Low-noise magnetic observatory variometer with race-track sensors

M Janošek¹, V Petrucha¹ and M Vlk²
¹Czech Technical University in Prague, Technicka 2, 166 27 Prague, Czech Republic
²Institute of Geophysics, Bocni II/140, 141 31 Prague, Czech Republic

E-mail: janosem@fel.cvut.cz

Abstract. We present a low-noise, high-stability observatory magnetometer with race-track sensors, as developed by the Czech Technical University in Prague for National Observatory of Athens. As opposed to the standard instruments, we used our novel race-track fluxgate sensors with planar oval core which were cut by state-of-the art pico-second UV-laser. The noise performance of the complete electronics and sensor chain is below 6 pT/√Hz @ 1 Hz. The electronics uses 24-bit 200-Hz A/D converter with simultaneous sampling and all digital processing is done in FPGA. The variometer with the sensors mounted on a MACOR cube has been successfully calibrated by scalar method.

1. Introduction

The requirements on observatory variometers, as they are in service either officially in IAGA network, or for other purposes, are very demanding. It is necessary to achieve very high stability and low noise to record truly the diurnal Earth’s field variations and possible magnetic storms (the IAGA dynamic range requirement is ± 3000 nT). Standard full-field magnetometers can be used for this purpose, if their limited dynamic range (about 130 dB for 24-bit converters) is not a problem. However, if there is a requirement of achieving very low noise, i.e. < 20 pT/√Hz @ 1 Hz, compensation of the main Earth’s field components (horizontal and vertical in the northern hemisphere) is inevitable [1]. Such low noise variometer, if having suitable bandwidth, can be used for advanced ionospheric or geomagnetic studies (i.e. observing Schumann resonances and other effects). We have implemented a low noise compensation of the main field components, which allowed us to use our low-noise race-track sensors (< 6 pT/√Hz) in the variometer.

2. Magnetometer construction

For the variometer, we used in-house race-track fluxgate sensors with laser-cut cores, slightly modified and downscaled of the heritage CTU sensor [2]. Two of the sensors (N-S and vertical) have an additional coil wound, which is used for main field component offset in the respective direction. For that purpose, we have implemented an ultra-low-noise (< 0.5 pT/√Hz) current source using LTC6655 reference, which feeds the additional coil wound directly on top of the feedback coil of the sensor. In that manner, the possible mutual angular imperfections and mainly their temperature instabilities are minimized. The sensor triplet (each sensor dimension are approx. 30x8x1mm³) is mounted on a solid MACOR holder maintaining large thermal conductivity and geometric stability,
nevertheless, also the temperature of the holder is monitored – see Fig. 1. The sensor holder is attached to marble base plate, which is to be leveled. The “standard part” of the magnetometer electronics relies on a “standard low-noise magnetometer” manufactured by the CTU and CSRC (Czech Space Research Centre) company, it uses FPGA for signal clock generation and ADC driving and the power supply for the analog part is galvanically isolated. The electronics returns uncalibrated ADC data on RS232 for the three magnetometer axis and also the head temperature measurement. With the help of the low-noise current-source for the NS and vertical field offsets, the baseline noise due to electronics/ADC resolution is less than 1 pT/√Hz@ 1 Hz in the final variometer range of ±3750 nT.

Figure 1. The presented variometer – left: the triaxial race-track fluxgate triplet mounted on MACOR holder on marble base plate, right: the electronics (cover removed).

3. Variometer calibration

A non-trivial task is variometer calibration. We used following approach using scalar calibration technique [3, 4]:

- First, the offset fields have been disabled and the magnetometer has been operated in ±75000 nT range, and a scalar calibration was done. The calibration RMS error was < 2nT.
- After the calibration, the sense resistor (the magnetometer is feedback operated) was measured.
- The resistor has been replaced with 20x larger value (again precisely measured after soldering), and the gain coefficients have been recalculated.
- In this manner, we can use the scalar calibration results, which are comparable or superior to standard techniques utilizing coils and flux density standards [5].

Valuable information has been obtained in trial tests of the magnetometer (before range expansion) during 1-month testing at the Budkov observatory (IAGA BDV). As seen from table 1, we could see ageing of the sense resistors (Vishay PLT thick film series) – the values changed by 250-300 ppm after one-month burn-in. $T_c$ of the gain channels could be also computed: it was 8, 16 and 9 ppm/K, respectively which is a combination of thermal expansion of the compensating coil and sense resistors. From the table, it can be also seen that the mutual angular position was stable with temperature.

From the comparison of the total field computed from the variometer and values from standard instruments at the observatory, we can see that the gains have finally settled after 14 days (Figure 3).
Table 1 – The calibration results – after one month of running and with changed temperature.

| Calibration date | temp [°C] | S1 [normalized] | S2 [normalized] | S3 [normalized] | O1 [nT] | O2 [nT] | O3 [nT] | Φ1 [°] | Φ2 [°] | Φ3 [°] |
|------------------|----------|----------------|----------------|----------------|--------|--------|--------|--------|--------|--------|
| 14.12.2014       | 12       | 1.2996         | 1.3068         | 1.2935         | -18.77 | -189.59| 8.46   | 0.71   | -0.09  | 0.11   |
| 23.1.2015        | 19       | 1.2991         | 1.3064         | 1.2933         | -17.30 | -190.25| 7.95   | 0.72   | -0.08  | 0.08   |
| 23.1.2015        | 6        | 1.2989         | 1.3062         | 1.2931         | -18.22 | -197.94| 9.58   | 0.71   | -0.09  | 0.08   |

Fig. 3 – Instrument stability (before range expansion and with offsets off) – 14 days of total field (F) are displayed. Blue – CTU variometer, red and black – instruments of BDV observatory

4. Noise performance

Since the sensor head is too large to be tested in our in-house magnetic shield and also because of the need of creating a low-noise counter-acting magnetic field (simulating the NS and vertical Earth’s field component), we have decided to do this test in the calm magnetic field at the BDV observatory. Typical record is depicted in the spectrogram on Figure 4: it can be seen that even at the quiet locality, man-made AC noise is present in the low-frequency spectra. AC traction noise at 16 2/3 Hz from Austria / Germany railways is also visible as burst. The source of the 3 Hz noise is still unknown.

Fig. 4 – The 0.01-20 Hz spectrogram during 8-hours of logging (vertical axis)
If we have chosen a quiet part of the day, we were able to compute noise spectra as depicted in Fig.5: it can be seen, that in the vertical axis, the measured magnetic noise PSD was better than $6 \text{pT}/\sqrt{\text{Hz}} @ 1 \text{Hz}$; however the EW and NS axes were noisier which is presumably by the magnetic field noise at the locality since the sensors in the triplet perform equally well.

![Fig. 5 – The magnetic field noise at the BDV observatory as logged with the variometer.](image)

5. Conclusion

We have successfully built and calibrated a closed-loop operated, observatory variometer with race-track sensors. Its measured noise performance in real conditions of $< 6 \text{pT}/\sqrt{\text{Hz}} @ 1 \text{Hz}$ is up to our knowledge on the state of the art in the field. We have used a simple yet effective calibrating method to obtain the instrument parameters. Further improvements are sought in terms of fluxgate sensors performance with a target of $< 3 \text{pT}/\sqrt{\text{Hz}}$. In this case however, from our experience, a large shielded room and low-noise artificial magnetic field generator would be necessary to confirm the instrument performance.

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