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A QUASI ABSOLUTE OPTICALLY PUMPED MAGNETOMETER FOR THE PERMANENT RECORDING OF THE EARTH'S MAGNETIC FIELD VECTOR (OPC)

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ABSTRACT

Despite the advance of technology, the fully automatic recording of absolute magnetic field vector variation at observatories remains an elusive goal. Primary difficulties are the long term stability of sensor orientation and the stable operation of the sensor system. In standard practice, definitive data are produced through the combination of continuous operation of a variometer and the occasional absolute measurements that are used for calibration of the variometer data. A single, automatic instrument that can continuously acquire absolute vector measurements with 1-second resolution is desired. We introduce a device that will fulfil these requirements. Data are acquired using Serson's method: the ambient magnetic field is modulated by superposed fields. This method has been applied, mostly in connection with Proton magnetometers, for many years. In general it requires that the applied fields have a strength on the order of the Earth's magnetic field. But the sampling rate is limited for most existing systems. In contrast, our system only requires applied fields of about 5000nT, and the switching rate of polarities is 5Hz. This is possible because we use a fast self oscillating Cs-magnetometer. The self oscillating Cs-magnetometer is calibrated by a Cs-He cell during times without additional fields (tandem-magnetometer).

Keywords: Earth's magnetic field measurements, Vector magnetometer, Optical controlled alignment

1 INTRODUCTION

The absolute measurements for the orientation of the field vector are nowadays manually performed by means of a DI-flux consisting of an iron free theodolite and a one axial fluxgate magnetometer mounted on the telescope. The theodolite serves to determine the coordinate system (horizontal plane, azimuth). The results of the full measurement are the declination angle, the inclination angle, and the total intensity from a scalar magnetometer at a definite time. The measurement procedure includes the determination of all systematic errors, but the quality of the measurement results depends strongly on the experience of the observer and the accuracy in performing the procedure (Jankowski & Sucksdorff, 1996). Regular absolute measurements are difficult to realize in remote areas due to the lack of manpower. Therefore it is desirable to develop fully automated instruments, which do not require manual operations. This is the prerequisite to fill the gaps in the global geomagnetic observatory network in remote areas.

At the Niemegk observatory, two different types of instruments were developed in parallel to address this challenge. One instrument should replace the DI-flux. The automated instrument GAUSS was introduced for the first time at the XIIth IAGA Workshop on Geomagnetic Observatories Instruments, Data Acquisition and Processing, in Belsk (Poland), in June 2006 (Auster et al., 2006). The second prototype of this instrument has been in operation without interruption since April 2008 (Hemshorn & Pulz, 2008).

Moreover, high time resolution (1 second means) and field resolution data are requested from observatories in complementation to the modern satellite magnetic data. DIdD magnetometers recording the field components by means of coil systems around proton magnetometers have been in use for several years. An improvement was obtained by the introduction of the Overhauser Effect Proton magnetometers in connection with suspended coils (Hegymegy, 2005). However, still only the recordings of total intensity are absolute in these instruments. The instability of the coil orientation remains a problem. The second type of instrument, that we are developing and which is described in this paper, aims at fulfilling the requirement of continuous (quasi-) absolute recordings. The instrument consists of a Cs, He-Cs sensor with a coil system that is optically controlled for orientation. It delivers every second a complete set of the Earth's magnetic components.

2 THE MAGNETOMETER

A Cs, Cs-He tandem magnetometer (Blinov et al., 1984; Kuleshov et al., 1994) was selected for the new instrument. Our experiences gained from developing and manufacturing the Potassium-tandem magnetometers in the nineties (Pulz, Jäckel, & Linthe, 1999) were used to build up a magnetometer with very fast response and high resolution in field measurements as well as in time. The theoretical accuracy of this instrument is about 0.1nT. Our first Cs,Cs-He magnetometer was compared with our potassium magnetometers over more than 10 years, and it was found out that the actual accuracy is even better. Apart from accuracy and resolution, low noise is very important.

