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Overhauser vector magnetometer POS-4: application prospects In the geomagnetic measurements practice

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SUMMARY

We present some development results of the absolute vector proton magnetometer POS-4 based on the switching bias magnetic fields method. Magnetometer POS-4 has a high absolute precision and stability and suitable for geomagnetic observatories and for oil and gas well directional drilling support. We discuss the some basic measurements errors and show the long-term experience in the testing on magnetic observatory Arti (Urals).

Векторный оверхаузеровский магнитометр POS-4: перспективы применения в практике геомагнитных измерений

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РЕЗЮМЕ

Представлены результаты использования абсолютного верктороного магнитометра POS-4, основанного на методе переключения подмагничивающего поля. Прибор разработан в лаборатории Квантовой магнитометрии УрФУ и опробован на нескольких геомагнитных обсерваториях в сети INTERMAGNET. Благодаря высокой абсолютной точности и стабильности имеется хорошая перспектива использования и внедрения таких оверхаузеровских компонентных магнитометров на долговременных пунктах наблюдения векового хода геомагнитного поля и автономных магнитных обсерваториях. Магнитометр POS-4 может быть использован в качестве опорной базовой магнитного станции для поддержки направленного бурения нефтяных и газовых скважин. Обсуждаются основные погрешности измерений и демонстрируется многолетний опыт в испытаниях на магнитной обсерватории Арти (Урал).

Introduction

This report covers some results of the developing an absolute vector proton magnetometer POS-4 based on the switching bias magnetic fields method. Magnetometer POS-4 has a high absolute precision and stability and suitable for geomagnetic observatories and for oil and gas well directional drilling support. We discuss the some basic measurements errors and show the long-term experience in the testing on magnetic observatory Arti (Urals).

The measurement method based on switched bias fields

The physical base of proton Overhauser magnetometry is a Larmor precession of nuclear magnetic moments in a magnetic field. Proton magnetometers determine an absolute value of the measured magnetic field induction T_0 (Denisov at al, 2014):

$$T_0 \equiv \left|\mathbf{T}_0\right| = \gamma_p^{-1}\omega_0, \qquad (1)$$

where $\gamma_p = 2\pi 0.0425764$ rad/(nT·s) denotes the proton gyromagnetic ratio and ω_0 is the frequency of proton precession (Denisov at al, 1999). These magnetometers are well-known as high precision stable sensors of magnetic field absolute value. They are widely used in various applications including geophysics and observatory measurements (Narkhov at al, 2017).

We developed the absolute vector proton magnetometers based on the switching of bias magnetic fields (Sapunov at al, 2006). In recent years, the development of proton vector magnetometers achieved significant progress due to implementation of the Overhauser effect – dynamic nuclear polarization (DNP) due to electron subsystem excitation. Fig.1 (left) shows the general scheme of proton precession Overhauser DNP measurement (Overhauser magnetometer). This provides stronger proton signal from smaller sensor size and thus allows reducing dimensions of the magnetic switching systems and as consequence, to improve sensitivity of measurements.

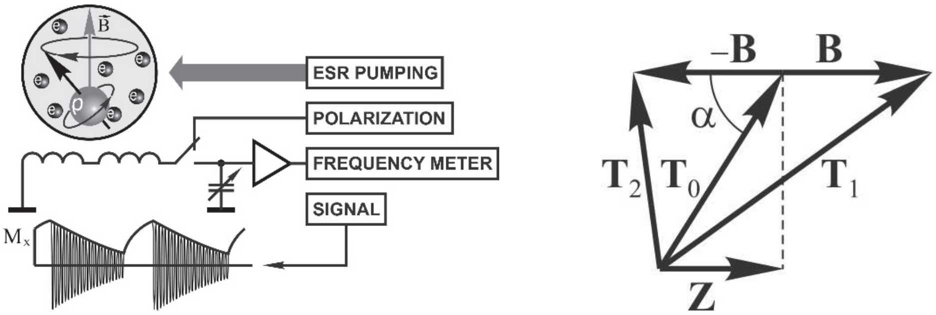

***Figure 1** General scheme of dynamic nuclear polarization measurement (left) and vector diagram of switching method for component measurements (right).*

There is a number of methods of the geomagnetic field components measurements with proton (scalar) magnetometer. We discuss the installation based on the switching of bias magnetic fields **B** (current cycle: +I, –I, 0) with the measurement of resulting total field. The vector diagram for a switching method is presenting at fig.1, right. The formula (2) for calculation of the field component Z along switching bias field is shown below:

$$Z = \frac{1}{2\sqrt{2}}\frac{T_1^2 - T_2^2}{\sqrt{T_2^2 + T_1^2 - 2T_0^2}}, \quad \mathbf{T}_{1,2} = \mathbf{T}_0 \pm \mathbf{B}. \qquad (2)$$

The sensitivity of component measurement is the best at $\alpha = 0$, $T_0/B = 0.5$ when the loss of sensitivity is $\sigma(Z)/\sigma(T) \sim 0.57$. Unfortunately, this case is not relevant for application because the increase of the bias field causes an increase of its gradient that means too high requirements for the switching magnetic system. In addition, there is a restriction on the bias field amplitude due to the dynamic range of the proton magnetometer (usually 20000–100000 nT). More interesting is the intermediate range, when the sensitivity of component measurements does not depend on the orientation of the bias magnetic field and total intensity. This bias field should be approximately 70% of the geomagnetic field, with a factor 3 in the sensitivity deterioration.

