. However, in numerous instances the work will have to be done at the observatory. A medium-priced single-lens reflex camera, 24 by 36 millimetres, with an objective of focal length 50 millimetres, will give good results. Construct a suitable frame, adjustable in height, to carry the camera and the lamps for illumination of the magnetograms. Four hundred-watt bulbs mounted in reflectors and evenly spaced around the platform carrying the magnetogram will give satisfactory illumination. Make sure that the optical axis of the camera lens is perpendicular to the platform. From a look at professional gear you may pick up useful ideas for the construction of your own equipment. When photographing the magnetograms, release the shutter of the camera by means of a cable in order to avoid moving the camera when actuating the shutter. Use fine-grain document film and fine-grain developer. Develop the film in a tank. For best results, it will be necessary to keep to the temperature specified by the manufacturers of the developer. Warm or cool the developer and the developing tank in a water bath before pouring the developer into the tank. It is useful to take a few test photographs with different shutter and aperture settings, from which the best are chosen. The background of the negative should be of medium grey for good results in reproduction. It may be useful to enlarge a small section of the film to original size in order to see whether your product is of adequate quality. For sending the film to a world data centre, obtain cardboard cartridges and special envelopes from your dealer in photographic articles. Roll the film into a fairly small roll, but do not try to reduce the diameter of the film roll by pulling the end, because you will scratch the film in doing so. Send the film by airmail to one or more of the world data centres collecting information on geomagnetism, whose addresses are: World Data Center A, Environmental Data Service, ESSA, Rockville, Maryland, 20852 (United States); Word Data Centre B, Molodezhnaya 3, Moscow B-296 (U.S.S.R.); World Data Centre C1, Danish Meteorological Institute, Charlottenlund (Denmark); World Data Centre C2, Geophysical Institute, Kyoto University, Kyoto (Japan).

The contribution of information to the world data centres may appear to be an irksome burden. However, once you have overcome the initial difficulties, you will find that the additional labour is comparatively small. By choosing to be a regular contributor to one or more of the world data centres, you ensure that your data are processed at an early stage and that your information, which has cost you such efforts to produce, is used rapidly for the benefit of science. You should in any case send microfilm copies of monthly tables and magnetograms to a data centre if your observatory is in a unique position, say, under the electrojet, or when there is no other observatory within a radius of a thousand kilometres or more.

Geomagnetic survey work

Objectives of a geomagnetic survey

347 The purpose of a geomagnetic survey is to obtain data for the description of the geomagnetic field of the whole Earth, of a continent or of a country, in a condensed form.

The geomagnetic field vector measured on the surface of the Earth, in the air or in space is made up of three components, namely:

The main field. This has its origin in the Earth's core. Since the measurements are made at a distance of about 3000 kilometres from the surface of the core, this part of the geomagnetic field appears as a regular function of latitude and longitude. The description of the main field, which varies slowly with time (secular variation) is one of the ultimate objectives of a geomagnetic survey.

The crustal field. This appears as an irregular superposition on the main field and emanates from the Earth's crust, probably from its outer shell of 18 to 25 kilometres thickness. The irregularities caused by the crustal field (anomalies), which usually do not exceed a few per cent of the main field, are most prominent when measurements are made on the surface of the Earth. In airborne surveys, especially those flown at high altitude, their amplitude is much reduced and in satellite flights little can be seen of them. The anomalies are caused by differences in the magnetic properties of the various geological formations and are therefore of interest in connexion with prospection for certain mineral deposits. In rare instances, the anomalies may reach values comparable with the main field, when measured on the ground. Small and medium anomalies are generally constant with time.

The time variations (see paragraphs **51-5**). Since the time variations of the geomagnetic field are mostly irregular, they make it difficult to compare the results obtained at different field stations at different times. Geomagnetic surveys are usually made at a sun-spot minima because then the time variations are smallest.

348 The separation of the three parts of the geomagnetic field is performed by first removing the time variations by comparing the field observations with records obtained at a geomagnetic observatory not too far away from the surveyed area. From the corrected data, the main field is obtained by treating the results statistically. For the whole earth, the parameters are determined by harmonic analysis (IUGG Monograph No. 11) and for smaller areas by least-square fitting of polynomials of the form

$$f = f_0 + a\Delta\varphi + b\Delta\lambda + c\Delta\varphi^2 + d\Delta\lambda^2 + e\Delta\varphi\Delta\lambda \qquad (84)$$

for f = D, I, H, X, Y, Z, F where: $\Delta\varphi = \varphi - \varphi_0$; $\Delta\lambda = \lambda - \lambda_0$. φ_0 and λ_0 are conveniently chosen values of latitude and longitude near the centre of the surveyed area. These expressions are called normal fields. For small areas the determination of f_0, a, and b may suffice. Normally, the fitting of the different elements is done independently. One may pay attention to the fact that the geomagnetic field is a potential field by introducing additional conditions, thus obtaining mutually consistent normal fields. The methods of statistical treatment of survey data are dealt with in *Instruction Manual II on World Magnetic Survey*. Finally the crustal field (anomaly) at any place of observation is obtained by subtracting the normal field from the observed value.

349 Thus a scientific representation of the results of a geomagnetic survey should contain:

Lists of all observed components corrected for time variations (i.e. reduced to epoch), and isomagnetic charts.

Expressions for the normal fields of all observed components (the normal fields may be shown on the isomagnetic charts in a different colour).

Lists and charts of the anomalies of all observed components.

Elimination of time variations

350 It has been noted earlier that the geomagnetic field varies with time at any place of observation. All observations made during a survey have therefore to be reduced to one instant or 'epoch'. Old surveys were reduced to the middle of the year in which they were made, for instance, 1910.5, 1915.5 . . . because the annual means of an observatory are valid for that epoch. Some time ago, IAGA recommended reduction to the beginning of years which are multiples of five, such as 1960.0, 1965.0 . . .

