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Three-component variometer based on a scalar potassium sensor

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Abstract
A new variometer is developed comprising a fast-response scalar optically pumped potassium magnetometer inside a rotating magnetic field created by a two-dimensional coil system mounted on a quartz frame. The variometer measures three components of the Earth's field: the total field intensity and two transverse components. The theoretically predicted accuracy of the field component measurement is not worse than 0.1 nT. The noise-limited sensitivity measured in a quiet magnetic field has been proved to be not worse than 25 pT rms at 0.2 s and 30 pT rms at 1 min; comparison with a proton vector magnetometer and a fluxgate magnetometer shows 1.5 nT p–t–p daily deviation.

Keywords: geomagnetic instruments, magnetometer, variometer, magnetic field vector, optically pumped potassium magnetometer

1. General principles

Here we present yet another implementation of the idea [1–6] of using a scalar magnetic field measuring device for measuring a three-component vector field. As a scalar device we use a potassium M_x optically pumped sensor [7, 8] as it is much more sensitive, accurate and (what is most relevant for this application) fast than the proton magnetometer. Originally, the M_x magnetometer constitutes a sort of maser, oscillating at a certain frequency $\omega(H)$ strictly related to current scalar value H of the ambient magnetic field. This device can be rearranged into a three-component variometer by adding to its construction two orthogonal sets of magnetic coils, producing (a) an additional magnetic field $\mathbf{H}_\perp$, rotating on a plane perpendicular to the vector of the Earth's magnetic field $\mathbf{H}_0$ and (b) a slow-changing compensating magnetic field $\mathbf{H}_1$, lying in the same plane. The scalar sensor positioned exactly at the centre of the coil system measures the total magnetic field $\mathbf{H}$ which is the vector sum of $\mathbf{H}_0$ and $\mathbf{H}_\perp$.

Obviously, the scalar value $\mathbf{H}$ depends on the mutual orientation of $\mathbf{H}_0$ and $\mathbf{H}_\perp$; if $\mathbf{H}_0$ changes direction (a small transverse component $\Delta\mathbf{H}$ appears), $|\mathbf{H}(t)|$ is no longer constant but contains oscillating components with phases and amplitudes depending on the angle between $\mathbf{H}_0$ and $\mathbf{H}_\perp$. These oscillating components are used as an error signal for a feedback system, producing the small compensating magnetic field $\mathbf{H}_1 = -\Delta\mathbf{H}$ which brings the vector of dc magnetic field back to its initial position; and now from the knowledge of the components of the compensating field $\mathbf{H}_1$, we know the variation of the transverse components of $\mathbf{H}_0$ (figure 1).

The main advantage of this device over all its predecessors, including the proton magnetometer situated in additional magnetic fields with alternating polarity, is its capability of fast continuous measurement limited only by the frequency f of the field $\mathbf{H}_\perp$ rotation (several hundred Hertz, the frequency is limited by the Zeeman potassium resonance line splitting in the Earth's field).

2. The variometer design

The variometer (figure 2) consists of a fast-response scalar magnetometer installed inside a two-dimensional (x–y) coil system, producing the magnetic field $\mathbf{H}_\perp$ of magnitude of about $(H_0/10)$ rotating on the x–0–y plane around the z-axis with frequency f (where H_0 is the mean magnetic field of the Earth, and $f = 362$ Hz). Initially the z-axis of the coil system is positioned parallel to the Earth's field axis, so the output of the scalar magnetometer does not contain any modulation at frequency f.

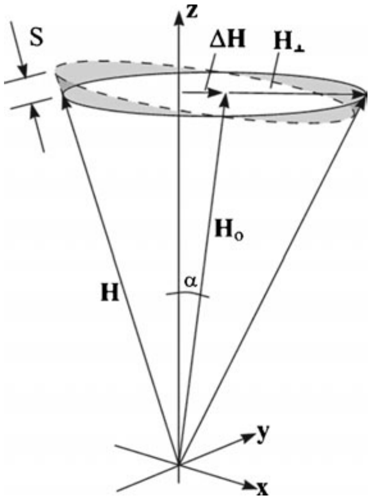

Figure 1. General principles of the vector variometer.

