COMPACT FULL-TENSOR FLUXGATE GRADIOMETER

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Using full-tensor gradiometers has various advantages over simplified uniaxial gradiometers or even scalar measurements. The full-tensor information is used mainly in geophysical prospecting and in security/military applications. Usually, three or more tri-axial probes are combined for the full-tensor measurement. However, in our new design we combined 10 small (20-mm) fluxgate sensors operating in feedback compensated mode into one compact head in the form of 46-mm cube. The sensors are multiplexed in order to save on electronics complexity and power consumption.

Keywords: gradiometer, full-tensor, fluxgate

1 INTRODUCTION

The primary advantage of using magnetic gradient measurement is in the effective suppression of background field and common mode noise and focusing on local magnetic anomalies of interest. In the simplest form, scalar measurements (*eg* from proton magnetometers) can be combined into gradient reading. More advanced designs utilize combination of axial sensors (typically in coaxial arrangement) like coils or fluxgates to acquire gradient along one axis. Additional factors become important in these cases, namely angular misalignement between the two individual sensors, gradiometric base and noise of the individual sensors. Rather rarely, intrinsically gradiometric designs are utilized, *eg* fluxgate sensor with combined homogeneous and gradient outputs [1], [2]. Typically, readings from two separate sensors are subtracted - either in electronics or in software - and the differential reading is used as the gradient estimate.

In any case, sensor spacing is critical for the quality of the gradient measurement. Ideally, the gradient would be measured as point-defined quantity, in accord with the pure mathematical definition. However, this is not practically possible and sensor size becomes one of the limiting factors. The smallest gradient base permitted by noise level should be used in order to measure the gradient precisely. The influence of the sensor size is discussed *eg* in [3].

The advantage of a tensor gradiometer over axial gradiometers or even "scalar gradiometer" is that the tensor components can be used in an inversion task not only to calculate the distance to a magnetic dipole, but also its strength and its location. Therefore full-tensor information is used mainly in geophysical prospecting and in security/military applications [4], [5], [6].

A standard approach for creating tensor gradiometer would be to use three or more triaxial sensor heads, however to decrease the gradiometer head size we decided to arrange 10 fluxgate sensors to one gradiometer head directly. The 20-mm size of our recently developed race-track sensors allowed the gradiometer head to be miniaturized – its size is 46×46×46 mm^3 (Fig. 1).

Fig. 1. The gradiometer head

As opposed to the solution presented in [7], all sensors in the gradiometer are feedback compensated (Fig. 2).

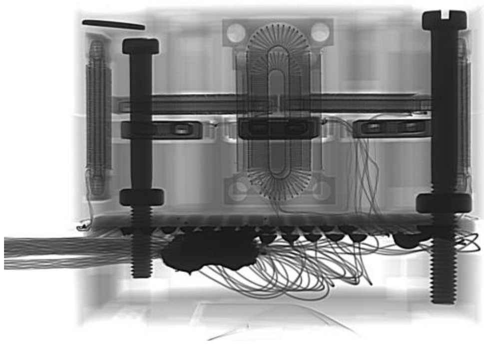

Fig. 2. X-ray picture showing the head structure

To avoid mutual influencing of the sensors, we have proposed a method of multiplexed reading of the ten sensors: at one time, only three orthogonal sensors are connected to standard triaxial magnetometer electronics. In this manner, during several sequences, complete information about the gradient tensor is obtained. This brings three important benefits over other solutions:

- Sensor stability – effect of the feedback compensated loop
- Low power consumption and complexity – only triaxial electronics is needed

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- Minimum mutual influencing of the sensors – only one orthogonal triplet is active at one time.

