Gauss' *H*-Variometer at the Helsinki Magnetic Observatory 1844–1912

Heikki NEVANLINNA

Finnish Meteorological Institute, Geomagnetism Unit, P.O. Box 503, FIN-00101 Helsinki, Finland

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During the early decades of the 19th century variations of the geomagnetic field at geomagnetic observatories were observed visually only. The most widely used method to observe changes of variometer magnets was Poggendorff's mirror-and-scale system aided with a telescope. Readings were made typically 1 ... 12 times per hour. For observations of the horizontal field, Gauss' bifilar *H*-variometer was in use at geomagnetic observatories. At the Helsinki observatory, founded in 1838, Gauss' bifilar instrument was continuously in operation for more than 60 years. During that time about 1,000,000 readings of *H* were accumulated. Most of the data are still unreduced and are available in original observational notebooks only. The quality of the *H*-data, at least in the period 1844–1848 studied here, seems to be reliable. Comparisons between Helsinki *H*-results and the present day Nurmijärvi observatory data, reveal similar daily variation curves at both observatories. In long-term changes, with varying number of annual sunspots, the daily range of *H* follows the same linear relationship as *H* at Nurmijärvi. We believe that the Helsinki *H*-data series is reliable and homogeneous and thus suitable for detailed studies of changes of the geomagnetic horizontal field component in the mid 19th century.

1. Introduction

Regular observations of magnetic field changes with thread suspended magnets started in the Paris observatory in the 1790's. This new type of variometer, developed by Coulomb and Cassini, rapidly superseded pivoted navigational compasses as tools of accurate observatory instruments (see e.g. Chapman and Bartels, 1940; Cawood, 1977, 1979). The accuracy of magnetic direction readings was later much enhanced by Poggendorff's invention (1826) of mirror-and-scale method. This observation method was adopted by Gauss in the Göttingen observatory and in the observatories belonging to the magnetic observation programme directed by the Göttingen Magnetic Union in the 1830's and 1840's. Variometers based on eye-readings were used for observations of declination (*D*), horizontal- (*H*), and vertical component (*Z*) of the magnetic field vector. The *D*-variometer was called a unifilar variometer as the magnet was suspended by a single thread usually made from silk. Gauss' invention of the bifilar variometer for observations of horizontal field changes was introduced in 1837. Two years later Lloyd published a description of the *Z*-field balance (see e.g. Chapman and Bartels, 1940). Compared with more modern variometers based on moving magnets, like the La Cour-system, magnets in old variometers were huge: weight about 2 kg, length 50–60 cm.

In the early decades of the 19th century, the number of permanent magnetic observatories increased rapidly. One of the first observatories was in operation in Paris in the 1810's. After activities by von Humboldt in Germany and France, Arago in France, Sabine in Great Britain, and Gauss in Germany, several tens of observatories were set up in Europe and in the oversea territories of Great Britain and France. In Finland the first magnetic observatory was founded in 1838 as a part of the Russian chain of magnetic observatories (for more details, see e.g. Nevanlinna, 1995). Continuous geomagnetic (and meteorological) observations started in 1844 according to the observation procedures introduced in Göttingen and in other observatories belonging to the Göttingen Magnetic Union. At the Helsinki observatory *D*- and *H*-observations were made 6 times per hour. *Z* was observed 3 times in an hour. These

observations were carried out almost uninterruptedly for 13 years in 1844–1857. After that observations continued hourly for the subsequent 55 years until 1912. During the 68 years when the observatory was operating, about 2,000,000 single observations (D , H and Z) of magnetic field values were made. Not many of these data were reduced in the 19th century but the original results have surveyed. Observations of D at the Helsinki observatory have recently been processed and the quality of the data has been shown to be high (see e.g. Nevanlinna and Kataja, 1993; Nevanlinna, 1995).

The aim of this study is to present the working principles of Gauss' bifilar H -variometer which was used at the Helsinki observatory. Some preliminary results of H -variations will be shown.

2. The H -Variometer

The principle of the bifilar magnetometer was invented by C. F. Gauss in 1837 one year later than his method for determining the absolute magnitude of the H -field was introduced. In the proceedings of the Göttingen Magnetic Union for 1837 (Gauss, 1838) there is a thorough description of the working principle and detailed pictures of the bifilar magnetometer. Similar types of bifilar H -variometers as at Göttingen were in use in many magnetic observatories through the 19th century (see e.g. Gauss, 1838; Kupffer, 1843, 1846; Basso Ricci *et al.*, 1997). For example in the late 19th century during the International Polar Year (1882–1883) at the Sodankylä observatory in Finland, there was in operation a bifilar H -variometer. The observation method was the same visual procedure as used earlier at the Helsinki and Göttingen observatories (Lemström and Biese, 1887).

At the Helsinki observatory, the H -magnet was identical to the magnet used in the unifilar declination magnetometer. Its weight was 1.8 kg and dimensions were 63 cm $\times$ 3.7 cm $\times$ 1.0 cm (see Fig. 1). The variometer was manufactured in Göttingen by the famous instrument maker Moritz Meyerstein.

