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MEASUREMENT OF THE TEMPERATURE DEPENDENCE OF THE SENSITIVITY AND ORTHOGONALITY OF A TRIAXIAL VECTOR MAGNETOMETER

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The temperature dependence of the sensitivity and orthogonality of a tri-axial vector magnetometer is measured with the use of a dedicated thermostatic system and a non-magnetic positioning platform. The dependency is obtained from the results of repeated scalar calibrations for different temperatures.

Keywords: magnetometer calibration, scalar calibration, sensitivity and orthogonality temperature dependence

1 INTRODUCTION

Sensitivity and orthogonality temperature dependences are basic parameters which characterize a vector magnetometer. Strict values of these parameters are required for applications that experience a wide range of temperatures (*eg* space exploration, underground drilling). The temperature dependence of the sensitivity depends on the properties of the sensor and on the stability of the signal processing electronics. Sensor sensitivity is usually defined by the constant of the compensation coil. The stability of the compensation coil constant depends on the support material and technology of the winding. The temperature dependence of the sensitivity can be measured with the use of a single or multiple-axis coil system equipped with a thermostatic box. There are strong requirements on the electrical and mechanical stability of the whole system if small sensitivity variation values are expected.

The orthogonality and the temperature stability of the orthogonality depend mainly on the mechanical design of the sensor and on the materials that are used. A vector coil system is used to measure the orthogonality. Alternatively, it is possible to employ a different approach which uses precise mechanical construction allowing rotations by exact angles. High preciseness of the system is again required if small angles are to be measured. This paper suggests the use of a scalar calibration technique with additional accessories to make precise measurements of the parameters mentioned above. The method is fast, reliable and, with some limitations, can use fairly inexpensive equipment.

2 SCALAR CALIBRATION

Scalar calibration is a well-known method that obtains nine intrinsic parameters which characterize a vector sensor of a magnetic field (*ie* three sensitivities, three orthogonalities and three offsets). The method uses data collection and mathematical processing of samples measured by the DUT (Device Under Test) to evaluate the parameters. A good introduction is given in Merayo [1]. A typical dataset consists of a couple of tens or hundreds of measured vectors. A greater number of samples can provide higher precision but some short-term drifts can negatively influence the processing if the data acquisition takes too long. The DUT should ideally measure a stable and homogenous field, *eg* the Earth's magnetic field. It should be noted that the method works the same for accelerometers, where the Earth's gravity field is sampled.

Specific additional equipment has been proposed in [2] in order to make the scalar calibration procedure easier and more convenient to conduct. An almost completely non-magnetic computer-controllable platform is used to rotate the DUT in such a way that a required set of samples is automatically measured. The advantage with respect to random "hand-driven" motion lies in the perfect uniformity of the acquired samples. The speed and repeatability of the measurement is also very good.

3 EXPERIMENTAL SETUP

A simplified block diagram of the whole system is shown in Fig. 1.

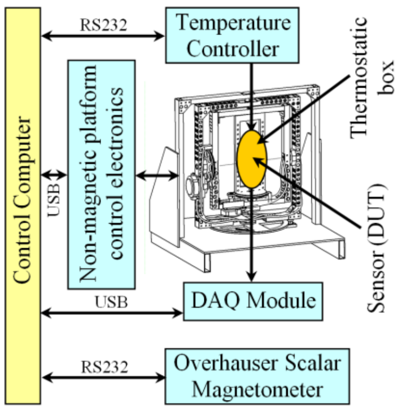

Fig. 1 Block diagram of the system for calibrating the temperature dependencies of sensitivity and orthogonality

The design has been customized to accommodate a vectorially-compensated vector fluxgate magnetometer. For

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details, see [3]. The sensor is a cuboid with dimensions of 48 x 40 x 40 mm. The expected working temperature range of the sensor is from -50°C to +100°C. During the measurement, the sensor is fixed in the center of the non-magnetic calibration platform. The fixation is provided by two heater plates, see Fig.2. The heater plates were developed in order to provide excellent magnetic cleanliness and sufficient power to maintain the desired temperature range. The base of the heater (a) is a plate milled from a standard 2mm thick FR4 PCB material. The second plate (b) is a thin copper plate (0.5 mm), which helps to eliminate temperature gradients. The heating element itself (c) is a double layered Kapton-based PCB with a bifilar meander track. On the sensor side, there is another 2mm thick copper plate (d) that helps to minimize the temperature gradients along the surface of the heater.

