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Baseline optimization for scalar magnetometer array and its application in magnetic target localization*

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Generally, a magnetic target can be described with six parameters, three describing the position and three describing the magnetic moment. Due to a lack of sufficient components from one magnetometer, we need more than one magnetometer when locating the magnetic target. Thus, a magnetometer array should be designed. The baseline of the array is an important factor that affects the localization accuracy of the target. In this paper, we focus on the localization of a static target by using a scalar magnetometer array. We present the scalar magnetometer array with a cross-shaped structure. We propose a method of determining the optimal baseline according to the parameters of the magnetometer and detection requirements. In the method, we use the traditional signal-to-noise ratio (SNR) as a performance index, and obtain the optimal baseline of the array by using the Monte Carlo method. The proposed method of determining the optimal baseline is verified in simulation. The arrays with different baselines are used to locate a static magnetic target. The results show that the location performance is better when using the array with the optimal baseline determined by the proposed method.

Keywords: scalar magnetometer array, baseline optimization, Monte Carlo simulation, magnetic anomaly

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1. Introduction

A target containing ferromagnetic material can generate a magnetic anomaly under the geomagnetic field. The magnetic anomaly can be used to locate the magnetic target. Recently, various magnetic location techniques have been used in many areas, such as unexploded ordnance detection,[1,2] magnetic target tracking,[3–7] and human medical investigation.[8,9] In these location techniques, the magnetic target is considered as a magnetic dipole, which has six parameters, three describing the position and three describing the magnetic moment.[7] In order to calculate the parameters, we should construct at least six nonlinear functions. Thus, an array with the magnetometers is widely used to locate the magnetic target. Wynn[10] proposed a method of magnetic dipole localization based on the magnetic gradient. Nara[11] obtained a localization formula for magnetic dipole localization by magnetic vectors and its spatial gradients. The method requires the measurement of the magnetic anomaly field, and the accuracy of localization is highly sensitive to the noise in the magnetic anomaly field. In order to suppress the effect of the geomagnetic field, magnetic gradient tensor arrays comprising multiple vector magnetometers were proposed to locate the magnetic target.[7,12] Lee[13] presented a gradient-based method of locating and identifying a magnetic object in the presence of a geomagnetic field. Sui[14] proposed a method based on multiple-order magnetic gradient tensors for locating a magnetic dipole. The magnetic gradient tensor can improve the detection resolution of the target. However, there are still some problems in locating the magnetic target.

Comparing with the vector magnetometer, the advantage of the scalar magnetometer is that the measurement is almost not influenced by the orientation of measurement coordinate axes.[15] We can assemble a scalar magnetometer array without considering the orientation. Meanwhile, some kinds of scalar magnetometers such as an optically pumped magnetometer also have high sensitivities. For the localization of a target by using scalar magnetometers, some methods were proposed. Mcfee[16] proposed to measure the magnetic field in a two-dimensional grid and estimate the target localization and magnetic moment. Zalevsky[17] presented a high-resolution automatic detection algorithm based on a Wavelet transform and a scalar sensor array. Nelson[18] designed a multi-sensor towed array to detect the buried unexploded ordnance. The above methods are based on the data fitting. Thus, we need a single magnetic sensor or sensor array to measure the magnetic field with a designed scan routine (scan several lines). Fan[19] proposed the method to locate the magnetic target based on the scalar sensor array. In Ref. [19], an optimization problem was built according to the relationship be-

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tween the total geomagnetic field measured by magnetometers and their positions, which was calculated by an improved particle swarm optimization algorithm. This method of locating the target can reduce the computing time. Thus, the methods based on the scalar magnetometer array are also very important for locating the magnetic target.

In this paper, we present an array with a cross-shaped structure and propose a method of optimizing the baseline. An appropriate baseline of the array is very important for magnetic anomaly detection with high performance. We use the traditional signal-to-noise ratio (SNR) as a performance index, and obtain the optimal baseline of the array by using the Monte Carlo method.

2. Scalar magnetometer array and target localization

2.1. Baseline of the magnetometer array

A magnetic target can be considered as a magnetic dipole when the distance between the target and the sensor is bigger than three times the largest dimension of the target. The magnetic field vector $\boldsymbol{B}_{\rm a}$ induced by the dipole[20] is a function of distance $\boldsymbol{R}$ and the magnetic moment of its own. The magnetic field produced by the dipole can be described as

$$\boldsymbol{B}_{\rm a} = \frac{\mu_0 M}{4\pi}\left(\frac{3(\boldsymbol{m}\cdot\boldsymbol{R})\boldsymbol{R}}{R^5} - \frac{\boldsymbol{m}}{R^3}\right), \tag{1}$$

where $\mu_0 = 4\pi\times10^{-7}$ H/m is the permeability of free space, M is the magnitude of the magnetic moment, $\boldsymbol{m}$ is the unit direction vector of the magnetic moment, $\boldsymbol{R} = (x,y,z) = (x_m - x_0, y_m - y_0, z_m - z_0)$ with (x_m, y_m, z_m) denoting the position of the sensor, and (x_0, y_0, z_0) being the position of the magnetic target.

