(*Lanza*)

1.1.4
Modern Magnetic Measurements

Since the Earth's magnetic field is a vector quantity, the field magnitude is absolute if expressed in terms of the fundamental quantities (for example mass, length, time and electrical current intensity), while the vector spatial orientation can be expressed for example in terms of D and I, angular dimensionless quantities. From the total field F magnitude and the angular quantities, the geomagnetic field components H, Z and also X, Y can be computed. Sometimes magnetic instruments give as outputs directly the geomagnetic components; it is self evident that once three independent elements are determined, the magnetic field measurement is considered complete.

Nowadays magnetic instruments that utilize magnets for their operation are only very seldom used in magnetic observatories. Moreover the measurement of declination and inclination angles is a procedure employed mainly for absolute magnetic measurements in magnetic observatories or at repeat magnetic stations. An instrument is called absolute when it gives the value of the measured quantity in terms of one or more of the absolute basic fundamental quantities of physics. For this reason in geomagnetism the term *absolute measurement* is still often used to indicate a procedure for the complete absolute determination of the magnetic field elements. An instrument is called relative when it measures the value of one element of the Earth's field as a deviation from a certain initial value not necessarily known. Many of these instruments require a reference initial value that must be determined independently, for example by means of an absolute instrument. The use of relative instruments can of course be very convenient especially in some field operations, for example when only the spatial variation of the magnetic field in an investigated area is required. A second case is when, at a given place, a time variation of the Earth's magnetic field needs to be recorded.

Instruments are delivered with information and data sheets that provide the values of the parameters necessary to evaluate their measurement capability. The most frequently used parameters are reported in what follows.

- *Accuracy:* indicates how an instrument is accurate, that is the maximum difference between measured values and true values.
- *Precision:* is related to the scatter of the measured values and refers to the ability of the instrument of repeating the same value when measuring the same quantity.
- *Resolution:* represents the smallest change of the measured quantity that is detectable by the instrument.
- *Range:* refers to the upper and lower (extreme) limits that can be measured with the instrument. The dynamic range is the ratio between the maximum measurable quantity and the resolution, normally expressed in dB, i.e. $20\log(A_{max}/A_{min})$.

- *Sensitivity:* indicates how many scale units of the instrument correspond to one unit of the measured physical unit.
- *Scale value:* is the reciprocal of sensitivity.

Magnetic instruments are nowadays not only devoted to magnetic measurement, they are also frequently equipped with electronic cards, able to memorize measured data and to interface to PCs for real-time or off-line data communication.

1.1.4.1
Absolute Instruments

Proton Precession Magnetometers and Overhauser Magnetometers

These instruments are based upon the nuclear paramagnetism, i.e. the circumstance that atomic nuclei posses a magnetic spin that naturally tends to orient itself along an external magnetic field. In these magnetometers the sensor is made up of a small bottle full of a hydrogenated liquid (such as propane, decane or other that can operate as liquid in a reasonable temperature range) around which a two coil system is wounded. A direct electrical current is applied to the first winding (polarization coil) by means of an external power supply and consequently generates a magnetic field inside the bottle. Protons in the bottle are then forced to align their spin along this magnetic field starting to precess at a frequency rate depending on the magnetic field magnitude. If the external current is interrupted, the artificial magnetic field is removed and then protons in the bottle will start precessing around the Earth's magnetic field direction at a frequency f given by

$$f = (\gamma / 2\pi)F \tag{1.17}$$

where γ is the so-called magneto-mechanical proton ratio (gyromagnetic ratio) a fundamental quantity, very precisely known in atomic physics (2.6751525×10^8 rad s^{-1} T^{-1}) and F is the external Earth's magnetic field. The proton precession generates at the ends of the second winding (pick-up coil) a time varying electromotive force (e.m.f.) with the same frequency, which can easily be measured to obtain the absolute total field F magnitude. In the average Earth's magnetic field (for example 45 000 nT) the frequency is very close to 2 kHz (1 916 Hz) (Fig. 1.9).

The loss of coherence inside the bottle allows only a small time window (about 2–3 s) for the detection of the e.m.f. frequency. This time is however now more than sufficient for modern electronic frequency meters to give the precession frequency. In fact due to progress in electronic technology, the measurement of frequency is in contemporary physics one of the most accurate techniques. Since it is only dependent on the measurement of a frequency, the measurement of the Earth's magnetic field by means of a proton precession magnetometer is both very precise and absolute: resolution reaches now easily 0.1 to 0.01 nT.

One disadvantage of proton precession magnetometers is the limitation due to the fact that the polarization current needs to be switched off in order to make a measurement. The operation is therefore discontinuous with a time interval of a few seconds between measurements. A continuous proton precession signal can however be obtained by taking advantage for example of the so-called Overhauser effect. The ad-

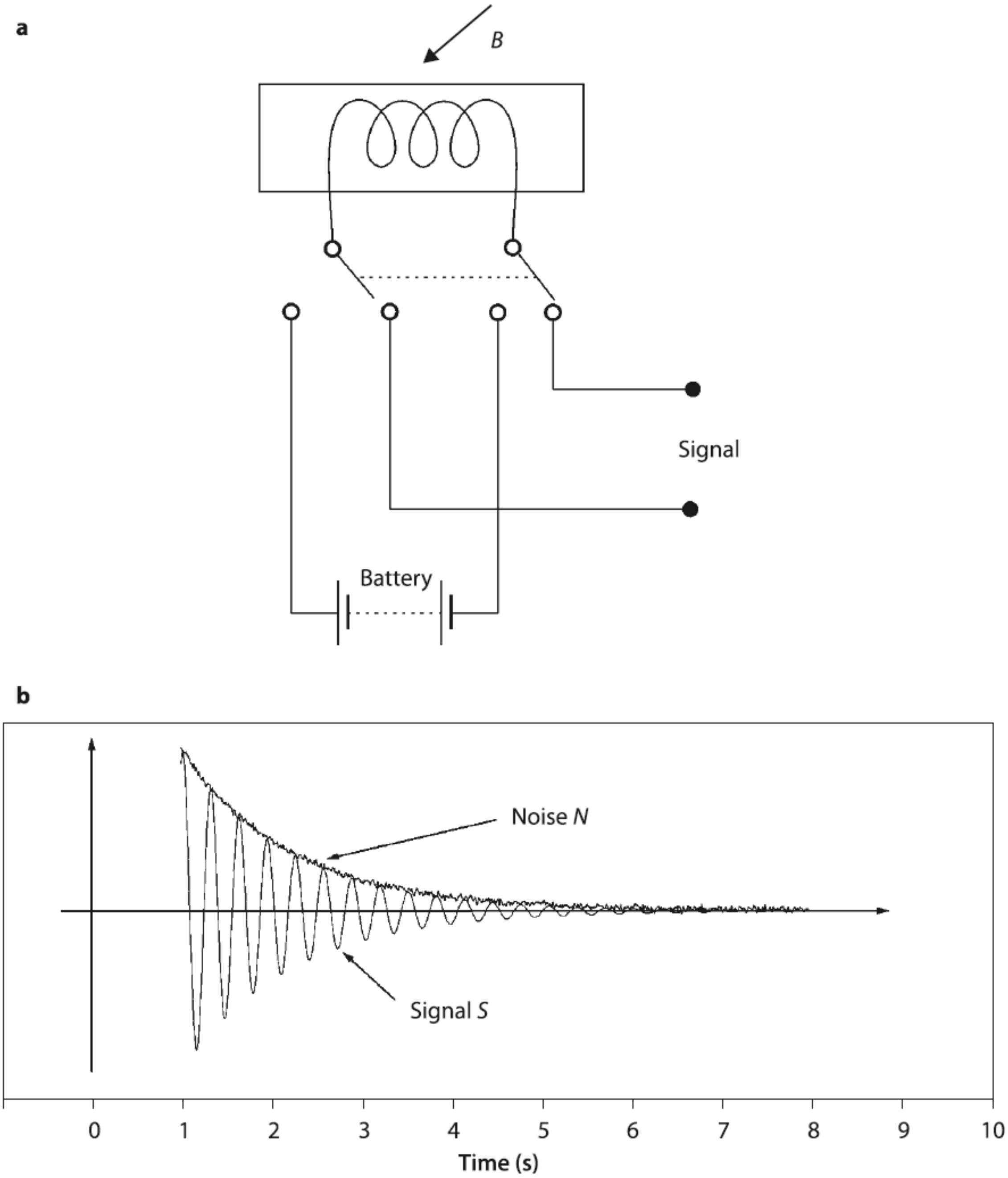

Fig. 1.9. Proton precession magnetometer; **a** electric circuitry schematics for measurement of field *B*. The measurement is performed in two steps: (1) generation of free proton precession by power injection; (2) signal detection after switching; **b** typical detected signal amplitude decrease. Signal to noise ratio is optimum for only a few seconds after polarization is turned off (from Jankowsky et al. 1996)

dition of free electrons into the liquid in the bottle and the application of a suitable radio frequency, can in fact increase the magnetization of the liquid sample. Without going into details, we will just remember here that as an alternative to applying a strong polarizing field, in Overhauser magnetometers the magnetization is increased by applying a suitable radio frequency electromagnetic field to put the free electrons into resonance. This electron resonant frequency that exceeds by 658 times the proton resonant frequency, has the role of increasing the proton level saturation making the pro-

(*Jankowski&Sucksdorff*)

4.9 Fluxgate magnetometer

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

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

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

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

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

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

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

which, by applying standard expressions for trigonometric functions, gives

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

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

Figure 4.16 illustrates the waveform of a single-bar fluxgate sensor. In the case with no external field, the output signal is symmetrical around the points $\omega t = 0$, π, 2π, etc., and there are no even harmonics. In the case of an additional external field, the core saturates more easily during one half-cycle of the excitation, and later during the next corresponding half-cycle, etc., and we have even harmonics in the output signal with amplitudes proportional to the external field. In a double core sensor the

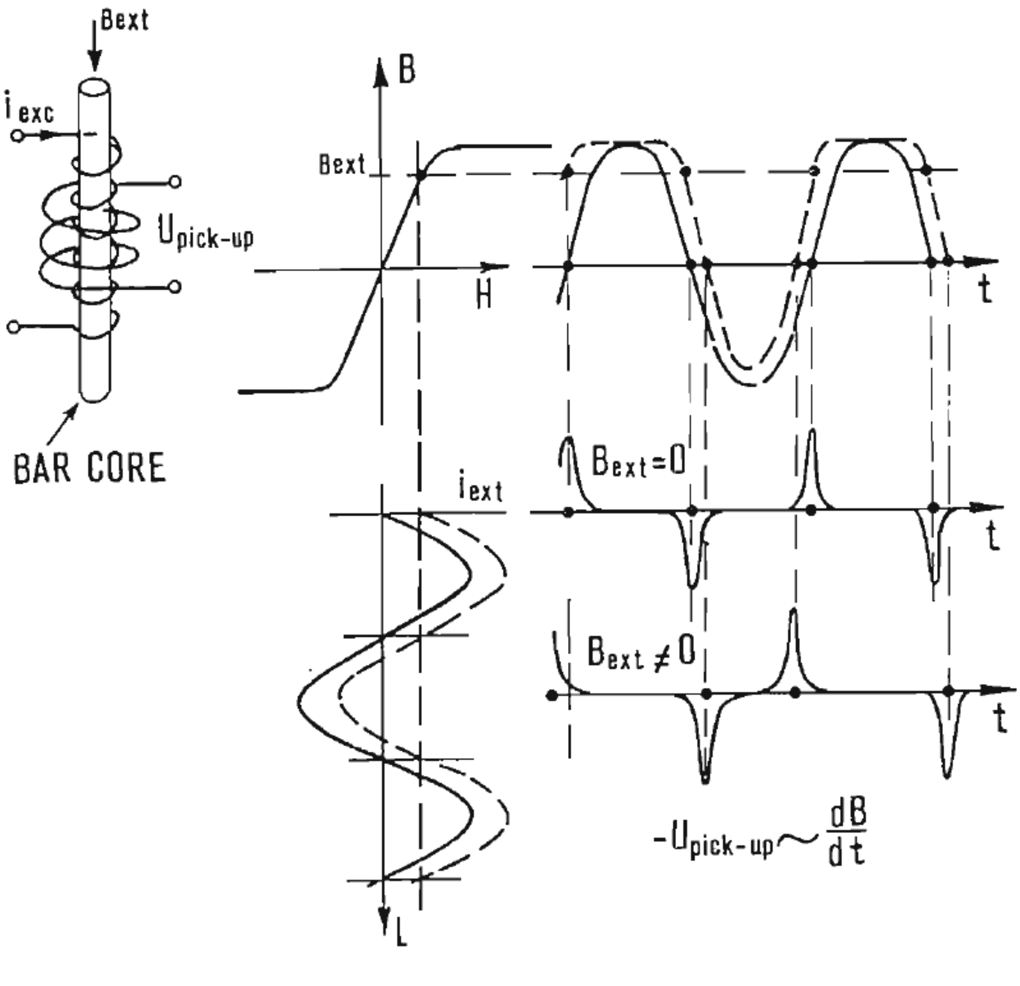

Figure 4.16. Waveforms of a fluxgate sensor with the core consisting of a single bar.