351 The time variations due to the sun's activity consist of a regular part caused by the sun's electromagnetic radiation, which has a pronounced period of 24 hours. The amplitude of this type of time variation is zero or very small during the morning hours between midnight and 4 a.m. local time and is largest some time after the sun's culmination. The irregular part of the time variations is caused by the sun's particle emission and, in its severest phases, causes geomagnetic storms. These storms occur almost simultaneously over the whole globe but are felt most strongly in the auroral belts and least strongly near the magnetic equator. From the above it follows that the elimination of time variations will be easiest for measurements made in undisturbed periods during the hours between midnight and 4 a.m. local time. The other periods between sunset and sunrise are almost equally good. During night hours, the regular part of the time variations is usually small. For this reason, all geomagnetic survey work near the electrojet should be done at night. The worst period is from 8 to 15 hours local time, when all components change rapidly under the influence of the sun's electromagnetic radiation. Before correcting for time variations, it has to be decided, by inspection of the magnetogram whether they are of the regular type or caused by solar particle emission. The observer may often feel uneasy about distinguishing between the two types of time variation. A hard-and-fast rule is to assume they are of the regular type only when the diurnal variation is well-pronounced and little or no disturbance is present. In this case, convert the difference in longitude between the observatory and the field station to time. If the field station is east of the observatory, add the time difference to, if west subtract it from, the time of observation and measure the magnetogram for the corrected time (assuming that the same local time is used at both places). If particle radiation is dominant, i.e. the traces are disturbed, the measurement on the magnetogram is made for the actual time of the field observation. Finally, add the ordinate to the base-line value, thus obtaining the value of the observed element at the observatory for the time of observation at the field station. The difference $f_{\text{field station}} - f_{\text{observatory}}$ can be considered constant for an area of 1000 by 1000 kilometres and for a period of about six months. Thus the difference affords a good check on the consistency of observations made at different times. The value for the field station at epoch is obtained by adding the difference to the value of the component at the observatory at epoch, as expressed in the equation:

$$f_{\text{observatory at epoch}} + (f_{\text{field station}} - f_{\text{observatory}}) = f_{\text{field station at epoch}} \qquad (85)$$

The value $f_{\text{observatory at epoch}}$ is the mean of the monthly means from July of the year preceding epoch to June of the year of epoch. The value for epoch 1965.0, for instance, is the mean of the monthly means from July 1964 to June 1965. Note that the mean of the annual means of 1964 (epoch 1964.5) and 1965 (epoch 1965.5) may not give the same result.

352 If a geomagnetic survey is spread over several years, the difference in secular variation between field stations which are far apart will cause distortion of the isolines. It will be necessary to repeat some stations, evenly distributed over the surveyed area, at the beginning of the survey, at epoch, and at the end of the survey. From the changes of the values $f_{\text{field station}} - f_{\text{observatory}}$, corrections to epoch for secular variation can be derived. Near a focus of rapid secular change, repeat observations will have to be made more frequently.

353 When correcting for time variations, one first reduces the individual observations of a component either to the time of the first observation or to the mean of the times of the first and last observation. In most cases it will suffice to measure the mean ordinate during the time interval of a set of observations. For practical work, it is useful to assemble all data pertaining to one component in a list, in order to obtain a check on the quality of the individual observation. This is indicated by the relative scatter of the values $f_{\text{field station}} - f_{\text{observatory}}$, as in the accompanying example (page 194). In this example, the computations have been made to the nearest tenth of a gamma. In most cases it will suffice to work to the nearest full gamma. When assembling the data, take care that they refer to the same level, either to the level of the observatory standard or to the IMS level. The final values at epoch should refer to the IMS level, if possible.

354 From the observed components reduced to epoch, the other components are computed. If one or other component has been computed from observed values and then reduced to epoch, check the consistency of the values reduced to epoch before using them for the computation of normal fields or reporting them to a world data centre.

Requirements for a geomagnetic survey

355 The statistical analysis of a geomagnetic survey requires, in theory, measurements at an infinitely large number of field stations. In practice one has to be content with a limited number of measurements distributed randomly in space. For the World Magnetic Survey, Vestine (IUGG Monograph No. 11) specifies a maximum distance from station to station of 200 kilometres. For national surveys, spacings ranging from 10 to 100 kilometres have been used in the past. It seems that spacings of from 25 to 50 kilometres are sufficient for most purposes, using the closer spacing for anomalous areas and the wider spacing in undisturbed regions.

356 In order to ensure random sampling, the distribution of the stations should approach a chess-board pattern. When such a distribution is achieved in areas with crustal anomalies, the values of many stations may be very different from the main field; these are excluded from the analysis when their deviation exceeds three or four times the standard deviation. Loss of stations can be limited by making a certain pre-selection of sites, by using geological indications or by basing the survey on a denser network of stations at which a single component has been measured, either vertical intensity with a field balance or total intensity with a proton magnetometer. The pre-selection should not be too strict, otherwise the data obtained may be biased.

357 For a statistical analysis of the geomagnetic field, the accuracy requirements are relatively low. Standard deviations of one minute of arc in declination and ten gammas in the intensities are acceptable. The statistician will prefer a large number of stations with comparatively low accuracy to a small number of stations with high accuracy. High accuracy is required at repeat stations for the determination of the secular variation or when the stations are used as base stations for a prospecting survey.

Reduction of geomagnetic survey data to epoch

Geomagnetic survey of South Germany. Observatory values are marked by Fu (abbreviation for Fürstenfeldbruck).