The magnet together with the torsion head was suspended by two 2.75 m long silver threads (see Fig. 1). In the bifilar system the magnet is kept in the EW-direction perpendicular to the magnetic meridian (NS) in order to minimize the influence of declination variations on changes of the magnet.

The basic equation governing Gauss' bifilar magnetometer is very simple. Let φ denote the angle between the magnet (with a magnetic moment M) and the magnetic horizontal field vector H , then the equation balancing the magnetic and mechanical torques is according to Lamont (1867)

$$MH \sin(\varphi) = \gamma \sin(\psi - \varphi), \quad (1)$$

where γ is the torsion constant of the fibres and ψ is the torsion angle in the bifilar threads that keeps the magnet in the position φ . γ depends on the separation (a) between the threads, on the length (l) of the suspension threads, and on the mass (m) of the magnet as follows (Lamont, 1867):

$$\gamma = \frac{mga^2}{4l} \quad (1')$$

where g is the gravitational constant.

Both M and γ in Eq. (1) vary with temperature changes which are corrected by including an exponential temperature factor as follows:

$$MH \sin(\varphi) = \gamma \exp[\alpha(t - t_0)] \sin(\psi - \varphi) \quad (2)$$

which takes into account temperature (t) changes (Δt) relative to a chosen reference temperature (t_0). α is the common temperature coefficient for both M and γ . Keeping ψ constant, then for small changes (Δ) of H and φ the following relationship can be derived from Eq. (2):

Fig. 1. The working principle of Gauss' bifilar variometer for observations of the horizontal field changes at the Helsinki magnetic observatory. The magnet (M) was suspended by two silver threads in the East-West position as shown in the upper panel. Changes in the direction of the magnet were observed by a telescope (T). A mirror, attached to the magnet, reflected the scale values (S) into the telescope (T) mounted on a solid pillar in a distance of $R = 7.3 \text{ m}$ from the magnet.

$$\frac{\Delta H}{H_0} = -[\cot(\psi - \phi) + \cot(\phi)]\Delta\phi + \alpha\Delta t \quad (3)$$

where H_0 denotes the magnetic field at temperature t_0 . By substituting both $\phi = 90^\circ$ and $\Delta\phi = \varepsilon_H(h - h_0)$ to Eq. (3), we get:

$$\frac{\Delta H}{H_0} = \varepsilon_H \tan(\psi)(h - h_0) + \alpha(t - t_0) \quad (4)$$

which gives the relative field changes as a function of changes in the variometer magnet angle and

temperature. Here ε_H is the optical scale value defined by:

$$\varepsilon_H = 1 \text{ rad}/2R = 3438'/2R = 0.237'/\text{mm}$$

where R ($=7265.1$ mm) is the distance between the scale and the mirror, h is the variometer reading (scale value, see Fig. 1) and h_0 the scale base-value.

Today variometers of magnet type, like La Cour, are calibrated by using small Helmholtz coils around the variometer sensor. By producing field increments in the direction of the component to be recorded, the scale values can be calculated from the known coil constants. In the early 19th century no such devices were available and the calibrations needed were carried out by measuring the oscillation periods of the recording magnets. The three types of variometers at Helsinki, the unifilar D -, bifilar H -variometer and Lloyd's Z -balance, were all calibrated by measuring the oscillations of the magnets in different positions.

According to Gauss (1838) and Lamont (1867), the torsion angle (ψ) of the fibres in Eq. (4) obeys the following relationship:

$$\frac{\sin(\psi - \varphi)}{\sin(\varphi)} = \frac{T_-^2 - T_+^2}{T_-^2 + T_+^2} \quad (5)$$

where T_+ is the oscillation period of the magnet in the normal north seeking position. T_- is the period when the magnet is in the opposite direction after turning the threads by the torque ψ . In its working EW-position ($\varphi = 90^\circ$), the oscillation period of the magnet is $T = \sqrt{T_+ T_-}$ (Gauss, 1838) and one can easily derive from Eq. (5) that the torsion angle ψ needed is given by:

$$\cot(\psi) = \frac{T_-^2 - T_+^2}{2T_+ T_-} = \frac{T_-^2 - T_+^2}{2T^2}. \quad (6)$$

The periods T_+ , T_- and T , taken from the yearbooks 1844–48 by Nervander (1850), were 17.3 s, 73.9 s and 35.7 s, respectively.

The sensitivity (S_H) of the H -variometer is defined by (cf. Eq. (4)):

$$S_H = \varepsilon_H H_0 \tan(\psi). \quad (7)$$

By putting the values of ε_H , H ($\approx 15,100$ nT) and ψ ($=26.28^\circ$ as calculated from Eq. (6)) into Eq. (7), we get $S_H = 0.520$ nT/mm which is about the same as for the H -variometer at the Sodankylä Polar Year station (Lemström and Biese, 1887).

