Measuring the absolute magnetic field using high-$T_c$ SQUID

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Abstract. SQUID normally can only measure the change of magnetic field instead of the absolute value of magnetic field. Using a compensation method, a mobile SQUID, which could keep locked when moving in the earth’s magnetic field, was developed. Using the mobile SQUID, it was possible to measure the absolute magnetic field. The absolute value of magnetic field could be calculated from the change of the compensation output when changing the direction of the SQUID in a magnetic field. Using this method and the mobile SQUID, we successfully measured the earth’s magnetic field in our laboratory.

1. Introduction
For some applications, it is necessary to measure the absolute magnetic field accurately. For example, the position on the earth can be precisely determined by measuring the amplitude and the direction of the earth’s magnetic field accurately. Long term monitoring the earth’s magnetic field is also a meaningful work.

A superconducting quantum interference filter (SQIF) made of high-$T_c$ Josephson junctions has been used for absolute magnetic field detection [1]. The absolute magnetic field can be estimated from the voltage change of the SQIF when adding or removing the magnetic shielding. The array of Josephson junctions in series must be prepared for this sensor.

The superconducting quantum interferences device (SQUID) has very good magnetic field sensitivity and has been used for many applications. The best field sensitivity of the high-$T_c$ SQUID is about 10 fT/$\sqrt{\text{Hz}}$ [2-3] with a wide bandwidth. However, the dynamic range of SQUID is only about several hundreds of nT and the SQUID normally can only measure the change of magnetic field instead of the absolute magnetic field.

Using a compensation method, we once developed the mobile high-$T_c$ SQUID [4]. For the mobile SQUID, the low frequency field was compensated, and the high frequency signal was not influenced, so the mobile SQUID could keep locked when moving in the earth’s magnetic field. As large as over 100 $\mu$T low frequency magnetic field could be compensated well for our previous mobile high-$T_c$ SQUID and the cut off frequency of the compensation could also be adjusted.

Using the mobile high-$T_c$ SQUID, we developed a method to measure the absolute magnetic field. When we change the direction of the mobile SQUID in a magnetic field, the compensation field of the mobile SQUID will also change. It is possible to calculate the amplitude and the direction of the magnetic field from the changes of compensation field.
2. Setup of the mobile high-$T_c$ SQUID

Figure 1 shows the setup of the mobile high-$T_c$ SQUID. To move it easily, the SQUID was put in a small cryostat with the size of $\phi 6.8 \text{ cm} \times 14.7 \text{ cm}$, and the plane of the SQUID was in vertical direction. The SQUID output signal was sent to the compensation circuit. A low pass filter was included in the compensation circuit. The dc and low frequency signals were feedback to the SQUID. By this way, the dc and low frequency signals of the SQUID output were cancelled. The cut off frequency of the compensation could be adjusted from 0 Hz to 1 kHz, it was 30 Hz in our experiments.

To supply big current to the compensation coil, a power amplifier was also included in the compensation circuit. The maximum output current of the power amplifier was about 200 mA. As large as 0.3 mT low frequency magnetic field, such as the earth’s magnetic field, could be compensated well using this compensation circuit.

A high-$T_c$ YBCO step-edge rf SQUID was used [5]. The effective area of the rf SQUID was about 0.53 mm$^2$, and the white magnetic field resolution was about 80 fT/$\sqrt{\text{Hz}}$. The compensation coil was wounded using 0.5 mm copper wire. It was 25 turns with the diameter of 4 cm. The compensation coil was connected to the compensation circuit through the compensation resistor of $R_c$. $R_c$ was 5 $\Omega$ in our experiments.

We measured the flux noise spectrum of the mobile SQUID by connecting the SQUID output to a vector signal analyzer. The measurements were done in our laboratory without magnetic shielding. Figure 2 shows the experimental results on flux noise. Spectrum (a) shows the flux noise spectrum of the rf SQUID when the compensation was off. The environmental noise was quite strong in our laboratory. The amplitude of the 50 Hz line interference was about 50 nT. The white flux noise was about 20 $\mu\Phi_0$/Hz. Spectrum (b) shows the flux noise spectrum when the compensation was on and the SQUID was kept static. We could see that the low frequency (below 30 Hz) noise spectrum was reduced due to the compensation and the high frequency noise spectrum was not influenced. Spectrum (c) shows the flux noise spectrum when the compensation was on and the SQUID was being moved in the earth’s magnetic field. The SQUID could keep locked when is was moved randomly by hand. We could see that low frequency noise spectrum was a little bit bigger than that of spectrum (b) and the high frequency noise spectrum was not influenced. The results proved that the compensation method could compensate the signal below the cut off frequency of 30 Hz and has less influence to the signal above the cut off frequency.