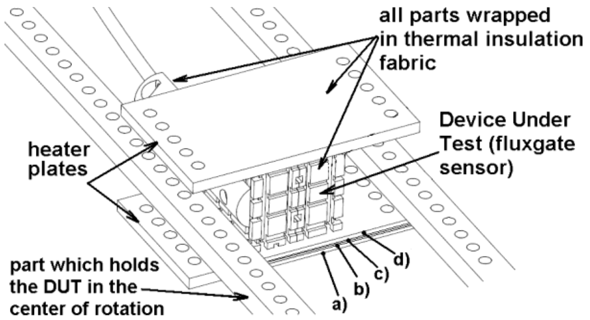

Fig. 2 The measured sensor is fixed by the heating plates and protected by thermal insulation

All the parts are fixed together by screws, and by a thermally conductive paste which was applied between the copper plates and the Kapton heating element. Experience now suggests the use of a double-layered heating element, but with the heating trace etched only on one side. The second side should be left untouched to improve the thermal conditions and simplify the construction. The sensor and heater plate assembly is protected by multi-layered thermal insulation made of PTFE-coated fabrics. The heater plates were supplied with current, and the temperature was controlled by a standard commercial temperature regulator (CoolTronic TC3215). The temperature sensing element was a PT1000 sensor, which is embedded close to the center of the fluxgate sensor. The absolute reference for the magnetic measurements was provided by a scalar Overhauser magnetometer (Gemsys GSM-19). The scalar magnetometer was placed approximately 20 meters away from the calibration platform. It provides the absolute reference for the calibration algorithm and compensates for the variations in the magnitude of the Earth's magnetic field during data acquisition. All the parts were controlled by a laptop computer with custom software equipment through multiple RS232 ports.

4 MEASUREMENTS

Two identical fluxgate sensors were used for the measurements. Two scalar calibrations were performed for each temperature. Sensor 1 was measured for two different temperatures, sensor 2 for three different temperatures.

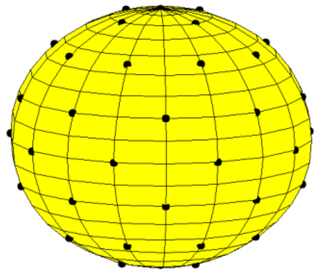

Fig. 3 The 55 measured vectors (black dots) uniformly cover the virtual sphere with a radius equal to the Earth's field magnitude

This gives ten scalar calibrations in total. The number of calibrations was limited by the available time. Although the number is not ideal, it provides a sufficient amount of information about the desired parameters. Each dataset was composed of 55 identical vectors (see Fig. 3), and it took approximately 5 minutes to collect each dataset. Much more time was needed between the measurements (20-40 minutes) in order to stabilize the temperature in the whole volume of the sensor. Due to some software problems with the heater control, the heating was switched completely off during the 5-minute calibration cycle. This means that there was a slight variation in the sensor temperature and probably also some thermal gradient in the volume of the sensor. It was originally expected that the heater would be switched off only during the period needed to take each sample (two seconds for output stabilization and one second for data acquisition) and that it would maintain a constant sensor temperature while the platform was being positioned.

5 RESULTS & DISCUSSION

The results are presented as graphs showing the temperature dependence of each parameter. All the measured values are plotted, together with a linear approximation of the dependency. The graphs can also be used to compare absolute values of the parameters for Sensor 1 and Sensor 2, see Figs. 4 and 5. The temperature dependencies are summarized in Table 1.