Magnetic declination (IMS)

Station	Date	Time (GMT)	D observed	n_D	$\Delta D^{(\prime)}$	D_{Fu}	Station minus (Fu)	Station 1965.0
					(D_0 = − 2°04.8′)		(D_{Fu} = − 2°08.7′)	
Haimbach	8.VIII.1964	07h02	− 2°50.5′	+ 5.1	− 2.5′	− 2°07.3′	− 0°43.2′	
		19	50.5	5.1	2.5	07.3	43.2	
		36	50.5	5.6	2.7	07.5	43.0	
		50	51.2	6.0	2.9	07.7	43.5	
						Mean	− 0°43.2′	− 2°51.9′

S_D = 0.484′/mm
positive n_D = negative $\Delta D^{(\prime)}$

Horizontal intensity (IMS)

Station	Date	Time (GMT)	H observed	n_H	$\Delta H^{(\gamma)}$	H_{Fu}	Station minus (Fu)	Station 1965.0
					(H_0 = 20 453.0)		(H_{Fu} = 20 519.0)	
Haimbach	8.VIII.1964	07h05	19 294.7	+ 17.2	+ 48.2	20 501.2	− 1 206.5	
		08	294.5	17.2	48.2	501.2	206.7	
		22	290.2	16.4	45.9	498.9	208.7	
		25	289.4	16.0	44.8	497.8	208.4	
		38	287.9	15.0	42.0	495.0	207.1	
		42	286.4	14.6	40.9	493.9	207.5	
		55	283.3	13.7	38.4	491.4	208.1	
		59	284.9	13.6	38.1	491.1	206.2	
						Mean	− 1 207.4	19 311.6

S_H = 2.80′/mm
positive n_H = positive $\Delta H^{(\gamma)}$

Total intensity (IMS)

Station	Date	Time (GMT)	F observed	n_H	n_Z	1.22 × n_H	2.39 × n_Z	$\Delta F^{(\gamma)}$ ($F_0 = 46\ 791.0$)	F_{Fu}	Station minus (Fu) ($F_{Fu} = 46\ 836.2$)	Station 1965.0
Haimbach	8.VIII.1964	07h11	47 390.6	+ 17.3	+ 8.9	+ 21.1	+ 21.3	+ 42.4	46 833.4	+ 557.2	
		29	390.2	16.6	8.5	20.3	20.3	40.6	831.6	558.6	
		45	386.5	14.6	8.1	17.8	19.4	37.2	828.2	558.3	
		08h08	382.7	14.0	6.4	17.1	15.3	32.4	823.7	559.0	
									MEAN	+ 558.3	47 349.5

$S_H = 2.80\ \gamma/\text{mm}$
positive n_H = positive $\Delta H^{(\gamma)}$

$S_Z = 2.68\ \gamma/\text{mm}$
positive n_Z = positive $\Delta Z^{(\gamma)}$

Survey report to a world data centre, observed (unreduced) values

Data for *World Magnetic Survey*

Country: Federal Republic of Germany
Sponsoring institution: Geophysical Observatory, Fürstenfeldbruck

Instrument	D	H	F
	HTM No. 523 930 HTM No. 590 249	HTM No. 523 930 HTM No. 590 249	Proton magnetometer Elsec No. 592/128
Instrumental correction to observatory standard	− 0.8′	+ 12 gammas	+ 28 gammas
Instrumental correction to IMS	0	0	0
Data determined	Every week throughout the field season		
Referred to observatory at	Fürstenfeldbruck		
Date of determination of constants	25 October 1963		
Estimated instrumental accuracy	± 0.5′	± 2 gammas	± 1 gamma

Station	Latitude (N.)	Longitude (E.)	Date	Time (GMT)	D	H (gammas)	F (gammas)	Altitude above mean sea level (metres)	Remarks
Haimbach	50°32.2′	9°37.4′	8.VIII.1964	07h02	− 2°50.5′			314	Substitute for Station Neuenburg, Reichsvermassung 1935.0
				05		19 295			
				08		294			
				11			47 391		
				19	50.5				
				22		290			
				25		289			
				29			390		
				36	50.5				
				38		288			
				42		286			
				45			386		
				50	51.2				
				55		283			
				59		285			
				08 08			383		

Reporting of geomagnetic survey data to world data centres

358 The best way of reporting geomagnetic survey data to a world data centre is to type them on sheets of 30 by 40 centimetres, which are then microfilmed. If microfilm equipment is not available, the world data centres are pleased to accept typed or even hand-written reports. There is still need for more data, and organizations which have not yet reported their data are invited to do so at their earliest convenience. Even the smallest contribution will be valuable.

359 The reporting of the observed (unreduced) values, as given in the accompanying example (opposite), should be given the highest priority. The form and the explanations are taken from Vestine's *Manual* (IUGG Monograph No. 11). Give the types and serial numbers of the instruments used in the survey and their corrections to observatory standards. The corrections to IMS are very desirable, though in many instances they may not be known. Write R after the station name if the station is a repeat station. Latitude and longitude should be given to the nearest tenth of a minute of arc, if possible.

Use Greenwich Mean Time (GMT).

Under D, H, F enter the observed (unreduced) values. If you have observed other components, modify the headings as appropriate.

D and I should be given to the nearest tenth of a minute of arc, the intensities to the nearest gamma.

The elevation above sea level may be given either in metres or feet (preferably metres).

Under 'remarks', enter any special observations on the character of the station, e.g. whether it is anomalous. Also enter date or epoch of any previous occupation.

360 A second report will contain the data reduced to epoch. In that report only one line per station will be required. The report may also include the other components computed from the observed components.