In practice, the magnetic field measured by the magnetometer includes the ambient geomagnetic field $\boldsymbol{B}_{\rm e}$ and the magnetic field $\boldsymbol{B}_{\rm a}$. When using a total field magnetometer to detect a remote target, we can assume that $|\boldsymbol{B}_{\rm a}| \le |\boldsymbol{B}_{\rm e}|$. In some approximation, the magnitude of the magnetic anomaly ΔB can be regarded as a projection of the magnetic field on the direction of the ambient geomagnetic field. Therefore, the measurement of the scalar magnetometer can be expressed as[21]

$$\begin{aligned} B_m &\approx B_{\rm e}\left(1 + \frac{\boldsymbol{B}_{\rm e}\cdot\boldsymbol{B}_{\rm a}}{B_{\rm e}^2}\right) + e_n \\ &= B_{\rm e} + \boldsymbol{u}\cdot\boldsymbol{B}_{\rm a} + e_n = B_{\rm e} + f(p) + e_n, \end{aligned} \tag{2}$$

where e_n is the noise of the scalar magnetometer, $f(p)$ is the magnetic anomaly generated by the target, with p denoting the parameter vector (x,y,z,M,θ,φ) of the target, $\boldsymbol{u} = [\cos I\cos D, \cos I\sin D, \sin I]$ denotes the unit vector of the ambient field, with I and D being the inclination and declination of the ambient geomagnetic field at the sensor position, respectively. Their values can be obtained from the international geomagnetic reference field (IGRF).

According to Eq. (2), we expand the function B_m into the Taylor series at the center of the array along with the x axis as shown in Fig. 1. Thus, the expression is given as

$$\begin{aligned} B_m &= B_{\rm e} + \frac{1}{1!}\frac{\partial f}{\partial x_m}\Delta x_m + \frac{1}{2!}\frac{\partial^2 f}{\partial x_m^2}\Delta x_m^2 \\ &\quad + \frac{1}{3!}\frac{\partial^3 f}{\partial x_m^3}\Delta x_m^3 + \cdots + e_n, \end{aligned} \tag{3}$$

where Δx_m is the variable quantity of x_m.

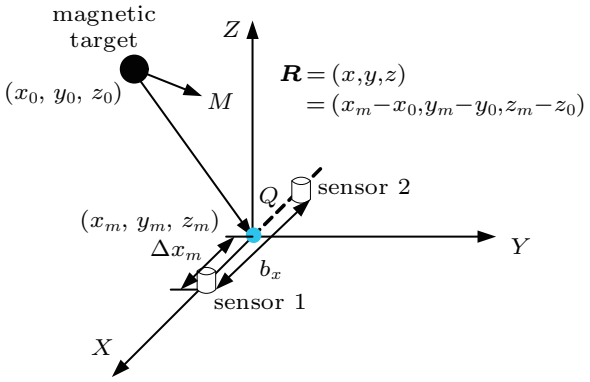


Fig. 1. (color online) Baseline analysis on the X axis.

Generally, the broad characteristics of the geomagnetic field are consistent over a local region. We can consider that its effect is the same as the measurement of each magnetometer in the array (shown in Fig. 2). Therefore, the magnetic field difference between sensor 1 and sensor 2 can be expressed as

$$\begin{aligned} B_{1m} - B_{2m} &= \frac{\partial f}{\partial x_m}(\Delta x_{1m} - \Delta x_{2m}) \\ &\quad + \frac{1}{3!}\frac{\partial^3 f}{\partial x_m^3}\left(\Delta x_{1m}^3 - \Delta x_{2m}^3\right) + \cdots + (e_{1n} + e_{2n}), \end{aligned} \tag{4}$$

where $e_{\rm in}$ denotes the noise of i-th magnetometer.

We define the baseline in the x direction as b_x. We can obtain that $\Delta x_{1m} = b_x/2$ and $\Delta x_{2m} = -b_x/2$. Thus, we can rewrite Eq. (4) as

$$B_{1m} - B_{2m} \approx G_x b_x + \frac{1}{24}\chi_3 b_x^3 + \cdots + (e_{1n} + e_{2n}), \tag{5}$$

where $G_x = \partial f/\partial x_m$ is the theoretical gradient value in the x-direction and $\chi_3 = \partial^3 f/\partial x_m^3$. Because the higher-order terms in Eq. (5) decay more rapidly, the higher-order terms may be neglected. Thus, the measured magnetic gradient can be approximated as

$$\tilde{G}_x \approx G_x + \frac{1}{24}\chi_3 b_x^2 + \frac{(e_{1n} + e_{2n})}{b_x}, \tag{6}$$

where $\tilde{G}_x = (B_{1m} - B_{2m})/b_x$ denotes the measured magnetic gradient.