The main construction material of the fluxgate sensor is PEEK GF30 (PolyEtherEtherKetone with 30% of glass filling). The manufacturer specifies the coefficient of linear thermal expansion as follows: an average value between 23 and 150°C is 30 ppm, an average value over 150°C is 65 ppm. The compensation coil windings are made of copper, which has a coefficient of linear thermal expansion of 17 ppm. So the final sensitivity of the compensation coil constant to temperature changes is given by a combination of the two values. The winding technique (*ie* the initial tension) can influence the result. An average value for the measured temperature dependencies is 37

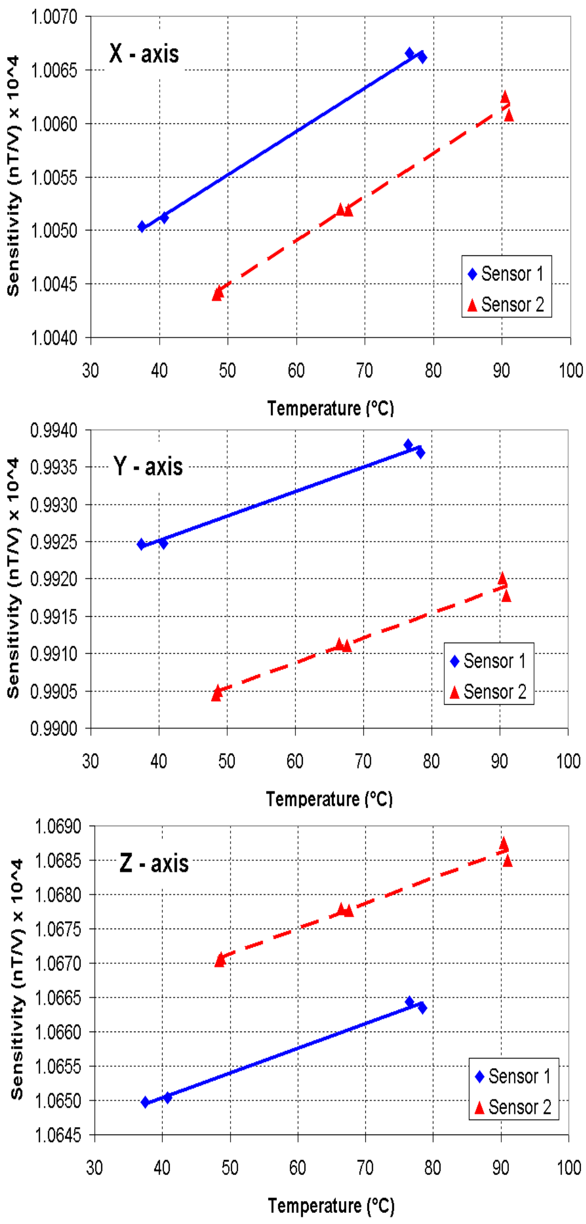

Fig. 4 Temperature dependence of sensitivity for Sensors 1 and 2

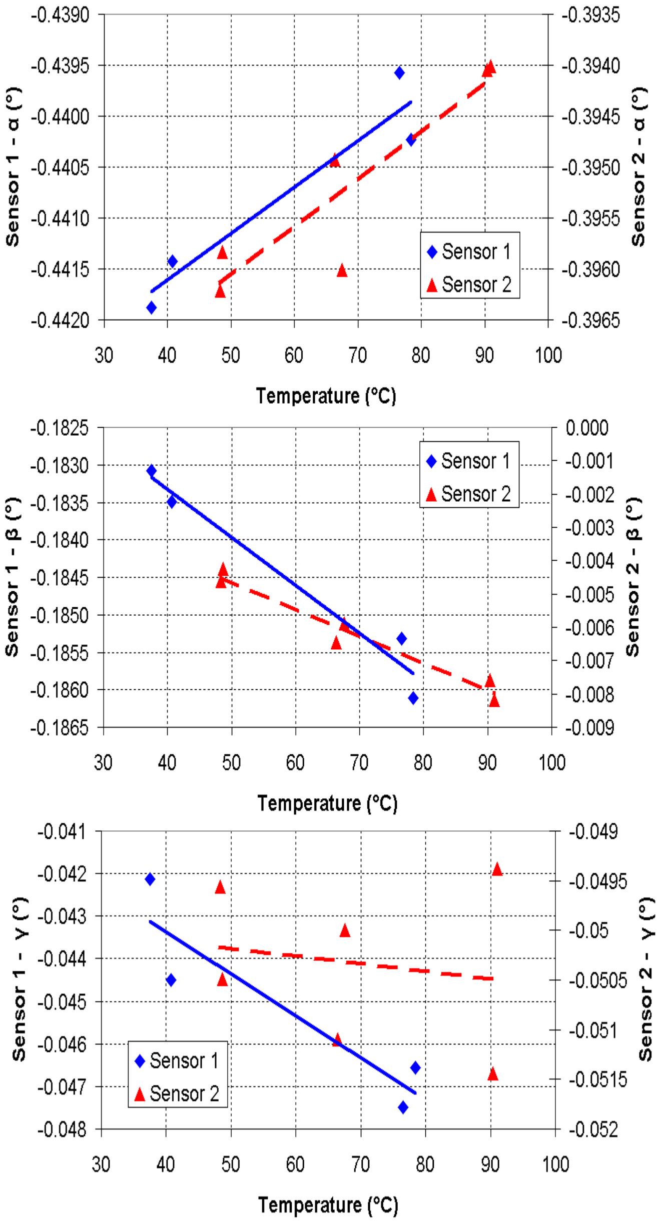

Fig. 5 Temperature dependence of orthogonality 2 for Sensors 1 and

ppm, which is in good agreement with the expected result. The different values for each axis could depend on the mechanical design of the compensation coil system (*eg* non-symmetry).

The orthogonalities were expected to have small and rather random dependency, but actually the measured values indicate relatively strong and quite precisely defined temperature sensitivity. This sensitivity is probably due to the mechanically asymmetrical design of the sensor, which is caused by manufacturing issues.

The scalar calibration also provides information about the offsets. The measured offset temperature coefficients range from 0.03 nT/°C to 0.3 nT/°C. In most cases, they correspond well to values measured by an alternative method (*ie* measurement in a multi-layered magnetic shielding equipped with a thermostatic box).

Tab. 1. Summary of all measured parameters.

Parameter temp. dep.	Sensor 1	Sensor 2
$SENS_X$ (ppm/°C)	+41	+41
$SENS_Y$ (ppm/°C)	+33	+34
$SENS_Z$ (ppm/°C)	+36	+37
Orthog. – α (arcsec/°C)	+0.18	+0.17
Orthog. – β (arcsec/°C)	-0.25	-0.29
Orthog. – γ (arcsec/°C)	-0.38	-0.02