Figure 2. The variometer design.

In this case the magnetic sensor measures the scalar value of the total field $|\mathbf{H}| = \left(\mathbf{H}_0^2 + \mathbf{H}_\perp^2\right)^{1/2}$, the z-projection of the field being recalculated from this measurement. A block scheme of the device is shown in figure 3. In the 'scalar' part of the variometer (scalar magnetometer) the magnetic-field-dependent frequency is generated by a voltage-controlled oscillator (VCO), locked to the atomic resonance. Then in the 'vector' part of the variometer this VCO frequency is converted back to a voltage signal using a low-noise detector, out of which two phase quadrature detectors select the feedback signals for the x and y coils. The feedback currents which bring the field back towards the z-axis are proportional to the x and y components of the field variation. Special precautions were taken to maintain the relative phase between signals in the x and y channels strictly equal to 90° with maximal error of the order of 10^{-4} rad (see figure 3) to avoid cross-talk between channels.

Of course, in the case of non-zero compensation field the stability depends on the value of the compensation field and, strictly speaking, the component measurements lose their independence [9]. The ideal solution would be using servo control of the coil system orientation instead of compensation fields.

As can be seen from figure 1, in the case of small field projection changes ($|\Delta\mathbf{H}| \ll |\mathbf{H}_0|$), the signal amplitude can be estimated as

$$S = k\Delta H, \tag{1}$$

where

$$k = H_\perp \big/ \left(H_0^2 + H_\perp^2\right)^{1/2} \tag{2}$$

is the factor of conversion of transverse field changes to the scalar field oscillating signal. It means that the transverse sensitivity of the device increases with rotating field amplitude; unfortunately, this amplitude cannot be increased infinitely since it would drastically decrease both stability and sensitivity of the measurement of the z-component of the field.

Let us estimate the maximal value of k, which will not decrease the stability of the measurement of the z-component. A scalar potassium magnetic sensor is characterized by very good long-term stability of the order of 10–20 pT (rms) for one year measurements [10], which corresponds to the relative value of (2–4) × 10^{-7} in the mean magnetic field of the Earth. The stability of the component measurements is limited by the instability of the magnetic field in the transverse coils, which is principally determined by the thermal expansion

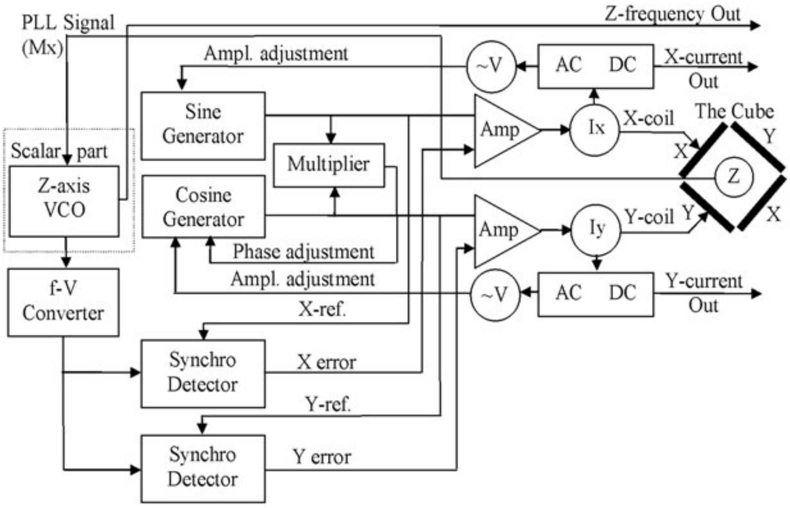

Figure 3. Block scheme of the K-variometer.