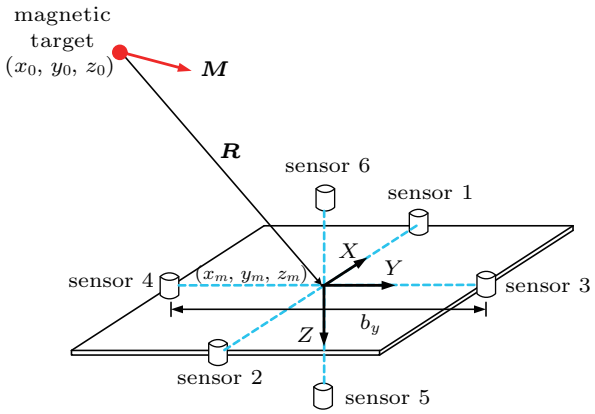


Fig. 2. (color online) Schematic diagram of scalar magnetometer array.

According to Eqs. (5) and (6), we can consider the measurement model of magnetic gradient based on the array as

$$\tilde{G}_x \approx G_x + e_{gx}, \tag{7}$$

where e_{gx} is the noise of the magnetic gradient. It is assumed that the noise e_{1n} and e_{2n} are independent random variables with mean 0 and variance σ_1 and σ_2. Thus, we can obtain the statistical distribution of e_{gx} as

$$e_{gx} \sim N\left(\frac{1}{24}\chi_3 b_x^2, \frac{\sigma_1^2+\sigma_2^2}{b_x^2}\right). \tag{8}$$

According to the 3σ principle of normal distribution, there are about 99.74% of e_{gx} dropping in the range $[\mu - 3\sigma, \mu + 3\sigma]$, which can be considered as a reasonable range of e_{gx}. The SNR is expressed as

$$\mathrm{SNR} = 10\log_{10}\frac{\left(\tilde{G}_x\right)^2}{\left(\frac{1}{24}\chi_3 b_x^2 + 3\sqrt{\frac{\sigma_1^2+\sigma_2^2}{b_x^2}}\right)^2}. \tag{9}$$

It is noted that the SNR is a function of array characteristic b_x, noise σ_i, relative position (x,y,z), and properties of the target (m_x, m_y, m_z). In order to determine the optimal baseline of the array, Monte Carlo simulation is carried out. The way to determine the baseline b_y and b_z (in the y direction and z direction) is similar to the method to determine b_x.

2.2. Baseline optimization based on Monte Carlo simulation

Monte Carlo simulation is a method to simulate a probabilistic based on the use of random number of variables.[22,23] It can be used to simulate the mathematics model many times with randomly choosing a value for each variable at each time. The output values in the simulation are collected and the statistical analysis on those values is obtained. Therefore, when using the Monte Carlo simulation for optimizing the baseline, we first generate a large number of random numbers of each variable according to its probability distribution. Then we calculate the value of SNR of each random number. Finally, we analyze the output values and determine the optimal baseline of the array.

2.2.1. Generating random numbers of each variable

In the baseline optimization, SNR is considered as a performance index. From Eq. (9), it is noted that SNR is a function of the variables $(b, \sigma, x, y, z, M, \theta, \varphi)$. Generally, the geomagnetic noise is of a Gaussian distribution with a mean of 0 nT and a standard deviation of $\sigma = 0.016$ nT.[24] The variables (x,y,z) are the position from the target to the measurement point. The variables (M, θ, φ) describe the properties of the target. Therefore, the probability distribution of parameters (x,y,z,M,θ,φ) can be considered as a uniform distribution, which can be determined by the detection requirements. Therefore, a large number (N) of random variables are generated according to their probability distribution.

2.2.2. Calculating value of SNR and analyzing output values

We substitute the random variables (x,y,z,M,θ,φ) and a certain b into Eq. (9) and calculate the SNR values. According to the threshold (H_s) of SNR, we count the numbers (S) of the random variables whose values are greater than H_s. Then,

