VECTOR DC MAGNETOMETERS CALIBRATION ERROR

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Abstract: The calibration system for vector DC magnetometers of Nurmijarvi Geophysical Observatory (Finland) is described. It is based on a three axes reference coil system and Observatory reference magnetometer. It is shown experimentally that the system allows to determine calibrated magnetometer parameters with an error about 0.02%. One important error source -influence of non-collinearity of reference and calibrated magnetometer axes - is analyzed and value of this error is estimated. Also additional possibilities of the Observatory infrastructure are described: determination of temperature errors of magnetometer's sensor and electronics and long-term temporal drift study of up to 9 magnetometers simultaneously.

Keywords: magnetometer, calibration, axes collinearity, error.

1 INTRODUCTION

The DC magnetometers are widely used in different branches of activity - from precise scientific measurements to industrial applications. For all of them the certified magnetometers only have to be used. The calibration of flux-gate magnetometers is a complicated metrological task because of deficiency of standard reference of weak magnetic field with error as small as required - about 1 ppm. That is why the most convenient way to calibrate high-class DC magnetometer is to build a reference three-components coil system which creates in known volume the reference magnetic field of given amplitude with inhomogeneity of the order of 1 ppm. Other difficult problem is the compensation of the Earth's magnetic field, also existing in the calibrated volume. Magnetic shielding with the help of mumetal shields is not efficient here because it is rather impossible to decrease the Earth's field with such an arrangement down to the necessary threshold value - about 1 pT or even 0.1 pT. Also to make active compensation system of so high performance is though possible but rather expensive and complicated. The common way to cancel Earth's field influence is the measurement of this field by an independent reference magnetometer and subtracting of measured values from the output signal of calibrated magnetometer which is equal to the sum of Earth's magnetic field component and calibrating magnetic field along given magnetometer axis [1].

2 SYSTEM DESCRIPTION

A three axes coil system following the design by Alldred and Scollar [2] was built at the Nurmijarvi Geophysical Observatory in 1986 and was installed in a calibration room to its present site in 1990 [3]. The system consists of three sets of four square coils with diameter from 1.6 to 2.1 m. It can produce a uniform field with the error less than 10^{-5} in a volume of diameter of about 30 cm at the center of the system and a non-uniformity less than 10^{-4} should be reached in diameter of 40 cm. The aluminum frames of the coils are sitting on a 70 x 70 cm^2 top of a concrete pillars. There is a pillar made of glass bricks and a marble plate on the concrete basement which serve as a non-magnetic stable base for the tested instruments. The room is temperature stabilized and made of non-magnetic materials.

The orientation of the coils was of the first measured using the sun as a direction reference. With the help of a theodolite the X-axis was directed to the geographic North and the Y-axis to the East. The vertical Z-axis is positive down as the Earth's magnetic field is in the northern hemisphere. A final orientation was done by measuring the direction of the magnetic fields generated by the coils. This was done with the non-magnetic theodolite having a magnetic sensor connected to its telescope. With this method the non-orthogonality of the magnetic axes of all the coil couples was found to be less than 0.5 arc minutes.

The coil constants were measured by using a proton precession magnetometer in the center of the coils. The Earth's field of two of the three components were first compensated to a value close to zero.

Then large positive and negative fields were generated in the third component and the field in the center of the coils was measured by using the proton magnetometer. By this method the coil constants can be measured with an accuracy of 0.005 %.

A reference magnetometer, which is in the variation room about 100 meters apart, is connected to the system through a local area network, and is used to record the natural field variations during the calibration.

The current control is organized by three channel 18 bit digital to analog conversion of the desired current values to control the voltages on the inputs of the three current sources. An analog memory is used to maintain the input voltage between the control sequences. The currents are regulated until they meet their nominal values with deviation less than 0.03 mA what corresponds to 1 nT magnetic field in the centre of the coils.

The current is measured using three one-ohm precise resistors. Their temperature dependences between 20 and 30 deg. C were measured and the effect corrected. A fourth current measuring unit was installed in the system also. It is based on extremely precise current comparator and now it allows to measure the currents up to ± 3 A with accuracy better than 0.002%. This new current meter is used to calibrate three other meters. The voltage over the resistors as well as the voltage from the output of the tested magnetometer is measured by a 24 bit analog to digital converter.

The software for the calibration system uses the C language in LINUX environment. During the operation the computer display shows the desired currents, the measured currents, voltage output of the tested magnetometer and the Earth’s magnetic field as measured by the reference magnetometer. The usual time step between current regulations is 10 seconds, but can be also changed as desired.