of the quartz base ($\mathrm{d}R/R/\mathrm{d}T \leqslant 2 \times 10^{-6}/^{\circ}\mathrm{C}$) mainly by current measurement accuracy (we estimate $\mathrm{d}I/I = 10^{-4}$–10^{-5}), so we will assume $\mathrm{d}H_{\perp}/H_{\perp} = 10^{-4}$–$10^{-5}$. Suppose that the transverse component variation of the Earth's magnetic field does not exceed 1000 nT, we obtain an estimation of the corresponding error $\mathrm{d}H_{\perp\max} = 0.01$–$0.1$ nT. The error in the measurement of the scalar value of the field $H_0 = \left(H^2 - H_{\perp}^2\right)^{1/2}$ can then be expressed as

$$\begin{aligned}\Delta H_0/H_0 &= \left(1\big/H_0^2\right)[(H\Delta H)^2 + (H_{\perp}\Delta H_{\perp})^2]^{1/2}\\ &\approx [(\Delta H/H)^2 + (k\Delta H_{\perp}/H)^2]^{1/2}.\end{aligned} \tag{3}$$

The first term in this expression $\Delta H/H = (2$–$4) \times 10^{-7}$. If we do not want the error caused by the drift of transverse component measurement to decrease our scalar stability more than, say, $\sqrt{2}$ times, we must choose $k\Delta H_{\perp}/H = k^2\Delta H_{\perp}/H_{\perp} \leqslant 2 \times 10^{-7} \Rightarrow k = \frac{1}{23}$–$\frac{1}{7}$.

In our case the rotating field amplitude was chosen to be $H_{\perp} = 5000$ nT, providing $k = 1/10$. So the total field intensity

$$H = \left(H_0^2 + H_{\perp}^2\right)^{1/2} \cong H_0 + (H_{\perp})^2/(2H_0) \cong H_0 + H_{\perp}/20. \tag{4}$$

Therefore the shift of the z-component is about 250 nT and the coefficient of conversion of the drifts of the transverse field $H_{\perp}$ to the drift of the total field H is $(\Delta H/\Delta H_{\perp}) \cong 0.05$.

As the stability of the variometer depends principally on the stability of the coil system, a cubic frame (~50 cm) of fused quartz tubes was chosen as a holder of the windings. Three equally spaced square coils (for each of two transverse directions) with 40, 22 and 40 turns of copper wire glued to quartz ribs of the frame provide a sufficiently uniform magnetic field at the centre of the frame where the spherical cell ∅50 mm is located. Stabilized phase-controlled sine and cosine currents at 362 Hz feed the coil system.

Even with all the precautions taken to stabilize the coil system, periodic calibration of the coil system is needed to provide base-line stability. This procedure does not require any external magnetometric equipment. It consists of several steps:

1. Equalization of the amplitudes of the ac fields produced by the X and Y coils; the equalization criterion is the absence of oscillations of the scalar field at the second harmonic of frequency f.
2. Measurements of the scalar value of the field and of the coil currents with rotating magnetic field on.
3. Measurement of the scalar value of the total field with rotating magnetic field off. To minimize the influence of the fluctuations of the Earth's magnetic field, steps 2 and 3 are repeated several times.
4. Calculation of the rotating field amplitude $H_{\perp}$ and the coil constants. As can be seen from (3), since we use a rotating field ~10 times smaller than the Earth's field, the total field intensity is $H \cong H_0 + H_{\perp}/20$. It means that we 'see' only 5% of the injected rotating field. It produces a corresponding decrease in the stability of the measurement of $H_{\perp}$ but does not reduce the accuracy of the reconstructed current value of H_0. We estimate the absolute accuracy of the total field measurement by the potassium sensor as about 0.1 nT, the sensitivity being much higher (~1 pT). However, the sensitivity of the measurement of the orthogonal components of the magnetic field is 10 times less. Their stability depends on their values, because they are extracted from currents in the corresponding coils. These currents should be measured with a relative accuracy better than 10^{-4}, which corresponds to errors as high as 0.1 nT at the limits of the full-scale change of the transverse component (±1000 nT).

