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Study on methods of sensitivity evaluation of JPM-4 proton magnetometer

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Abstract. The filtering algorithm is usually applied to eliminate the diurnal variation in sensitivity estimation for proton magnetometer. Two indirect methods for sensitivity estimation of proton precession magnetometer, the synchronous measurement and the gradient measurement, are discussed here in detail. Experiments have been done under different electromagnetic environments and the sensitivity has been estiamted based on the two methods. Results show that both the indirect methods can suppress the interference of environmental noise effectively. The gradient measurement method is more accurate than synchronization measurement method. Finally, the sensitivity of JPM-4 proton magnetometer under 54000nT geomagnetic environment is estimated by the indirect methods as 0.1nT@3s.

1. Introduction

The proton magnetometer is a scalar quantum magnetometer based on the principle of nuclear magnetic resonance (NMR). The related research can be traced back to the V-4910 proton magnetometer designed by Packard et al. in the mid-1950s [1]. As a high-precision magnetometer, proton magnetometer is widely used in geomagnetic measuring due to its low cost, stability, easy operation and portability. It has been used in the fields of earthquake prediction [2], aeromagnetic survey [3], geophysical exploration [4], mineral exploration [5] and archaeology [6].

Sensitivity, a statistical value of the reading uncertainty for the same magnetic field can be estimated by measuring a constant magnetic field for a long period of time. However, this direct method can only be adopted with very low electromagnetic interference and high stability of magnetic field. The development of magnetometer requires frequent evaluation of sensitivity, thus how to evaluate the sensitivity of magnetometer in outdoor environment is very important for the development of the magnetometer. For more than half a century, various aspects of studies to improve performance and application of proton magnetometers are abundant, but there is no much discussion on outdoor sensitivity evaluation.

In this paper, two indirect methods for sensitivity estimation in outdoor environment of proton precession magnetometer, the synchronous measurement and the gradient measurement, are discussed here in detail. First, the principle of proton magnetometer and the structure of the JPM-4 proton magnetometer are introduced. Then, the limitations of the direct method outdoor is analyzed and the indirect method is proposed. Finally, the sensitivity of synchronized JPM-4 and JPM-4G is tested with two different methods in varies outdoor environment.

2. Proton magnetometer working principle

Protons have nuclear spin angular momentum and spin magnetic moment. Its spin angular momentum

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is very small, only $5.27 \times 10^{-35} kg \cdot m/s$, the spin magnetic moment size is $1.41 \times 10^{-26} A \cdot m$. The spin angular momentum and the spin magnetic moment of the proton are parallel to each other, which means that the proton can be regarded as a small magnetic needle that can spin. When the proton is placed in the external magnetic field B_e, the magnetic moment of the external magnetic field causes the proton to precess in the direction of the external magnetic field. This is called the Larmor precession, as shown in figure 1.

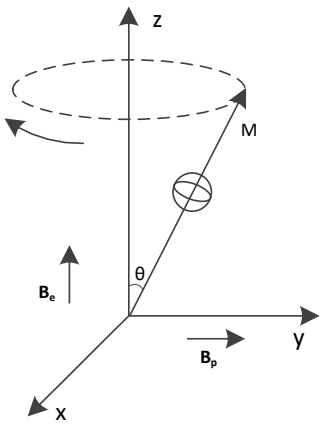

Figure 1. Schematic diagram of proton Larmor precession.

The angular frequency of Larmor precession is proportional to the magnetic induction magnitude of ambient magnetic field, giving the Larmor equation as equation (1).

$$\omega = \gamma_p B_e \tag{1}$$

In equation (1), ω is the proton Larmor precession angular frequency, γ_p is the proton's gyromagnetic ratio, which is the ratio of the spin magnetic moment to the angular momentum, and the size is $2.6752 \times 10^8 \mathrm{T}^{-1} \cdot \mathrm{s}^{-1}$[7], B_e is the intensity of the ambient magnetic field.