Fluxgate instrumenti robusni su za uporabu i nalaze se na mnogim satelitima i većini suvremenih opservatorija. Tipični problemi s fluxgate instrumentima uključuju termičku osjetljivost i potrebu za periodičnom apsolutnom kalibracijom (pomoću PPM-a) na opservatorijima. Instrument postiže zahtjevane točnosti mjerenja na geomagnetskim točkama uz uvjet da su instrumenti uspoređeni/kalibrirani prije i poslije svake izmjere.

Magnetometers

Ivan Hrvoic

GEM Systems, Inc., 135 Spy Court, Markham, ON, CANADA L3R 5H6

Synonyms - Geomagnetic Instruments

Definition

Magnetometers are devices/instruments that measure magnetic field/magnetic flux density in particular Earth's magnetic field either vectorially or scalarly.

1. Introduction

First measurements of magnetic field intensity have been introduced by Carl Friedrich Gauss (Kaufman et all 2009) in 1834. He has established a number of magnetic observatories to continuously measure magnetic field of Earth *(Geomagnetic Field, Measurement Techniques-Mioara Mandea, Anca Isac, Geomagnetic Field Secular Variations- Monika Korte).* Prior to that, compasses were in use for several centuries mostly for navigation but with no knowledge of the causes of magnetic needle behaviour. Since Gauss' times many methods of magnetic field measurement have been developed but there are two pillars of magnetometry discovered and developed in the 20th century:

a) fluxgate magnetometers for measurement of components of the vector of magnetic field (Primdahl 1979, Korepanov et al 2007)
b) scalar, quantum magnetometers with high precision of measurement and a possibility of measurements in motion (Abragam 1961, Alexandrov, Bonch-Bruevich 1992, Hrvoic 2004, Hrvoic 2008)

Presently absolute measurements of magnetic field direction by optical methods (DI Flux or DIM) based on fluxgate technology, and the scalar measurements (Proton precession, Overhauser or Potassium) of its magnitude set-up the limits of precision of the magnetic field vector measurement.

Magnetometry is a mature science/technology with myriad of applications. The need for better, more precise, smaller magnetometers fuels continuous research in the field.

This review will be treating separately vector and scalar magnetometers describing their principles of operation and main features, and with the view of their application in different fields of Geophysical exploration.

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Scalar magnetometers with their high precision and absolute accuracy now dominate measurements in mineral and oil exploration, volcanology, ordnance detection, archaeology and partially magnetic observatories while vector magnetometer's role is limited to magnetic observatories, partially space measurement (Acuña 2002) *(Equatorial Electrojets, Archana Bhattacharyya, Magnetic Methods Satelite, Dhananjay Ravat),* and in vertical gradiometers for archaeological research. *(Archeomagnetism, Don Tarling)* Scalar magnetometers are used to calibrate fluxgates. Some experiments with tensor measurements also include fluxgates and/or SQUIDs (Supercooled Quantum Interference Devices) (Clark 1993)

All modern magnetometers are computerized instruments with nonvolatile memory for display, storage and review of data.

2. Scalar (Quantum) Magnetometers

Advent of scalar magnetometers in the second part of the 20th century made a substantial contribution to measurement of both vector and scalar values of magnetic field. They offer precession frequency as a measure of magnetic field. Scalar magnetometer's sensitivities are determined only by achievable quality of precession signal, value of gyromagnetic constant, width of the spectral line (or time of decay of the precession signal) and signal to noise ratio. Scalar magnetometers have high sensitivity and accuracy of readings, virtually no drift with temperature or time. Measurements depend very weakly on sensor orientation or movement allowing for measurement in motion.

Proton, Overhauser and Alkali metal (optically pumped) magnetometers are now overwhelmingly used in mineral/diamond/oil exploration, weapons detection, volcanology, archaeology, magnetic observatories. Most of the current research is done in variations of optical pumping and the progress in the last 25-30 years is phenomenal. Sensitivities have been improved from some nT to fractions of pT, perhaps four orders of magnitude, far exceeding requirements for ground *(Magnetic Methods Surface, AV Golynsky),* airborne *(Magnetic Methods, Airborne, Mike Dentith)* or marine surveys. Speed of readings increased from perhaps once per second to tens and hundreds of readings per second limited only by increasing noise and/or possibility to usefully store a flood of data. With the development of instrumentation the use of gradiometers with two or more sensors has increased *(Magnetic Gradiometry - Harold von der Osten-Woldenburg).* It improves the quality of surveys, determination of depth of the anomaly producing body, following the direction and depth of the buried pipelines or electrical power lines etc.

Scalar magnetometer consists of a sensor, separated by a cable from electronics (to avoid its stray magnetic fields). Electronics has an analogue part that generates precession signal from the sensor and digital microprocessor based part that controls the operation, measures Larmor frequency, converts it into units of magnetic field and stores and/or outputs the data. Review of data is often possible.

Global positioning plays a big role in geophysical ground and airborne surveys. In stationary measurements GPS provides precise timing (1 μsec accurate pulses referenced to Greenwich standard time).

2.1 Background Physics

Scalar magnetometers are all based on a spin of subatomic particles – electrons and protons (Abragam 1961, Schumacher 1970).

Spinning charged particles make magnetic dipoles. The dipoles are precessing around ambient (applied) magnetic field following Quantum Physics rules. Precession frequency is proportional to magnetic flux density:

$$\omega_0 = \gamma \mathbf{B}$$

ω_0 is an angular precession frequency (Larmor frequency), B magnetic induction (flux density) and γ gyromagnetic constant.

Spinning protons (electrons) orient themselves in magnetic field. Only two angles of orientation are allowed acute (lower energy level) and obtuse (higher energy level). Since individual particles precess at random phases their dipolar magnetic field in the plane perpendicular to the magnetic field is averaged out. A projection of the dipolar magnetic fields in the direction of the applied magnetic field is static. Since orientation at the acute angle to the direction of the field is more populated than the one at the obtuse angle a minute "polarization" of precessing particles creates a magnetization M collinear with magnetic induction B:

$$M = \frac{N\gamma^2 h^2 / 4\pi^2 B}{4kT\mu_o}$$

N is the number of particles, γ gyromagnetic constant, h Planck's constant, T absolute temperature, k, μ_o constants.

When placed in the flux density B, M will reach its "thermal equilibrium" exponentially with the "longitudinal" time constant T_1.

When deflected by about 90^0 it will precess around the field by the Larmor frequency and decay exponentially by the "transversal" time constant T_2.[1] Particles at the lower energy level can accept energy in the form of magnetic field at Larmor frequency and flip to the higher energy level. Levelling of the two energy level populations eliminates M. This is saturation of the precession spectral line. Proportionality constant, the gyromagnetic constant (not always a constant) is precisely determined to better than one part per million accuracy only for protons in water (Hrvoic 1996):

$$\gamma_p = 0.2675153362 \text{ rad/nT}$$

Magnetization M is too small to produce detectable precession signal when deflected in the plane of precession. All scalar magnetometers therefore need to increase polarization and magnetization M and thus increase the sensitivity of the instrument. Polarization is increased in different ways:

- By temporarily increasing B to few hundreds Gauss (Proton magnetometers).
- Transferring thermal equilibrium polarization of electrons to protons in liquid sensors (Overhauser magnetometers).
- Using light polarization in alkali metals, and ^{4}He magnetometers.

2.2 Proton Magnetometers

Proton magnetometers are the oldest scalar magnetometers. The first commercial units were produced in early 1960s as portable instruments. In continuation airborne instruments appeared with optimized speed of readings and sensitivity, large sensors etc. Later development of Overhauser and optically pumped magnetometers has eliminated Proton magnetometers from airborne surveys. However they remain very popular in various ground surveys and observatories.

Proton magnetometer's sensor contains liquid rich in protons and polarizatrion/pick-up coil. Polarization is done by increasing flux density B for a time comparable with T_1 of the sensor liquid. Electrical current passing through polarization coil creates strong magnetic field that polarizes protons of the sensor liquid. The coil is usually immersed in liquid to maximize the coupling. Alternatively omnidirectional toroidal coil is used. Polarization field of few hundred Gauss must be roughly at the right angle to the measured field. Its removal must be fast to leave the newly formed magnetization in the plane of precession. Practical port-

[1] Time constants T_1 and T_2 depend on the aggregate state of the assembly of spinning particles. In liquids and vapours they may be several seconds long, while in solids T_2 time is only milliseconds and the precession signal disappears very quickly. This is why all scalar magnetometers have liquid or gaseous sensors.

able proton magnetometers achieve about 0.1nT sensitivity at a few seconds cycle, somewhat less in once per second measurements.

2.3 Overhauser Magnetometer

Overhauser effect originates from double resonance experiments in metals (Overhauser 1953). Russian and French scientists have greatly contributed to the development of modern Overhauser magnetometers based on nitroxyde free radicals (Abragam 1961, Pomerantsev 1968). Practical realization of the magnetometer is as follows: Sensor liquid containing protons is placed in an RF resonator. It has small concentration of a Nitroxide free radical – stable chemical with one unpaired electron. The unpaired electron is dwelling close to the nitrogen nucleus, in it's magnetic field of some 24 Gauss. It's electron paramagnetic resonance frequency in the Earth's magnetic field is about 30,000 times higher than the one of protons. Unpaired electrons couple with the protons of the sensor, creating a four energy level system. Coupling can be either scalar or dipole – dipole. If one of them predominates, saturating electron resonance at some 60 MHz, transfers part of electron magnetization to protons. Increased proton polarization (magnetization) needs a 90^0 deflection to be turned in the plane of precession. The deflection can be either pulsed ($\pi/2$ pulse) or stationary by applying a weak rotating magnetic field of Larmor frequency in the plane of precession. Transferred magnetization is far superior to any achievable by DC polarization (Proton magnetometers) and the measurement does not need to be interrupted; the RF saturating field can be present continuously. In pulsed mode repeated $\pi/2$ pulses interrupt measurement by about 25-30 msec. Low power consumption, higher sensitivity (10pT for 1 reading/sec), absolute accuracy, reasonable speed of readings (up to five per second), omnidirectional sensors, make Overhauser magnetometers very convenient and attractive for magnetic observatories, volcanological exploration, marine surveys and base stations for airborne surveys. Oersted and CHAMP magnetic satellites use continuous Overhauser magnetometers as reference to vector measurement of magnetic field.

2.4 Optically Pumped Magnetometers

This is the latest to be discovered and the most potent family of magnetometers. It consists of elements of the first column of the table of chemical elements. In gaseous form Alkali metals have an unpaired electron in their valence shell. Gaseous sensor is subject to a circularly polarized light (D_1 line) (Happer 1972). Polarization process lifts electrons from a higher energy level to a metastable state from which electrons fall back to both levels. Eventually all electrons are in the lower energy level while the upper one is depleted. Absorption of light is then reduced and the sensor is more transparent. Rotating RF magnetic field of the Larmor frequency will depolarize the sensor and increase absorption of the light. As a result the polarizing light will be modulated by the Larmor frequency. Its detection produces an electrical signal for the measurement of magnetic field. Helium

4 magnetometers that have two valence electrons need a weak discharge to lift one of them in a metastable state. Laser pumped Helium 4 magnetometer has sub pT sensitivity. Due to the influence of nucleus, all Alkali metal magnetometers have a number of spectral lines in their EPR spectrum (Breit and Rabi 1931). Potassium spectral lines are well spaced and its operation can be based on a single narrow spectral line. This ensures very high sensitivity and the absolute accuracy similar to the one of Proton/Overhauser magnetometers. Cesium and Rubidium lines are very close to each other and they overlap and make a relatively wide composite single line. Operation of the magnetometer in self-oscillating mode is at the peak of the composite line. Problem is the position of the peak depends on an angle between sensor axis and magnetic field direction. A heading error due to this effect can be reduced by a "split beam" technique which symmetrizes the composite line. Reduction of the heading error to some nT or even a fraction of nT is possible. However the split beam technique reduces the sensitivity by about one order of magnitude. Absolute accuracy of only few nT can be achieved by Cs and Rb magnetometers.