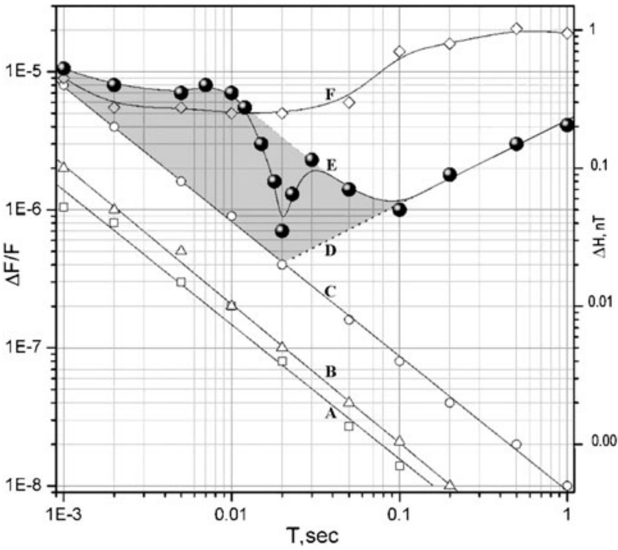

Figure 4. Allan variance of the K-magnetometer output in comparison with that of the reference generator and shot noise limited PLL: A—reference generator, B—PLL locked to the reference generator, C—PLL locked to the shot-noise limited signal, D—magnetic field variations at $T > 0.1$ s, E—K-magnetometer output in the real field and F—open PLL. The dip in the K-magnetometer noise reading at 0.02 s appears as a result of suppression of the 50 Hz ambient magnetic field component in the K-magnetometer electronics.

3. The results of the variometer test

The first result is that the general concept of the variometer has been proved to be working. Three feedback loops cooperate successfully, zeroing the transverse components with a time constant of about 0.1 s. The noise-limited sensitivity of the system is close to our calculations: about 1 pT rms at 0.2 s for the scalar measurement and about 25 pT rms for any component at 0.2 s (approximately corresponding to 1 Hz bandwidth).

As shown during the test procedures, the main factor limiting the sensitivity of the device (apart from the technical factors, such as VCO frequency noise) is the conversion of the spectral component of natural magnetic noise at frequency f to the measurement noise of the field transverse components. In other words, in order to achieve the ultimate sensitivity we must be sure that at time intervals corresponding to the period of the field modulation, the noise of the scalar magnetometer does not exceed the shot-noise limited level—otherwise it will be converted to the noise of transverse components with a conversion coefficient $1/k \approx 10$. Therefore we have made a series of investigations on the natural magnetic noise spectrum in comparison to the noise in our device and its components. Figure 4 shows the results of these investigations; the noise