We analyze the main contributions to the systematic error caused by various reasons occurring during vector measurements technique based on switched bias fields. The error caused by the “soft” magnetization of absolute magnetometer sensor can be fully eliminated by the calibration of the module sensor. The systematic error caused by the “hard” magnetization of the module sensors depends only on the angle between the internal proton sensor “hard” magnetization field and the bias field. It does not depend on orientation of Earth's magnetic field. This error can be determined for some orientation of the vector magnetometer in the the Earth's field and then can be used as a correction at any field angles of declination and inclination. This error can be even completely eliminated for a special orientation of the proton sensors to bias field.

Error caused by instability of the bias field or the power source is a technically important kind of the error since it defines the requirements to the stability of the magnetic bias system and source of the switched current. Estimate the requirements on stability for the bias field or $\Delta I/I$ in conditions close to optimum ($T_0/B \approx 1.5$, $B \approx 30000$ nT) and setting error $\Delta Z \approx 1$ nT. We find the value of $\Delta I/I \approx 10^{-4}$. Thus, requirements to short-term stability of the current and bias field can be met engineering-wise and we have errors of $0.1 \div 1$ nT for instability $10^{-5} \div 10^{-4}$. It is important to note that the long-term stability does not exert influence on the switching method in contrast to a method of the field component compensation.

The experimental research of the Overhauser vector magnetometers in laboratory conditions, shows that switching method has a dynamic error caused by fast changes of the geomagnetic field. To estimate the error caused by a field variation in the measurement cycle, the jump function model of a variation was simulated (Denisov at al, 2006). The analysis of this result shows that the drift error is due to a dynamic cross effect: there is an influence (error) at the presence of variations of perpendicular components; The error is proportional to speed of variation, more precisely it is proportional to field change during the measurement cycle (the discretized time derivative of field).

POS-4 design and results of testing

Due to the high absolute precision (sensitivity up to 0.01 nT and absolute scalar measurements error up to 0.1 nT at stability measurements $0.02 \div 0.05$ nT per year) scalar Overhauser magnetometer POS-1 has wide application in the magnetic observatories and hazard monitoring systems. The Quantum Magnetometry Laboratory designed and developed the new scalar/vector magnetometer POS-4 (Fig. 2) based on the module sensor POS-1.

Figure 2 *Vector/scalar Overhauser DNP magnetometer POS-4 (photo by Sergey Khomutov).*

The system consists of bias coils mounted on the titanium frame. Vertical solenoid provides a measurement of the vertical Z component. The solenoid consists of a cylindrical titanium pipe with perpendicularly welded plates. Precision machining ensures perpendicular to both the axis of the solenoid and the plates. Two perpendicular liquid horizon levels (accuracy of 10 to 20 arc seconds) mounted on top of the plane supplemented by installing electronic levels to within one arc second. Solenoid wire fits the groove geometry defined by the known Garrett solenoid conditions providing maximum uniformity of the field in the largest volume. The perpendicular Helmholtz coils or a more complex system with high uniformity of the horizontal component measurement is oriented generally for the direction north-south.

