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Study on sensitivity of JOM-4 Overhauser magnetometer

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Abstract. Overhauser proton magnetometer is a scalar instrument for measuring the total magnetic field intensity. Sensitivity, as one of the important specifications, reflects the ability to measure the change of magnetic field when detecting magnetic anomalies. It is very important to study the sensitivity estimation method for accurately evaluating the sensitivity specification of the magnetometer. In this paper, two methods, synchronous measurement method and gradient measurement method, are proposed to estimate the instrument sensitivity. The experimental results show that the lower the external environmental electromagnetic interference is, the more accurate the sensitivity estimation is. Furthermore, when the synchronization accuracy is about 1.7 milliseconds, the estimation results of the synchronization measurement method and the gradient measurement method are almost equal. Finally, in the environment with low electromagnetic interference, the sensitivity estimation of the JOM-4 magnetometers is 0.042 nT@3s.

1. Introduction

Overhauser proton magnetometer is a weak magnetic measuring instrument based on the principles of electron spin resonance (ESR) and nuclear magnetic resonance (NMR). It has the characteristics of high sensitivity and low power consumption. At present, it has been widely used in mineral exploration, underground buried objects and pipeline detection, archaeological site mapping, ferromagnetic material identification, satellite magnetic survey and other fields [1-4].

As one of the important specifications of magnetometer, sensitivity has been mentioned in many literatures, but the estimation method of sensitivity in the environment with electromagnetic interference is not mentioned [3-5]. JOM series Overhauser magnetometers are developed by the College of Electronic Science and Engineering, Jilin university. The sensitivity of the JOM-1 was estimated with a stable set of data as 0.14nT [5]. This method cannot eliminate the influence of diurnal variation, which will cause gross error. In order to improve the accuracy of the sensitivity estimation, magnetic gradiometers JOM-2 and JOM-3 Overhauser based on DSP and ARM were developed. The sensitivity of the two gradiometers were estimated as 0.043nT [6] and 0.047nT [7]. To accurately evaluate the sensitivity of a single magnetometer. The JOM-4 Overhauser magnetometer is designed with two types, the JOM-4SF Overhauser magnetometer and JOM-4SFG Overhauser gradiometer. In this paper, the sensitivity estimation of the Overhauser magnetometer is studied with the JOM-4 Overhauser magnetometers.

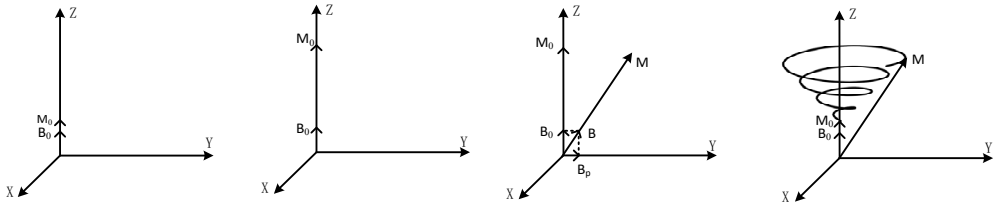
Sensitivity estimation is usually tested in field-free magnetic space [8]. However, in the process of instrument development, most experiments often need to be carried out in an outdoor environment. In this environment, the magnetic field usually contains diurnal variation and electromagnetic interference. In this paper, the synchronous measurement method and the gradient measurement

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method are proposed to eliminate the diurnal variation, and the environmental electromagnetic interference. The influence of synchronization precision on sensitivity estimation is discussed and compared with the gradient measurement method in different environmental electromagnetic interference.

2. Principle of operation

The free radical solution of the Overhauser proton magnetometer selects an aqueous solution rich in unpaired electrons, in which both the electron spin system and the proton spin system exist. Because of the effect of the geomagnetic field B_0, hydrogen protons in solution will be magnetized to produce magnetic moment M_0 along the direction of B_0, as shown in figure 1(a). By radio frequency (RF) polarization, the magnetic moment of hydrogen proton increases along the direction of geomagnetic field B_0, as shown in figure 1(b). At the same time, a DC source is added to the low-frequency receiving coil to generate a magnetic field B_p perpendicular to B_0 in the sensor. At the moment, the magnetic moment M_0 will gradually shift to the direction of B, forming combined magnetic moment M, as shown in figure 1(c). After a period of time, the RF polarization and DC bias signals are turned off at the same time, and the excited protons will make precession around the magnetic field B_0 to form Larmor precession signal, as shown in figure 1(d), and finally return to the state shown in figure 1(a).



(a) Natural state (b) RF polarization (c) DC bias (d) Freedom precession

Figure 1. Polarization process of Overhauser magnetometer.