2.5 Measurement of Frequency

In the magnetic field of Earth (20 – 65μT) precession frequency of Protons is an acoustic frequency in a range of some 850Hz to 3kHz, while Alkali metal optically pumped magnetometers produce 70 kHz to 450 kHz, ^{4}He 280kHz to about 2MHz. Considering achieved precisions of measurement – one part per million or a small fraction of that for Proton and Overhauser magnetometers respectively and even few parts per billion for ^{4}He and ^{39}K or ^{41}K we are resolving Larmor frequency to a millihertz precision. Times of all zero-crossings of precession frequency are taken and an average period is measured by the least squares fit. Zero-crossing times must be understood as a phase information too (0^0, 180^0, 360^0 etc) and this allows us to measure to the sub Hz precisions. Measurement of phase difference to obtain the frequency, results in an unusual noise dependence on the speed of readings. Most of measurements concerned with the noise bandwidth specify noise as per square root of Hz. Doubling the bandwidth increases noise by square root of two. Not so in precession frequency measurement. When we double bandwidth by doubling the number of readings per second the noise goes up by two square roots of two or $2^{3/2}$ instead of $2^{½}$. Defining noise as per square root of Hz is therefore deceiving, although it may be calculated correctly for a particular number of readings per second.

An assessment of the sensitivity of magnetometers is possible using the following formula (Alexandrov and Bonch-Bruevich 1992):

Another peculiarity of precession frequency measurement is a phenomenon of "outliers" or "spikes" that occur when a zero-crossing time is either missing or modified by a spike of phase noise usually showing lower value of magnetic field. Preponderance of outliers increases dramatically as signal/noise ratio of precession signal decreases.

2.6 Absolute Accuracy and Precision

Absolute accuracy of measurement can be determined directly for Proton (Overhauser) magnetometers only. Proton gyromagnetic constant gets periodically refined by national standards institutions of a number of major countries (NIST, USA; NPL, U.K; VNIIM, Russia; NIIM, China)

Absolute accuracy of better than one part per million is possible to achieve. Besides the precise gyromagnetic constant it requires a number of conditions to be fulfilled: sensitivity must always exceed the absolute accuracy, frequency reference precision must be adequate, phase stability of the signal and time determination of a zero-crossing must be proper (Hrvoic 1996). Since we measure frequency of rotating magnetic moment, rotation of the sensor in the plane of precession introduces error (rotational Doppler). This error, insignificant for optically pumped magnetometers, may be significant for Proton and Overhauser magnetometers (about 23nT offset for 1 cycle per second rotation of the sensor).

Alkali metal magnetometers have only Potassium capable of high absolute accuracy (comparing its readings with Proton/Overhauser magnetometers) (Alexandrov, Bonch-Bruevich 1992). Cesium and Rubidium operate on lumped spectral lines, (and ^{4}He has a very wide spectral line) and their absolute accuracies are in few nT range.

Great majority of nowadays measurements does not require high absolute accuracy but only sensitivity and repeatability or relative accuracy of readings. Exceptions are magnetic observatories, space measurements and perhaps some standards measurements derived from magnetic measurements (determination of electrical current standard for example).

Sensitivities of scalar magnetometers vary. Details depend heavily on particular design, but an order of magnitude can be assessed. Proton magnetometers are nowadays used for ground exploration or calibration of vector magnetometers (fluxgates) only. Slow rate of readings can produce about 0.1nT sensitivity and absolute accuracy. Up to two readings per second are possible, but at this rate the noise is in nT range. Overhauser magnetometers achieve 0.01nT at one reading per second, maximum rate five per second. High absolute accuracy Overhauser magnetometers are standard at magnetic observatories and very prominent in marine and ground surveys, and base stations for airborne surveys. Composite spectral line Alkali vapor magnetometers (Cesium, Rubidium) have similar sensitivity to Overhauser at one reading per second, but their top speed of readings is over 20/sec. Their absolute accuracy is only few nT. Laser pumped ^{4}He reaches sub pT sensitivities at one reading/sec. Maximum speed of readings is limited to one half of modulation frequency. Potassium has reached 0.05 pT sensitivity at one reading /sec. Practical potassium assemblies for ground and airborne surveys feature sub pT once per second and about 7 – 10pTrms noise at 10 readings per second. Like

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Cesium and Rubidium, maximum speed of readings exceeds 20/sec. Increase of noise is rather a practical limit to a number of readings/sec. Cesium magnetometers are prominent in airborne surveys while Potassium covers top of the field, especially in gradiometry due to it's high absolute accuracy. Potassium is exclusively used in some new high sensitivity magnetic observatories and Earthquake study centers.

3 Vector Magnetometers

Vector magnetometers are generally used for static measurements (observatories) or in vertical suspension (archaeology) or rarely in the component airborne surveys where only computed total field may reach 0.1nT sensitivity, while components stay useless due to changes in aircraft attitude. In some recent attempt accelerometers are used to account for attitude changes and apply corrections.

Main characteristics of most of vector magnetometers are (except for SQUIDs):

1. Good sensitivity of measurement 0.1nT common, 0.01nT or somewhat lower (Korepanov et all 2007) the best reported.
2. Very precise determination of the direction of measurement. One arc second change in direction means a fraction of one nT difference in readings, depending on an angle. In some orientations vector magnetometers can resolve 0.01 nT field and well below one arc second angle.
3. Relatively substantial temperature dependence (0.1nT/^{0}C or more).
4. Relatively substantial time variation – aging (2nT or more per year).

Consequences of the above are difficulties in orienting 3 component magnetometers in magnetic field and determination of the orthogonality of the 3 components. Due to their temperature dependence/aging the vector magnetometers at the magnetic observatories need calibration by Proton/Overhauser magnetometers.

3.1 Fluxgate Magnetometer

Main vector magnetometer today is the fluxgate. Its operation is based on nonlinearity of magnetic properties of steel (ferromagnetic material) (Primdahl 1979). When placed in strong magnetic field steel will lose its high magnetic permeability in saturation i.e. relative permeability will fall from several hundreds to close to one. A coil is wound around a layered core of steel and alternating current is driving the core to saturation in two opposite directions alternatively. When not saturated, the core will concentrate the magnetic flux of the applied magnetic field. When saturated the flux will deconcentrate itself. Pick-up coil wound around the core will detect changes in the flux passing through the core. With no external magnetic field the saturations on positive and negative sides will be symmetrical i.e. the pick-up voltage will have only odd harmonics. When the external magnetic field is present, the saturations become unsymmetrical and second harmonic appears in the pick-up voltage, its amplitude proportional to the strength of magnetic field. Phase detected second harmonic is then a measure of applied magnetic field in the direction of the core. It is convenient to use two pieces of the core with excitation windings in opposition and the pick-up coil encompassing both cores as this eliminates pick-up voltage due to the original driving current. Instead of double iron core, a ring or "racetrack" shaped core can be used. Ring core allows for measurement of two orthogonal components, on one core.

Today's fluxgates can achieve 0.1nT/^{0}C temperature coefficient with some nT/year aging. Composition of iron cores/ring cores plays a big role in quality of fluxgates. Some recent new developments (Korepanov 2007) claim better noise and aging characteristics.

During the Second World War a vertically suspended single fluxgate was used to detect submarines. ASQ-10 instrument had about 0.1nT sensitivity and the vertical orientation of the sensor was kept by feedback electronics/mechanics.

3.2 Absolute Measurement

Declination/Inclination magnetometer (DI-Flux or DIM) is a variation of fluxgate measurement (Jankowski and Sucksdorff 1996). Fluxgate magnetometer sensor is mounted collinear with the optical axis of (nonmagnetic) theodolyte, in horizontal plane. Theodolyte is rotated and two zero field angles are marked. The telescope is then reversed and two more zero readings determined. Magnetic north in arbitrary coordinate system is then calculated from angles of the four zero field measurements. The calculated angle is then referred to a known marker to determine true declination angle related to north direction. To determine inclination the theodolyte is oriented in just determined magnetic declination plane and four zero field positions are determined in that plane. Averaging will give the angle off horizontal, i.e. the inclination.

Simplified version of DIM is the Declinometer. It has a suspended magnet on a torsionless fibre, a mirror attached to it at the right angle to its magnetic axis and in front of a telescope. The theodolyte is turned until the telescope becomes at right angle to the mirror. Direction of magnetic meridian is read from the base of the theodolyte. This is referenced to a known reference mark to determine real declination angle.

Weakness of this measurement is an angle mirror-magnetic axis of the magnet that has to be 90^0. This is mitigated by using two magnets of different magnetic moments.

3.3 Quantum Vector Magnetometers

SQUID is a vector magnetometer of exceptional fT range sensitivity. It operates at cryogenic temperatures (liquid Helium or liquid Hydrogen) (Clark 1993). It is used sporadically in Geophysics for tensor calculations or short base gradiometers.

DIdD (Delta inclination delta declination) is a vector magnetometer with two orthogonal bias coils and a scalar magnetometer (Overhauser or Potassium). Coils are oriented at right angles to magnetic field direction, one in a horizontal plane, one in vertical magnetic declination plane. A sequence of four biased fields and one unbiased allows for determination of departures of the field from the preset one. Orientation of one bias coil in vertical direction and the other in the horizontal East-West direction (now possible with the precise GPS direction determination or a North seeking gyroscope) will convert dIdD instrument into an absolute D and I instrument. Potassium magnetometer can provide superior sensitivity and absolute accuracy and the stability of the instrument as for temperature and aging can be superior to the best fluxgates. This instrument is still in development.

4 Summary

Magnetic measurements are an essential part of Geophysical exploration for minerals and oil, archaeological, volcanological explorations, research of atmosphere, Sun's influence, crustal studies, earthquake research and many other. Scalar magnetometers are dominant in most fields. They are described in some detail – their physics, principles of operation, details of design, sensitivities and absolute accuracy. Vector magnetometers, are essential in magnetic observatories, space measurements and many scientific investigations. Fluxgate magnetometers and variations of absolute determination of magnetic field direction have been described in some detail. Quantum magnetometers as vector magnetometers are briefly described

Cross-References

Geomagnetic Field, Measurement Techniques, Mioara Mandea
Geomagnetic Field Secular Variations, Monika Korte
Equatorial Electrojets, Archana Bhattacharyya
Magnetic Methods Satelite, Dhananjay Ravat
Archeomagnetism, Don Tarling
Magnetic Methods Surface, AV Golynsky
Magnetic Methods, Airborne, Mike Dentith
Magnetic Gradiometry, Harold von der Osten-Woldenburg

Literature

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Abragam A (1961) The Principles of Nuclear Magnetism, Oxford University Press

Acuña MH (2002) Space-based magnetometers Review of Sci. Instr. 73:11

Alexandrov E, Bonch-Bruevich V (1992) Optically pumped atomic magnetometers after three decades, Optical Engineering 31, 4:711

Breit G, Rabi II (1931) Measurement of nuclear spin, Phys. Rev. 38:2082

Clark J (1993) The New Superconducting Electronics (eds Weinstock H, Ralston RW) Kluwer Dordrecht pp. 123-180

Happer W (1972) Optical pumping, Review of Modern Physics vol. 44

Hrvoic I (1996) Requirements for obtaining high accuracy with proton magnetometers. In: Rasson JL (ed) Proceedings of the VIth workshop on geomagnetic observatory instruments data acquisition and processing 70-72. Also available at www.gemsys.ca