The magnetic field signal T of the magnetometer is a frequency f with a strictly linear dependence and contains only atom physical constants:

$$T\ [\mathrm{nT}] = f\,[\mathrm{Hz}]\ /28.0236888.$$

3 THE MEASURING METHOD

In Serson's method (Jankowski & Sucksdorff, 1996; Serson, 1962), an additional field is added to the component to be measured. The coil axis is aligned with the direction of the component. Three measurements are necessary to determine the field strength in the direction of the coil axis: one without bias fields and two in both polarities.

The aim is to produce a complete set of magnetic field values every second. A set of two coils is necessary to obtain the full vector, with two measurements in each direction of coil axis and one measurement without bias fields. That means 5 measurements per second are needed. Therefore, there are 200ms for each reading. Additionally one must take into account that it takes time to read out the frequency counter and the time that the coil current takes to overcome the mutual induction. The frequency measurement time per reading therefore is 180ms. This time period is a multiple of 50Hz so that we always have a full period of our European main power at each reading. This acts like a filter. The sequence of operation is shown in Figure 1.

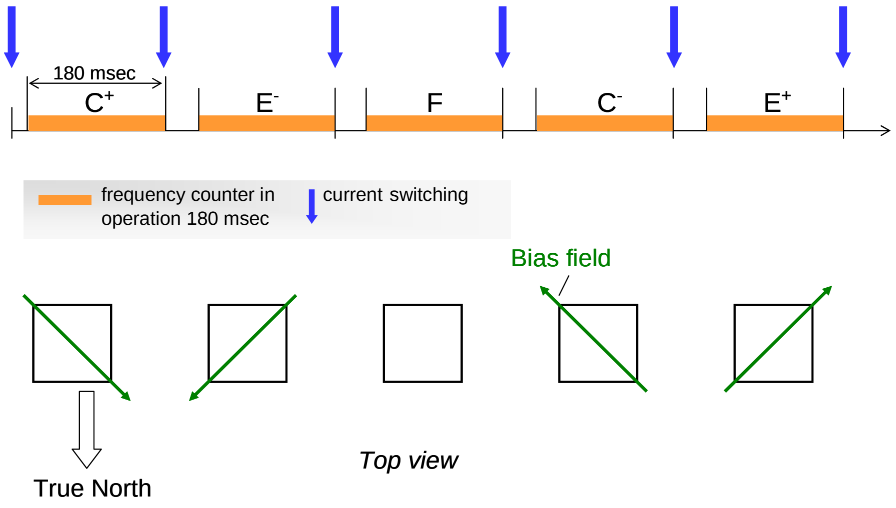

Figure 1. Sequence of operations to determine the field intensity and two perpendicular field components

The centre lines of both coils for generating the additional magnetic fields are perpendicular to each other and lie in the horizontal plane (in opposition to a DIDD). The system has to be levelled in the horizontal plane, and one axis should be oriented to the true north direction (to measure the magnetic X-component). Both coils are connected in series. The advantages of this orientation and connection are the following:

- only half the current is necessary,
- all 5 readings per second contribute a part to each component,
- the noise level has nearly the same order in each direction,
- the perpendicular error is eliminated.

This certainly requires a coordinate transformation into the true north direction.

All measuring sequences are controlled in real-time by a PC. The coil currents are switched by non delaying electronic transfer switches. The whole arrangement is shown in Figure 2. We compute the generated bias fields from the measured frequencies. The knowledge of current and coil scale factors are not needed.