The relation between Larmor precession angular frequency ω_0 and geomagnetic field B_0 as equation (1).

$$\omega_0 = \gamma_p B_0 \tag{1}$$

Where, gyromagnetic ratio γ_p=2.67512×10^{8}T^{-1}S^{-1}.

The geomagnetic field B_0 can be given by equation (2).

$$B_0 = 23.4874 f_p \tag{2}$$

Where, the unit of B_0 is nT, and the unit of f_p is Hz.

Therefore, by measuring the f_p value, the magnetic field B_0 value can be obtained.

3. Schematic of the system

The schematic diagram of JOM-4 Overhauser magnetometer is shown in figure 2, mainly composed of the sensor, analog board, and digital board. The sensor consists of the free radical solution containing unpaired electrons in a high frequency resonant cavity and a low frequency coil. The high frequency oscillator is used for generating RF signal, which makes free radical solution in the sensor produce dynamic nuclear polarization. The low-frequency coil is used for both generating the magnetic fields perpendicular to the geomagnetic field and inducing the Larmor precession signals.

The analog board finishes generating the RF and DC excitation signals for the sensor, and carries out the signal conditioning work such as amplification, filtering and shaping for the Larmor signals received by the low frequency coil.

The digital board applies the ARM+CPLD dual chips design. The ARM model is STM32F407ZGT6 produced by the ST Company, mainly completing the measurement timing sequence control as shown in figure 3, the polarization coordination signal control, AD signal conversion and data storage, etc. The CPLD model is EPM1270ATI144-10N produced by the

ALTERA Company, mainly used as a frequency meter to measure the frequency of Larmor signal.

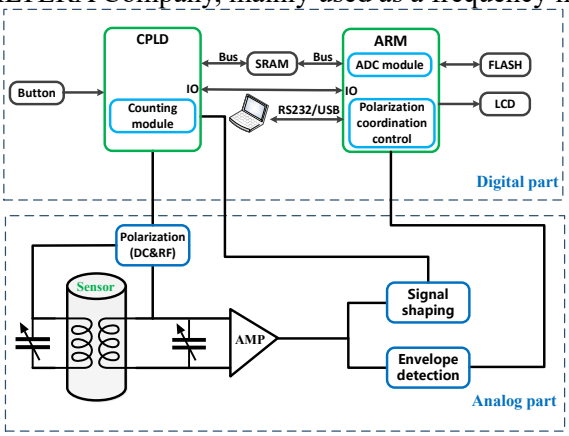


Figure 2. Schematic diagram of JOM-4 Overhauser magnetometer.

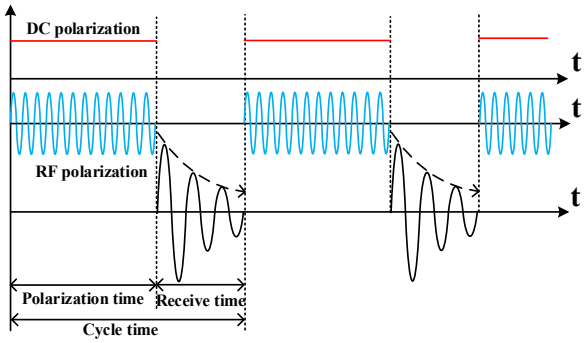


Figure 3. The time sequence diagram of magnetometer measurement.

4. Experimental results

The magnitude of random noise is evaluated by standard deviation. The data measured by the magnetometer show the characteristics of random noise without the influence of electromagnetic interference and diurnal variation. When there is diurnal variation or environmental electromagnetic interference in the measured data, we use the synchronous measurement method or the gradient measurement method to estimate sensitivity according to equation (3).

$$\sigma = \frac{1}{\sqrt{2}}\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(x_{1i}-x_{2i}+\frac{1}{n}\sum_{i=1}^{n}\left(x_{2i}-x_{1i}\right)\right)^{2}} \tag{3}$$

Where, n represents the number of magnetic field values, x_{1i} and x_{2i} represent the measurement data of the magnetometers.

4.1Synchronous measurement method

The method of synchronous measurement is to obtain the sensitivity estimation by synchronous measurement of two magnetometers. In order to study the effect of external electromagnetic interference on the synchronous measurement method, tests are carried out in different environmental electromagnetic interference.

4.1.1Low environmental electromagnetic interference sensitivity estimation. The experimental site is selected in a place in Changchun city, which is far away from buildings, roads and cables. The environmental electromagnetic interference is low and the magnetic field is stable. The sensors are placed 1.5m apart in the east and west direction. The measured cycle time is 3 seconds. Two JOM-4SF Overhauser magnetometers are used for synchronous measurement for 25 minutes. The test results are shown in figure 4.