From equation (1), the relationship between the external magnetic field and the proton precession frequency can be calculated as shown in the equation (2).

$$B_e = 23.4874 f \tag{2}$$

In equation (2), the unit of ambient magnetic field magnitude B_e is nT, and the unit of Larmor precession frequency f is Hz.

The design of proton magnetometer utilized the proton Larmor precession effect to calculate the magnetic field magnitude by measuring the Larmor frequency. The sensor of proton magnetometer mainly consists of a core filled with liquid which is rich in proton solution and winded by copper coil. Normally the precession phase of the proton magnetic moment is random as shown in figure 2(a), the combined magnetic moment is zero. Therefore, first generate polarization magnetic field by applying polarization current to the coil, to align the proton magnetic moment in the same direction as shown in figure 2(b).

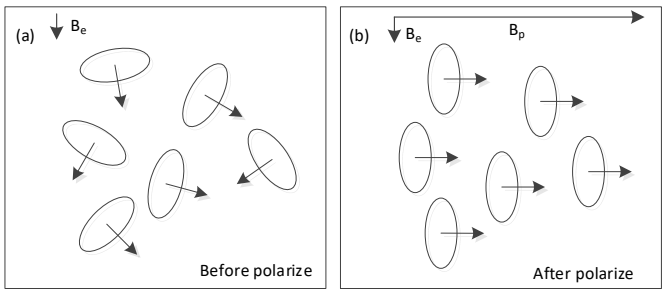

Figure 2. The status of proton magnetic moment before and after polarization.

When the polarization current is turned off, the polarization magnetic field B_p disappears. The

proton combined magnetic moment will precess in the direction of external magnetic field B_e, meanwhile there is magnetic flux change occurs in the coil and induced voltage signal is generated. Since the precession phase of the proton is randomized by the collisions between protons during the precession, the induced voltage signal will attenuat exponentially with time, as shown in figure 3.

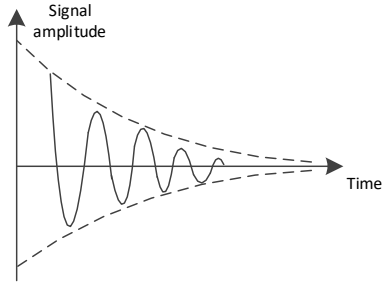

Figure 3. Induced voltage signal.

In figure 3, the frequency of the induced voltage signal is equal to the Larmor frequency. After measuring the frequency of the signal and calculating it using equation (2), the external magnetic field intensity can be obtained. It can be seen in equation (2) that the variation of the Larmor frequency caused by the change of the external magnetic field magnitude B_e of 1 nT is only 0.043 Hz. Therefore, how to obtain the high signal-to-noise ratio induced voltage signal and accurately measure the frequency is the key to the development of proton magnetometer.

3. Schematic of the system

The JPM-4 proton magnetometer consists of sensor, analog circuit and digital circuit. The schematic of the system is shown in figure 4.

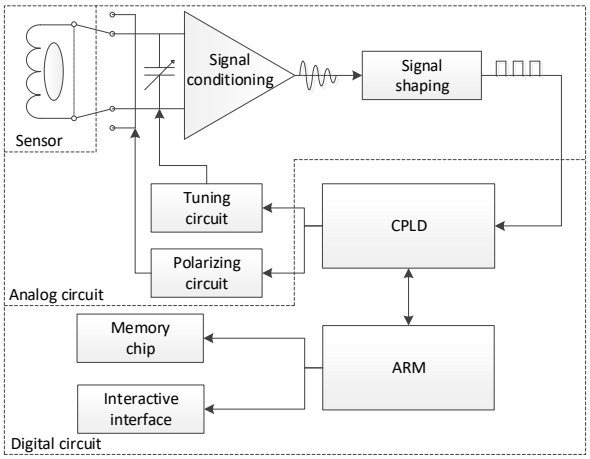

Figure 4. Schematic of the JPM-4 proton magnetometer.

The sensor consists of a container filled with a hydrogen-rich proton solution (kerosene) and a coil placed therein. The coil is used to generate polarized magnetic field and receive Larmor induced electromotive force signal.