We expect that the matching between the alternative methods will be improved when the temperature of the sensor is better stabilized during scalar calibration. Currently, there was a difference in the sensor temperature ranging from 0.3 to 6.2°C between the beginning and the end of the 5-minute calibration period. An average value of the temperature was plotted into the graphs. The aim is to maintain the temperature within ±0.1°C in the sensor area, and thus to eliminate the temperature gradient in the sensor body below ±1°C.

5 CONCLUSIONS

The results obtained with the use of the system described here correspond well to the expected theoretical values in the case of sensitivities. There is good agreement between alternative measurement methods in the case of offsets, and there is valuable new information concerning the temperature dependency of orthogonality. The average measured temperature sensitivity dependence value of 37 ppm/°C is unfortunately above the value that is required for high-precision instruments (~10 ppm/°C). A possible way to improve the values is by changing the main construction material for the sensor. The precision and accuracy achieved with the current system should be satisfactory for measurements made with the improved sensor.

The main way to improve the system now is by extending the operating temperature range. The upper value ~100°C is limited by the construction materials. The lower temperature limit could be extended simply by applying dry ice (solid carbon dioxide) to the thermostat. In this way, a measurement point at approximately -70 °C could be achieved.

Although quite complex and expensive equipment was used during the measurements, the setup can be greatly simplified. The positioning platform can be made “hand-driven”, and the absence of the Overhauser scalar magnetometer will only slightly reduce the performance. The heating plates can be replaced by a non-magnetic heating wire wound around the sensor. Of course, the overall precision and comfort of operation will be reduced, but the results can still be well usable in practical applications.

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