The software has three main operation modes. In the manual mode the operator writes the current values one by one using the keyboard. This is mostly used for testing and calibrating the system itself. In the second mode an input file with current values is written in advance and the software runs this file. This allows to design special magnetic field configurations like a rotating field. With the third mode an automatic calibration can be done. The software asks for certain parameters like the maximum current or field and the number of measurements, and then it starts running the calibration. After execution all the measurements it calculates the results. This cycle can be repeated so that a file with measured data of arbitrary length is collected. Thereafter, the output file can be analyzed to get statistically reliable results and also to study possible temporal drifts in the data sets.

2 CALIBRATION EXAMPLE

The calibration system has been used to calibrate mostly flux-gate type magnetometers. Some torsion photoelectric magnetometers have also been tested. As an example the results of a calibration that was done for one Ukrainian flux-gate magnetometer of LEMI—004 model which was manufactured in the Lviv Centre of Space Research are given. The magnetometer has measuring range ± 5000 nT (with initial magnetic field compensation possibility in the limits of ± 120000 nT) and its noise level is less than 20 pT r.m.s. in frequency band from 0.01 to 1 Hz.

The automatic mode of calibration was used. The field values generated by the system were random between chosen limits. One calibration cycle consisted of 30 random field values generated every 10 second and the calibration result was calculated after every cycle. The calibration was running until about 10 cycles were measured. All the data were collected in a file and by using other program were analyzed to get the final results. During this test the whole calibration procedure was done three times by using different maximum field limits: ± 1000 nT, ± 2000 nT and ± 4000 nT.

Table 1. Results of three calibrations of the LEMI-004 magnetometer

Field limits (nT)	± 1000	±2000	±4000
Number of recordings	436	465	490
X transformation factor (nT/mV)	0.4928	0.4928	0.4928
Y transformation factor (nT/mV)	0.4949	0.4948	0.4949
Z transformation factor (nT/mV)	0.4971	0.4971	0.4971
Angle between X and Y (deg)	90.150	90.150	90.149
Angle between Y and Z (deg)	89.836	89.836	89.840
Angle between X and Z (deg)	89.899	89.898	89.896

The results show (Table 1) that the transformation factors of the magnetometer remain stable to the fourth digit and can be measured with about 0.02% accuracy. Orthogonality of sensors is seen from the angles between the sensors as they differ from 90 degrees. The fourth digit is stable again and therefore the error of the angle measurements is less than ± 0.5 arc minutes. The program gives also the orientation of the magnetometer sensors with respect to the coil axes. This allows calculation of an angle correction matrix which reduces data recorded by the magnetometer to the orthogonal co-ordinate system defined by the coil axis. If the magnetometer will be installed in a satellite or any other platform with known coordinates, this information can be utilized.

For this tested magnetometer the matrix is:

$$\begin{bmatrix} \mathrm{Cxx} & \mathrm{Cxy} & \mathrm{Cxz} \\ \mathrm{Cyx} & \mathrm{Cyy} & \mathrm{Cyz} \\ \mathrm{Czx} & \mathrm{Czy} & \mathrm{Czz} \end{bmatrix} = \begin{bmatrix} 0.998 & 0.066 & 0.001 \\ -0.069 & 0.998 & 0.02 \\ -0.002 & 0.001 & 1.000 \end{bmatrix}$$

Offsets of the magnetometer's components are important parameters as well. They can be measured inside a good magnetic screen if the sensors are small enough comparably to the volume of the screen. However, the coil system can be used to measure the offsets of all size of magnetometers. First, a zero field is generated and the magnetometer sensor is installed in the centre of the coils. Then the output of the magnetometer is read at first in this initial position and then after rotating all the sensors by 180 degrees. It was shown experimentally that when the Earth's magnetic field is not disturbed the accuracy of the method is about ± 1 nT.

The next important feature of the magnetometer is the drift of the readings with respect to temperature. The calibration room has a special wooden chamber standing on a pillar, which can be heated without heating the pillar. The tested sensor can be installed inside the chamber and the temperature can be increased and decreased in a controlled manner. The recording is compared with that of the observatory magnetometer, which is recorded in the special variation room with stabilized temperature. The test can be done separately also for the electronics unit of the magnetometer. By this method the temperature drift of the sensors of the LEMI-004 magnetometer was measured to be less than 0.2 nT/deg. C.