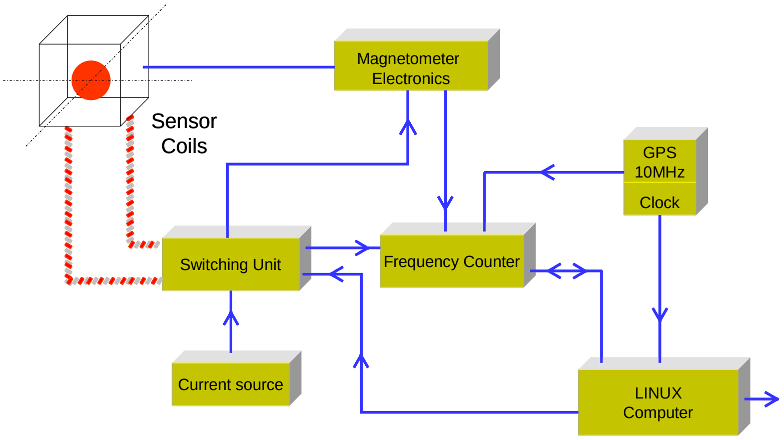

Figure 2. Block diagram

4 THE COIL SYSTEM

The simplest type, namely Helmholtz coils, was selected for the system. The design is easy, but the dimensions are large due to the required homogeneous area. The whole construction has to be without any metal parts to avoid eddy currents, which would result from switching of the coil currents. The orthogonal coil system has to be suspended in order to guarantee a good stability in case the pillar tilts. The coil system has to be turnable because a levelling of the coil-system is possible only by means of turning.

The turntable of our first sketch has a diameter of about 500mm. It consists of three columns which are carrying the suspended coil system. A high-accuracy electronic angle scale was installed further along with a turning support. The coil system is suspended by means of a swivel joint. The magnetometer sensor is situated in the centre of the coil system. The sensor cannot rotate with respect to the coil system. It was mentioned above that the orthogonal coils are connected in series. However, both coils have to generate the same magnetic fields and that by different diameters. That was realised by choosing different numbers of windings. (Figure 3)

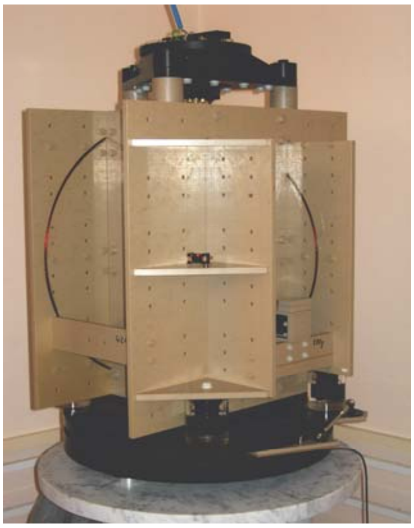

Figure 3. The complete coil system with turntable and mirror

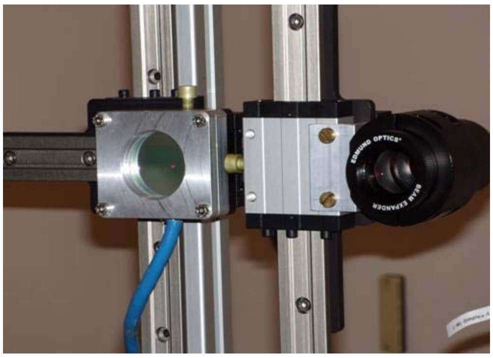

Figure 4. Laser and Sensitive Diode (PSD) (preliminary set-up)

5 ESTIMATIONS AND LIMITS

The required additional field strength depends on the noise of the arrangement. The noise has different sources: first, the magnetometer noise; second, the noise of the bias fields; and third, the artificial noise at the observatory site. The resolution is so high that the noise of the reference frequency of the counter plays an important role, too. We found out that the total noise is less than 5 pT rms at 180ms reading time. Based on this result, we estimated that the additional field has to be in the order of 5000nT. The same noise of 5pT rms for the magnetic components results under these prerequisites.