Choice of instruments

361 The progress of field work depends much on the availability of suitable equipment. In the present state of the art, combinations of classical instruments with a portable proton magnetometer are most promising. In the following table (page 198), six combinations of instruments are listed, though many other combinations are possible. It is assumed that the azimuth is determined astronomically. If objects of known coordinates are used for the determination of azimuth, the azimuth-measuring equipment can be omitted and the time-keeping equipment can be reduced to a wrist-watch and a midget transistor radio. The geomagnetic instruments have been selected in such a manner that all components can be determined with sufficient accuracy, with the exception of combination V which fails in F and Z at high latitudes. This combination is universally applicable if the earth inductor is replaced by a BMZ. When using a magnetic travel theodolite for measuring H, it may suffice to observe deflections using the small deflection

Combinations of instruments for geomagnetic surveys

Number of combination	Azimuth-measuring equipment	Geomagnetic instruments	Time-keeping equipment
I	Geodetic theodolite, or theodolite attachment to travel theodolite, or black mirror to travel theodolite	Base of magnetic travel theodolite, declinometer attachment, 1 to 3 QHMs for I > 45°, 1 BMZ for I < 45°, proton magnetometer	I-VI: Box chronometer, or pocket chronometer, or precision watch; stop-watch, or stop-watch chronograph; radio receiver
II	GSI magnetometer	GSI magnetometer, proton magnetometer	
III	Geodetic theodolite or astronomical telescope on QHM base	QHM base, 1 to 3 QHMs, 1 BMZ	
IV	Compass theodolite, or theodolite with compass tube attachment	Compass theodolite, or theodolite with compass tube attachment for D, QHM base, 1 to 3 QHMs, 1 BMZ	
	Theodolite attachment to magnetic travel theodolite, or black mirror	Base of magnetic travel theodolite, declinometer attachment, deflection accessories, oscillation box for long tours, earth inductor attachment, field balance for Z	
VI	Compass theodolite, or theodolite with compass tube attachment	Compass theodolite or theodolite with compass tube attachment for D; field balance for H; field balance for Z	

distance only, provided the deflection angle is sufficiently large. If the instrument is frequently compared with an observatory standard, the method will yield satisfactory results. When observing H with a travel theodolite on expeditions lasting several months, it is advisable to observe oscillations once every week. Except for combinations III and IV, one instrument is available for the rapid measurement of Z (field balance) or F (proton magnetometer). Both these instruments are useful for testing the magnetic homogeneity of a station site and for observations at intermediate stations. When using combinations III and IV, the BMZ has to serve this purpose.

Combination VI requires an entirely different approach to the planning of survey traverses, because field balances show drift and erratic changes. It is necessary to pass several traverses through conveniently chosen key stations. First, the values of the (frequently occupied) key stations are adjusted. The closing errors of the partial traverses are then evenly distributed. For this type of work Fanselau balances and the knife-edge balances of Ruska or Askania are most suitable. Field balances have to be transported with great care in order to minimize the possibilities of erratic changes.

Valuable contributions to the World Magnetic Survey can be made by observing F only. Numerous geological survey departments are in possession of proton magnetometers which are used in prospecting surveys. Since geological field-survey parties usually cover large distances when travelling from one field of operation to another, observations of F should, if possible, be made every ten kilometres at places that can be identified on the map. Eventually the whole country will be covered by traverses. The reduction and assembly of data will have to be done at a geomagnetic observatory.

Transport and other equipment

362 The most convenient means of transport is a $^3/_4$-ton van which will carry all the equipment and personnel of the field party. Sometimes a station wagon may suffice. If large distances have to be covered without possibility of refuelling, a truck may be necessary. Four-wheel drive is useful for covering trackless ground, and may save the field party many hours of hard labour. There is no need to stress that for journeys off the beaten track the vehicle has to be in perfect condition. It will be wise to carry some spare parts, especially breaker contacts. Extra petrol may be transported either in original tins, which are thrown away after the petrol has been consumed, or in jerry-cans. Jerry-cans are also useful for carrying water, provided that they have not already contained petrol. Water with traces of petrol can be made fit for preparing tea by boiling for 15 minutes. When car transport is used, it is convenient to carry the equipment in a large crate with upholstered compartments for the instrument cases. Upon arrival at the field station the whole crate can be lifted from the vehicle. If the field work is not expected to last long, blankets will suffice for wrapping around the instrument boxes.

363 Caravan transport involves limitations on the weight of packages. Porters will carry loads of 30 to 40 kilos, depending on the local customs. Since porters usually insist on the loads being weighed in their presence, it is useful to carry a spring balance. For animal transport, packing units of 40 kilos are the most convenient. Mules, donkeys, horses and oxen will carry pairs of units of this weight, while camels carry four. Although camels carry up to 200 kilos, it is not prudent to utilize their full capacity on long trips without food or water. For caravan transport, it is necessary to pack the instruments in upholstered boxes and to indicate by arrows on the side of the boxes in which position they have to be carried.

364 People commonly try to excuse their inactivity in geomagnetic surveying by the lack of a motor vehicle. A whole country may often be surveyed using the railway or bus system. The survey party may travel from station to station and hire transport locally for carrying the equipment to observation sites. Many countries have been surveyed in this manner. There are still some geomagnetic surveyors alive who have carried their equipment on their own backs or on bicycles.

