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Advanced Proton Magnetometer Design and its Application for Absolute Measurement

Volker AUSTER, Olaf HILLENMAIER, Ronald KROTH
and Markus WIEDEMANN

Magson GmbH,
Carl-Scheele-Strasse 14, 12489 Berlin, Germany
e-mail: office@magson.de

Abstract

A new processor controlled Proton Magnetometer design and its application for an automated absolute measurement will be presented in this paper. The new design is based on an online signal processing of single period measurements of the sensor signal, aiming to improve the resolution and to valuate the signal quality. Applying a cylindrical coil for auxiliary fields, optimized for high homogeneity, a measurement of the geomagnetic field vector can be realized. To demonstrate the need for homogeneous coils, the relation between the homogeneity of the probe volume and the relaxation of the resulting sensor signal will be shown. In order to perform an absolute measurement, the system is equipped with a telescope, aligned along the coil axis and it can be rotated by a motor about its vertical axis. In contrast to conventional methods, the requirements on manual skills of the observer are quite moderate. Furthermore, an option for full automation is provided.

1. Introduction

Methods of measuring components of the Earth magnetic field by using proton magnetometers have been developed between 1950 and 1970. Bias fields of well known direction and intensity were applied to determine field components. In contrast to the "classical" measuring technique, using a suspended magnet as the sensing element, the bias field in this case cannot be generated by permanent magnets, because they produce a very inhomogeneous magnetic field. Thus, special compensated coil systems are used. Examples of well known coil systems, consisting of some pairs of coaxial rings, are named after Helmholtz, Braunbeck, and Fanselau. Design and dimensions of bias coils and proton sensor have to be balanced between contradictive requirements. On the one hand, the proton sensor signal quality increases with the sensor volume, and on the other hand, it needs a homogeneous bias field over the whole sensor volume. Typical requirements are an accuracy of 0.1 nT and a measurement range of 20-100 µT, allowing a wide range of bias fields. An overview on methods to measure the geomagnetic field by proton vector magnetometers (PVM) is given by De Vuyst (1973). He also described a stationary PVM, consisting of a Helmholtz coil with a diameter of approximately one meter, which can be turned around its vertical and horizontal axis. Due to the fact that PMV measurements are not affected by offset or scaling errors, only the misalignment between coil axis and nominal measurement axis have to be taken into account in order to determine the field vector absolutely. By rotation about the axis of measurement direction, this alignment error can be eliminated.

A similar device, however of smaller dimensions, has been described already by Serson (1962). The bias coil of his PVM consists of two pairs of coaxial rings with equal diameter. The mechanical system was comparable with that of a "classical" magnetic absolute theodolite. Between 1980 and 1990, a PVM with a special cylindrical bias field coil was developed at Niemegk Observatory (1983). The coil has two layers, which are individually compensated up to the sixth order. The proton sensor itself was designed as a double probe in order to suppress electrodynamics noise. To perform a rotation about the vertical axis for the measurement of *D* and *H*, the cylindrical coil was mounted on the top of a non-magnetic ZEISS-theodolite 020B (Fig. 1).

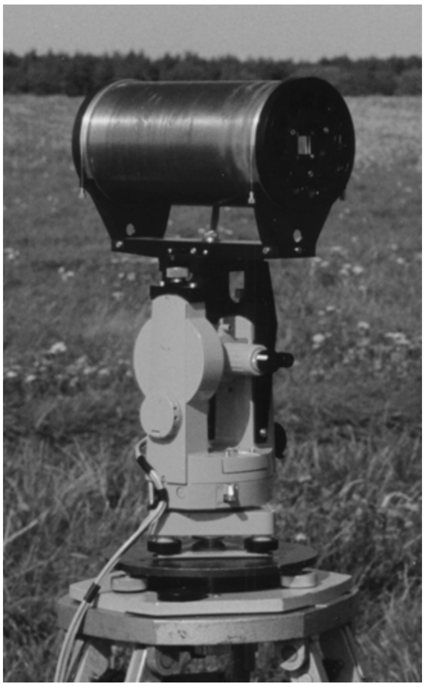


Fig. 1. Absolute measurement at repeat station with a PVM mounted on a non-magnetic theodolite.