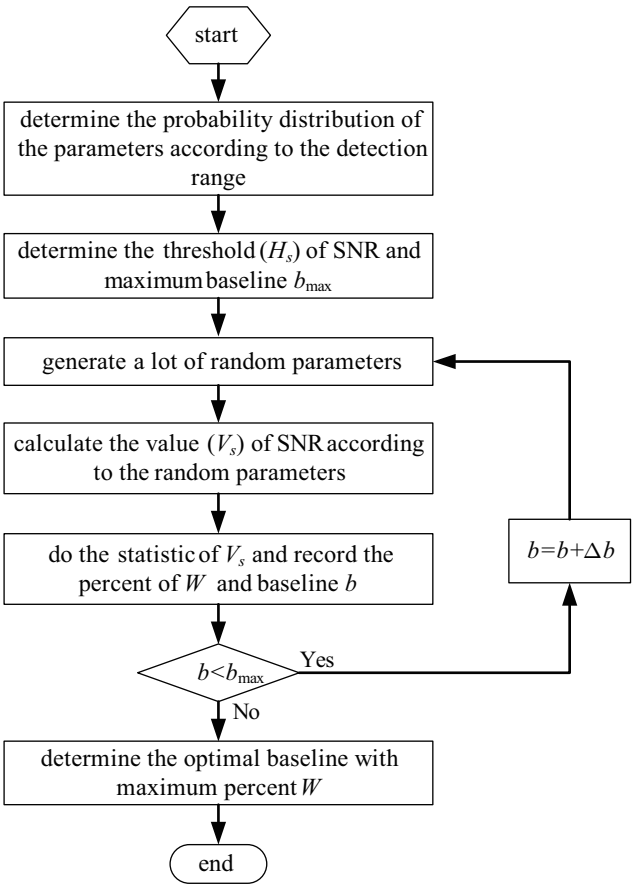


Fig. 3. Diagram of the baseline optimization by using Monte Carlo simulation.

we can calculate the percent as follows:

$$W = \frac{S}{N} \times 100. \tag{10}$$

When the baseline b is changed, the numbers (S) change as well. Thus, the present W can be considered as a function of baseline b. We can determine an optimal baseline with the maximum W. The diagram of the optimization using Monte Carlo simulation is shown in Fig. 3.

2.3. Target localization based on array

Measurement of magnetic gradients can effectively minimize regional effects and eliminate temporal magnetic variations.[25] Therefore, the gradient of the magnetic anomaly is commonly used in locating the magnetic target. The gradient of the total magnetic anomaly can be expressed as

$$\nabla f = \frac{\partial f}{\partial x} i + \frac{\partial f}{\partial y} j + \frac{\partial f}{\partial z} k. \tag{11}$$

Three components of total magnetic anomaly are expressed as

$$G_x = \frac{\partial f}{\partial x} = \frac{\alpha(\boldsymbol{M}\cdot\boldsymbol{R})}{R^7}\left[5(\boldsymbol{u}\cdot\boldsymbol{R})x - u_x R^2\right] - \frac{\alpha(\boldsymbol{u}\cdot\boldsymbol{M})}{R^5}x - \frac{\alpha(\boldsymbol{u}\cdot\boldsymbol{R})}{R^5}M_x, \tag{12}$$

$$G_y = \frac{\partial f}{\partial y} = \frac{\alpha(\boldsymbol{M}\cdot\boldsymbol{R})}{R^7}\left[5(\boldsymbol{u}\cdot\boldsymbol{R})y - u_y R^2\right] - \frac{\alpha(\boldsymbol{u}\cdot\boldsymbol{M})}{R^5}y - \frac{\alpha(\boldsymbol{u}\cdot\boldsymbol{R})}{R^5}M_y, \tag{13}$$

$$G_z = \frac{\partial f}{\partial z} = \frac{\alpha(\boldsymbol{M}\cdot\boldsymbol{R})}{R^7}\left[5(\boldsymbol{u}\cdot\boldsymbol{R})z - u_z R^2\right] - \frac{\alpha(\boldsymbol{u}\cdot\boldsymbol{M})}{R^5}z - \frac{\alpha(\boldsymbol{u}\cdot\boldsymbol{R})}{R^5}M_z, \tag{14}$$

where $\alpha = -3\mu_0/4\pi$.

Equations (12)–(14) are high-order nonlinear functions. We can use the nonlinear optimization method to solve the equations. The most common approach is to determine an objective error function when using the optimization method. According to Eqs. (12)–(14), the objective error function is defined as

$$E = \sum_{i=1}^{N}\left[\left(\tilde{G}_{ix} - G_{ix}\right)^2 + \left(\tilde{G}_{iy} - G_{iy}\right)^2 + \left(\tilde{G}_{iz} - G_{iz}\right)^2\right], \tag{15}$$

where i denotes the i-th measuring point; G_x, G_y, and G_z refer to the calculated gradients of magnetic field.

It can be seen that equation (15) represents the mean-squared error between the measured gradient and the calculated gradient of the magnetic field. Therefore, it is a least squares problem. The solution can be calculated by the optimization method which minimizes the objective error. The common algorithms include genetic algorithm (GA),[26] particle swarm optimization (PSO) algorithm,[4,19,27] Levenberg–Marquardt (LM) algorithm,[12,27] etc.