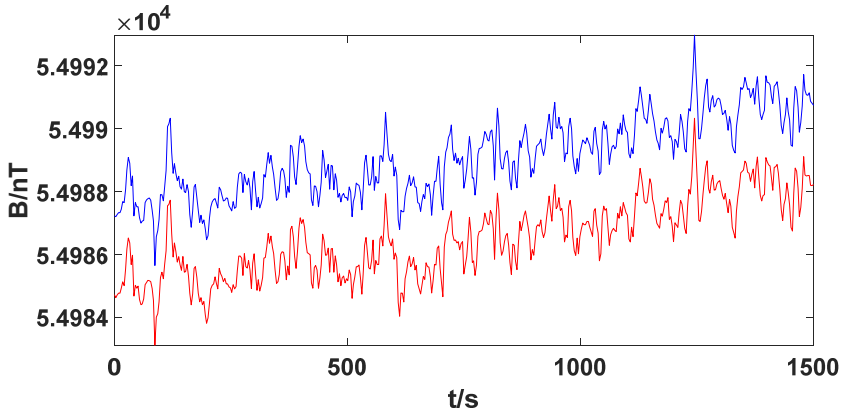


Figure 4. Magnetic field in low electromagnetic interference.

As can be seen from figure 4, the consistency of the two groups of data is high, which is due to the high synchronization accuracy and low electromagnetic interference. The sensitivity estimation is 0.046nT@3s through the calculation of equation (3).

4.1.2High environmental electromagnetic interference sensitivity estimation. The experimental site selection is carried out on the campus of Jilin university where existed high electromagnetic interference. The sensors are placed 1.5m apart in the west and east direction. The measurement cycle time is 3 seconds and measurement time is 25 minutes. The test results are shown in figure 5.

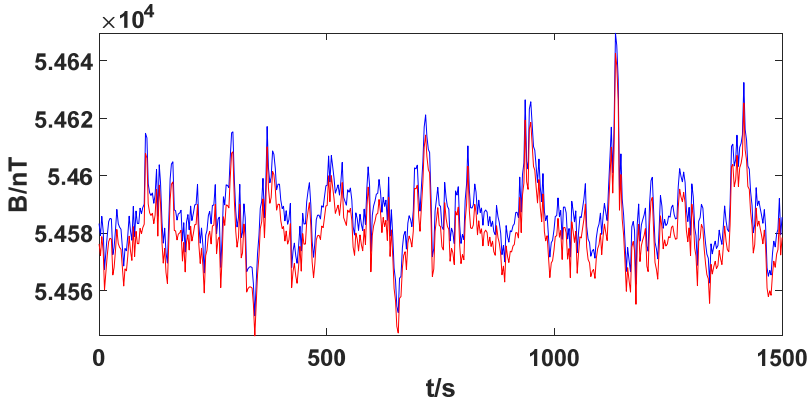


Figure 5. Magnetic field in high electromagnetic interference.

As can be seen from figure 5, the consistency of the two groups of data is relatively high. The sensitivity estimation is 0.049nT@3s. The sensitivity estimation of the synchronous measurement method in different environmental electromagnetic interference are shown in table 1.

Table 1. Sensitivity estimation results of synchronous measurement method.

Environmental electromagnetic interference	Sensitivity (nT)
Low	0.046
High	0.049

It can be seen from table 1 that the lower the environmental electromagnetic interference is, the more accurate the sensitivity estimation will be. This is due to the lower the electromagnetic interference, the smaller the difference between the two groups of data. However, the reason for the small difference in estimates is that the synchronization accuracy is 1.7 milliseconds. Even in high environmental electromagnetic interference, we can also eliminate the diurnal variation and external electromagnetic interference to obtain accurate sensitivity estimation.

4.2Gradient measurement method

The synchronous measurement method uses the time of one instrument in two magnetometers to set the time of the other magnetometer, which usually results in a synchronization error of a few

milliseconds. The gradient measurement method is triggered by the same signal. The polarization control of the two channels of the gradiometer starts the measurement at the same time, and the synchronization error is 0 milliseconds. Theoretically, the estimation of gradient measurement method is more accurate than that of synchronous measurement method. The gradient measurement method will be studied below.

4.2.1Low environmental electromagnetic interference sensitivity estimation. The test environment and sensor placement are the same as those in section 4.1.1. After 25 minutes of testing with a single JOM-4SFG magnetic gradiometer, and the test data are shown in figure 6.