In the time period mentioned above, this instrument was applied successfully for absolute measurements at repeat stations and for the geomagnetic survey. Recently, further development of this PVM has been carried out by MAGSON GmbH. The proton magnetometer electronics has been redesigned to improve accuracy and to increase the control and data processing capability as described in Section 2. In Sections 3 and 4 the paper describes the development of a new coil system, which combines bias field coil, sample coil and the optical device (telescope or optoelectronic components) for the geodetic adjustment of the PVM as well as the development of a measurement procedure and a mechanical base to perform absolute measurements of D and H with a high degree of automation.

2. New Proton Magnetometer Design

The PM2005 is a new developed classical proton magnetometer with an internal processor for controlling the signal generation and signal processing. The measurement can either be started manually, by a serial command, or by a trigger signal. The measured field value is displayed on an LCD and stored in a data file on a removable flash RAM card. Additional information as signal quality, selected range, sample counter, date, and time are also stored in the data file. The instrument can be combined with a GPS receiver. The GPS information will be used to synchronize the instrument clock and to estimate the earth magnetic field using the integrated IGFR model which will be used as an initial range selection. Furthermore, the instrument provides features that are used in the component measurement application. So a controlled current source to apply bias fields is included.

The main feature of this device is the implementation of an online regression algorithm applied on results of a period measurement of the sensor output signal. Amplitude and length of each period of the proton AC voltage are measured directly. Circuitries like frequency multipliers are removed. For a number of N consecutive periods of the proton AC signal, each period length p_n with n = 1...N is measured. Instead of calculating the arithmetic mean value, the average period length is derived by using a linear regression algorithm. For each period length p_n the accumulated sum

$$s_n = \sum_{i=1}^{n} p_i \,, \qquad (n = 1 \dots N) \tag{1}$$

is calculated. Assuming equal period lengths ($p_i = p$, (i = 1... N)), s_n can be expressed by the linear equation

$$s_n = p \cdot n + q \,, \tag{2}$$

where the period length p represents the slope and q the offset of the straight, which is equal to 0 for equal period lengths p_i. For real, unequal period lengths p_i, the coefficients p and q can be determined by using the linear regression algorithm:

$$\frac{\partial}{\partial p}, \frac{\partial}{\partial q} \left(\sum_{n=1}^{N} \left(\left(p \cdot n + q \right) - \sum_{i=1}^{n} p_i \right)^2 \right) = 0 \,. \tag{3}$$

Then, the coefficient p represents an average period length of the proton AC signal.

The regression algorithm takes much more care for the relaxation specific of the proton signal and allows a better suppression of disturbing signals (e.g. 50 Hz) compared to arithmetic averaging of period measurements. The noise could be reduced by a factor of two and the instrument becomes more robust against spatial and temporal field gradients. In Fig. 2, a 24 h registration at the Geomagnetic Observatory Niemegk is plotted, comparing PM2005 and a GEM-System Overhauser magnetometer. The noise of the much simpler proton magnetometer sensor is at least in the same order. The noise of both magnetometers, measured during a magnetically quiet period, is about 0.1 nT RMS. Furthermore, the measurement of the signal amplitude makes always an evaluation of the signal quality possible.