365 In a field survey it is necessary to protect the classical instruments for intensity measurements against solar radiation, in order to keep them at a fairly constant temperature. In periods of quiet weather, a surveyor's umbrella made of non-magnetic material is convenient for providing shade. Three cords are run from the top of the umbrella to the ground, where they are tied to pegs, so that the umbrella will stand on hard ground without the attendance of an assistant. In windy and rainy weather, a tent offers more protection. Any type of tent can be used, provided the floor area is about two by two metres, the height about two metres and the fittings made of brass or aluminium. In a sunny climate a double roof is useful. When QHMs and BMZs are used, the tent should be made of fairly transparent material so that sufficient light is available. Carry a sufficient number of spare pegs, which are usually made of hard wood. In most cases the observer will have to design his own tent and to get it made locally. Useful ideas for tent construction can be found in the report on Land Magnetic Observations, 1905-1910, of the Carnegie Institution of Washington (1912) (see also Fleming, 1939). A sheet of canvas and a couple of short poles should be available for making a shade for the instruments not in use. The QHMs especially should not be exposed to sunshine (paragraph **164**).

366 An important piece of equipment is a pair of powerful field glasses, needed for identifying objects of known coordinates and for reconnaissance when travelling over difficult ground. A lens is useful for reading the thermometers of instruments and fine details of maps. A tape of 30 metres length (linen) and a pair of surveyor's beacons are required for measuring distances. A good pocket compass is necessary for navigation and for setting up the sensor of the proton magnetometer, and the tent. When the field party travels frequently over trackless areas, a fluid compass mounted on the wind-shield of the vehicle, in front of the driver or navigator, may not be a mere luxury. A prismatic compass may be a useful supplement to the navigational aids.

367 Writing and drawing materials such as pencils, erasers, a pen-knife or pencil sharpener, a ruler and a protractor are kept conveniently in a small bag. A tool box should contain a set of mechanic's screwdrivers, adjusting spanners of various sizes, and tweezers.

368 A field party may consist of one to five persons. Provided the equipment is well chosen and the survey activities take place in a populated area, one physically fit observer may do all the work alone, including driving the vehicle. An educated assistant for recording observations is of great help, though not essential. On journeys off the beaten track the field party should consist at least of three, better of four persons. Every extra hand is useful if the vehicle gets stuck.

Planning a geomagnetic survey

369 Start from the funds at your disposal. Try to cover your country evenly with field stations within the available budget. Some money should be reserved for contingencies and for the reoccupation of stations at which serious errors are detected when the results are computed. The minimum coverage, as has been mentioned before, is a distance of 200 kilometres from station to station. Usually a better coverage will be possible.

370 Before you plan the distribution of stations, find from the literature what geomagnetic work has been done in the past. Do not forget to consult the three volumes of *Land Magnetic Observations* of the Carnegie Institution of Washington. In all probability, Carnegie observers have occupied a few stations in your country. Excellent descriptions of the station sites and the results of observations are contained in these volumes. If you are not in possession of the publication, ask any IAGA officer concerned with geomagnetic survey work for an extract of the relevant part. Unfortunately, in many recent surveys no attention has been paid to previous work. It is of the greatest importance to make repeat observations at old geomagnetic field stations, for deriving the secular variation. The network of old stations should therefore provide the skeleton of the new survey. In some instances, the old stations will themselves provide sufficient coverage. If not, the next step will be to select stations in-between the old stations, in such a manner that an even distribution is achieved. For this work a small-scale map is needed.

371 When selecting sites for new stations, use geological maps in order to avoid areas with magnetically disturbed geological formations (ultrabasics). Additional information on the degree of disturbance of a site may be obtained from airborne magnetic or ground prospection surveys. Note that in the neighbourhood of an anomaly in F and Z, anomalies in D and H will occur. When using data from prospection surveys for the selection of station sites, the chosen limits of permissible anomaly should not be too narrow, in order to avoid bias (paragraph **356**). When no prospection survey has been made previously, one may observe one element, either F or Z, along the roads one travels, with a station spacing of five to ten kilometres. The data obtained will help in avoiding magnetically disturbed sites.

372 Once you have made up your mind as to the approximate locations of the stations to be occupied, procure large-scale maps (1 : 25 000 to 1 : 100 000) containing the selected sites. Get two copies of each sheet, one for the office and one for field use, because a map once used in the field is usually so damaged that accurate measurements cannot be made on it. Plot the sites of the old stations, using the geographic coordinates and descriptions, and try to fix sites for the new stations using the details of the maps. If it is intended to use the geodetic network for azimuth determinations, trigonometric stations have to be occupied. The geodetic survey department will help you in selecting easily accessible trigonometric stations, from which objects of known coordinates are visible. Select for every magnetic station at least two trigonometric stations, so that you have a station in reserve in case one of them is not fit for occupation. Trigonometric stations have the advantage that they are marked by monuments, which are well maintained, especially at stations of high order. Inquire at the survey department whether iron has been used in or below the monuments. If the monument contains iron, occupy a site a few metres away. Note that for the correction to the true bearings computed from the coordinates of the trigonometrical station and the azimuth marks, the distance and bearing from the occupied site to the monument have to be observed. If you intend to determine the azimuth from sun observations, you will have more freedom in the choice of stations but also the responsibility for choosing the station in such a way that it can be found in the future. The description of the site has to be more elaborate. When choosing station sites, be sure that they are far enough from towns and villages. Many old stations have been lost because they were built over in the course of time. A safe distance from a large town is 15 kilometres, from a village two to three kilometres. Finally, assemble all information pertaining to a station, old or new, on a file card or a sheet of paper. Make two copies for each station, one for the office and one for field use.