2 THEORY

The full tensor of magnetic (first order) gradient is described by a 3x3 matrix of individual components:

$$\nabla \boldsymbol{B} = \boldsymbol{G} = \begin{bmatrix} \frac{\partial B_x}{\partial x} & \frac{\partial B_x}{\partial y} & \frac{\partial B_x}{\partial z} \\ \frac{\partial B_y}{\partial x} & \frac{\partial B_y}{\partial y} & \frac{\partial B_y}{\partial z} \\ \frac{\partial B_z}{\partial x} & \frac{\partial B_z}{\partial y} & \frac{\partial B_z}{\partial z} \end{bmatrix} \qquad (1)$$

However, not all of these components are mutually independent. We can normally assume that the gradient matrix has off-diagonal symmetry ($\partial B_i/\partial_j = \partial B_j/\partial_i$). Furthermore, from Maxwell equation $\nabla \cdot \boldsymbol{B} = 0$ we can assume

$$\frac{\partial B_x}{\partial x} + \frac{\partial B_y}{\partial y} + \frac{\partial B_z}{\partial z} = 0 \qquad (2)$$

further reducing the number of free parameters. Thus the gradient tensor has only 5 independent components.

Practically, the gradient is estimated from differential measurement of field in two points of space, *eg*

$$\frac{\partial B_x}{\partial x} = \lim_{d \to 0} \frac{B_{X1} - B_{X2}}{(x_1 - x_2)} \cong \frac{B_{X1} - B_{X2}}{d} = \frac{\Delta B_x}{\Delta x} \qquad (3)$$

The gradiometric base *d* clearly influences the estimate of the magnetic gradient, especially for magnetic field with higher order spatial derivates. For a magnetic dipole, it can be stated that the error in gradient estimation will be < 10% for distance from source $z > 3d$ [8]. This emphasizes the need for small gradiometric base in a practical device.

In our design, the individual components of the full-tensor gradient are determined from field measurements by 10 small (overall size 20-mm) fluxgate sensors - see Fig. 3, (also compare with Fig. 1, Fig. 2). The gradiometric base is 20, 27 and 41-mm, respectively in this case.

From the individual sensor readings, various components of the full-tensor gradient are obtained using electronics as shown in Fig. 4. Note that not all mutual combinations of individual sensor readings are required.

Also note the multiplexing stage that facilitates two conflicting features of the gradiometer. On one hand side, feedback loop compensation can be active during measurement, thus providing better sensor stability.

On the other side, only a subset of mutually orthogonal sensors are active at any moment, preventing disturbing of one sensor by another one's feedback field. (Of course, the use of multiplexing limits the overall bandwidth of the device – the switching speed was about 1 Hz, but the bandwidth was 200 Hz). The multiplexer controller also supplied an analog signal, identifying the currently active sensor triplet

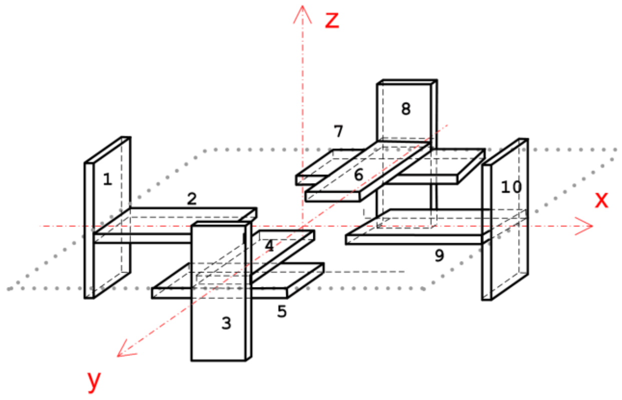

Fig. 3. The individual sensors in the gradiometer head

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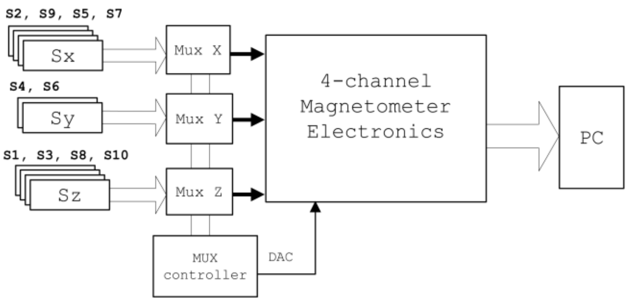

Fig. 4. The use of individual field sensors for full-tensor gradient estimation

3 EXPERIMENTS

The gradiometer was calibrated at magnetically calm facility at Budkov geomagnetic observatory (Intermagnet: BDV) located in southern Bohemia, Czech Republic. Experimentally, it was verified that the gradient in the observatory building (used for absolute measurements) is less than 5 nT/m. The approach of multiple scalar calibrations was used, similar to that presented in [9]. The triplets, required to obtain the five independent components, are defined in Tab. 1.