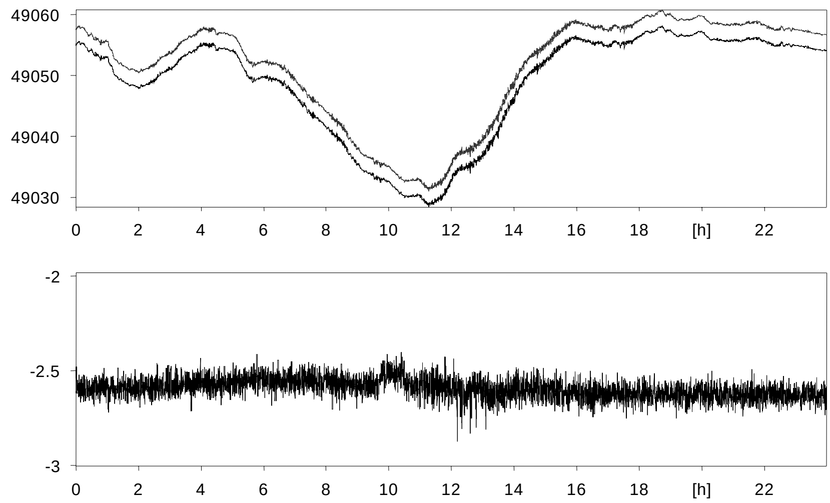


Fig. 2. Comparison of PM2005 (upper recording in upper panel) and GEM-System Overhauser (lower recording in upper panel) and difference between both.

3. Bias Coils

The method of component measurement is based upon the application of bias fields of equal intensity but opposite direction ($+H_b$ and $-H_b$) and measurement of the intensity of the resultant vectors F_+, F_-, and F_0 (without bias field). The calculated values for the component of the earth magnetic field in the coil axis direction H_a and for the bias field intensity H_b are:

$$H_b = \sqrt{\left(\frac{F_+^2 + F_-^2}{2} - F_0^2\right)}, \qquad H_a = \frac{F_+^2 - F_-^2}{4H_b}. \tag{4a, b}$$

The field component in direction of the bias coil axis is independent of bias field intensity, but the inhomogeneity of the bias field over the sensor volume has to be small because the proton sensor signal quality depends on it. To determine the magnetic field component absolutely, the direction of the magnetic axis of coil has to be known precisely with respect to a geophysical reference system. Usually coils consisting of several rings (e.g. Helmholtz coils) are used as bias coils. Due to the fact that no access to the proton sensor is necessary, we prefer to apply compensated cylindrical coils which are able to fulfill the requirements on homogeneity and axis alignment much better. The axis of cylindrical coils is well defined because windings are defined by threads which can be inserted precisely by the machine accuracy of a lathe in the carrier material of the coil. Threads with non unique pitches can be used to increase the field homogeneity. To estimate which field gradient ΔH is tolerable, the decay function of the proton magnetometer in dependency on two different angular frequencies ω_1 and ω_2 – related to different field magnitudes – shall be described by the following equation, where T_2 is the relaxation time of the proton signal.

$$A(t) = A_0 e^{-\frac{t}{T_2}} (\sin \omega_1 t + \sin \omega_2 t) . \tag{5}$$

Introducing the averaged angular frequency ω and the difference angular frequency Ω which is proportional to the product of field gradient and gyromagnetic ratio γ_H for hydrogen

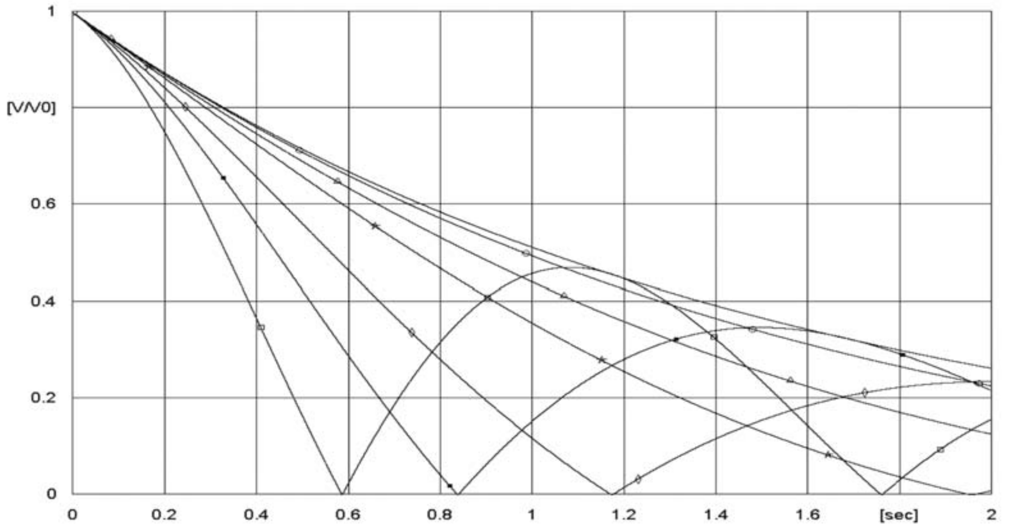
$$\omega = \frac{\omega_1 + \omega_2}{2} , \qquad \Omega = \frac{\omega_1 - \omega_2}{2} = \pi \Delta f = \pi \Delta H \gamma_H , \tag{6a, b}$$