373 The survey work can be done on journeys lasting from one to three weeks, depending on the size of the country. For planning survey trips, road maps are very useful. Careful consideration should be given to details such as the possibilities of refuelling and filling the water tanks. To enter certain areas in some countries a special permit may be required. The tours should be arranged in large loops starting and ending at the observatory. When crossing a previous survey traverse, reoccupy the nearest station of that traverse. This will give a check on the accuracy of your observations. However, try to concentrate reoccupations on ten to twenty evenly distributed stations. These stations will later serve as secular-variation stations. It is good practice to provide two alternative sites for repeat stations, a few kilometres apart, in order to reduce the risk of losing one of these important stations. Every return to the observatory is utilized for a comparison of the field instruments with the observatory standards. Three sets of observations will be adequate. At the end of the field season, minor corrections to the constants of the field instruments can be derived from these comparisons, so that the results of observations may be reduced either to the level of the observatory standards or, preferably, to the IMS level.

Practical field survey operations

374 It is assumed that you are a novice in geomagnetic surveying. If you have not had the opportunity to attend a course in practical astronomy, you may have difficulties with the sun observations. Mark a spot in the compound of your observatory over which you set up the theodolite. Observe a number of sun azimuths, starting with the sun near the horizon. Later, try observations at other times of the day, always using the same azimuth marks. Compute the observations and see how much they scatter. After a few practice runs, you should find that the scatter has come down to half a minute of arc or less, which is good enough for geomagnetic surveying.

375 The next step is to try all your field equipment, magnetic and astronomical, under field conditions. You will find out what parts of your equipment require perfecting and what else may be useful. Try to keep the auxiliary equipment to a minimum. Your first field tour should last one or two days and will serve as a final check on your equipment and the methods of observation. After this experience you can finalize the selection of your equipment.

376 Another question to be settled at the beginning of your survey activities is whether you intend to live in a field camp or to stay in hotels, inns or government rest houses. The field camp will give you independence. You can start and stop whenever you like. Living in hotels will involve extra travel and late starts. Usually, you will lose one station per day as compared to living in a field camp. Consult your geodetic survey department on these questions. They have long experience and may even help you with suitable camp equipment.

377 The recording of observations has been discussed in paragraphs **74-9**. If you use a field book, you may begin the entries of a journey with a brief description of your equipment, including the serial numbers of the instruments. The field book may also contain notes on the journey, say, time of start, intake of water and fuel, details on the road, difficulties encountered during the journey, and the camps. Your successor in office will be grateful for such notes. A special diary may be kept for this purpose if forms are used for recording observations.

378 It is of great importance to make a note of the standard time you use, in the form of an equation:

$$\text{Standard time} + n \text{ hours} = \text{Greenwich Mean Time}$$

When you use Greenwich Mean Time, all watches, including your wrist-watch, should show GMT. Standard time may be shown by the clock on the dashboard of the car. Do not try to carry standard time and to convert it mentally to GMT, because mistakes will certainly be made.

379 Upon arrival in the vicinity of the station, stop on the road and start the search for the monument. When you have to occupy an old station not marked by a monument, look for the exact locality with the description of the station in hand. The appearance of the site may have changed considerably since the previous occupation. Try to imagine what the place looked like according to the description. In case of doubt, interrogate villagers in a friendly manner. Tell them that your activities have nothing to do with the income tax office or property boundaries. This remark is always helpful. You may get some useful hints. If not, you will have to resort to more subtle methods. When the description contains the true or magnetic bearings of at least three prominent objects, you may find the approximate position of the station using the declinometer or prismatic compass, allowing for the secular change of declination. Next, measure the angles to the three objects by means of the theodolite. Compare the angles between adjacent objects given in the description with those you have observed. You will obviously have to move in the direction in which the observed angle is smaller than the angle given in the description. By successive shifts of the theodolite you will ultimately arrive at a close agreement of the angles, which indicates that you are at the proper position. If the description contains bearings on only two objects, you must be content with an approximate occupation found by means of the declinometer. When the station is disturbed by recently erected buildings or other structures, a substitute site must be found for the station. If the original site is only moderately disturbed, observe there and then move to the substitute site.

380 When you observe at a new site which is not a trigonometrical station, make sure that it can be pin-pointed on a large-scale map. It is important that there be some permanent features in the vicinity of the site to which tie-in measurements can be made, so that the exact place of observation can be determined later from your description. The station should preferably be on waste land or on public property which is accessible all the year round. Avoid arable land if possible. Milestones on roads, road signs, telephone poles and electrical power pylons are unsuitable for tying in a station. Experience has shown that such objects may be shifted or removed. They may however be used as azimuth marks, though not alone. Giant trees are longer lasting. Churches, temples, large monuments in cemeteries, tombs of saints, wells and large boulders are safe to use.

381 Inspect the surroundings of the station for magnetic objects such as iron masts, bridges, old fortifications such as pillboxes, and pipelines. Keep away from such objects by a distance of at least 200 metres. If the bridge is a large structure, move to a distance of several hundred metres. A rough rule is that one ton of iron in the Earth's magnetic field produces an anomaly of one gamma at a distance of 50 metres. Do not observe on roads because they are usually magnetically anomalous. Archaeologists make use of this fact to trace old roads. Near high-voltage power lines, the proton magnetometer may fail to give consistent readings because of the high noise level.

382 Before you decide on the exact site of a station, make sure that you can see a sufficient number of azimuth marks, that the marks will remain visible in the future, and that the sun will not be hidden by trees in the course of the day if you have to depend on sun observations. The azimuth marks should be prominent and at least 200 metres away from the station (see also paragraph **245**). Finally, check whether the ground is suitable for driving in tent pegs and is not too soft for setting up the tripod.