The analog circuit mainly consists of polarization circuit, coordination circuit, amplifying circuit and shaping circuit. The polarization circuit provides a DC polarization current to the probe coil and controls signal receiving. The coordination circuit and the amplifying circuit are used for amplifying and filtering the signal from micro-volt level to volt level, then turn the sinusoidal signal into square wave signal by the shaping circuit for frequency measurement.

CPLD and ARM are used in the digital circuit. The CPLD cooperates with the temperature-compensated crystal oscillator to perform accurate frequency measurement and send the measurement result to ARM. ARM is used to process the frequency value returned by CPLD and control the measurement, other than that ARM controls memory chip and human-computer interaction

module.

4. Evaluation method of sensitivity

The sensitivity of proton magnetometer is a statistical value of the reading uncertainty when repeated measurements are made under the same magnetic field. It is the minimum magnetic field that the apparatus can resolve, represented by the standard deviation of a set of measured values without considering the drift of the apparatus, as shown in equation (3).

$$\delta=\sqrt{\sum_{i=1}^{N}(B_i-\bar{B})^2/(N-1)} \tag{3}$$

In equation (3), B_i is the ith measurement of magnetic field intensity, $\bar{B}$ is the average of all the measurement results and N is the number of measurements.

The direct method is to measure with single magnetometer, calculate sensitivity using equation (3), and the filtering algorithm such as MAF can be used outdoors to improve the estimated value.

However, the noise existing in the outdoor environment includes not only low-frequency diurnal variation noise, but also unpredictable electromagnetic noise such as AC interference and radio interference. The complexity of these noise components is difficult to filter. In order to eliminate both diurnal variation and environmental electromagnetic interference, a method for indirectly estimating the sensitivity is proposed. The composition of the magnetic field measured by the magnetometer outdoors can be expressed by the equation (4).

$$B=B_e+B_{env}+B_n \tag{4}$$

In equation (4), B is the magnetic field value measured by magnetometer, and its composition includes the earth magnetic field B_e, the environmental noise B_{env} and the apparatus noise B_n.

Sensitivity is defined by the standard deviation of B_n. Out of which, the affect of ambient noise B_{env} to the two sensors nearby are similar, therefore, an indirect measurement method of sensitivity is proposed, that is, obtain the data through two synchronized single apparatus or one gradiometer then calculate the sensitivity by equation (5).

$$\delta_{Bn}=\frac{1}{\sqrt{2}}\sqrt{\sum_{i=1}^{N}(\Delta B_i-\Delta\bar{B})^2/(N-1)} \tag{5}$$

In equation (5), ΔB_i is the difference of the ith measurement, $\Delta\bar{B}$ is the average of the difference of all the measurement results and N is the number of measurements.

Equation (5) removes ambient noise and preserves the noise content of the apparatus. The sensitivity of the magnetometer can be expressed by δ_{Bn}.

5. Experimental results and data analysis

In order to observe the effect of indirect method on the sensitivity of JPM-4 in different noise environments, we use two synchronized JPM-4 proton magnetometers and JPM-4G gradiometer to perform 3s cyclic magnetic measurement in the field and on campus respectively. The main reason for choosing these two test sites is that their environmental magnetic field components are different. The field is far away from human activities, the environmental magnetic field interference is very low, and there are many unpredictable magnetic field interferences in addition to the diurnal variation on the campus. The test results are shown in figures 5 and 6.

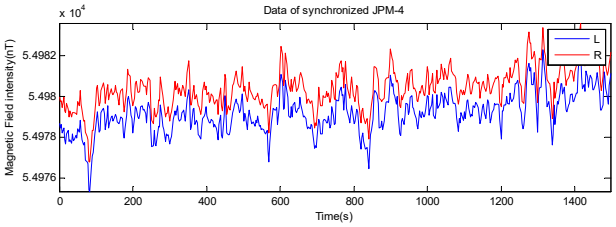

Figure 5. Field JPM-4 synchronous measured magnetic field value.