![Figure 1. The setup of the mobile high-$T_c$ rf SQUID](image-url)
Figure 2. The flux noise spectrum of the mobile high-\(T\) rf SQUID measured in our laboratory. (a) The flux noise spectrum when the compensation was off. (b) The flux noise spectrum when the compensation was on and the SQUID was kept static. (c) The flux noise spectrum when the compensation was on and the SQUID was moved in the earth’s magnetic field.

3. Measuring the absolute magnetic field using the mobile SQUID

For any magnetic field \(B\), it has three components: \(B_x\), \(B_y\), and \(B_z\). If we rotate the SQUID 180° along a direction, such as \(X\), the change of the compensation output will be 2\(B_x\). Thus, \(B_x\) can be measured from the change of the compensation output. Using the same method, \(B_y\) and \(B_z\) can also be measured. And then the amplitude and the direction of the magnetic field \(B\) can be calculated.

Figure 3 (a) The way of rotating the SQUID direction in the earth’s magnetic field. (b) The compensation output when the direction of the SQUID was moved from A to B, B to C, C to D and D to E. (c) The SQUID output when the SQUID was moved. The line interference of 50 Hz with the amplitude of about 50 nT could be observed.
Using this method, we successfully measured the earth’s magnetic field in our laboratory. First we supplied a signal to the compensation coil to calibrate the compensation field. We found that 24.08 μV voltage of the compensation output corresponded one Φ0 (3.87 nT). Then, we moved the SQUID in the earth’s field. Figure 3 (a) shows the way of moving. First, the SQUID was along A direction, then rotated it to B direction, then to C direction, then to D direction, and to E direction. At the same time, the compensation output and the SQUID output were monitored through a data acquisition board. Figure 3 (b) shows the changes of the compensation output. It changed a lot when the SQUID was moved. Figure 3 (c) shows the SQUID output, where, the dc level was zero and the 50 Hz line interference with the amplitude of about 50 nT could be observed. From the changes of the compensation output, we could estimate the earth’s magnetic field.

For the SQUID directions of A, B, C, D, and E, the compensation outputs were \( V_A = 52.60 \) mV, \( V_B = 168.2 \) mV, \( V_C = -108.2 \) mV, \( V_D = -223.8 \) mV, and \( V_E = -285.8 \) mV. \( (V_A+V_C)/2 = (V_B+V_D)/2 = 27.80 \) mV corresponded the compensation output when the component of the magnetic field was zero along the SQUID direction. \( (V_A+V_C)/2 \) and \( (V_B+V_D)/2 \) were matched. It means that the process works.

Then, we could calculate \( B_X, B_Y, B_Z \) and \( B \).

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\begin{align*}
B_X &= \frac{V_A - V_C}{2} \times \frac{3.87 \text{nT}}{24.08 \mu \text{V}} = 12.93 \mu \text{T} \\
B_Y &= \frac{V_B - V_D}{2} \times \frac{3.87 \text{nT}}{24.08 \mu \text{V}} = 31.51 \mu \text{T} \\
B_Z &= \left( \frac{V_A + V_C}{2} - V_E \right) \times \frac{3.87 \text{nT}}{24.08 \mu \text{V}} = 36.64 \mu \text{T} \\
B &= \sqrt{B_X^2 + B_Y^2 + B_Z^2} = 50.03 \mu \text{T}
\end{align*}
\]

The earth’s magnetic field in our laboratory was measured using the mobile SQUID. It was about 50.03 μT. Using a normal magnetic field sensor made of magnetoresistor, we also measured the magnetic field in our laboratory. The value was about 50.0 μT, which was similar as the result measured with SQUID.

**4. Conclusion and discussion**

Using the mobile high-\( T \) SQUID, we successfully measured the earth’s magnetic field. It is about 50.03 μT in our laboratory. Since the SQUID has high sensitivity, it is possible to measure the absolute magnetic field more accurately after all the parameters were calibrated carefully.

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