The calibration room has altogether nine pillars. Nine magnetometers can be operated simultaneously on the pillars, respectively. The room is good environment to compare the outputs of the magnetometers. The temperature is the same for all the instruments and the external field variations are also the same because their origins are in the ionosphere and magnetosphere. The room itself has been built from non-magnetic materials and the surrounding is free of magnetic disturbances. A good reference for the comparison recordings is the observatory magnetometer in the variation room.

3 ERROR ANALYSES

It is seen from the given example that in spite of that the reference field inhomogeneity can be made lower than 10 ppm in enough big volume and current amplitude measurements can be made better than 0.001% and the reference magnetometer of the system can provide measurements with accuracy ±1 nT or about 0.001% of the whole field value, the calibration accuracy does not allow to get error less than 0.02%. The analysis of error sources shows that one of possible cause may be the unknown residual angle between the axes of reference and calibrated magnetometers, which should be collinear. Let us analyze possible influence of this error source.

Let two magnetometers - reference and calibrated ones - have axes X_i, X_i' (*i* = 1,2,3) (Fig. 1). The angles α_i determine mutual orientation (collinearity) errors of both magnetometer axes.

$$\left.\begin{aligned} &\sin\Theta(t)\cos\varphi(t)\,0.5\alpha_1^2 << \Delta H_{n,1}\left|\vec{H}_T\right|^{-1}, \\ &\sin\Theta(t)\sin\varphi(t)0.5\alpha_2^2 << \Delta H_{n,2}\left|\vec{H}_T\right|^{-1}, \\ &\cos\Theta(t)\,0.5\alpha_3^2 << \Delta H_{n,3}\left|\vec{H}_T\right|^{-1}, \end{aligned}\right\} \quad (1)$$

where Θ, φ are angles between Earth's magnetic field vector and reference magnetometer axes, $\Delta\vec{H}_T$ - maximum Earth's magnetic field vector beviation, $\Delta H_{n,i}$ - admissible deviation between *i*-component readings of reference and calibrated magnetometers.

The upper numeric estimation of the error introduced by non-collinearity of axes of both magnetometers in the case of random orientation of these axes relatively to $\vec{H}_T$ vector gives the following value. Let us take for estimation $\Theta = \varphi = 45°$(in this case cos Θ (or φ) = sin Θ (or φ) ≈ 1). Then

$$\left.\begin{aligned}\alpha_1 &<< 2(\Delta H_{n,1}|\vec{H}_T|^{-1})^{0.5},\\ \alpha_2 &<< 2(\Delta H_{n,2}|\vec{H}_T|^{-1})^{0.5},\\ \alpha_3 &<< (2^{1.5}\Delta H_{n,3}|\vec{H}_T|^{-1})^{0.5},\end{aligned}\right\} \qquad (2)$$

and substituting $\Delta H_T=2\cdot 10^3$ nT and $\Delta H\approx(0.1\text{-}1)$ nT we get from (2) $\alpha_i \approx (5\text{-}15)'$.

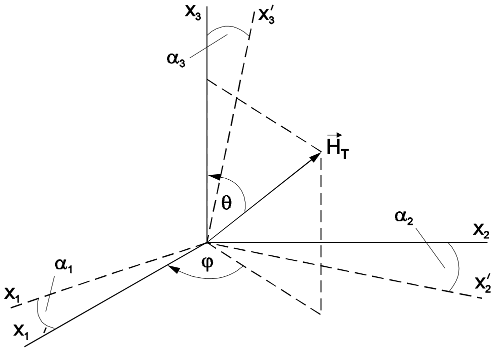

Fig. 1. Mutual orientation of reference and calibrated magnetometers axes

It is certain that such collinearity error can not be achieved, what requires further problem study in order to compensate the error introduced in calibration data.

4 CONCLUSION

A system for calibrating and testing DC field magnetometers built in the Nurmijarvi Geophysical Observatory in Finland allows measuring the following parameters:

1. Transformation factors of the sensors in the range ± 100 000 nT.
2. Linearities of the sensors in the range ± 100 000 nT.
3. Angles between the sensors.
4. Angles between the sensors and the geographic directions.
5. Correction matrix for the sensor direction errors.
6. Temperature drift separately for the sensor and the electronics.
7. Long term stability.
8. Simultaneous comparison of up to 9 magnetometers.

Computer control improved the accuracy of the system and its efficiency and flexibility. Fast calculation of the angle error enables fast adjusting of the sensor axes directions during assembling and tuning. Rotating and other special fields can be generated. Presently, the system is extended for measuring the magnetic cleanliness of satellites and other instruments. Further improvement of its parameters and calibration data processing methodology is under progress and will allow diminishing available calibration errors.

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