Hrvoic I (2004) Short Review of Scalar Magnetometers, unpublished www.gemsys.ca

Hrvoic I (2008) Development of a new high sensitivity Potassium magnetometer for geophysical mapping, First Break 26:81-85 www.gemsys.ca

Jankowski J, and Sucksdorff C (1996) Guides for magnetic measurements and observatory practice, IAGA iaga_sg@gfz-potsdam.de

Kaufman AA, Kleinberg RL, Hansen R (2009) Principles of Magnetic Methods in Geophysics, Elsevier

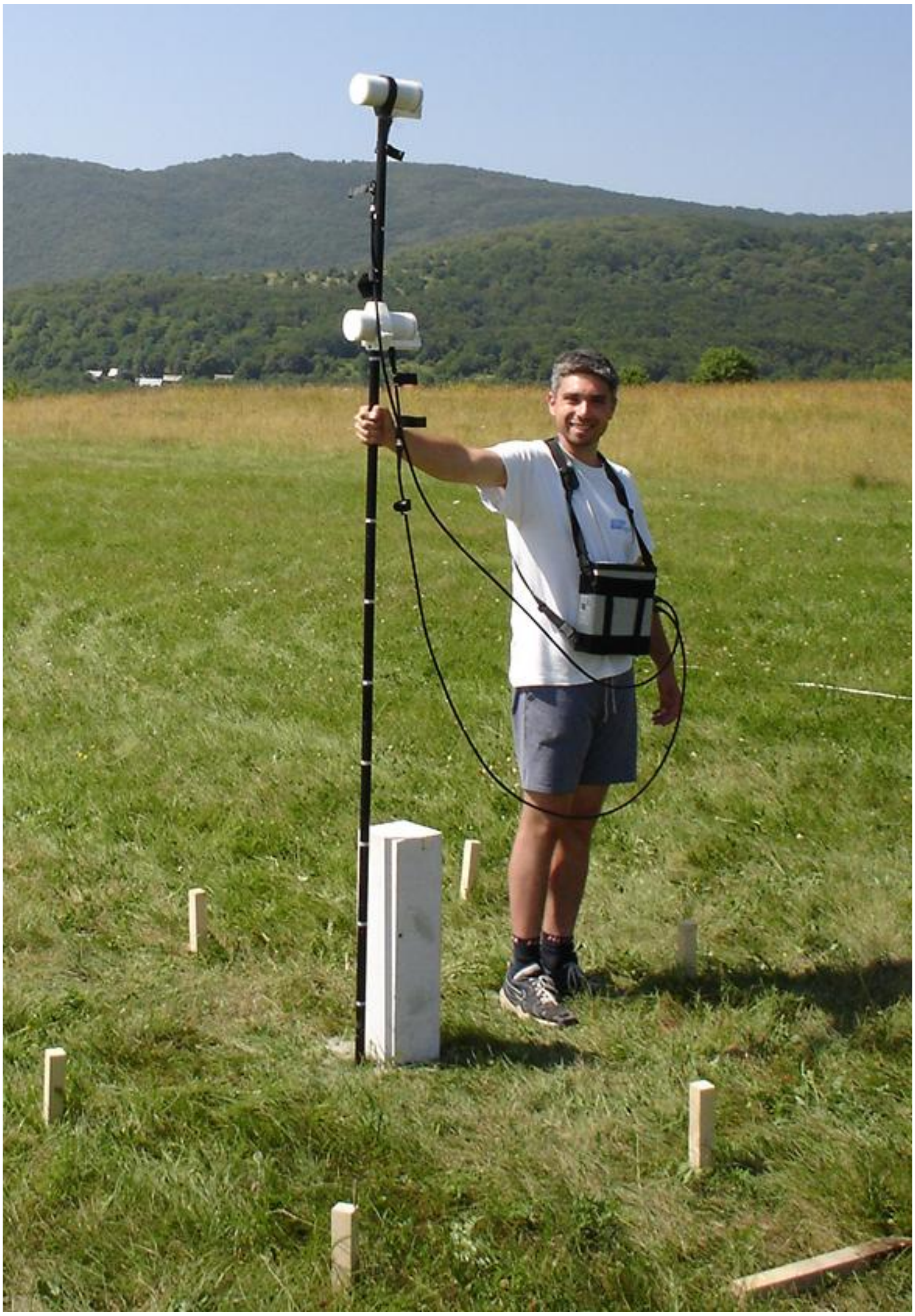
Korepanov V, Klymovych Ye, Kuznetsov, Pristay A, Marusenkov A, Rasson J, (2007) NEW INTERMAGNET Fluxgate Magnetometer XII IAGA Workshop, Publs. Inst. Geophys. Pol. Acad. Sci, v. C-99 (398), 291-8

Körmendi A (2008) Private communication, alpar44@freemail.nu

Overhauser WA (1953) Phys. Rev. 92:411

Pomerantsev NM (1968) Quantum Magnetometry, Joint Publication Research Service JPRS 46444

naš PPM: GEM Systems GSM-19G Overhauser magnetometar/gradiometar



Slika. *Ispitivanje nemagnetičnosti stabilizacije.*

Overhauser

Magnetometer / Gradiometer / VLF (GSM-19 v6.0)

Specifications

Performance

Sensitivity:	< 0.015 nT / √Hz
Resolution:	0.01 nT
Absolute Accuracy:	+/- 0.1 nT
Range:	10,000 to 120,000 nT
Gradient Tolerance:	> 10,000 nT/m
Samples at:	60+, 5, 3, 2, 1, 0.5, 0.2 sec
Operating Temperature:	-40C to +55C

Operating Modes

Manual: Coordinates, time, date and reading stored automatically at minimum 3 second interval.

Base Station: Time, date and reading stored at 3 to 60 second intervals.

Remote Control: Optional remote control using RS-232 interface.

Input / Output: RS-232 or analog (optional) output using 6-pin weatherproof connector.

Storage - 4Mbytes (# of Readings)

Mobile:	209,715
Base Station:	699,050
Gradiometer:	174,762
Walking Mag:	299,593

Dimensions

Console:	223 x 69 x 240 mm
Sensor:	175 x 75mm diameter cylinder

Weights

Console with Belt:	2.1 kg
Sensor and Staff Assembly:	1.0 kg

Standard Components

GSM-19 console, GEMLinkW software, batteries, harness, charger, sensor with cable, RS-232 cable, staff, instruction manual and shipping case.

Optional VLF

Frequency Range: Up to 3 stations between 15 to 30.0 kHz

Parameters: Vertical in-phase and out-of-phase components as % of total field. 2 components of horizontal field amplitude and total field strength in pT.

Resolution:	0.1% of total field

Overhauser (GSM-19) console with sensor and cable. Can also be configured with additional sensor for gradiometer(simultaneous) readings.

The GSM-19 v6.0 Overhauser instrument is the total field magnetometer / gradiometer of choice in today's earth science environment -- representing a unique blend of physics, data quality, operational efficiency, system design and options that clearly differentiate it from other quantum magnetometers.

With data quality exceeding standard proton precession and comparable to costlier optically pumped cesium units, the GSM-19 is a standard (or emerging standard) in many fields, including:

- Mineral exploration (ground and airborne base station)
- Environmental and engineering
- Pipeline mapping
- Unexploded Ordnance Detection
- Archeology
- Magnetic observatory measurements
- Volcanology and earthquake prediction

Taking Advantage of the Overhauser Effect

Overhauser effect magnetometers are essentially proton precession devices -- except that they produce an order-of-magnitude greater sensitivity. These "supercharged" quantum magnetometers also deliver high absolute accuracy, rapid cycling (up to 5 readings / second), and exceptionally low power consumption.

The Overhauser effect occurs when a special liquid (with unpaired electrons) is combined with hydrogen atoms and then exposed to secondary polarization from a radio frequency (RF) magnetic field.

The unpaired electrons transfer their stronger polarization to hydrogen atoms, thereby generating a strong precession signal -- that is ideal for very high-sensitivity total field measurements.

In comparison with proton precession methods, RF signal generation also keeps power consumption to an absolute minimum and eliminates noise (i.e. generating RF frequencies are well out of the bandwidth of the precession signal).

In addition, polarization and signal measurement can occur simultaneously -- which enables faster, sequential measurements. This, in turn, facilitates advanced statistical averaging over the sampling period and/or increased cycling rates (i.e. sampling speeds).

Other advantages are described in the section called, "GEM's Commercial Overhauser System" that appears later in this brochure.

naš DIM: Bartingtonov Mag-01H D/I sustav

Slika. *Opažanje deklinacije null metodom. Fluxgate Mag A sonda montirana je na durbin teodolita, a magnetometar Mag-01H udaljen je nekoliko metara od opažača. Zapisničar bilježi vriemena i očitanja 4 položaja u formular, te u notebook, koji služi i za računanje opažane deklinacije.*

Slika. Očitanje nule na zaslonu Mag-01H.

Mag-01H

Single Axis Fluxgate Magnetometer

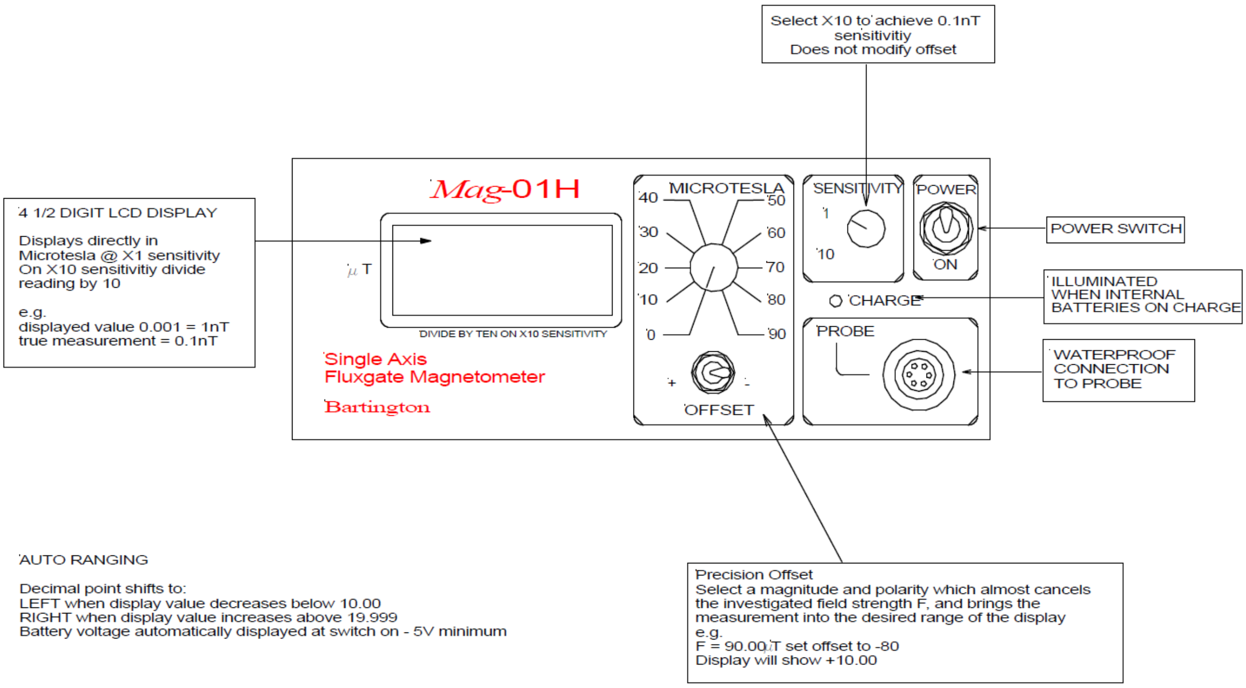


Figure 3 – Mag-01H FRONT PANEL FUNCTIONS DR0222 (4)