we get the following equation for the proton signal:

$$A(t) = A_0 e^{-\frac{t}{T_2}} \cos(\Omega t) \sin(\omega t) = A e^{-\frac{t}{T_2}} \cos\left(\pi \Delta H \gamma_H t\right) \sin(\omega t) . \tag{7}$$

In Fig. 3 the proton signal is drawn for field gradients between 0 and 10 nT. Assuming that the frequency measurement is reliable until $A_0/2$, the measurement time decreases from 1 s under undisturbed conditions to 0.3 s in case of a 10 nT field gradient. Thus we need a bias coil which ensures a field gradient of less than 1 nT for typical bias fields of 32,000 nT. This corresponds with a homogeneity requirement of better 3×10^{-5} over the probe volume.

A two cylindrical coils approach for optimizing the field homogeneity leads us to a coil with different pitches at central and outer region. Details about the coil dimensioning can be found in the formulary of the Magson homepage (http://www.magson.de). To avoid the influence of the screwing character of winding, a second coaxial and concentric coil, calculated in the same way as the first one, is winded anticlockwise. This double layer design has the advantage, that connector pins are located at the same side which allows a supply via a twisted pair harness. In Fig. 4 the homogeneity of a compensated cylindrical coil is compared with the homogeneity of a Helmholtz coil with identical diameter. The volume of homogeneity better than 10^{-5} of the compensated cylindrical coil exceeds that of the Helmholtz coil at least by a factor of 64 (factor of 4 in each dimension). The homogeneity is good enough up to a distance of 1/3 of the coil radius from the center. Using a cubic probe with an edge length of 4 cm, we need a bias coil with a diameter of 12 cm. An adequate Helmholtz coil has a diameter of half a meter.



– ΔH = 0.1 nT, ○ ΔH = 1 nT, Δ ΔH = 21 nT, * ΔH = 3 nT, ◊ ΔH = 5 nT, ■ ΔH = 7 nT, □ ΔH = 10 nT

Fig. 3. Relaxation behaviour for field gradients ΔH = 0.1 nT, 1 nT, 2 nT, 3 nT, 5 nT, 7 nT and 10 nT over the probe volume. Parameters: T_2 = 1.5 s (water sample), γ = 0.042576 Hz/nT.

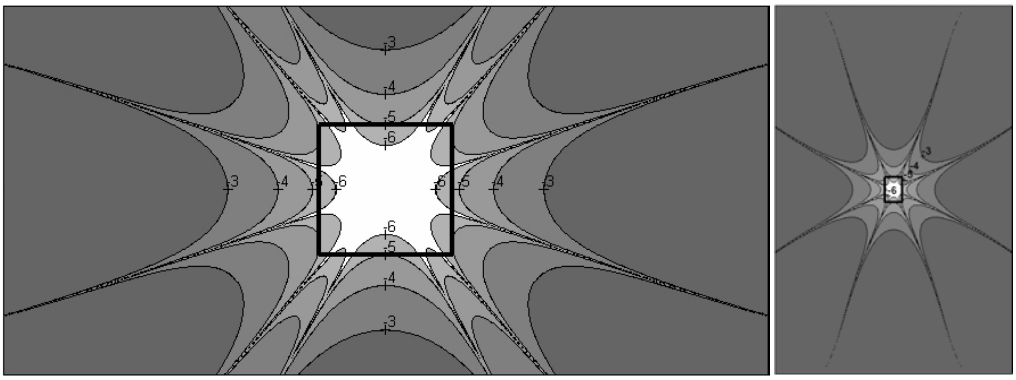


Fig. 4. Relative difference between nominal field and induced field for a compensated cylindrical coil (left side) and a Helmholtz coil (right side). For both coils equal diameters are assumed. The region of homogeneity better than 10^{-5} is marked by squares. The scaling is given in exponents to the base of 10.