The theoretical estimation of the tilt errors of the coil system gave the following results: a deviation of +/- 1arcmin from the horizontal plane in a north-south direction leads to an error in the X component of +/- 13nT. A deviation from +/-1arcmin of the azimuth angle gives an error in the X component of +/-1E-03nT and 5.5nT in the Y-component.

6 INSTALLATION OF THE INSTRUMENT

There are several old small wooden huts in the Niemegk Observatory. In one of them the sensor and the coil system were installed and in a second one, about 20m away, the electronic units including the control computer. Unfortunately, it was realised too late that the pillar carrying the coil sensor system has no proper basement. The heavy sandstone was put down only into the sand.

The instrument should be close to an absolute instrument. That means controlling the orientation of the coil-system is the important task. The first step is the exact levelling of the coil system. This was done by means of rotation of the coil-system. The same absolute values have to occur in the horizontal component every 90 degrees. For this purpose the coil system consist of some trim screws. After this operation the horizontal component is measured with an absolute accuracy of about +/-1nT. The problem becomes how to get the reference to true north? To install a gyro makes no sense because of the problem of how to bring the coil axis and the gyro axis in parallel. The same is true for a theodolite. To solve this problem, it is necessary to get the declination angle from the observatory up to now. At first the coil-system must turn into the zero position of the declination, and then we use the declination angle to shift the coil-system into the true north direction. The comparison of the north- and east-components with the observatory values is then a good check for the position.

The remaining task to get stable measurements is a continuous check of the exact orientation. The position is permanently checked by means of a set, which consists of a laser beam, a mirror, and a Position Sensitive Diode (PSD) (Figure 4). The PSD delivers very important information about changes both of levelling and turning. The optical device is aligned in a north-south direction (Figure 5). A turning of 1arcmin results in a 5mm deviation at the PSD. Therefore, we have a very good resolution. Additionally, the temperature close to the sensor coil system is recorded.

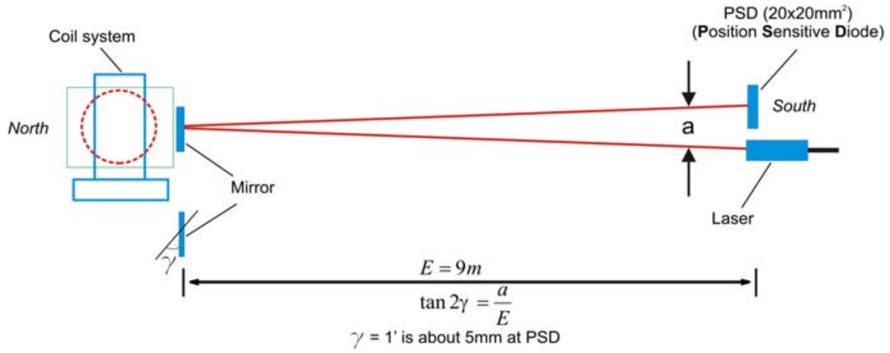

Figure 5. Set-up of the laser system

7 RESULTS

Figures 6 to 9 show some results from the current setup of the instrument. Figure 6 shows a comparison of one second mean scalar values of the Cs-He magnetometer (OPC) at which the reading time is only 180ms with the NGK K- tandem magnetometers, one located in the variation house about 50 m away and one located at a distance of only 2 m. It can be seen clearly that all magnetometers work excellently.

