Proton and Overhauser Magnetometers Metrology

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A b s t r a c t: Some of the principal experimental and theoretical results concerning metrological parameters of proton and Overhauser magnetometers are studied. In particular, the effect of operating modes, processing algorithms, a sensor design and registration path on the absolute and random errors of geomagnetic field is discussed.

The methods of testing and metrological certification used by the laboratory in producing magnetometers are considered in this repot. In particular, simplest laboratory testing, testing by means of special laboratory standard based on a magnetic shield and the certification with a reference magnetometer under conditions of magnetic field standard are described.

The measurement systematic error resulted from the thermoelectromotive generated at the polarization or in the presence of temperature gradient is shown for proton and Overhauser sensors. Methods for this defect removal are offered.

Key words: Proton, Overhauser, Magnetometer, Metrology

1. Introduction

Proton magnetometers are well known as precise total field measuring instruments. Such position is based on world constant - proton gyromagnetic ratio. In this report we shall try to destroy this statement and we shall briefly discuss some general metrological aspects of the proton and Overhauser magnetometers which can be used for development and exploitation.
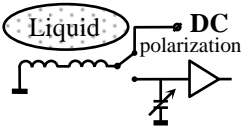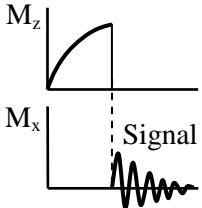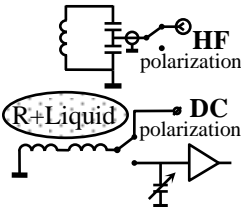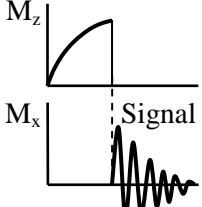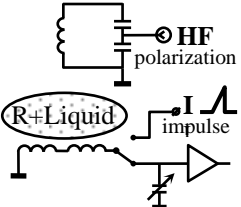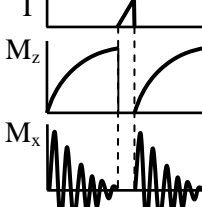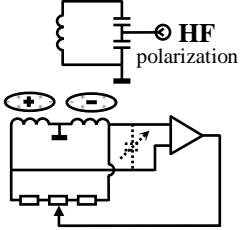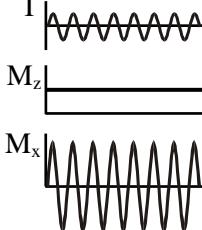
Four principles of proton magnetometers action are commonly used now (Table 1). The first is well known Packard-Varian scheme, namely polarization by field approximately a hundred oersteds. The second is the Overhauser precession magnetometer. It is analogous with the first, but polarization is carried out at the field of tens oersteds, while an effective polarization field is thousands oersteds due to radicals and Overhauser effect. For the third and the fourth principles the polarization and the registration are performed at the geomagnetic field. The signal is excited by short impulse or it is continuous for the Salvy scheme. The signal's value for continuous devices is also larger than for proton magnetometers. Although at the area below 40 000 nT the signal abruptly falls and approaches to the proton magnetometer signal because of physical construction and Overhauser radical properties.

Table 1. Proton and Overhauser Magnetometers Design. B_P – polarization magnetic field,

B$_{eff}$ – effective polarization field equals to B$_P$ multiplied by Overhauser amplification factor

N	Scheme	Time Diagram	Notes
1	Liquid — DC polarization	M$_z$ / M$_x$ Signal	Packard-Varian method Precession is stimulated by very rapid switch off. B$_P \approx 100 \div 300$ Oe
2	HF polarization / R+Liquid — DC polarization	M$_z$ / M$_x$ Signal	Precession by switch off Radicals: Diphenyl NO stable, wide ESR line easy saturated, USTU Trityl, stable (?), supernarrow ESR single line, IAU-DTU B$_P \approx 3 \div 50$ Oe B$_{eff} \approx 500 \div 5000$ Oe
3	HF polarization / R+Liquid — I impulse	I / M$_z$ / M$_x$	Polarization in geomagnetic field Precession by short impulse Radical: PROXYL, Stable , narrow ESR lines, GEM Systems B$_P = 0.2 \div 1.5$ Oe B$_{eff} \approx 200 \div 1500$ Oe
4	HF polarization	I / M$_z$ / M$_x$	Continuous precession by feedback Radical: TEMPO stable, narrow ESR lines, LETI B$_P \approx 0.15 \div 1$ Oe B$_{eff} \approx 300 \div 1500$ Oe

2. Absolute and random errors

Both cycling and continuous magnetometers have sources of an absolute error. They can be divided into three principal kinds: electronic, magnetic and thermal ones.