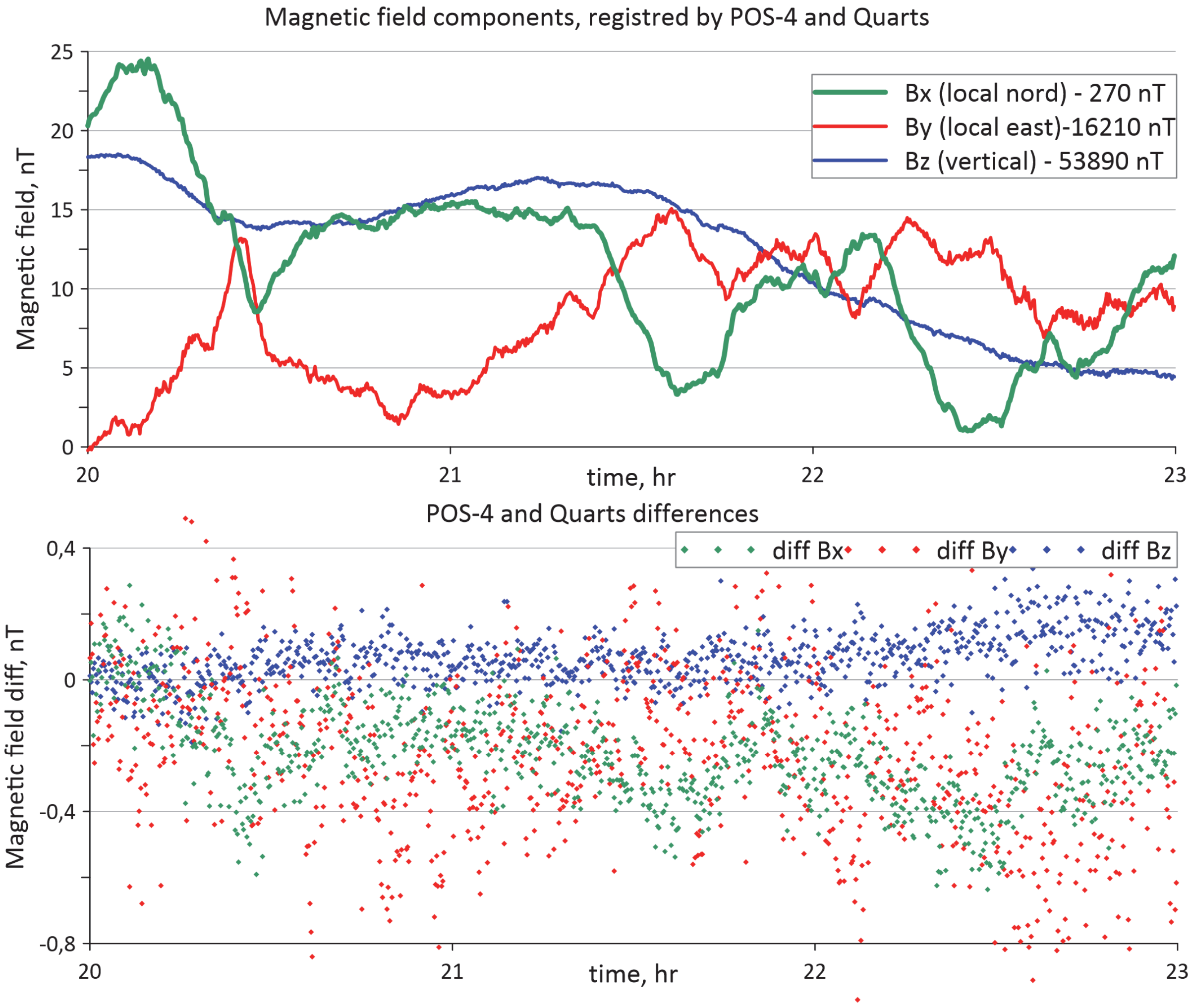

Figure 3 *An example of magnetic field components variations measured by variometer Quartz-4 and POS-4 (curves are practically coincide, constant shift removed) and difference in X, Y, Z components registered by POS-4 and Quartz-4. RMS ≈ 0.1 nT. Date of record is 2016:08:11 time is UTC. Observatory Arti.*

The electronics unit POS-4 provides five scalar values of bias magnetization and an actual geomagnetic field via RS232 serial port. Computer controls and backups the data using custom software adapted to the magnetic observatories tasks. We tested this new magnetometers at the magnetic observatories Arti (Urals) and Paratunka (Kamchatka) for several years. Variant POS-3 measuring module and the only vertical component under the observatory Arti and monitoring points of secular variation of the Earth's magnetic field around town Arti (Sverdlovsk region) are used. The first POS-4 full vector magnetometer (IdD+F) was tested at the observatory Paratunka for two years (Khomutov at al, 2016). In addition to the state standard of magnetic field in metrology institute, St. Petersburg we used the equipment of the magnetic observatory Arti to test the metrological parameters in comparation with stationary installed vector magnetometers. We investigated the metrological parameters and calibration methods including self-calibration. Our studies shows the sensitivity of magnetometers for modul of field is about 0.02 nT, and for the field's components is 0.1 ÷ 0.3 nT with 1 second measurement cycle (the total cycle is 5 seconds). Fig. 3 display the examples of actual records in Arti.

Conclusions

The new IdD+F POS-4 magnetometer is an analogue of the famous Canadian dIdD+F magnetometer applied both in observatories, autonomous stations and for directional drilling support of oil and gas wells (Sapunov at al, 2016). The difference is in the absolute component measurement with the vertical orientation. The azimuth angle declination to the geographical north is provided by the telescope on the POS-4 magnetic system and GNSS markup that will be a DI+F absolute vector Overhauser magnetometer.

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