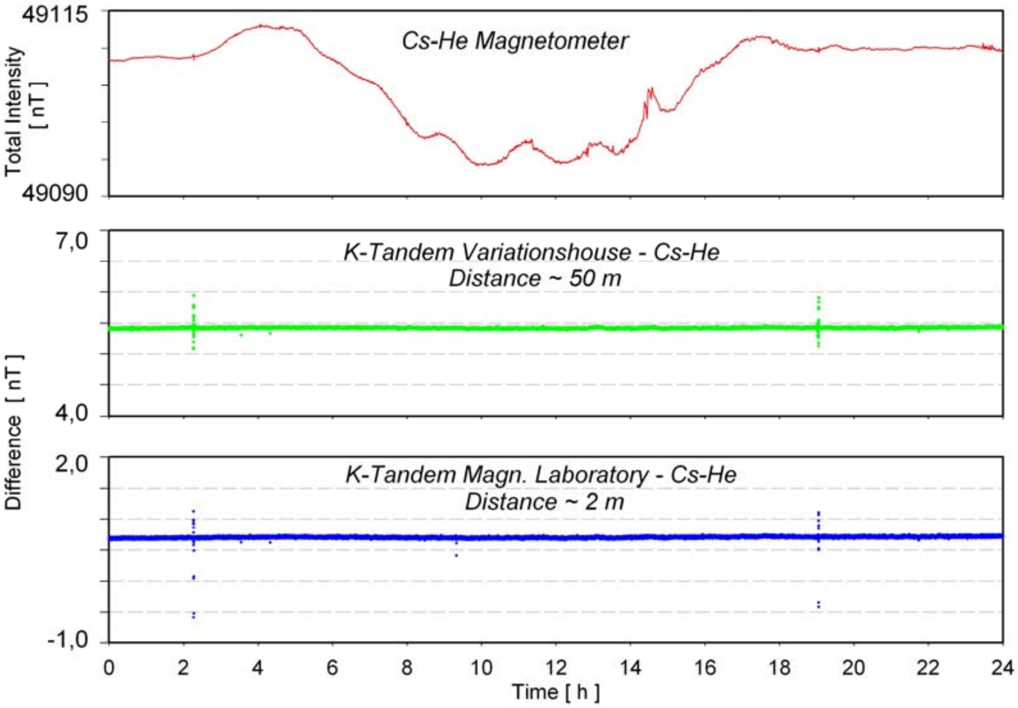

Figure 6. Total field intensity comparison at 2008-05-18.

The upper window shows the total intensity registration of the OPC with a reading time of only 180 ms; the lower windows show the difference between those readings and the recordings of two K-tandem magnetometers in distances of 50m and 2m, respectively.

A comparison between two successive readings was used for the estimation of noise. The bias magnetic field was switched off during these measurements (Figure 7, 5pT@180ms).

Figures 8 and 9 show one day's recordings of the components X and Y of the OPC in comparison with the observatory's Danish FGE. A day with high variations was deliberately selected. There is a very good agreement of both recordings, but unfortunately a small drift due to the temperature is clear seen. The wooden hut where the sensor is situated has no temperature control. The investigation of the temperature dependence shows that the Y component has a strict linear temperature coefficient of 0.1nT/degree, and the X component even has a strict linear temperature coefficient of 0.5nT/ degree. (Figure 10)