3. Simulation

The simulation was designed to verify the effectiveness of the proposed method of optimizing the baseline. Firstly, we used the proposed method to determine the optimal baseline of the array. The Monte Carlo simulation method was used to determine the optimal baseline of the array, according to the requirements. The sensor array was designed for locating a target in a range of magnetic moment from 200 A·m^2 to 600 A·m^2. The maximum detection range of the array was 15 m, and the SNR should be greater than 15 dB. The result is shown in Fig. 4. It is noted that the percentage of SNR whose value is greater than 15 dB increases with the increase of baseline when the baseline is less than 1.8 m. Then, the percentage of SNR greater than 15 dB decreases with the increase of baseline. From Fig. 4, we find that the optimal baselines b_x, b_y, and b_z are 1.8 m.

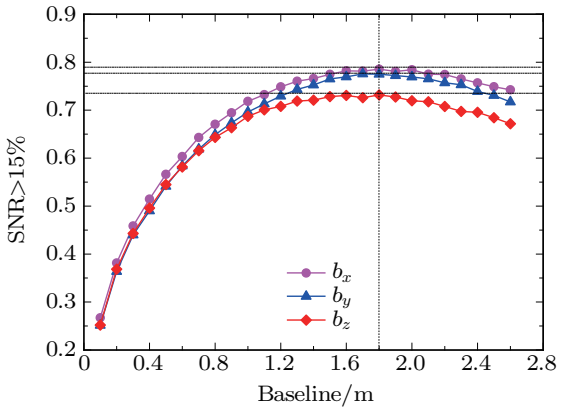


Fig. 4. (color online) Plots of percentage of SNR greater than 15 dB versus baseline (maximum detection range: 15 m).

Secondly, the arrays with different baselines were used to locate a magnetic target. The target was located at the point (1 m, 1 m, 1 m) and its magnetic moment was (348.18 A·m^2, −61.39 A·m^2, 353.55 A·m^2). The array moved on the path which was parallel to the X axis, starting at the point (−6 m, 9 m, 0 m) and ending at the point (6 m, 9 m, and 0 m). The sampling interval was 0.5 m. In addition, we considered that the measure noise at each magnetometer was of a Gaussian distribution with a mean of 0 nT and a standard deviation of 0.016 nT.[25] We used the localization method based on the array to locate the target. The results are shown in Figs. 5 and 6. The frequency histograms of calculated positions of the target are shown in Fig. 5 based on the sensor arrays with the different baselines. It is noted that the frequency of the calculated position of the target, which is close to the true value, is high when using the sensor array with an optimal baseline. The frequency histograms of calculated moments of the target are shown in Fig. 6. It is also noted that the frequency of the calculated moment of the target, which is close to the true value, is high when using the sensor array with an optimal baseline. It means that the proposed method of determining the optimal baseline of the array is effective.