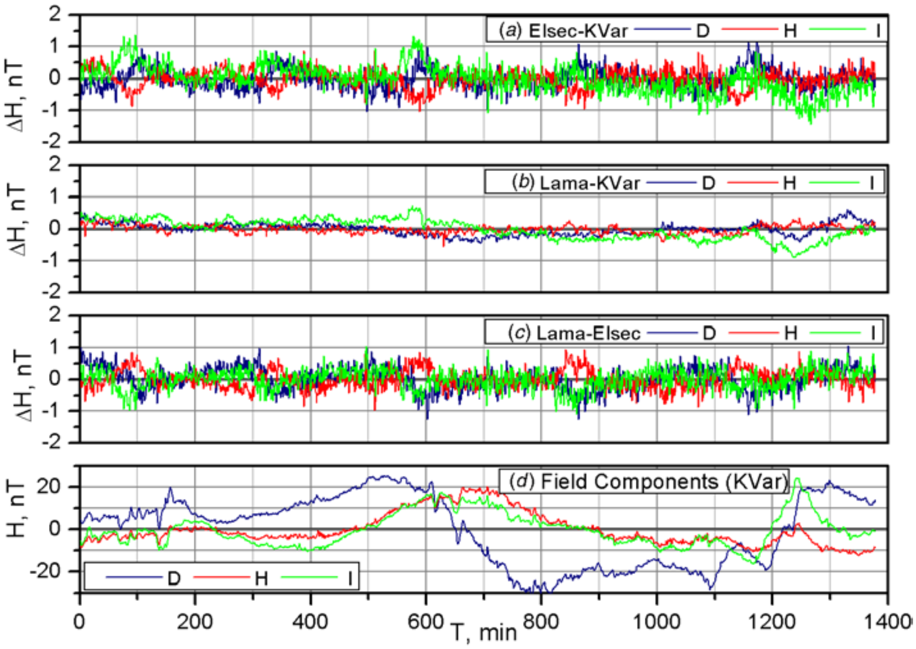

Figure 5. 24 h record, 1 December 1999. Reading differences between (*a*) Elsec8200 and K-variometer, (*b*) Lama fluxgate and K-variometer, (*c*) Lama fluxgate and Elsec8200 and (*d*) the Earth's magnetic field components measured by K-variometer. Notation here and after: D—field declination, I—field inclination, H—field scalar value; KVar—K-variometer, Elsec—Elsec8200 variometer, Lama—Lama fluxgate.

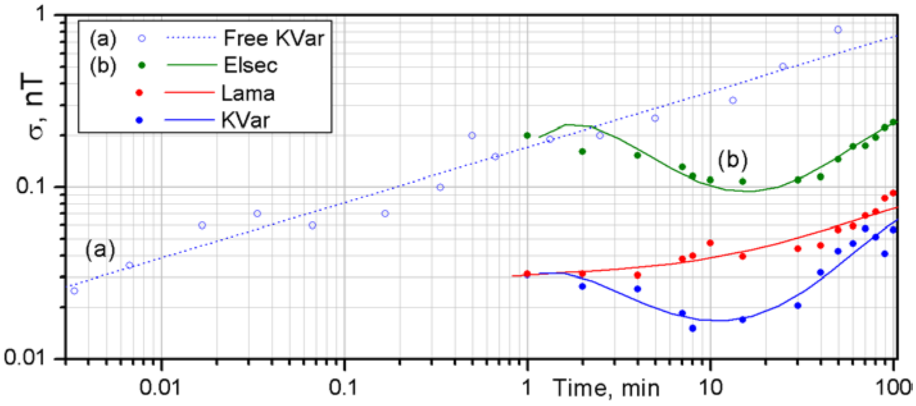

Figure 6. (a) Free KVar—Allan variance of stand-alone K-variometer readings in the Earth's magnetic field; (b) Allan variances of K-variometer, Elsec8200 and Lama fluxgate calculated from their reading differences (figure 5)-declination channel: KVar—K-variometer, Elsec—Elsec8200 variometer, Lama—Lama fluxgate.

of the K-magnetometer output (D, E) here is compared to the noise of A—reference generator, B—PLL locked to the reference generator instead of the real signal and C—PLL locked to the shot-noise limited signal from the reference generator. In the last case we used a special 'imitator of ideal signal' consisting of a LED and a low-noise stable current source; the LED current was modulated by the reference generator signal. The LED light intensity on the photodetector corresponded to that of real pumping light passing through the cell, and the modulation amplitude corresponded to that of the real signal. One can see that (1) the noise of the locked loop is negligibly small as compared to the shot-noise limit; (2) in time intervals from 1 ms to 100 ms the K-magnetometer noise level exceeds the shot-noise limit up to a factor 8 (corresponding to the area shown in grey on the plot) because of fast magnetic field fluctuations and (3) the VCO noise significantly exceeds the shot-noise limited level at times in excess of 1 ms.