4. Usage for Absolute Measurement and Automation Approach

The geographic reference system is defined by the vertical direction and an azimuth mark. To measure an earth magnetic field component correspondingly to this reference system, we accommodate a special proton magnetometer sensor, consisting of four single coils and two samples, which allow integrating a telescope inside our proved compensated cylindrical bias field coil. To determine the deviation of this mechanical axis with respect to the magnetic axis and furthermore to adjust the cross wires of the telescope, the bias coil can be rotated about its mechanical axis. On one end of the coil a non-magnetic ocular (focal length 10 mm) is placed, on the other end a lens (focal length 230 mm) is located (see Fig. 5). For the automatic version of the PVM the ocular has been replaced by a CCD circuit with a suitable alignment mechanism.

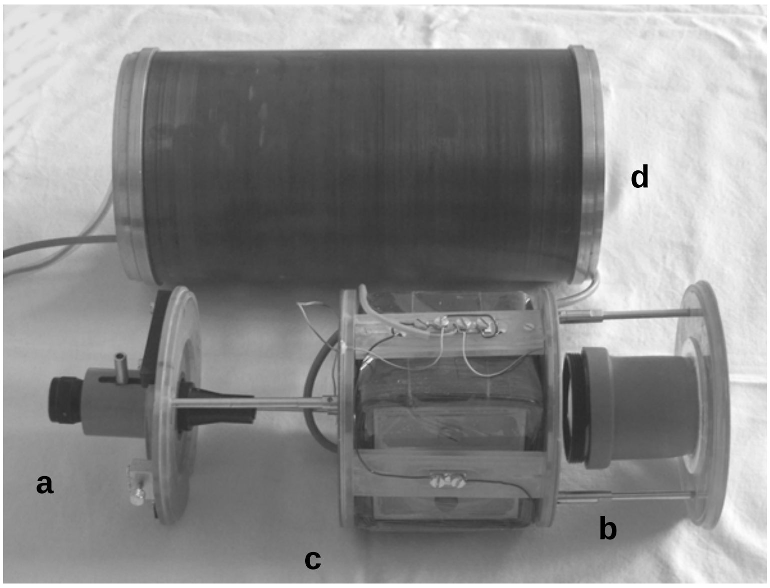


Fig. 5. Disassambled proton magnetometer sensor: Non-magnetic ocular (a), lens (b) and the probe with coils and samples (c) will be mounted inside the bias coil (d).

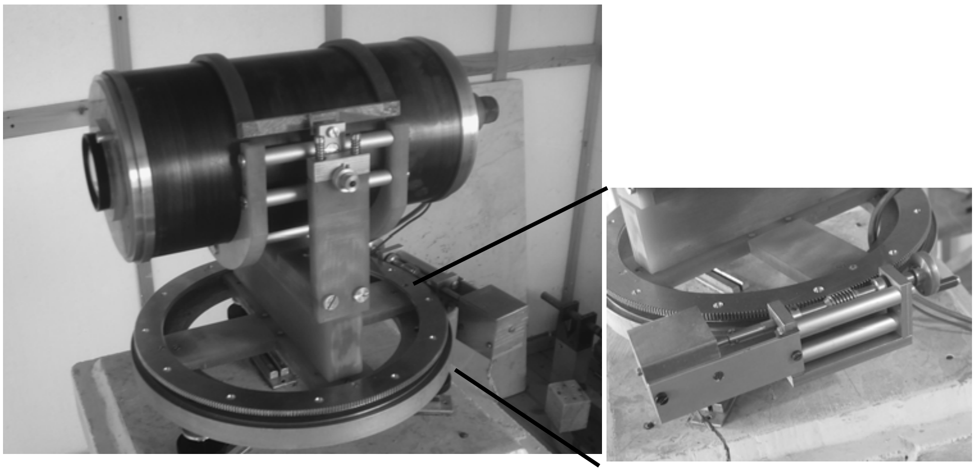


Fig. 6. The prototype of the PVM used for a (semi) automated absolute measurement. The system can be rotated manually by a hand crank or automatically by a step motor.