Specification - Mag-01H instrument	
Measuring range	0.1nT to 0.2mT
Bandwidth - x1 sensitivity	DC to 10Hz (-3dB) @ 20 µT p-p. Roll off -12dB per octave
Calibration accuracy	0.1%
Maximum resolution	0.1nT
Zero field offset	±1nT
Offset drift	0.01nT/°C
Scaling temperature coefficient	<10ppm/°C
Liquid crystal display x1 sensitivity x10 sensitivity	41/2 digit autoranging Displays 0 to 20 µT with 1nT resolution and 20 to 200 µT with 10nT resolution Displays 0 to 2 µT with 0.1nT resolution and 2 to 20 µT with 1nT resolution
Front panel on/off switch probe input charge indicator offset control sensitivity control	 switches on internal battery 6 pole waterproof Fischer connector illuminated when external supply connected allows ±90 µT in steps of ±10 µT to be subtracted from the field at the probe increases the sensitivity by a factor of 10
Rear panel battery charger inlet analog output x1 sensitivity x10 sensitivity output impedance	 2.1mm socket 6-18V d.c. 0.5A max., polarity protected, continuous or intermittent use 4mm insulated sockets 100 µT/V, ±500 µT max., 1nT resolution 10 µT/V, ±50 µT max., 0.1nT resolution 1kΩ
Enclosure	high impact ABS
Operating temperature	-10 °C to +50 °C
Relative humidity	80% non-condensing
Dimensions (mm)	155 x 170 x 68
Weight (g)	950

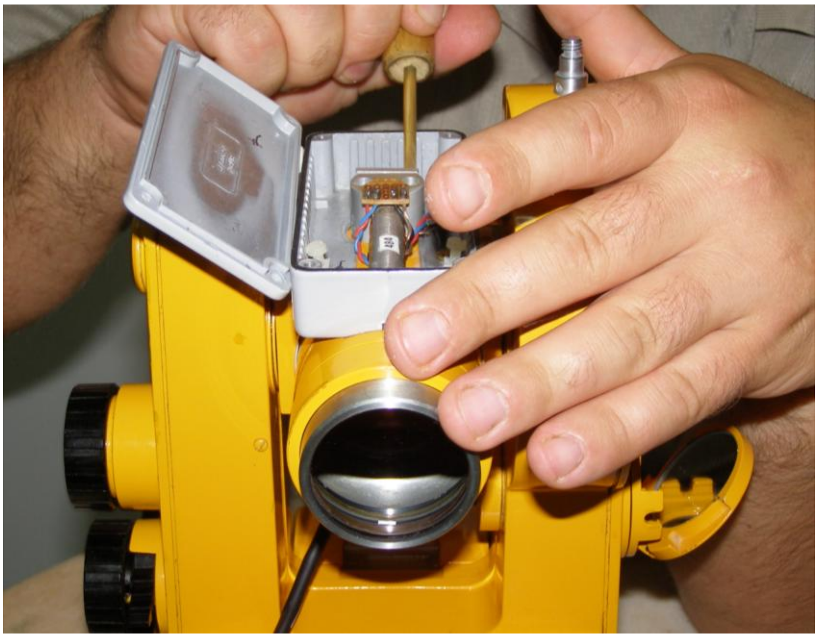
Mag A Probe

The linear fluxgate element within this probe features superb angular stability. The probe alignment will normally be stable to 1 minute of arc over the suggested 2-year calibration period and re-adjustment is seldom required.

The element converts the static terrestrial field into an alternating signal. The Mag-01H instrument converts this signal into a feedback current which is applied to a precision solenoid within the probe to maintain the element in null field. The magnetometer converts this current into a precise and stable measurement of the field.

A mechanically isolated enclosure protects the sensor from accidental misalignment. The probe has a strong but highly flexible 5-metre cable for connection to the Mag-01H instrument.

Each probe is individually calibrated to a standard which is traceable to the UK National Physical Laboratory.



Slika. Rektifikacija neparalelnosti osi fluxgate sonde i kolimacione osi.

Specification - Mag Probe A	
Calibration accuracy	0.1%
Collimation error	<20 seconds (collimation adjustment by joystick and clamp)
Fluxgate element	temperature coefficient <10ppm/°C, length 55mm, with precision feedback solenoid
Protective enclosure	aluminium housing, mechanically isolated from element mounting
Operating temperature	-20°C to +80°C
Dimensions (mm)	100 x 24 x 58
Weight (g)	250
Connecting cable length core-screen capacitance resistance	4-core overall screened high flexibility audio grade with 6 pole Fischer connector 5m standard (alternative lengths available) 160pF/m 92Ω /km

(interna skripta Geomagnetska izmjera, GF)

naš teodolit: Zeiss THEO 010B

Teodolit je geodetski instrument koji služi za mjerenje horizontalnih i vertikalnih pravaca, odnosno kutova (kao razlike dvaju pravaca). U geomagnetskoj izmjeri koriste se mehanički teodoliti. Glavni dijelovi mehaničkog teodolita su (*slike*):

- *podnožje* - sastoji se od podnožne ploče (1) s tri podnožna vijka (2), koja se centralnim vijkom spaja na mjerni stativ instrumenta
- *gornji okretni dio* (alhidada) (3) koji se okreće oko glavne (vertikalne - VV) osi teodolita, a sadrži:
    - o durbin (4) - dalekozor kroz koji presjecištem horizontalne i vertikalne niti nitnog križa prolazi kolimacijska - KK ili vizurna os teodolita,
    - o vertikalni limb (5) - kružna (kružni vijenac) staklena inkrementalna podjela (o kojoj ovisi točnost očitanja instrumenta) za očitanje vertikalnih pravaca, koji se zajedno s dubrinom okreće oko horizontalne - HH osi teodolita,
    - o alhidadnu libelu (6) koju tangira LL os teodolita, a služi za fino horizontiranje instrumenta
    - o dozna libela (7) koja služi za grubo horizontiranje instrumenta
    - o vijke za fini pomak alhidade (8) i durbina (9)
    - o kočnice alhidade (10) i durbina (11). Na slici u zakočenom položaju.
    - o vijak za koincidenciju (mikrometarski vijak) (12)
    - o reiteracijski (repeticijski) vijak (13). Dodiruje reiteracijsku kočnicu.
    - o durbin za očitanje (14)
    - o vijak za prebacivanje između očitanja horizontalnog i vertikalnog limba (15). Na slici u položaju za čitanje vertikalnog.
    - o durbin optičkog viska pomoću kojeg centriramo instrument na mjernu točku (16)
    - o ogledalo za osvjetljenje očitanja (17)
- *horizontalni limb* - kružna (kružni vijenac) staklena inkrementalna podjela za očitavanje horizontalnih pravaca (nalazi se unutar alhidade).

Zeissov THEO 010B je demagnetiziran tj. potpuno je odstranjena kontaminacija kako bi se mogla garantirati magnetska čistoća. Zbog nemagnetičnih materijala od kojih je sastavljen, instrument nije prikladan za radove u uvjetima visoke vlažnosti.

Sekundni teodolit THEO 010B pogodan je za sve geodetske radove dajući srednju kvadratnu pogrešku od ± 1" za pravac mjeren jednom u oba položaja durbina (I. položaj / II. položaj). Rektifikacija se izvodi samo kada je to zaista potrebno, kod eliminacije pogrešaka sustava.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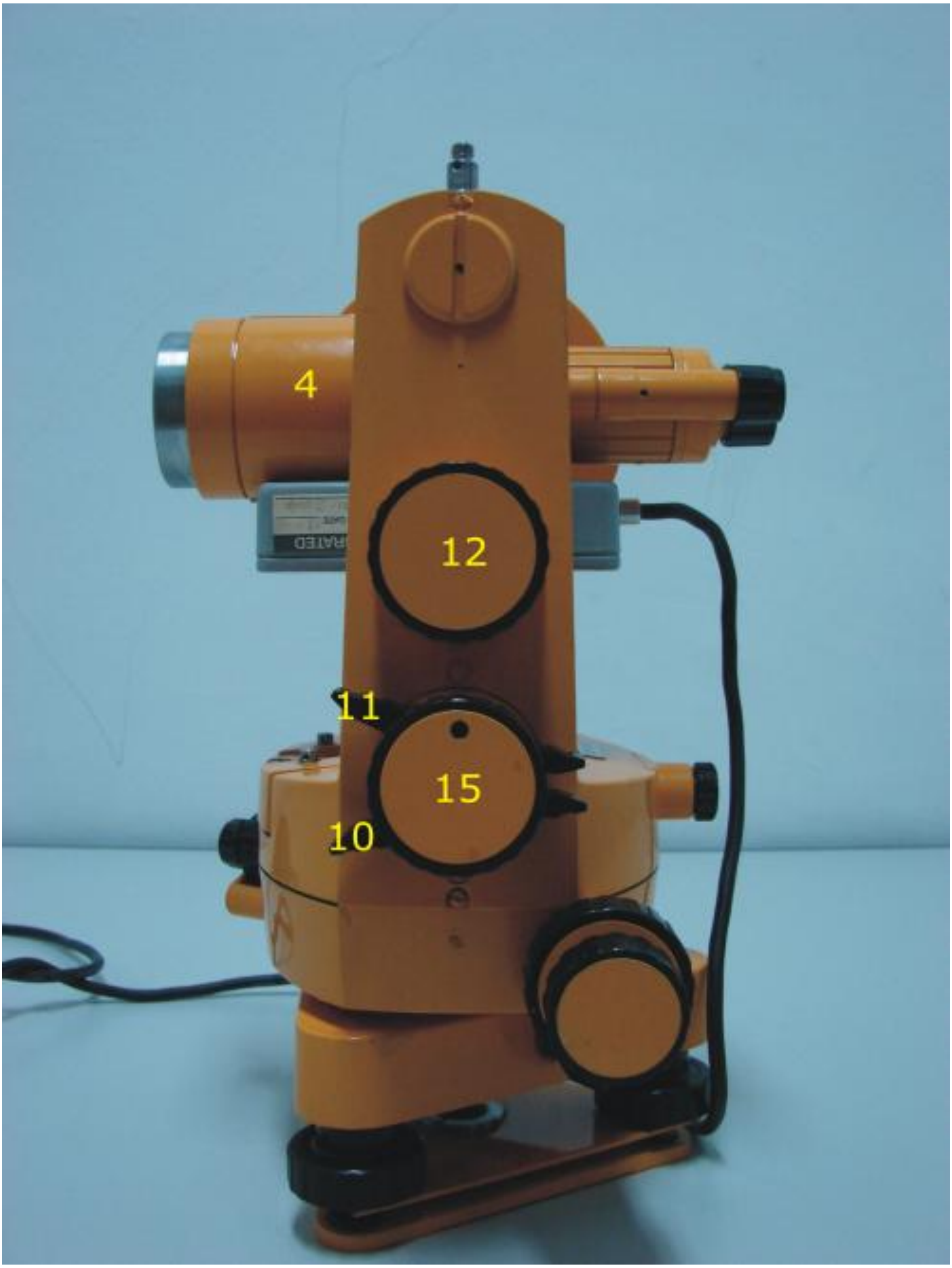
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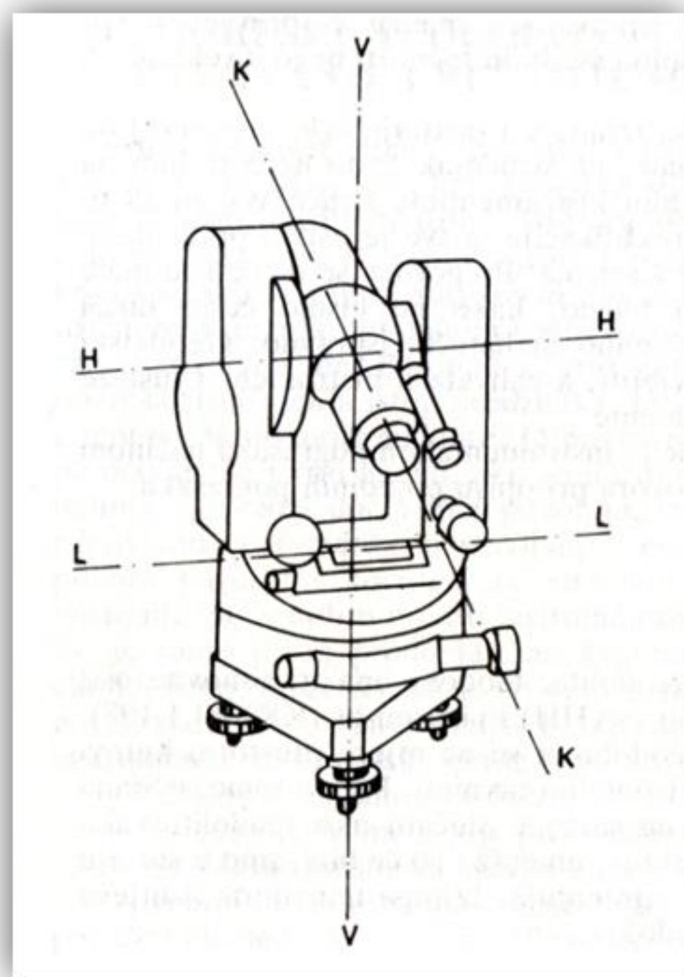
Glavni uvjeti teodolita

Četiri glavne osi teodolita (slika):

- VV - vertikalna ili glavna os
- HH - horizontalna ili nagibna os
- KK - kolimacijska ili vizurna os
- LL - os alhidadne libele



Slika: Glavne osi teodolita

Međusobni položaji osi teodolita tvore tzv. uvjete teodolita:

1. LL ⊥ VV - os alhidadne libele okomita na vertikalnu (glavnu) os
2. KK ⊥ HH - kolimacijska (vizurna) os okomita na horizontalnu (nagibnu) os
3. HH ⊥ VV – horizontalna (nagibna) os okomita na vertikalnu (glavnu)os
4. horizontalna nit nitnog križa durbina mora biti horizontalna u prostoru

Uvjeti 1., 3. i 4. postižu se preciznim centriranjem i horizontiranjem teodolita (vidi npr. Benčić i Solarić: *Mjerni instrumenti i sustavi u geodeziji i geoinformatici*).