383 Once you are satisfied on all these details, start with the homogeneity survey of the site. If you use a field balance (with its tripod legs fully extended) or a BMZ, begin with observations at the centre, i.e. the spot you plan to occupy. Observe at another point 30 metres north or south of the centre and a third point about the same distance east or west of the centre. If the results of the three points do not agree within 10 gammas, observe again at the centre in order to see whether you have not been fooled by strong time variations, although this is not likely at middle or low latitudes. Usually a better site will have to be found. When you use a proton magnetometer you can carry out a more elaborate test of a possible station site in a shorter time. Observe at the centre, at two metres from the centre in the four cardinal directions, again at the centre, in order to have a check on the time variations, and then at a distance of 30 metres from the centre in the four cardinal directions. The homogeneity test is completed by another observation at the centre. Use the sensor on a staff or tripod at least one metre above the ground. The site is acceptable when the five inner points show differences not exceeding five gammas and when the differences between the four outer points and the centre are not larger than ten gammas. Sometimes it may happen that a homogeneous site cannot be found. In this case, a very precise description of the site has to be made so that future observations can be made on exactly the same spot; it may also be of value to note the height of the instrument above the ground.

384 You will previously have made sure that the vehicle can be driven to the site. Reconnoitre the approach again. Walk with the driver over difficult passages and instruct him in detail. Then have the vehicle driven to the site and unload the equipment. Set up the shade for the instruments 15 metres from the centre and open the instrument cases so that the instruments can assume the temperature of the air. Remove the vehicle to a distance of 75 metres from the station. If it is morning, start with the sun observations, i.e. with the sun as near to the horizon as possible. In the afternoon, the sun azimuth will be the last observation to make. In cloudy weather it will be best to set up the astronomical theodolite 5 to 10 metres away from the magnetic theodolite and to make the observations when the sun appears. In this case, one must not forget to measure the distance between the two theodolites and to take a sighting with the astronomical theodolite on the magnetic theodolite or vice versa, so that the true bearings to the azimuth marks obtained with the astronomical theodolite can be computed for the magnetic theodolite. When tripods have to be exchanged, mark on the ground the centre of the tripod which was used first, by means of a plumb, and centre the second theodolite exactly if the azimuth marks are near the station. In quiet weather, use the umbrella. In windy or rainy weather, set up the tent in the direction you have found best from previous experience.

385 Upon completion of the observations but before removing the tripods and the tent, run through the notes and check them for completeness. See that auxiliary azimuth marks observed with the QHM telescope have been related properly to the main azimuth marks, that the sightings on all prominent objects including those near by, which will be required for the description of the station, have been taken.

386 Finally you have to describe the station in such a way that you or any other person can find the site and occupy it within 30 cm or one metre, depending on the magnetic homogeneity of the site. The more homogeneous the magnetic field at the site, the less care is required in the description. Start with a sketch containing all important details. Indicate north by an arrow. Pace out or measure by tape the distances to near-by objects. Estimate larger distances. Take photographs of the site from several directions with the tripods *in situ*. Formulate a description in words. Start with the directions and distances to the more remote objects, towns and villages, and end with the smaller details in the vicinity of the station. The description should guide you to the site. In this respect, the descriptions given by the observers of the Carnegie Institution are perfect examples. Again it may be useful to ask villagers for details. The description is completed in the office with the exact distances and true bearings. The sketch is converted to a properly scaled plan.

Geodetic survey departments usually require their staff to compute their observations before packing up, so that defective observations can be repeated immediately on the site. However, in magnetic survey work this is not so important. The observer should be able to do the comparatively simple routine faultlessly. If the observations are defective, they can be repeated on one of the next survey tours.

387 It has often been recommended that repeat stations should be marked in some permanent manner if they are not situated at a trigonometrical station. The marks should be heavy so that they cannot be removed easily. As it is difficult to transport a sufficient supply of marks, it is better to carry a mould for casting marks on the site, using cement and gravel obtained from a near-by village. A group of letters or a number may be inscribed for easy identification. In areas with outcrops of rock, one may apply marks of weather-resistant paint to protected areas of rock. Occasionally, a cairn may be built. Note that a marked station also should be well described in case the mark is removed by the population or by natural causes. From among the stations occupied, one should select for repeat stations those which are on magnetically homogeneous terrain, near permanent features to which the observing position can be reliably tied in, and with at least three prominent azimuth marks whose bearings give a good intersection at the observing position, so that the station can eventually be reoccupied by means of the method described in paragraph **379**.

388 When you observe at intermediate stations with a field balance or proton magnetometer, take a reading at the centre of the station before packing up. After packing, move the vehicle away and check carefully whether anything has been left behind. Here it may be mentioned that small objects like lenses, tools and magnets should never be put on the ground. Return them to the proper place in the packing cases immediately after use. The intermediate stations should, if possible, be chosen so that they can be pin-pointed on the map. In featureless country, the car mileage may be used for interpolating their positions.

389 When travelling off the beaten track, a note of car mileage and compass bearings is a necessity at every point that can be identified on the map, at all intermediate stations and whenever changing course. The reduction factor of the car speedometer should be known from a comparison with mile or kilometre posts on a road. When trying to plot the position from car kilometres and compass bearings, allow a few per cent for slip of wheels and for detours. In desert areas and in wild country which is not properly mapped, it may be necessary to determine the position astronomically. Practice observation and computation at home. Your safety may depend on finding your correct position. The longitude may be determined from the rising or setting sun at elevations higher than 10°. In the northern hemisphere, the latitude can be derived easily from observations of Polaris at dawn or dusk with practically no computations, thanks to the tables which are found in the *Nautical Almanac* or any other astronomical ephemeris. For these procedures, consult a primer on spherical astronomy.

Review and outlook

It is hoped that the object of these notes, namely, to show the novice in geomagnetic work the road to sound professional practice, has been achieved. Before concluding, some further explanations may be useful.