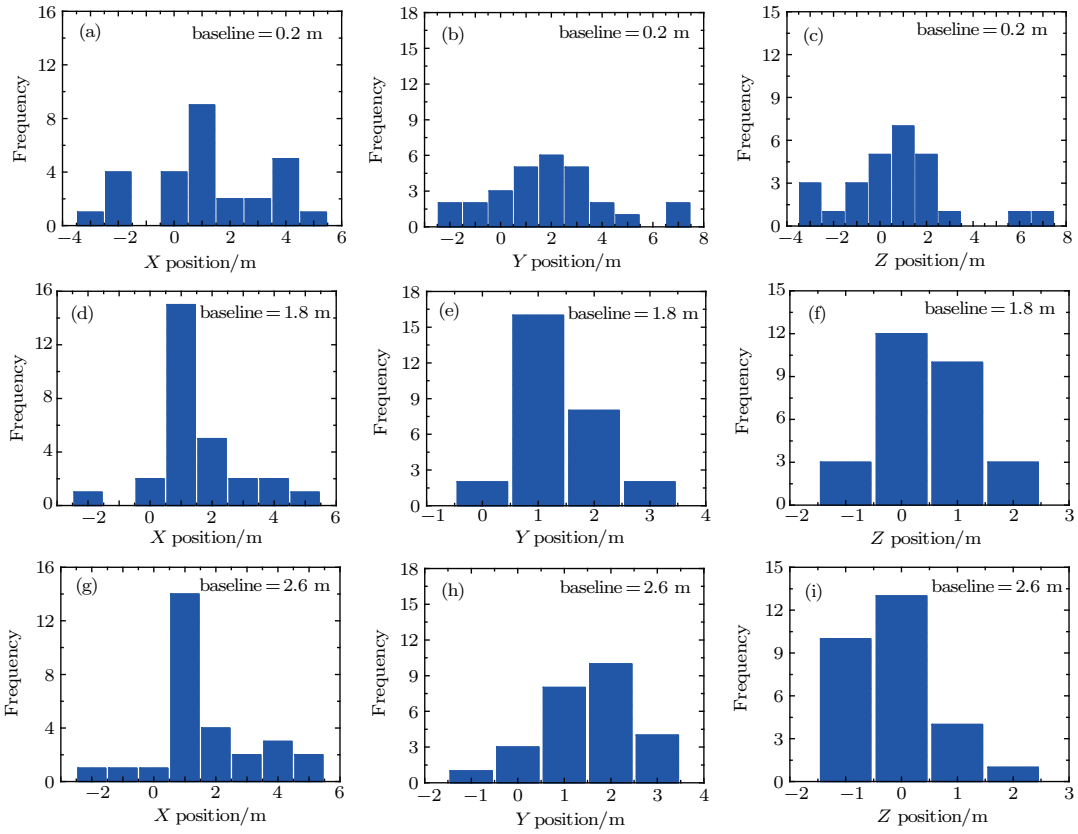


Fig. 5. (color online) Frequency histograms of the calculated position of the target. (a) Calculated X position with 0.2-m baseline; (b) calculated Y position with 0.2-m baseline; (c) calculated Z position with 0.2-m baseline; (d) calculated X position with 1.8-m baseline; (e) calculated Y position with 1.8-m baseline; (f) calculated Z position with 1.8-m baseline; (g) calculated X position with 2.6-m baseline; (h) calculated Y position with 2.6-m baseline; and (i) calculated Z position with 2.6-m baseline.

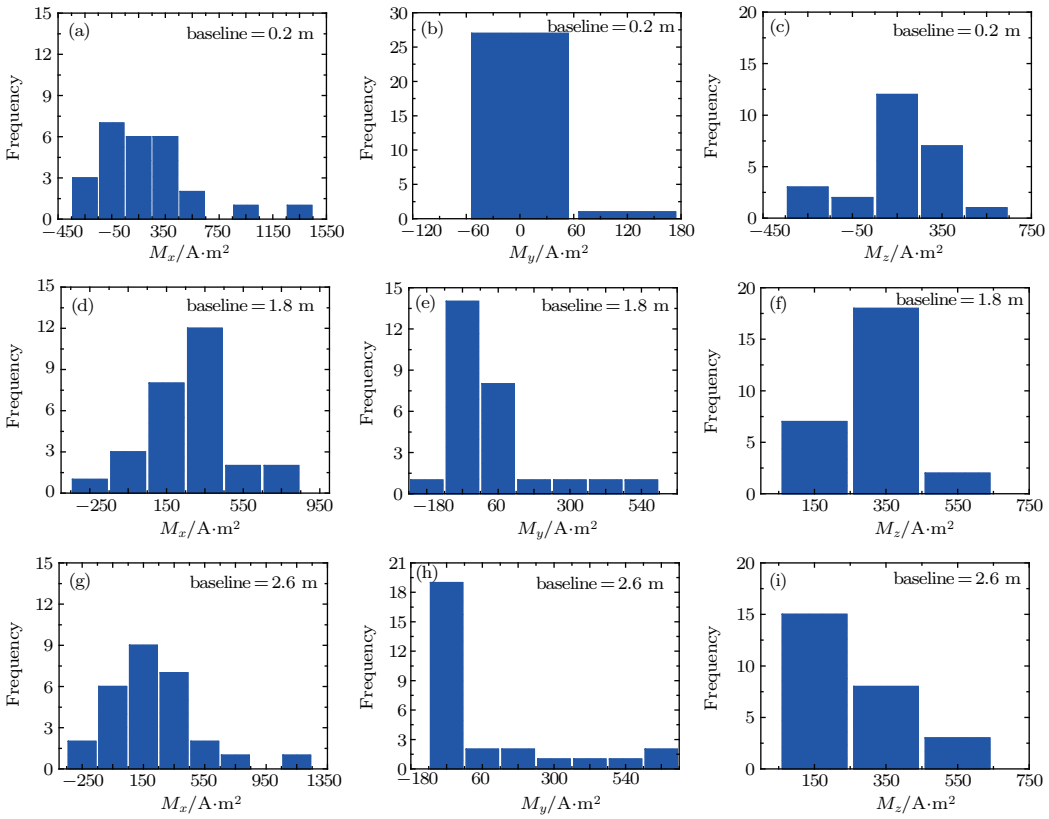


Fig. 6. (color online) Frequency histograms of calculated magnetic moment of the target. (a) Calculated magnetic moment M_x with 0.2-m baseline; (b) calculated magnetic moment M_y with 0.2-m baseline; (c) calculated magnetic moment M_z with 0.2-m baseline; (d) calculated magnetic moment M_x with 1.8-m baseline; (e) calculated magnetic moment M_y with 1.8-m baseline; (f) calculated magnetic moment M_z with 1.8-m baseline; (g) calculated magnetic moment M_z with 2.6-m baseline; (h) calculated magnetic moment M_y with 2.6-m baseline; and (i) calculated magnetic moment M_z with 2.6-m baseline.