(*Newitt*)

CHAPTER 4 Siting and Installation of a Repeat Station

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

4.1 Choice of Location

4.1.1 Choice of absolute station site

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

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

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

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

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

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

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

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

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

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

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

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

4.1.2 Choice of variometer site

The following considerations influence the choice of variometer site.

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

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

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

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

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

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

4.1.3 Choice of azimuth marks

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

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

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

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

4.2 Total-field Gradient Measurements

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

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

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

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

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

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

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

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

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

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

Document the results of the gradient survey and keep them on file. A possible format is illustrated in Fig. 4.2. During subsequent re-occupations, remeasure the gradients of **F** and compare them with earlier results to check for any change in the magnetic environment. Changes caused

(interna skripta Geomagnetska izmjera, GF)

Izmjera

Planiranje. Usporedba instrumenata na OBS, prije i poslije izmjere. Pronalazak točaka. Magnetometrija. Gradiometrija. Određivanje razlike POM – SV/KP. Stabilizacija SV/KP, POM i GOT točaka kamenim blokovima/PA6 kolcima odnosno poligonskim točkama. Određivanje koordinata Trimble R8 GNSS mjernim uređajem, oslanjajući se pritom na CROPOS; obrada uz pomoć jedinstvenog transformacijskog modela T7D 2009 (Bašić 2009, Šljivarić 2010). Rezultati obrade iskorišteni u računanju azimuta s SV/KP točaka na GOT (položajni opisi).

Izmjera DIF sredinom godine, rano ujutro i kasno navečer, min. 4 seta po sesiji, više dana. Na pomoćnu točku (POM) najprije se postavlja PPM, a teodolit se postavlja u radni položaj iznad geomagnetske točke (SV/KP). Apsolutna mjerenja obavljaju se na fiksnoj visini vertikalno iznad stabilizacije. Za postavljanje teodolita iznad točke služi nemagnetični stativ. Stativ, osim čvrstog povezivanja s teodolitom preko centralnog vijka mora osigurati stabilnu podlogu i pogodnu visinu teodolita za opažanje. U slučaju veće razlike u temperaturi između mjesta skladištenja i vanjskog prostora, treba pustiti instrument da se prilagodi novim uvjetima kroz nekoliko minuta. Bilo bi dobro teodolit zaštitiit od utjecaja Sunčevih zraka nemagnetičnim kišobranom.

Slika. *Izmjera deklinacije (DIM) na sekularnoj (SV) i totalnog intenziteta (PPM) na pomoćnoj točki (POM). Uz GPS-om određene orijentacijske točke (GOT), za orijentaciju instrumenta mogu se koristiti i crkve.*

Primjer: rezultati gradiometrije PRM točke PALA.

(a) vertikalni gradijenti

POINT Z-GRAD
.13
.25
.37
.43
.46
.78
1.02
1.04
1.80

(b) gradijenti okolice

RADIAL GRADIENTS (nT/m)

-.22	-.17	-.24	-.21	-.02	.16	-.13	-.11

(c) gradijenti unutrašnje mreže F

X-GRAD F

.12	1.78	.62	.74
.72	1.10	1.03	.82
.53	1.03	.90	.96
1.27	.59	.95	.69
.45	1.07	.52	1.27

Y-GRAD F

2.99	2.39	3.07	2.66	2.58
2.47	2.66	2.73	2.86	2.72
3.06	2.33	2.77	2.73	3.00
3.32	4.14	3.66	4.09	3.50

Z-GRAD F

3.48	3.46	3.75	3.89	3.83
2.91	3.05	2.87	3.00	3.48
2.01	2.33	2.64	2.46	2.60
1.32	1.57	1.92	2.07	2.03
.53	1.01	1.30	.85	1.64

(d) gradijenti vanjske mreže F

X-GRAD F

-.67	-1.11	-.61	-.06	.14	1.11	2.55	4.53	5.86	7.12
-.49	-.48	-.01	.10	.84	1.23	2.03	3.52	4.38	3.13
-.04	.27	.25	.60	.74	1.14	1.88	2.29	2.84	.86
.50	.78	.29	.78	.90	1.00	1.26	1.41	1.23	-.19
.70	.90	.96	.51	1.05	.69	.87	1.14	.62	-.05
.70	1.05	.98	.49	1.34	.91	.92	.50	.69	.20
.63	.53	.49	1.21	.97	1.13	.77	1.02	.39	.62
.36	.62	.53	.96	1.13	1.20	1.04	.96	.67	.77
.58	.77	.61	.77	1.29	1.30	1.58	1.07	1.28	1.25
.73	1.12	.74	.99	1.00	1.25	1.46	1.25	.93	1.31
1.06	1.12	.60	.78	1.20	1.14	1.20	.92	.75	1.22

Y-GRAD F

-1.90	-2.08	-2.71	-3.31	-3.47	-4.16	-4.29	-3.76	-2.75	-1.27	2.73
.16	-.29	-1.04	-1.30	-1.80	-1.70	-1.61	-1.46	-.23	1.30	3.58
1.18	.64	.13	.09	-.09	-.25	-.10	.52	1.40	3.02	4.06
2.47	2.27	2.16	1.48	1.75	1.59	1.90	2.29	2.55	3.16	3.02
3.48	3.48	3.33	3.31	3.33	3.04	2.82	2.77	3.42	3.35	3.10
2.64	2.71	3.23	3.73	3.00	3.38	3.15	3.30	2.78	3.07	2.65
2.69	2.95	2.86	2.82	3.07	2.91	2.84	2.57	2.63	2.36	2.21
3.81	3.59	3.45	3.37	3.56	3.40	3.30	2.77	2.66	2.04	1.56
3.10	2.94	2.59	2.46	2.24	2.54	2.59	2.70	2.52	2.88	2.81
1.55	1.23	1.22	1.36	1.57	1.36	1.47	1.74	2.07	2.24	2.33

Z-GRAD F

2.80	2.32	1.57	.67	.55	.14	.60	.87	3.37	8.58	16.00
4.08	3.62	3.05	2.73	2.37	2.46	2.69	3.17	5.07	8.51	11.75
3.48	3.55	3.51	3.57	3.48	3.58	3.30	4.41	5.23	6.80	8.28
3.44	3.75	3.57	3.25	3.73	3.78	4.28	4.46	4.71	5.50	5.39
2.26	2.48	3.07	3.35	3.17	3.05	3.42	3.32	3.64	3.26	3.30
1.71	1.44	1.75	1.82	1.71	2.42	2.12	1.85	2.41	2.66	2.62
.53	.66	.48	.55	.76	1.07	1.23	1.33	1.48	1.42	1.46
-.28	-.17	-.28	-.03	-.03	.39	.12	.76	.83	.89	1.03
-1.80	-1.51	-.82	-1.23	-1.10	-.55	-.48	-.39	.41	.28	.82
-3.35	-2.82	-2.41	-2.07	-2.03	-2.23	-1.30	-1.05	-.32	.05	.07
-4.62	-3.75	-3.12	-3.05	-2.94	-2.80	-2.28	-1.55	-1.07	-.35	-.01

Primjer: položajni opis SV točke PALA.

REPUBLIKA HRVATSKA
Državna geodetska uprava

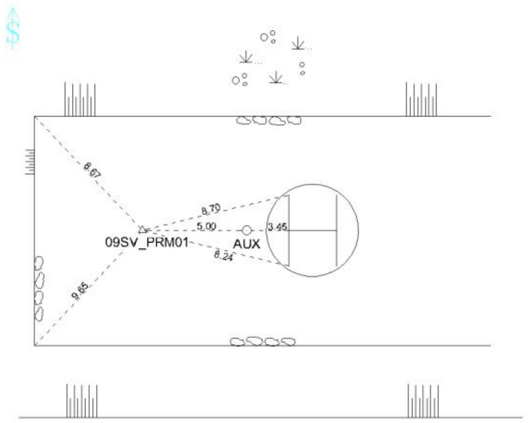
POLOŽAJNI OPIS GEOMAGNETSKE TOČKE

Županija : Splitsko-dalmatinska
Naselje - grad :
Mjesto : Otok Palagruža
Rudina :

Ime geomagnetske točke

09SV_PRM01

Isječak aero snimka



KOORDINATE:

HR 1901 (Bessel 1841)

$\varphi = 42^\circ 23' 34''.6178$
$\lambda = 16^\circ 15' 43''.7551$
H = 33.86 m

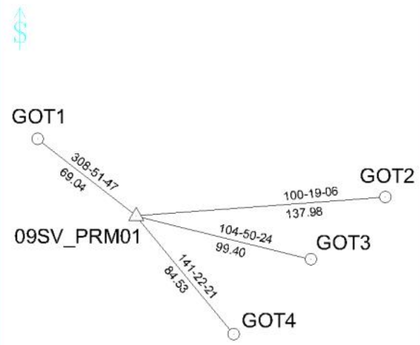
ETRS89 (GRS80)

$\varphi = 42^\circ 23' 35''.2287$
$\lambda = 16^\circ 15' 26''.6637$
h = 77.70 m

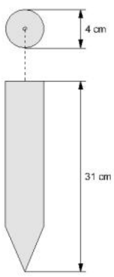
HTRS96/TM

y = 480027.24 m
x = 4694862.54 m
H = 33.86 m

Veza SV prema GOT (azimuti i dužine)



Stabilizacija
PA6 kolac



Fotografija

PRIMJEDBE :

Stabilizirali: Brkić, M. , Špoljarić, D. , Šugar, D. , Pavasović, M. , Kranjec, M.

Dana: 27. 04. 2008.

Opis izradili: Brkić, M. , Špoljarić, D. , Šugar, D. , Pavasović, M. , Kranjec, M.

Postavljanje PPM-a

Kod mjerenja F na pomoćnoj ili primarnoj sekularnoj točki instrument u baznom načinu rada opaža sa samo jednim senzorom na vertikalno postavljenoj šipki. Senzor se po mogućnosti orijentira u smjeru E-W. Na instrumentu je prije opažanja potrebno postaviti točno vrijeme UTC ili, još bolje, napraviti sinhronizaciju preko GPS uređaja.

PPM u postavi gradiometra se sastoji od dva odvojena senzora. Senzori se postavljaju na aluminijsku šipku i priključe putem odgovarajućih kablova na konzolu. Konzola dolazi u visinu trbuha opažača čime se preko tipkovnice i display-a ostvaruje potpuna kontrola nad mjernim procesom. Mjerenja gradijenata totalnog intenziteta izvode se u gradient modu.