It has seemed advisable to limit the treatment to the more important methods which are in use at many observatories. Much space has been devoted to the QHM and BMZ, but a systematic treatment of the magnetic theodolite and earth inductor was thought to be of equal importance, because at some observatories these instruments (occasionally even Schmidt theodolites) have been left aside, obviously because the observers do not get on well with them. In order to simplify the computation of the results, the fitting of the coefficients Q and P and the control of the moment of inertia has been omitted here. The method described is in use successfully at a number of observatories.

Objections may be raised to the numerous trivial examples of computation. However, a simple example often conveys more information, especially to the technician, than a long explanatory text. Examples and explanations are so designed that the observational and computational procedures can be followed without understanding much of the scientific background. Unfortunately there was no space for detailed arguments and derivation of formulae. Once he masters the techniques, the scientifically trained worker will wish to understand what he is doing. For that purpose he will have to consult textbooks, mainly the older ones. Much useful information, scientific and technical, will be found in the *Journal of Terrestrial Magnetism and Electricity*, which should be in the library of every observatory. Other sources of information are old scientific papers and observatory yearbooks, in which authors took delight in describing every detail of an experiment with painstaking accuracy.

The beginner may have difficulty in following the numerous instructions. In the beginning he may just manage to stumble through a procedure, but with increasing proficiency he will be able to pay more attention to details and after a few months of practice he will do the work more or less automatically without thinking much about the various points to be considered. The observer should, however, beware of letting his routine observations become empty rites. He should carry out the operations effortlessly, unhurriedly and yet with concentration. Becoming a good observer is not only a question of training and practice but also of aptitude. Almost anyone can become an average observer but only a few will produce perfect results, because they are not only good with their hands but also have the correct attitude of mind. An observer must have almost infinite patience but at the same time he must be endlessly curious about the behaviour of his instruments and about the nature of the phenomena he is observing.

In addition to studying books and manuals, an apprenticeship at a well-established observatory may be useful. Unfortunately, fellowships for that purpose are rare and even rarer are observatories which will accept apprentices. Naturally, no observatory will want to take on a complete novice. An observatory worker should master the basic techniques and should have studied the problems of his own station before he tries to obtain training elsewhere. Only then will a stay at a foreign observatory, which need not be longer than three to four months, be profitable.

The accuracy obtainable in measurements has scarcely been discussed because it depends to a large extent on the magnitude of the quantities to be measured and the layout of the whole observatory. There is therefore no point in postulating any target of accuracy. At top-ranking observatories the error, at least in absolute measurements of intensity, may be one gamma or less, and a small group of observatories aims for this accuracy. However, at the average observatory the error will be somewhere between two and three gammas for an hourly mean, and this accuracy can be obtained with a little care and classical equipment. Considerable effort is required to improve the quality of data beyond this level.

Some readers may find that the examples have been computed more accurately than required. It is a good rule to carry out the computations one digit further than the observations merit, in order to avoid errors of approximation. The number of digits to be carried will be determined by the scatter of results. When, for instance, the scatter in an element is ten gammas it is a waste of time to compute the results to one-tenth of a gamma.

An attempt to standardize symbols was given up at an early stage of writing these notes. It seemed better to adhere to symbols used in the older literature. This applies especially to the QHM and BMZ, where the introduction of new symbols would have a devastating effect. In practice, some symbols denote several quantities (for instance, φ, which stands for both geographic latitude and the deflection angle). However, the risk of confusion is generally small.

In order to avoid lengthy explanations, the treatment of some problems has not been rigorous, though accurate enough for practical purposes. In many instances it has not been stressed that a formula is valid for small angles only. It is hoped that the mathematician will see it at a glance and that the technician will in most cases not be tempted to stretch a formula beyond its range of validity.

The many imperatives used in the text may create the impression that it is intended to standardize geomagnetic work to the last detail and that there is only one proper way of making certain measurements, namely, the one described in the text. It has been pointed out in the introduction that no such intention exists. However, when reporting to world data centres and preparing magnetic yearbooks, it may be useful to abide by certain standards which have been given in the text and which are not difficult to follow.

The final output of a standard magnetic observatory is the yearbook, which usually contains about 80 000 bits of numerical data. If one takes into account that, for producing these data, an average staff of three people is required, not to mention the non-technical staff such as guardians and night-watchmen, etc., the over-all efficiency may seem to be low. Several expedients for raising the efficiency have been mentioned, namely, temperature stabilization in the variometer room, automatic data processing and the direct scaling of absolute values. Up to 75 per cent of the labour of computation may be saved by such measures, but this does not necessarily mean that the staff can be reduced to the same extent, especially when the observatory is a self-contained unit.

A description of methods of digital recording and automatic data processing is beyond the scope of this booklet. The reader is referred to descriptions of an automatic system, which requires no control of base-line values, by Alldredge (1960) and Alldredge and Salducas (1964). Both papers are excellent introductions to the subject. Meanwhile, other methods have been developed which are equally promising. There is no doubt that the introduction of digital methods of data recording has become imperative, because at the present time microfilm copies of magnetograms required for research purposes have to be digitized by a cumbersome process in which some of the original accuracy of the data is lost. How long it will take to introduce the new systems is difficult to guess. Estimates of experts range from five to fifty years. For the time being, the high cost of equipment is the most serious obstacle to the modernization of existing observatories. If, however, an entirely new observatory is planned, it may be worth while to compare the total cost of buildings, equipment, operational maintenance (including staff) and data reduction on two bases: firstly, a traditional observatory; and secondly, an observatory fitted with the latest automatized recording and data-reducing systems. Taken over a twenty-year period and with such aspects as the improved presentation of final data in mind, the result of such a comparison may well support a decision in favour of the second alternative.

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Index [1]

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[1] References are to paragraph numbers.