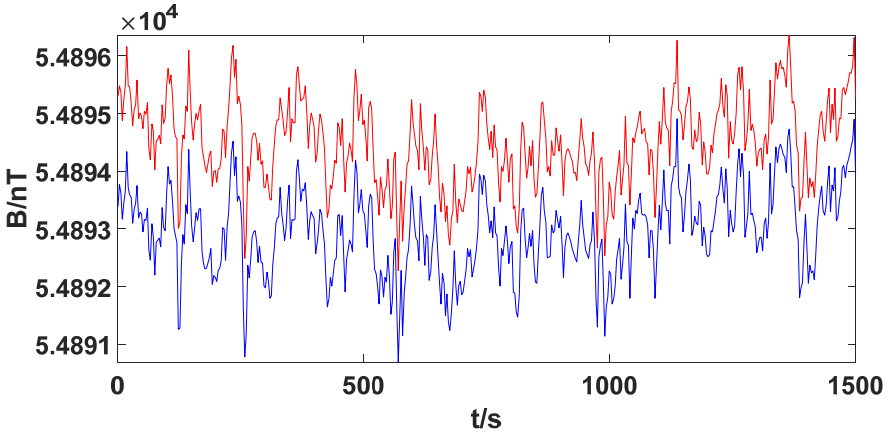


Figure 6. Magnetic field in low electromagnetic interference.

As can be seen from figure 6, the magnetic field value varies within the range of 5nT, indicates that the local magnetic field value is stable. The sensitivity estimation is 0.042 nT@3s.

4.2.2High environmental electromagnetic interference sensitivity estimation. The test environment and sensor placement are the same as those in section 4.1.2. After 25 minutes of testing with a single JOM-4SFG magnetic gradiometer, and the test data are shown in figure 7.

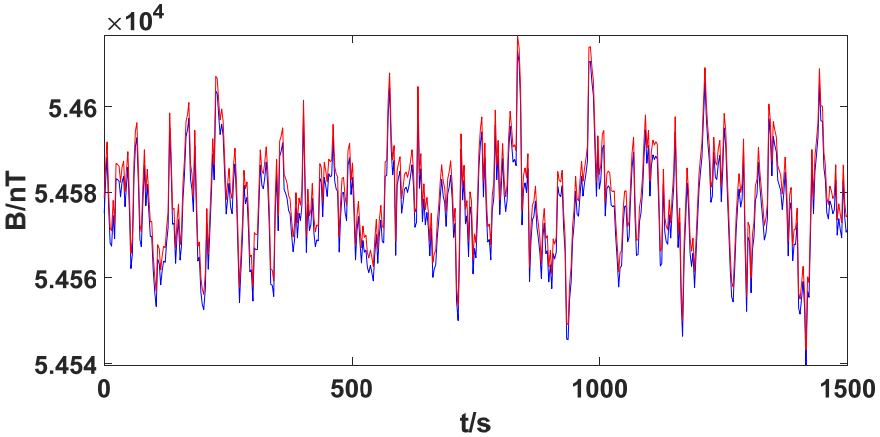


Figure 7. Magnetic field in high electromagnetic interference.

As can be seen from figure 7, the consistency of the two groups of data is very high, this is due to its synchronization error of 0 milliseconds. The sensitivity estimation is 0.044 nT@3s. The sensitivity estimation of the gradient measurement method in different environmental electromagnetic interference are shown in table 2.

Table 2. Sensitivity estimation results of gradient measurement method.

Environmental electromagnetic interference	Sensitivity (nT)
Low	0.042
High	0.044

It can be seen from table 2 that the lower the electromagnetic interference is, the more accurate the sensitivity estimation of the gradient measurement method will be. In the same electromagnetic interference, the gradient measurement method is more accurate than the synchronous measurement method, but the difference is very small. The reason for the accuracy of gradient estimation is that there is no synchronization error. The reason for the small difference is the high synchronization accuracy, which is usually only 1.7 milliseconds. Therefore, synchronization measurement method can be considered to eliminate diurnal variation and external electromagnetic interference.

5. Conclusions

Two methods for sensitivity estimation with JOM-4 magnetometer are discussed in this paper. The influence of external environmental electromagnetic interference on sensitivity estimation is talked in detail. The experimental results show that the synchronization measurement method requires high synchronization accuracy of the instrument. When the synchronization error is about 1.7 milliseconds, the estimation values of the synchronization measurement method are almost equal to the gradient measurement method. Both methods can accurately estimate the sensitivity of the instrument and have low requirements for the electromagnetic environment. Finally, the sensitivity of JOM-4 magnetometer is estimated as 0.042nT@3s.

Acknowledgments

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