Noise of the gradiometer was measured in a 6-layer permalloy shield: we have found that the vertically oriented sensors were influenced by the smaller shielding factor in that direction, so the noise was higher in these cases – see Fig. 6. The noise was about 1.5 nT/m/√Hz @ 1Hz, the components with smaller gradiometric base and/or in the orientation with smaller shielding factor experienced noise about 2-3 times larger. It would be more suitable to measure in a large shielded room or even using a magnetically quiet part of a day at magnetic observatory which will be sought in the future development of the instrument.

Tab. 1

G_{ij} / G-base	G from	Cal X	Cal Y	Cal Z
G_{xx} 20 mm	2-9	1	6	2/9
G_{yy} 20 mm	4-6	1	9	4/6
G_{xy} 27 mm	5-7	1	4	5/7
G_{zx} 41 mm	1-10	4	2	1/10
G_{zy} 41 mm	3-8	4	9	3/8

After multiple scalar calibrations, using the triplets above (only the last sensor in the triplet is changed in the two scalar calibrations at all times to keep the same orthogonal frame), the residual error could be decreased below ± 10 nT/m – see Fig. 5.

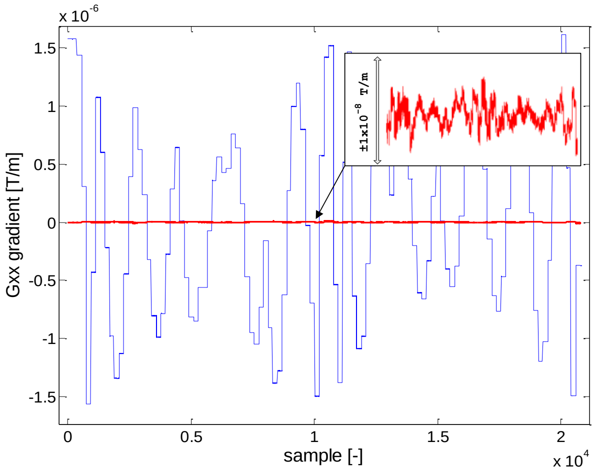

Fig. 5. Raw (blue) and astatized (red) gradiometer output – G_{xx} component during calibration sequence

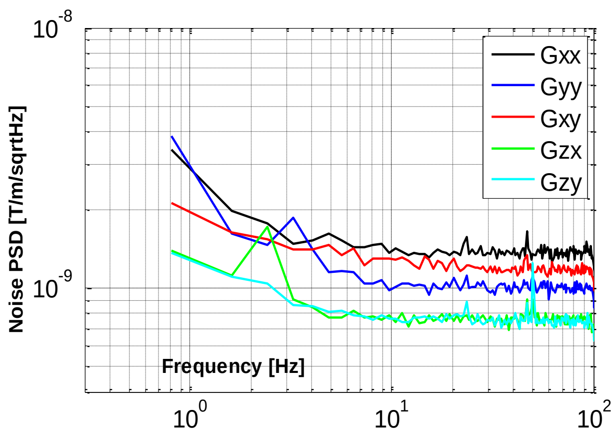

Fig. 6. Gradiometer noise

4 CONCLUSIONS

We have presented a compact, 46×46×46 mm^3 full-tensor magnetic gradiometer with fluxgate sensors exhibiting noise about 1-2 nT/m/√Hz @ 1 Hz. Thanks to feedback-loop compensation of the fluxgate sensors, the gradiometer calibration could be determined by scalar calibration, avoiding the inherent difficulty of obtaining transverse gradients for calibration [7]. Feedback compensation also improves gradiometer stability and the use of closed-core race-track sensors assures very low offsets – they are below 20 nT in all axes. Moreover, the multiplexed feedback-loop design of the gradiometer relies on standard triaxial magnetometer electronics, thus saving power – the overall instrument power consumption was about 2.8 W.

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