4. Experiment

An SUV as the target with a constant velocity (−0.87 m/s, 0 m/s, and 0 m/s) was moved along the plan trajectory in the horizontal plane, starting from the point (17.0 m, 18.25 m, 0 m) and ending at the point (−25.5 m, 18.25 m, 0 m). The magnetic moment of the SUV was about 485.8 Am^2.

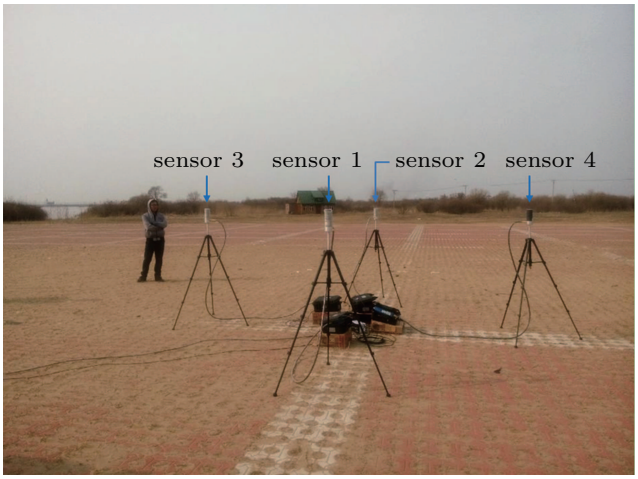


Fig. 7. (color online) Magnetometer array in experiment.

There were only four scalar magnetometers (CS-L) in the experiment. The array was designed as shown in Fig. 7. Thus, the magnetic anomaly in the Z direction was obtained by using the simulation method according to the position and magnetic moment of the SUV. The array was designed for locating a target in a range of magnetic moment from 450 A·m^2 to 550 A·m^2. The maximum detection range of the array was 40 m, and the signal-to-noise ratio (SNR) should be greater than 15 dB. The results are shown in Fig. 8. From Fig. 8, we find that the optimal baselines are respectively $b_x = 4.0$ m, $b_y = 3.8$ m, and $b_z = 3.8$ m. In the experiment, we used arrays with different baselines to locate a moving target. The baselines of one array are $b_x = 4.0$ m, $b_y = 4.0$ m, and $b_z = 3.8$ m. The baselines of the other array are $b_x = 8.0$ m, $b_y = 8.0$ m, and $b_z = 8.0$ m.

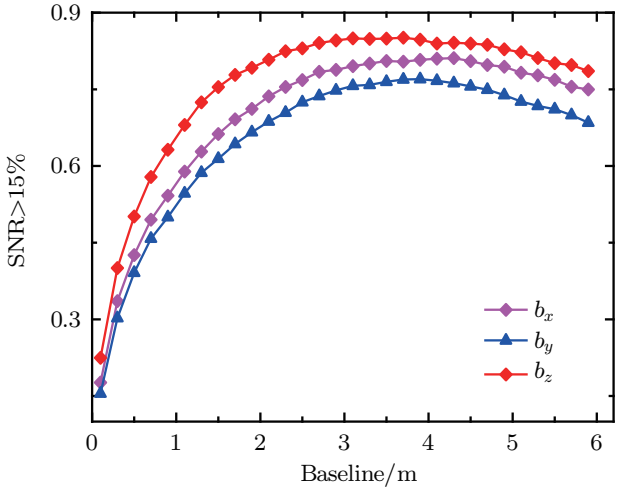


Fig. 8. (color online) Plots of percentage of SNR greater than 15 dB versus baseline (maximum detection range: 40 m).

We used the localization method based on the array to locate the target. The results are shown in Figs. 9–11. As shown in Fig. 9, the localization results are in accordance with the real object positions. The localization by using the array with 4-m baseline is better than that by using the array with 8-m baseline. From Fig. 10, we can see that the averages of the estimated velocity of the target are $v_x = -0.82$ m/s and $v_y = 0.03$ m/s when using the array with 4-m baseline. However, the averages of the estimated velocity of the target are $v_x = -0.68$ m/s and $v_y = 0.03$ m/s when using the array with 8-m baseline. The estimated magnetic moment of the target is shown in Fig. 11. The error of the estimated magnetic moment by using the arrays with the different baselines are not much larger.