To measure the field vector completely, the bias coil is mounted on a rotation table with a diameter of 270 mm and a ring gear on its periphery (360 teeth). The alignment error between the rotation axis of the table and the vertical axis is monitored by an electronic inclinometer. A self blocking drive unit for the rotation table is realized by a worm gear engaging with a ring gear. The rotation table can be rotated either manually or by a step motor. In the manually operated system, the worm gear axle is connected to a hand crank (see Fig. 6). In this case the rotation angle α (versus geographic north) is measured by an incremental counter. The resolution is 500 pulses per revolution of the worm gear axle which corresponds to an accuracy of 0.12 arcmin. The magnetic field at the rotation angle α can be expressed as a function of declination D, horizontal force H, vertical field component Z and the tilt angle versus horizontal plane γ.

$$H(\alpha) = H\cos(\alpha + D)\cos(\gamma) + Z\sin(\gamma)\,. \tag{8}$$

In the first step the system is set either by observer and telescope or automatically by an optoelectronic device into the direction α_0 of a well known target. From this position, n single measurements are started with the angular distance of $\Delta\alpha$.

$$\Delta\alpha = \frac{360°}{n}\,, \qquad \alpha_n = \alpha_0, \alpha_0 + \Delta\alpha, \alpha_0 + 2\Delta\alpha, ..., \alpha_0 + (n-1)\Delta\alpha\,. \tag{9}$$

For each measurement direction the proton magnetometer measurement range for positive and negative bias fields can be determined using approximate values for D, H and F and a suitable bias field H_b by the following equation:

$$F_{\pm} = \sqrt{Z^2 + H_b^2 + H^2 \pm 2H_b H\cos(\alpha_n + D)}\,. \tag{10}$$

$H(\alpha)$ will be calculated by Eq. 4 for all set angles α. After reduction of the variation we perform a harmonic analysis:

$$H(\alpha) = A_0 + A_1\cos(\alpha) + A_2\sin(\alpha) \tag{11}$$

with

$$A_0 = \frac{1}{n}\sum_n H(\alpha_n)\,, \tag{12a}$$

$$A_1 = \frac{2}{n}\sum_n H(\alpha_n)\cos(\alpha_n)\,, \tag{12b}$$

$$A_2 = \frac{2}{n}\sum_n H(\alpha_n)\sin(\alpha_n)\,. \tag{12c}$$

Using amplitude and phase we can rewrite Eq. 11:

$$H(\alpha) = A_0 + A\cos(\alpha + \varphi) \tag{13}$$

with

$$A = \sqrt{A_1^2 + A_2^2} \quad \text{and} \quad \varphi = \mathrm{arctg}\left(\frac{A_2}{A_1}\right). \tag{14a, b}$$

Note, that the arctg function is multivalued with $+/-k\pi$ ($k = 0$, 1, …).

If we compare the coefficients of Eq. 8 and Eq. 13 now, we get:

$$Z \sin\gamma = A_0 \,, \qquad H \cos\gamma = A \,, \qquad D = \varphi \,. \tag{15a, b, c}$$

With an iteration procedure

$$H_1 = A\left(1 - \frac{A_0^2}{F^2 - A^2}\right)^{-0.5} , \qquad H_n = A\left(1 - \frac{A_0^2}{F^2 - H_{n-1}^2}\right)^{-0.5} , \tag{16}$$

we get finally the horizontal force $H = H_n$. For tilt angles less than 20°, $n = 6$ iteration steps are sufficient to suppress the error below a 0.1 nT threshold.

5. Summary and Outlook

A new designed proton magnetometer equipped with a compensated cylindrical bias coil has been used for absolute measurement of the Earth's field components. Advantages of the signal processing based on a regression algorithm, influence of field gradients on the proton magnetometer signal, high homogeneity of the compensated bias coil as well as the algorithm for components determination by rotation of the PVM are presented. Steps of automation are already done and will be object of further developments.

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