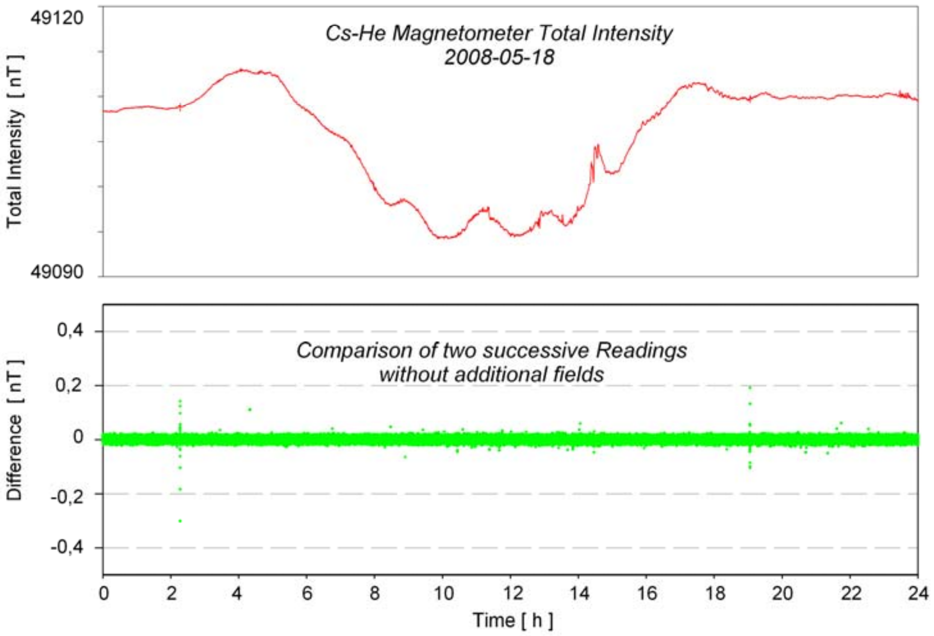

Figure 7. Comparison of two successive readings

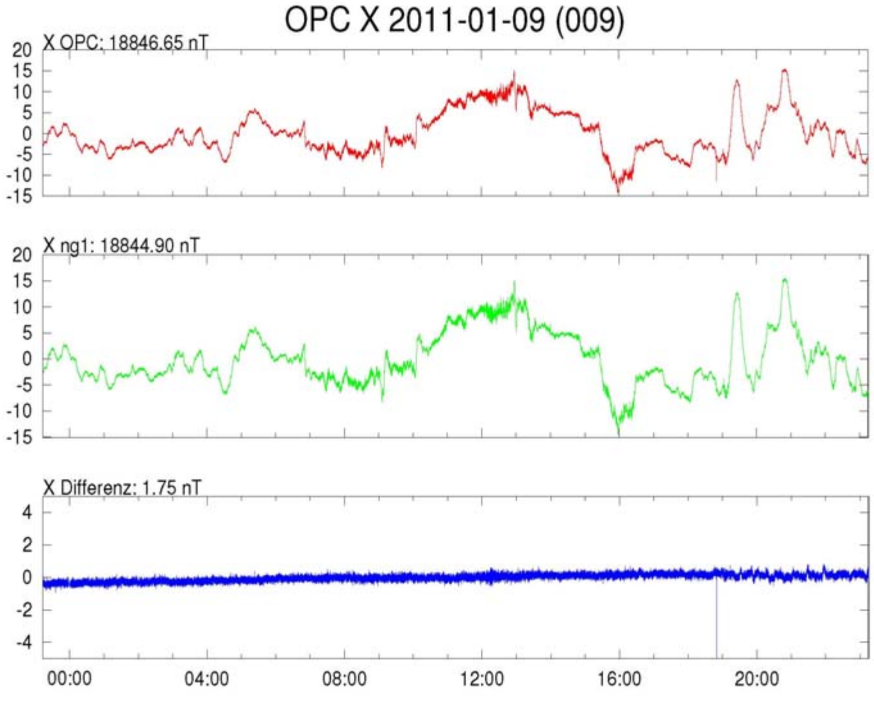

Figure 8. A comparison of the X-Component between the OPC (top) and the standard Niemegk Observatory FGE recordings (middle). The difference is shown in the bottom panel. (distance about 80m)