Direct information about the temperature sensitivity coefficient (α) in Eq. (4) is not available. However, it can be determined afterwards rather reliably by correlating variometer and temperature readings during wintertime under magnetically quiet conditions and when the temperature changed several degrees within a day. The slope of a simple linear regression line is the temperature coefficient. We get $\alpha_{H_0} = -4$ nT/ $^\circ\text{R}$, where the temperature is measured in units of the Réaumur ($^\circ\text{R}$) scale ($1^\circ\text{R} = 1.25^\circ\text{C}$).

3. Results of H - and D -Observations

Figure 2 displays the average diurnal variations of H and D at Helsinki 1844–45 and at Nurmijärvi 1955 under similar solar activity conditions near sunspot minimum. As can be seen, the mean daily

Fig. 2. Comparison of diurnal variation of hourly mean values from Helsinki (1845) (solid symbols) and Nurmijärvi (1955) (open symbols) under similar solar activity conditions near the sunspot minimum.

Fig. 3. Average daily range (ΔH) of horizontal field variation at Helsinki (1844–48) (dots) and Nurmijärvi (1953–1994) (circles) as function of annual sunspot numbers (R). The linear fit is for the Nurmijärvi data.

Fig. 4. A sample of smoothed (6 points) 10-minute observations (dots) of the horizontal component (H) at Helsinki observatory in June 1847. There were 144 readings of H for each day and the total number of observations was about 4300 per month. June 1847 was magnetically quiet but enhanced activity can be observed during the second week.

variations of H and D are practically identical at both observatories demonstrating the reliability of the magnetic observations at Helsinki.

A convincing example of real long-term changes in the daily variation of H at Helsinki is shown in Fig. 3 depicting the daily range of H versus annual sunspot number (R). The daily range of H at Helsinki during 1844–48 has been rising with increasing R at almost the same rate as has been observed at Nurmijärvi under comparable solar activity conditions 11 sunspot cycles later. For both Nurmijärvi and Helsinki the linear relationships of the annual mean of daily range of declination (ΔD) and horizontal field (ΔH) with annual R , are

$$\Delta D \text{ (nT)} = 27 + 0.15R,$$

$$\Delta H \text{ (nT)} = 23 + 0.16R.$$

The good correlations between the Helsinki and Nurmijärvi observations support the conclusion that the H -observations made at the Helsinki observatory are well suited for analyzing hourly and daily magnetic variations. This conclusion is supported by Fig. 4 which displays a typical example of the H -data observed at 10 minute intervals (June 1847). The characteristic regular daily variation is clearly seen in a homogeneous time series of the data.

REFERENCES

- Basso Ricci, M., L. Cafarella, A. Meloni, and P. Tucci, *Due Secoli di Strumenti Geomagnetici in Italia (1740–1971) (Two Centuries of Geomagnetic Instruments in Italy (1740–1971))*, 234 pp., Istituto Nazionale di Geofisica, Roma, 1997.

- Cawood, J., Terrestrial magnetism and the development of international collaboration in the early nineteenth century, *Ann. Sci.*, **34**, 551–587, 1977.
- Cawood, J., The magnetic crusade: Science and politics in early Victorian Britain, *ISIS*, **70**, 493–518, 1979.
- Chapman, S. and J. Bartels, *Geomagnetism Vol. I*, 542 pp., Oxford University Press, London, 1940.
- Gauss, C.F., Bemerkungen über die Einrichtung und den Gebrauch des Bifilar-Magnetometers, in *Resultate aus den Beobachtungen des Magnetischen Vereins im Jahre 1837*, edited by C. F. Gauss and W. Weber, pp. 20–37, Göttingen, 1838.
- Kupffer, A. T., *Annuaire Magnétique et Météorologique—Année 1841*, 674 pp., Imp. Acad. Sci., St. Petersburg, 1843.
- Kupffer, A. T., *Annuaire Magnétique et Météorologique—Année 1844*, 870 pp., Imp. Acad. Sci., St. Petersburg, 1846.
- Lamont, J., *Handbuch des Geomagnetismus*, 468 pp., L. Voss, Leipzig, 1867.
- Lemström, S. and E. Biese, *Exploration Internationale des Régions Polaires 1882–1883 et 1883–1884. Tome II: Magnétisme Terrestre—Observations Faites aux Stations de Sodankylä et de Kultala*, 170 pp., Acad. Scient. Fennica, Helsingfors, 1887.
- Nervander, J. J., *Observations Faites à L'observatoire Magnétique et Météorologique de Helsingfors 1844–1848*, Vol. I–IV, Acad. Scient. Fennica, Helsingfors, 1850.
- Nevanlinna, H., New geomagnetic activity index series published for 1844–1880, *EOS*, **76**, 233–234, 1995.
- Nevanlinna, H. and E. Kataja, An extension of the geomagnetic activity index series *aa* for two solar cycles (1844–1868), *Geophys. Res. Lett.*, **23**, 2703–2706, 1993.