Centriranje i horizontiranje teodolita

Postupak centriranja i horizontiranja se u praksi izvodi na sljedeći način: teodolit se približno centrira te se nakon toga vizira optičkim viskom centar stajališne točke djelujući na podnožne vijke teodolita. Nakon toga se obavi grubo horizontiranje tako da se vrhuni dozna libela teodolita produljivanjem ili skraćivanjem nogu stativa. Slika točke centra će se pritom malo pomaknuti. Nakon toga se provede horizontiranje teodolita alhidadnom libelom djelujući na podnožne vijke te precizno centriranje optičkim viskom pomicanjem tedolita po glavi stativa. Naposljetku treba kontrolirati horizontiranje. Geodetska vizurna os optičkog viska mora se podudarati s vertikalnom osi teodolita. Ako to nije slučaj, pri horizontiranom teodolitu ta će os biti iskošena. Zbog toga treba (ako se okularni dio s prizmom optičkog viska nalazi na alhidadi, što je slučaj u većine konstrukcija) nakon centriranja okrenuti alhidadu teodolita za 180° i polovinu eventualnog odstupanja centra nitnog križa od slike točke ispraviti pomicanjem teodolita po glavi stativa. Ako alhidadna libela stalno vrhuni, teodolit je horizontiran.

Postavljanje Mag-01H magnetometra

Kabel sonde magnetometra spoji se s Mag-01H elektronskom jedinicom magnetometra koja se nakon toga uključi. Prije početka mjerenja odlučuje se koju postavku osjetljivosti upotrijebiti. Savjetuje se izvesti pokusno nul mjerenje na postavci x10 osjetljivosti (za rezoluciju mjerenja 0,1 nT). Ukoliko se uoči smetnja koja prelazi 0,5 nT tada se upotrebljavaju postavke x1 osjetljivosti. Doprinos (šum) komponenti Mag-01H instrumenta opažanju je malen tako da se komponente postavljaju nekoliko metara dalje od teodolita sa sondom. Kabel koji povezuje sondu i magnetometar neće utjecati na postupke mjerenja te će funkcionirati i u uvjetima veoma niskih temperatura.

Orijentacija Zeiss THEO 010B teodolita

Nakon što se teodolit horizontira i centrira iznad stajališne točke prelazi se na viziranje geomagnetske orijentacijske točke (GOT). Štap trasirke iznad GOT-a najprije se grubo vizira te se zakoče alhidada i durbin. Nakon toga slijedi dioptriranje i izoštravanje slike oznake geomagnetske orijentacijske točke. Vertikalna nit nitnog križa dovodi se precizno na uviziranu oznaku. Vijak za očitanje postavi se na horizontalno. Kočnica gumba za reiteraciju odmakne se te se pritiskom na i vrtanjom gumba za reiteraciju dovodi na očitanje (cjelobrojne vrijednosti kuta i desetice minuta) izračunate vrijednost azimuta (smjerni kut + konvergencija meridijana). Jedinice minute i sekunde postavljaju se uz pomoć gumba optičkog mikrometra, dok se uz pomoć gumba za reiteraciju koincidiraju dijametralno suprotne crtice horizontalnog kruga. Na kraju se zakoči poluga kočnice gumba za reiteraciju. Orijentacijsku točku dobro je vizirati prije i poslije svakog niza opažanja kako bi se utvrdila stabilnost instrumenta kroz vrijeme.

Nul metoda opažanja deklinacije i inklinacije

Kod *nul metode* opažanja se dobivaju služeći se nemagnetičnim teodolitom na kojemu je sonda orijentirana okomito na smjer Zemljina magnetskog polja jer je tada sonda najosjetljivija na male promjene smjera polja. Krajnja točnost ove metode mjerenja ovisit će o izboru teodolita i terenskim okolnostima.

Određivanje vrijednosti deklinacije i inklinacije kod nul metode mjerenja obuhvaća četiri opažanja za izračun deklinacije te četiri opažanja za izračun inklinacije. Svi položaji kod mjerenja deklinacije i inklinacije su prikazani po redoslijedu opažanja na slici.

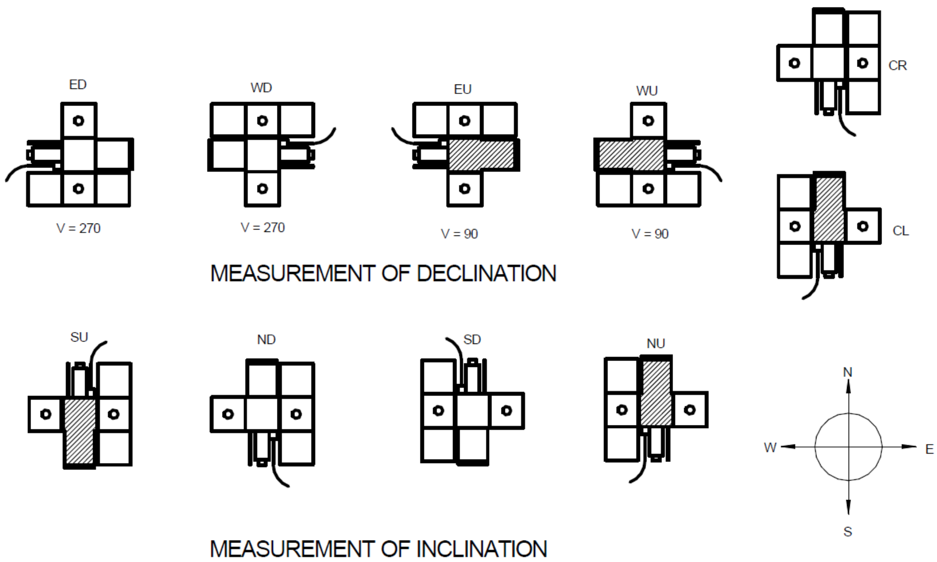


Figure 5 – PLAN VIEW OF OBSERVATION POSITIONS FOR D & I DR0611 (2)

Opažena deklinacija izračuna se iz sredine opažanja ED (*East Down*), WD (*West Down*), EU (*East Up*) i WU (*West Up*).

$$D = [(ED + WD + EU + WU)/4] - 180^0$$

Referentni smjer za deklinaciju je geografski meridijan (GM). Ako geodetska referenca nije GM, već smjer +*x* osi kartografske projekcije, dobivenu deklinaciju potrebno je popraviti za vrijednost konvergencije meridijana.

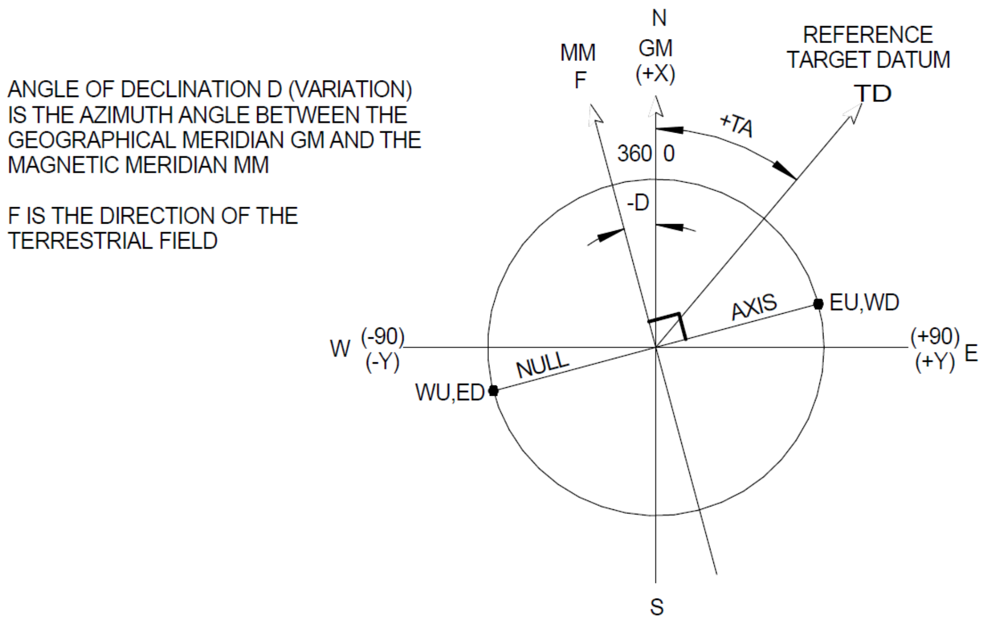


Figure 6 – OBSERVATIONS OF DECLINATION IN THE HORIZONTAL CIRCLE DR0612 (2)

Primjer: zapisnik D-I-F opažanja

```
**************************************************************************
* University of Zagreb                  Program <D-I-F survey> v.1.0       *
* Faculty of Geodesy                    Authors: prof.dr.sc. Mario Brkic   *
* Chair for mathematics and physics                mr.sc. Marko Sljivaric *
* Kaciceva 26, Zagreb, Croatia                            Marko Pavasovic *
**************************************************************************
*           Data is PROPRIETARY of the Faculty of Geodesy!                 *
*           For requests please mailto: mario.brkic@geof.hr                *
**************************************************************************
          Date: 26.04.2008      File name: MagNetE_PALA_26.04.2008(1).txt
       Station: 09SV_PRM01_PALA  Created at: 23:55:37
       Session: 1
Field surveyor: D. Sugar, M. Pavasovic
    PPM height: 1.56 m
    DIM height: 1.63 m
==========================================================================
<1st SET OF MEASUREMENTS>
ED  272.5006   16:51:20   46590.6   SU  121.0640   16:59:35   46590.1
WD  092.4606   16:52:30   46590.3   ND  301.0617   17:01:21   46590.7
EU  092.4507   16:53:46   46590.1   SD  238.5704   17:03:46   46590.6
WU  272.5321   16:55:09   46590.1   NU  058.5726   17:06:11   46590.6
--------------------------------------------------------------------------
      2.4835   16:53:11   46590.2        58.5523   17:02:43   46590.5
```

Za opažanja inklinacije koristi se opažana vrijednost deklinacije za postavljanje sustava u magnetski meridijan. Inklinacija se izračunava iz sredine četiriju opažanja SU (*South Up*), ND (*North Down*), SD (*South Down*) i NU (*North Up*).

Referenca za inklinaciju je horizontala koja se automatski dobiva iz njihala kompenzirane vertikalne reference unutar teodolita.

Opažanja se ostvaruju na vertikalnom krugu, čija je ravnina paralelna sa magnetskim meridijanom. U slučaju Hrvatske je I < 90° pa je opažena inkilnacija

$$I = \left[\left(180^0 - SU\right) + \left(360^0 - ND\right) + \left(SD - 180^0\right) + NU\right] / 4$$

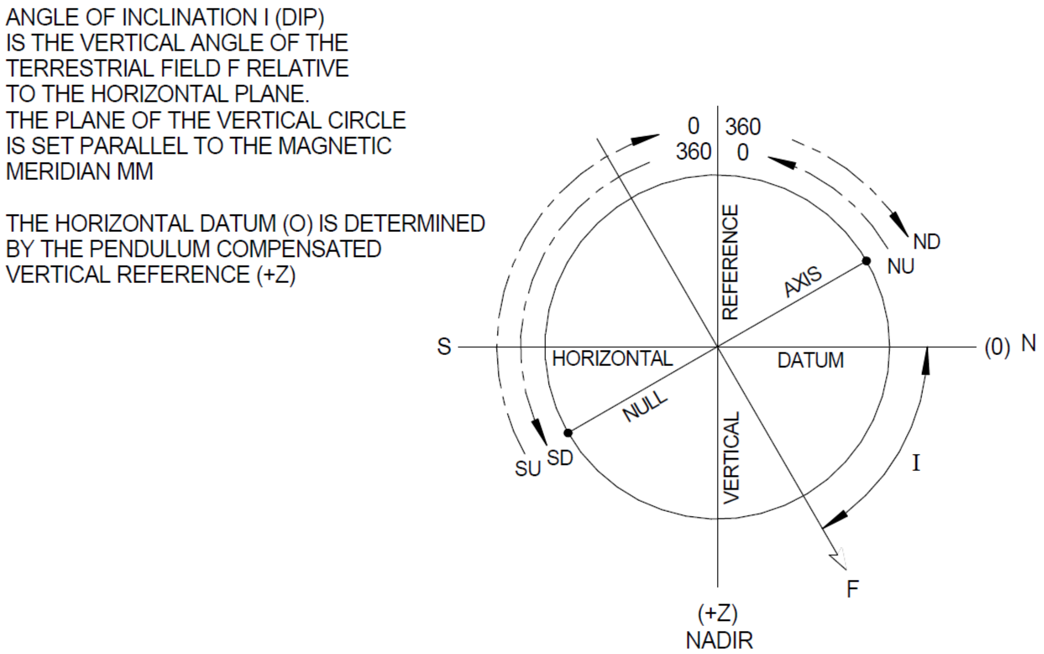


Figure 7 – OBSERVATIONS OF INCLINATION IN THE VERTICAL CIRCLE DR0613 (2)

Nul metodom mogu se poništiti pogreške teodolita, ali ne i one zbog nestabilnosti stativa. Opažač isto tako može uzrokovati pogreške zbog neiskustva i drugih razloga. Pogreške se mogu smanjiti pažljivim postavljanjem instrumenta i savjesnim opažanjem. Opažanja valja učiniti u što kraćem vremenu. Ne zaboravimo pritom i zaštitu instrumenta od Sunčevih zraka.