The electronic errors are caused by a number of reasons. First is the accuracy and stability of internal time standard. The transient process, so called ringing of receiving circuit induced by inaccurate tuning and deficiency of delay time, also is important to cycling magnetometers. Table 2 is presented to compare accuracy of different processing algorithms, in this case sensor's merit factor equals to 30, signal to disturbance ratio at the start is 10.

Table 2. Example of Transient Process Absolute Error (nT). S_0 – initial signal amplitude, T_m – measurement time, C_0 – initial amplitude of transient process, τ_c – noise decay time, ΔB – absolute accuracy of magnetic field value, $\gamma_p = 2\pi \cdot 0.0425764$ rad/(nT·s) – proton gyromagnetic ratio.

Method	Calculation formula	Measurement time, sec		
		1.5	0.5	0.1
Simple periodometer	$\langle \Delta B^{SP} \rangle \leq \dfrac{1}{\gamma_p T_m} \dfrac{C_0}{S_0}$	**0.25**	**0.75**	**3.7**
Introcycling periodometer	$\langle \Delta B^{IP} \rangle \leq \dfrac{9\tau_c}{2\gamma_p T_m^2} \dfrac{C_0}{S_0}$	**0.004**	**0.03**	**0.9**
Least squares method	$\langle \Delta B^{LS} \rangle \leq \dfrac{6\tau_c}{\gamma_p T_m^2} \dfrac{C_0}{S_0}$	**0.005**	**0.05**	**1.1**

The none-zero comparison level can be the next source of the absolute error, giving rise to smooth change of a measured period for a damping signal. This error usually is small, but in principle, it is easy to make a few nT mistake under using ordinary comparators and for the fast measurements especially.

In the continuous magnetometers (the fourth construction) mainly developed in France the errors can be related to the phase in a feedback circuit.

Induced and intrinsic magnetic moments are sources of the sensor's magnetic error. Induced moment is the result of sensor's materials susceptibility. This error can be excluded by selecting materials, sensor form or inserting corrections. Intrinsic magnetic moment is related to the material ferromagnetic impurities. The error value depends on polarization field. That is why the polarization field decreasing and application of Overhauser effect are useful for metrology. The control of induced and intrinsic magnetic moments is a critical point of sensor's production technology.

As for the measurement random error, it depends on measurement time and signal to integral noise ratio or signal to noise density for different processing algorithms. Random errors rigorously calculated as a function of measurement time (*Denisov et al., 1999*) are presented in Fig. 1.

Simplified formulas for engineering estimations of magnetometer sensitivity are also useful:

$$\sigma_B^{SP} \cong 6.8 \cdot 10^{-10} (A_0 T_2)^{-1} \sqrt{rw_r/Q}$$

for optimum $T_m \approx 1.1 T_2$

$$\sigma_B^{IP} = \sigma_B^{LS} \cong 2.5 \cdot 10^{-9} A_0^{-1} \sqrt{r/T_2^3}$$
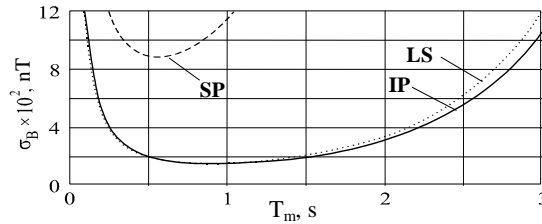
for optimum $T_m \approx 1.8 T_2$

Fig.1. Random error for different processing algorithms (Sensors parameters: $A_0 = 10$ mkV – initial input voltage, $Q = 15$ – Q-factor, $w_r = 2\pi \cdot 2$ kHz – natural frequency, $r = 0.5$ kOmh – resistance, $T_2 = 0.5$ sec – relaxation time)

3. Thermal effects

Problems concerning thermal effects for total and component proton magnetometers are not discussed enough. Such effects result from temperature gradient. Often they can not be detected by comparing one-type devices. The identity of magnetometers can be better then 0.1 nT, while the absolute error of one magnetometer can be obtained up to a few nT. The error sources are thermoelectromotive in the electrostatic shield or in the high-frequency resonator of the proton and Overhauser sensors (Fig. 2). To reduce harmful currents the cutting of current-conducting shell is used. For the component proton magnetometers the thermal effect can be caused by micron shifts of magnetic bias system due to the temperature gradient.
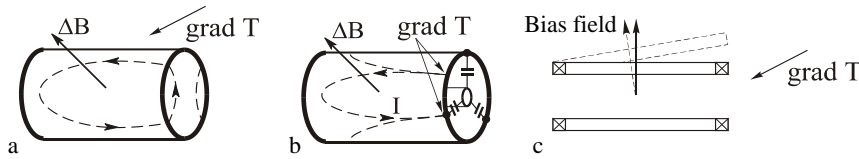
Fig.2. Thermo-effects in electrostatic shield (a), HF-resonator (b), magnetic bias system (c)