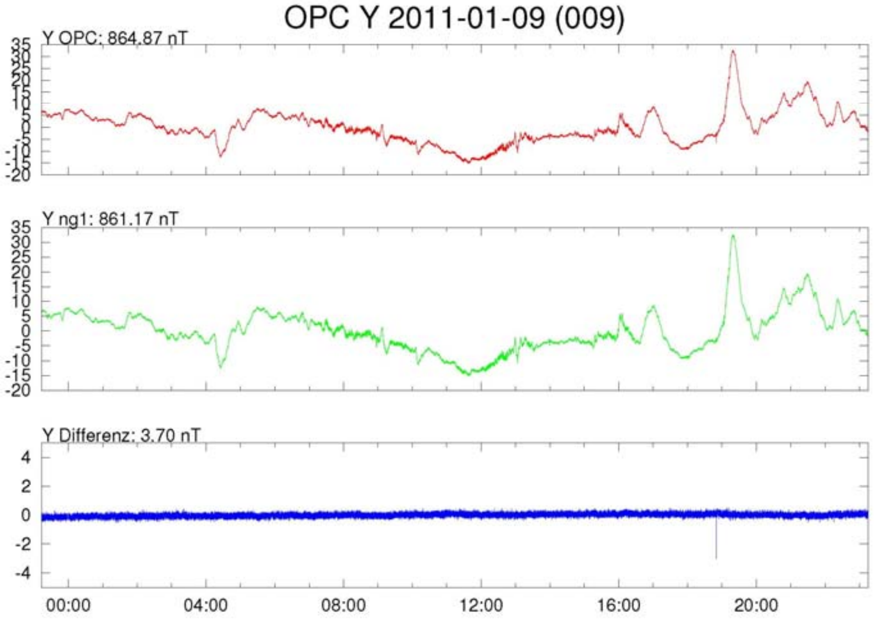

Figure 9. A comparison of the Y-Component between the OPC (top) and the standard Niemegk Observatory FGE recordings (middle). The difference is shown in the bottom panel.

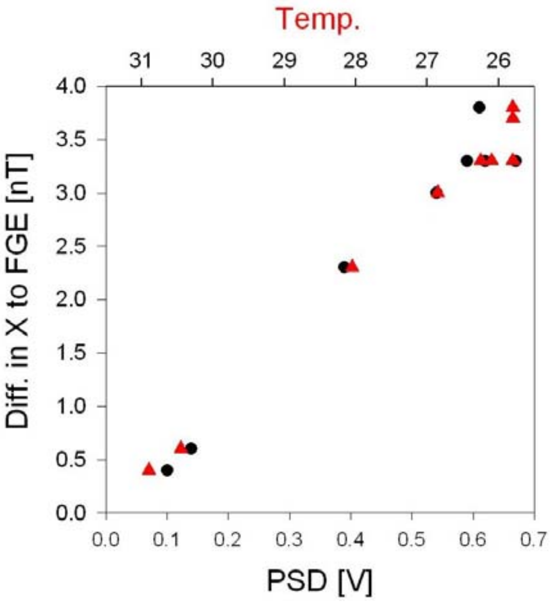

Figure 10. The comparison of differences in the X component recordings between the OPC and standard observatory FGE against temperature (red, top scale) and deviation seen by the PSD (black, bottom scale) clearly shows the temperature dependence of the sensor orientation.

As the relations are linear, one can easily correct the temperature drift by means of the PSD recordings and the temperature recordings, respectively (see Figure 10). In order to reduce the temperature dependence, we changed some parts of our coil system, for example, the springs of the swivel joint. So far we have had success only for the east-west component. But we will further investigate this problem.

8 CONCLUSIONS

A very fast and low noise magnetometer based on the Cs, Cs-He tandem principle, which is equipped with a two dimensional coil-system to record the magnetic field components, was developed and built. The instrument is able to generate high-accuracy datasets every second. Software, running under Linux, was written for controlling the coils currents as well as the frequency counter and also facilitates the data transfer to the host computer.

The component recordings of the OPC show some temperature dependence, which can be compensated using the PSD recordings. Although the instrument was completed at the end of 2009, a lot of modifications have since been done. Therefore we cannot present reliable data for the long-term stability of the OPC. Preliminarily, we can conclude that the stability is in the order of +/- 0.3nT over a temperature range of 30 degrees. We will investigate in a long-term test how well the aim was reached.

The most critical part is the coil system, which is going to be re-designed to reduce the observed temperature dependence. The aim of the instrument is to offer stability so that the number of additional absolute measurements can be significantly reduced. This instrument will be able (in the future) to record the complete field information, which, up to now had to be obtained from three different instruments.

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