Considering these results we had to increase the frequency f of the field rotation from 80 to 362 Hz in order to diminish the influence of the Earth's magnetic field noise. A further increase of f did not seem to be a good idea because of the risk of mixing Zeeman components of the K spectrum and distorting our working transition line ($F = 2m_{\mathrm{F}} = 1 \leftrightarrow F' = 2m_{\mathrm{F'}} = 2$) by its closest neighbour ($F = 2m_{\mathrm{F}} = 0 \leftrightarrow F' = 2m_{\mathrm{F'}} = 1$). In the Earth's magnetic field the distance between these transitions is just about 500 Hz. The exact value of the frequency f was chosen to be widely different from industrial frequencies and their harmonics set.

The device was tested in the Earth's magnetic field at the Magnetic Observatory of Dourbes, Institut Royal Météorologique de Belgique, without using any magnetic shields or stabilizers. The first tests of the device sensitivity were conducted under relatively quiet magnetic conditions without any external reference. As can be seen from figure 4(C), the intrinsic K-magnetometer noise is about 0.5 pT rms at 1 s, so we can expect (taking into account the 10× difference between K-magnetometer and transverse K-variometer sensitivities) the transverse sensitivity of the K-variometer 1 s to be about 5 pT. Furthermore, it can be deduced from figure 4 that at times longer than 0.1 s the natural magnetic field variations should exceed those of the K-variometer. Our records confirm this—in time intervals between 0.1 and 10 000 s the Allan variance of the Earth's magnetic field transverse components measured with K-variometer (figure 6(a) shows the same time dependence as in figure 4(E).

The time response of the device was measured to be 0.15 s. The sensitivity in the Hz-scale was estimated by directly recording the Earth's magnetic field transverse components with the K-variometer (the Allan variance of this record is shown in figure 6(a). The sensitivity measured on the quiet intervals where the magnetic field showed no drift was 25 pT rms at 0.2 s.

For the tests of noise and stability, a reference Lama fluxgate variometer was placed approximately 5 m away from the K-variometer to avoid field distortions created by the K-variometer coil system; a second reference variometer, Elsec8200 (based on a proton magnetometer), was situated approximately 50 m apart. The recording device had a digital resolution of 0.1 nT (1 s) and the readings were taken once a minute. The differences between the readings (a) Elsec8200 and K-variometer, (b) Lama fluxgate and K-variometer and (c) Lama fluxgate and Elsec8200 are shown in figure 5. The mean values of all the field components in figure 5 are subtracted, and the fluxgate readings are proportionally rescaled to minimize their difference from the readings of the Elsec8200. Timing error is removed from the readings of the Elsec8200. One can see that all three devices show good correspondence of their readings, though the Elsec8200 seems to have some higher level of noise at minute intervals than the Lama fluxgate and K-variometer—though this noise can also be attributed to the magnetic field gradient at 50 m.

Figure 6(b) shows Allan variances of all three devices calculated from the differences of their field declination readings, using the formula $\sigma_i^2 = \left(\sigma_{ij}^2 + \sigma_{ik}^2 - \sigma_{jk}^2\right)/2$ (i, j, k denote three independent devices) [11].

The differential daily drifts between any two devices do not exceed 1.5 nT. And the relatively low short-term noise of the fluxgate gives us the possibility of obtaining another independent estimation of the sensitivity of the K-variometer (still including the noise of the magnetic field gradient)—not worse than 30 pT rms at 1 min and 20 pT rms at 10 min (figures 5 and 6).

4. What is in prospect?

A new modification of the vector variometer is now being considered to make it more compact and cheap. The main idea is to restore the original project of the vector field stabilizer declared in [12]. The new model should be supplied with a third coil system to reduce the full field value. If the field intensity is chosen to be $\leqslant$10 000 nT, then a caesium cell could be used instead of a potassium one, because at such a weak magnetic field the magnetic resonance spectrum of caesium merges into a strong single line. The cell diameter can then be reduced to ∼∅30 mm and the quartz frame dimensions can be halved. The new device will produce less perturbation of the external field by its reduced rotating field, though still making some dc perturbation.

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