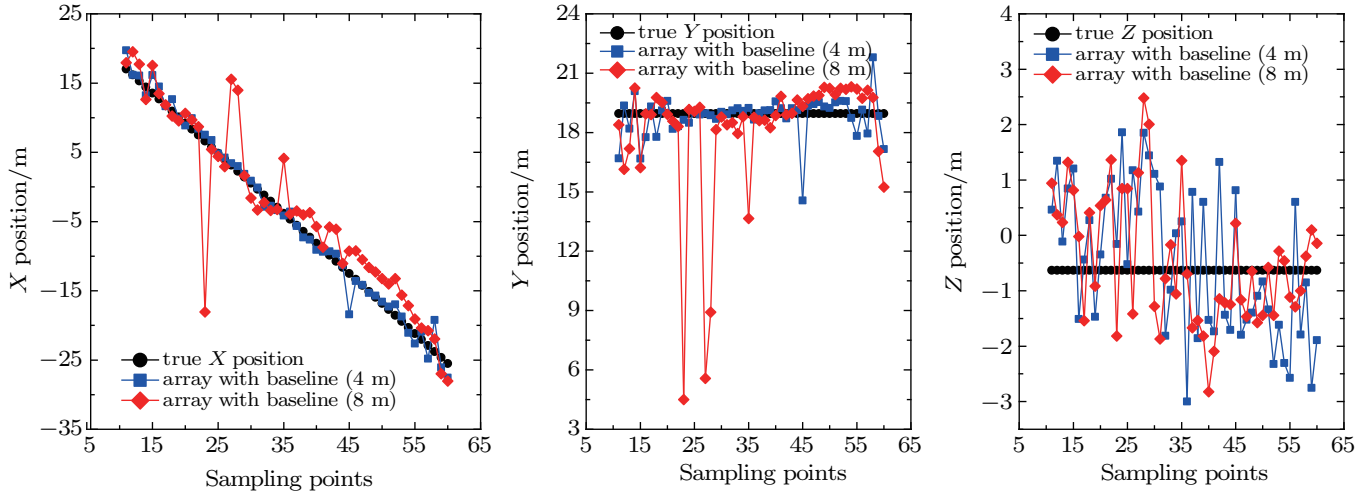


Fig. 9. (color online) Estimated parameters of moving magnetic target based on arrays with different baselines.

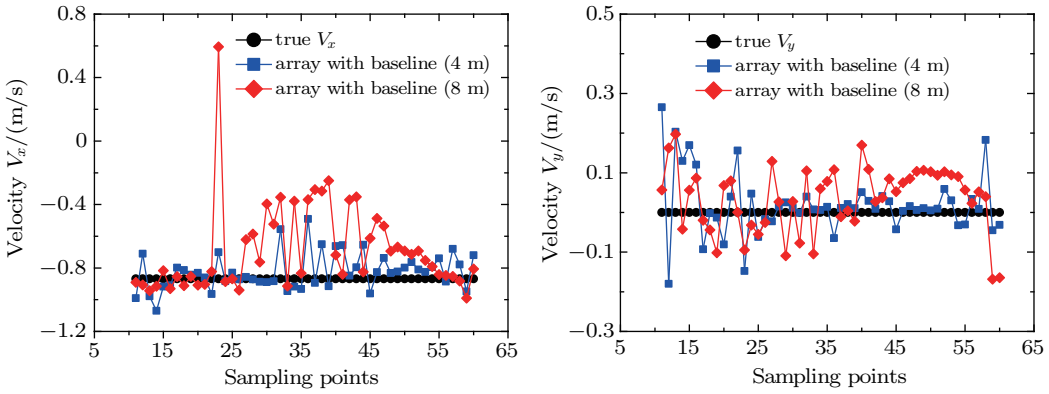


Fig. 10. (color online) Estimated velocities of the moving magnetic target based on arrays with different baselines.

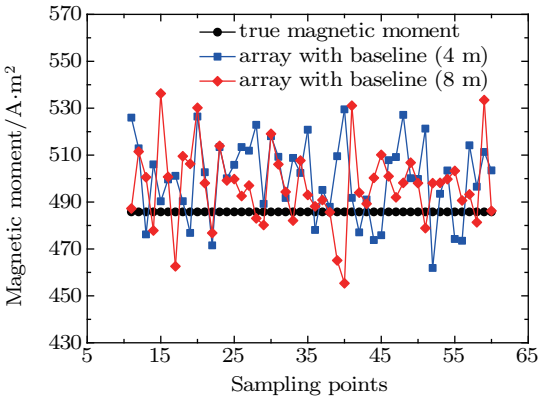


Fig. 11. (color online) Estimated magnetic moments of moving target based on arrays with different baselines.

5. Conclusions and perspectives

Generally, a sensor array is used to locate a magnetic target. The baseline of the array is an important factor that affects the localization accuracy of the target. Therefore, we present a method of determining the optimal baseline of a scalar sensor array with the Monte Carlo method. According to the detection requirements, the optimal baseline can be determined by the proposed method. The proposed method of determining the optimal baseline is verified by the simulation. In the simulation, the arrays with different baselines are used to locate a static magnetic target. The location performance is better, when the sensor array has the optimal baseline determined by the proposed method.

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