Opažanje deklinacije

Prije samih opažanja treba osigurati potpunu *magnetsku higijenu*. To znači da opažač ne bi smio imati nikakav magnetični dio ni na sebi niti u sebi. Npr. odjeća ne bi smjela imati metalne remene ili kopče i sl. (Ne)magnetičnost se može provjeriti na očitanjima magnetometra pomicanjem ruku, glave i trupa blizu sonde. Tada očitanja ne smiju varirati više od 0,2 nT. Tijekom opažanja jedino se ruka kojom se djeluje na vijak za fini pomak alhidade smije približiti sondi magnetometra. Pritom valja pripaziti da je tijelo maksimalno udaljeno i postrance u odnosu na sondu.

Prvi mjerni položaj je **ED** (*East Down*). Durbin se rotira tako da bude u horizontalnoj poziciji dok je sonda magnetometra u poziciji dolje (down), ispod durbina. Očitanje vertikalnog kruga postavlja se na 270° 00' 00" na slijedeći način. Nakon što se durbin zakoči, pomoću mikrometarskog vijka postavlja se očitanje desetica minuta i sekunda na vertikalnom krugu. Pomoću vijka za fini pomak durbina koincidiramo crtice tako da dobijemo očitanje 270° 00' 00". Otpušta se kočnica alhidade te se okretanjem instrumenta traži na zaslonu elektronske jedinice izlazna vrijednost što bliža nuli. Kada se postigne vrijednost blizu nule, alhidada se pričvrsti upotrebom kočnice te se uz pomoć vijka za fini pomak traži par vremenskih sekundi stabilna nula na zaslonu elektronske jedinice magnetometra. Sada se očita vremenski trenutak. Prije samog očitanja vrijednosti pravca potrebno je postaviti na horizontalno očitanje te pomoću mikrometarskog vijka koincidirati slike dijamentralno suprotnih crtica u prozoru vidnog polja mikroskopa. Nakon toga zapisuje se očitanje ED (East Down).

Slika 51. Položaj ED (East Down).

Slika 52. Položaj WD (West Down).

Kočnica alhidade se otpusti te se teodolit okreće za 180° oko vertikalne osi. Na taj način se dobiva nul izlazno očitanje u suprotnom smjeru odnosno u poziciji **WD** (*West Down*) – (slika 52). Uz pomoć vijka za fini pomak alhidade ponovno se traži nula na zaslonu elektronske jedinice magnetometra. Nakon što se koincidiraju crtice pomoću mikrometrijskog vijka, bilježi se vremenski trenutak i vrijednost pravca odnosno drugo očitanje. Na taj način se došlo do očitanja WD (West Down).

Slika 53. Položaj EU (East Up).

Položaj WU (West Up).

Slijedeći mjerni položaj je **EU** (*East Up*) – (slika 53). Otkoči se durbin te se rotira za 180° tako da bude ponovno u horizontalnoj poziciji, ali sa sondom magnetometra u poziciji gore (up). Očitanje vertikalnog kruga će sada biti 90° 00' 00''. Točna vrijednost postiže se pomoću vijka za fini pomak durbina, vijkom optičkog mikroskopa te koincidiranjem crtica u prozoru vidnog polja mikroskopa. Pomoću vijka za fini pomak alhidade traži se izlazna vrijednost nule na zaslonu magnetometra. Kod postizanja nul očitanja zabilježi se vremenski trenutak i očitanje pravca. Napominje se da vijak za prijenos slike horizontalnog kruga u vidno polje mikroskopa treba uvijek biti okrenuto u donjem položaju. Prije samog očitanja koincidiraju se crtice te se također ubilježi vremenski trenutak.

Preostaje četvrti položaj odnosno **WU** (*West Up*). Alhidada se otkoči te se zarotira za 180°. Ponovo se traži izlazna vrijednost nule na zaslonu elektronske jedinice magnetometra najprije grubo pa fino uz pomoć vijka za fini pomak alhidade. Zabilježi se vremenski trenutak očitanja i očita se vrijednost horizontalnog pravca.

Opažanje inklinacije

Opažanje inklinacije se obavlja u ravnini magnetskog meridijana, zbog čega se uvijek najprije pristupilo opažanju deklinacije, a nakon toga inklinacije. Obzirom da je zadnji položaj prilikom određivanja deklinacije bio WU (*West Up*), sonda magnetometra se nalazi u poziciji gore (*up*). Dobivenoj vrijednosti deklinacije pridodaje se kut od 180° 00' 00" te tu vrijednost treba postaviti na horizontalnom krugu. Alhidada se okreće oko vertikalne osi teodolita sve dok se ne dobije dano očitanje. Zakoči se alhidada te se pomoću mikrometarskog vijka postavi vrijednost desetica minuta i sekundi. Pomoću vijka za fini pomak alhidade koincidiraju se crtice u prozoru vidnog polja mikroskopa. Instrument je sada postavljen uzduž magnetskog meridijana te se sada treba odrediti položaj **SU** (*South Up*) – (slika 56). Traženo očitanje tog položaja dobiva se tako što se durbin otkoči i traži nula na elektronskoj jedinici magnetometra pomoću vijka za fini pomak durbina. Kada se postigne nul očitanje na zaslonu magnetometra, zabilježi se vrijeme, prebaci na vertikalno očitanje, koincidiraju crtice uz pomoć vijka mikrometra, te zapiše vrijednost očitanja.

Slika 56. Položaj SU (South Up).

Slika 57. Položaj ND (North Down).

Slijedi položaj **ND** (*North Down*) – (slika 57). Najprije se otkoči kočnica durbina te se durbin prebaci u položaj ND odnosno zarotira se za kut od 180° oko horizontalne osi. Prije navedeni postupak se ponavlja. Zakoči se durbin te se vijkom za fini pomak durbina dovede vrijednost elektronske jedinice na nul očitanje (što bolja moguća vrijednost nule). Zabilježi se vrijeme očitanja nul vrijednosti te se prije samog očitanja vertikalnog kuta koincidiraju crtice. Tako se dobiva vrijednost očitanja za položaj ND (North Down).

Slijedi položaj **SD** (*South Down*) – (slika 58). Otpuste se kočnice alhidade i durbina. Očitanje horizontalnog pravca najprije se postavlja na dobivenu vrijednost azimuta magnetskog meridijana (očitanje deklinacije) okretanjem alhidade, mikrometarskim vijkom, te koincidiranjem pomoću vijka za fini pomak alhidade. Durbin se otkoči i traži se nula na zaslonu elektronske jedinice. Zabilježi se vremenski trenutak, koincidiraju crtice i zapiše očitanje vertikalnog kruga.

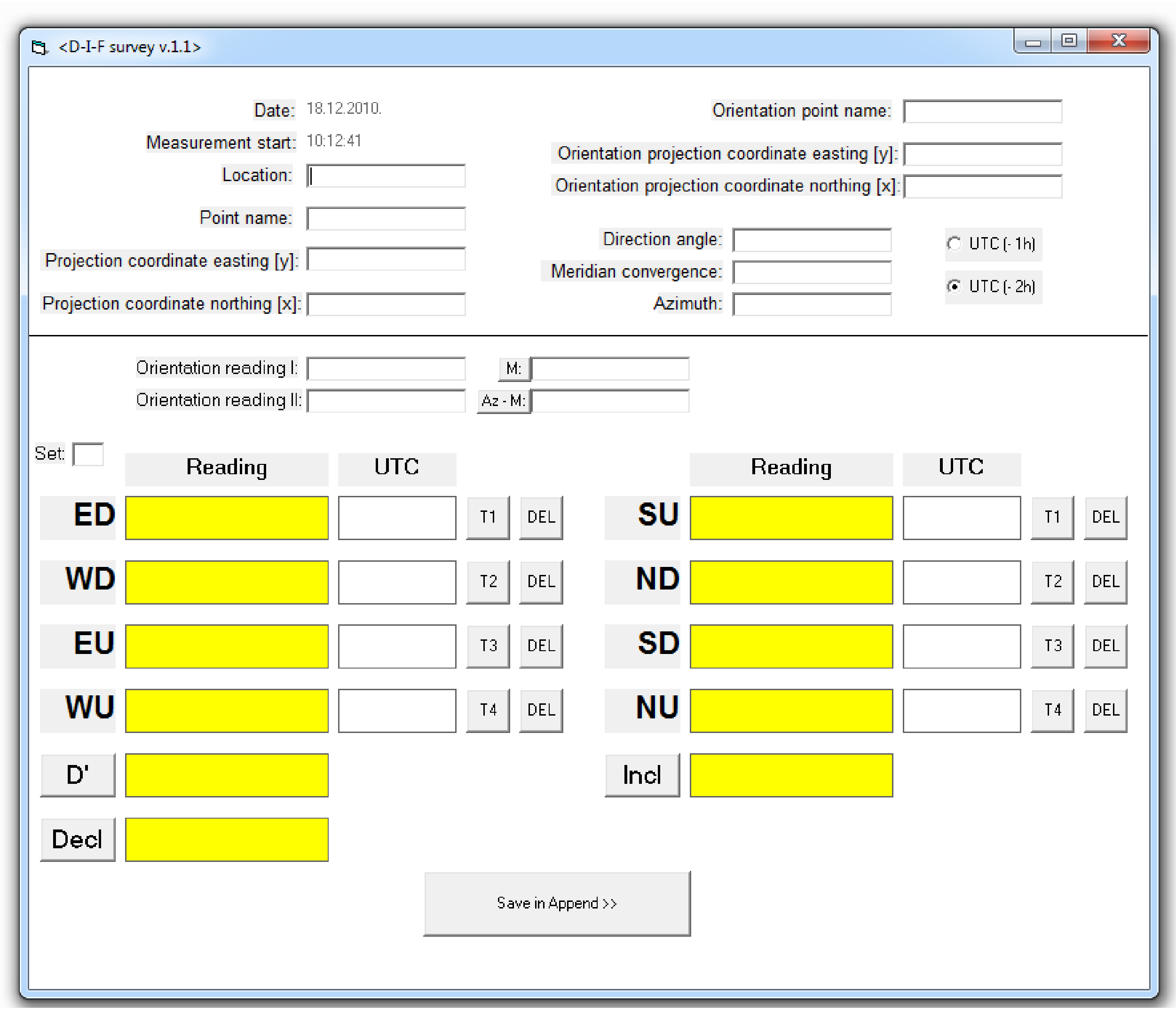
Slika 58. Položaj SD (South Down).

Slika 59. Položaj NU (North Up).

Na kraju preostaje položaj **NU** (*North Up*) – (slika 59). Najprije se otkoči durbin te okrene za 180° u traženi položaj. Okretanjem durbina vrijednost na elektronskoj jedinici magnetometra približavat će se nuli. Blizu nule durbin se zakoči te se vijkom za fini pomak durbina traži nula na zaslonu elektronske jedinice. U tom trenutku se zabilježi vrijeme, koincidiraju crtice i zapiše i očitanje vertikalnog kruga.

Terenski zapisnik opažanja

Tijekom apsolutnog opažanja deklinacije i inklinacije popunjava se odgovarajući obrazac. Na terenu se osim u obrascu apsolutnih mjerenja deklinacije i inklinacije izračunavanje deklinacije i inklinacije izvodi na notebooku pomoću programa *D-I-F Survey*.



Palagruža 2010