To geophysical illustration, we shall give an example presented by Kazakh researchers (Ghirov, Alma-Ata, Seismology Institute). One of our old-construction Overhauser sensors had an absolute error approximately 0.2 nT at the field standard. But thermo-effect on the level of 0.5-1 nT was revealed at presence of the bright sun and clouds with the help of Russian felt boot (valenki) (Fig. 3).
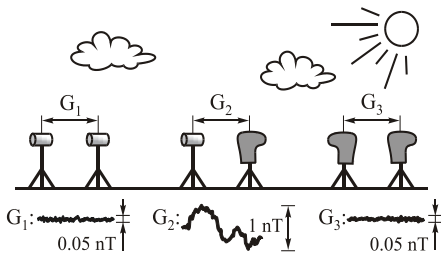
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Fig.3. Geophysical illustration of thermal gradient effects

Resuming incomplete list of main error sources, it is to be emphasized that the absolute error was spoken about, which provides the measurement equality of different type devices. To meet such conditions our Quantum Magnetometry Laboratory uses following methods underlying the Russian certificate laws.

4. Calibration of proton magnetometers

For initial laboratory electronic testing the etalon low-frequency generator is applied. The loop inducing electromotive force about value of precession signal is thrown on. The signal amplitude, supply voltage, magnetometer's temperature are regulated. Such an electronic testing does not exclude errors from another sources.

Rough rejection of sensor's magnetic impurities is carried out in the magnetic shield in which a magnetic field is checked by reference magnetometer (Fig.4). The reference magnetometer is verified against the first-class field standard, which is produced on bases of three-component Helmholtz coils 2.2 m in size. The field standard is supplied with quick-action field stabilizer on the basis of optical pumped cesium sensor. The first-class field standard also has a reference proton magnetometer annually verified by the State Field Standard.
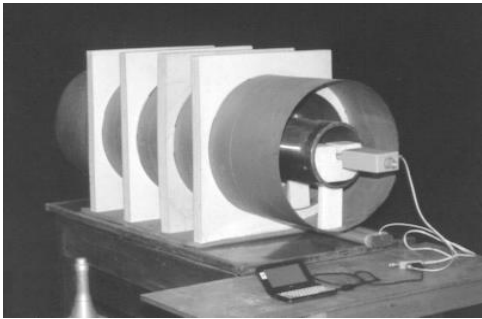

Fig.4. Laboratory field standard

Quantum Magnetometry Laboratory experience in development of the Ural and Kazakh first-class field standards has shown drift below 0.1 nT in 10 years for our reference Overhauser magnetometers. Above-mentioned verification scheme is an ordinary in Russia for geological survey. The key moment is the State Primary Standard of International System units guarded in Metrology Institute, St.-Petersburg.

5. Measurement quality control

In the proton magnetometers we employ introcycling processing algorithms. Every period of free precession signal is measured for subsequent statistical treatment. It increases the sensitivity and it gives new opportunities for quality control of the proton magnetometers. Processing algorithm allows device sensitivity to be measured in units of magnetic field in single measurement cycle, in spite of field variations. It was realized in POS-1 magnetometer as measurement quality criterion (QMC).
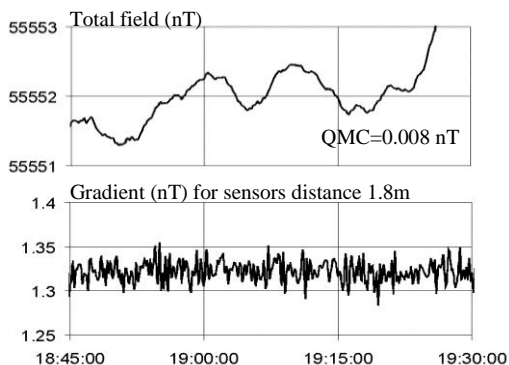

Fig.5. Experimental results of measurement quality control, ARTY observatory, 07.01.99

QMC testing for an observatory and geological surveys makes possible control of measurement conditions, disturbances and gradient influence. The example of record in ARTY observatory is shown in Fig. 5. The gradiometer was used to estimate sensitivity independently. Gradiometer application in observatory also allowed man-caused variations of the order of a few nT to be extracted.

6. Conclusion

Due to physical principle of operation the proton and Overhauser magnetometers are precise devices, which are able to secure an absolute accuracy up to 0.1nT at drift up to 0.05 nT/year and sensitivity 0.01 nT. To meet the absolute accuracy in the order of 0.1-1 nT all sources of errors. A key point to precision measurements both in observatory and in field is a reference magnetometer and field standard application being guided by laws of International System of Units.

References

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