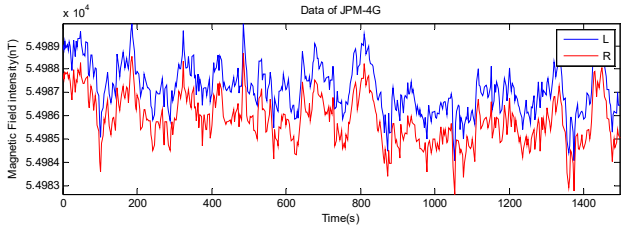

Figure 6. Field JPM-4G measured magnetic field value.

Figures 5 and 6 show the measured magnetic field values in the Jingyue forest area, and the indirect sensitivity estimates is 0.11nT (synchronous JPM-4) and 0.11nT (JPM-4G). It can be seen from the results that in such quiet environment the sensitivity evaluation requires low synchronization accuracy of apparatus. Using indirect method to calculate the synchronization data and the gradient data, relatively accurate instrument sensitivity estimation could be obtained. In order to observe the accuracy of the indirect method sensitivity estimation when the ambient noise is loud, the test was carried out in the school campus, and the results are shown in figure 7 and 8.

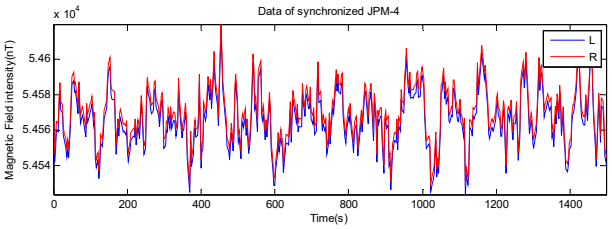

Figure 7. Campus JPM-4 synchronous measured magnetic field value.

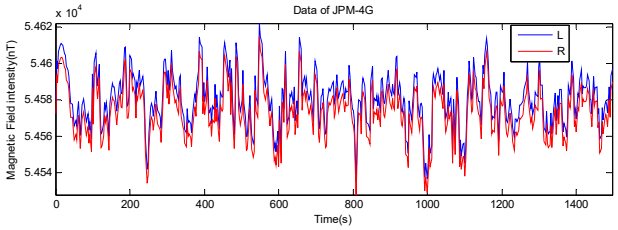

Figure 8. Campus JPM-4G gradiometer measured magnetic field value.

Figures 7 and 8 are the results measured by synchronized JPM-4 and JPM-4G on the campus. The sensitivity is estimated to be 0.16nT (synchronous JPM-4) and 0.10nT (JPM-4G). It can be seen that the estimated results of the synchronization measurement method on campus are worse than the results in the field. However accurate evaluation can still be obtained by using the gradiometer. This is caused by the fact that the synchronization accuracy of the two synchronized magnetometers is lower than the gradiometer. The indirect method sensitivity estimations for both environments are shown in table 1.

Table 1. Sensitivity evaluation results in different environments.

	Field	Campus
Syn- measurement (nT)	0.11	0.16
Grad- measurement (nT)	0.11	0.10

It can be seen from table 1, that when the indirect method is used, the synchronous measurement data can obtain a higher sensitivity estimation in the field, but lower on campus. The sensitivity value of the gradiometer on campus is similar to that in the field. In result, the sensitivity of JPM-4 is estimated to be 0.1nT@3s.

6. Conclusion

Two indirect methods for proton magnetometer sensitivity estimation are proposed in this paper, which are synchronization method and gradient method. The experimental results show that sensitivity estimated by gradient method is almost free from the environmental electromagnetic interference. For

the two magnetometers cannot be as rigorously synchronized as the gradiometer, the sensitivity estimated by synchronous method is vulnerable to environmental electromagnetic interference. For the proton magnetometer with 0.1nT sensitivity, the general environment can obtain accurate sensitivity estimation by indirect method. The indirect estimation method requires higher consistency of the apparatus, otherwise the converted sensitivity loses objective accuracy. The sensitivity of JPM-4 is estimated as 0.1nT@3s with the indirect methods mentioned above.

Acknowledgments
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