Research on Improving Artillery Firing Accuracy by Using Meteorological Data along Ballistic Trajectory for Artillery Firing

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Abstract. In traditional artillery shooting, meteorological information is provided by meteorological unit, but because of the inconsistency between meteorological observation sites and shooting sites, there are errors in meteorological data, which affects shooting accuracy. In order to reduce the influence of meteorological data errors on firing accuracy, it is proposed to acquire multi-meteorological data along the ballistic trajectory by using the dropsonde carried by the UAV, and calculate the meteorological data along the ballistic trajectory for artillery firing. Through simulation calculation, using meteorological data along the ballistic for artillery firing can effectively improve firing accuracy.

1. Introduction
In traditional artillery firing, meteorological stations or meteorological units are used to provide meteorological information for artillery firing. Because meteorological stations can only detect meteorological elements in one place, there must be some errors in replacing meteorological elements in the whole ballistic trajectory with meteorological elements in this place. Even in the case of stable weather conditions, this error will cause a deviation of 5% to 10% between the actual range and the range on the fire table. Especially in artillery long-range strike, the errors caused by meteorological elements will increase with the increase of range, and because of the larger range, the meteorology between artillery position and target point may change greatly. The errors caused by replacing meteorological elements of the whole ballistic trajectory with meteorological elements of one location will be greater. Therefore, the use of meteorological data along the trajectory for artillery firing is proposed to reduce the errors caused by the inconsistency of time and place in meteorological preparation and improve the firing accuracy.

2. Acquisition of meteorological data along trajectory
The acquisition of meteorological data along the trajectory can be detected by UAV. Firstly, UAV drops several dropsondes along the trajectory. During the falling process, the sounder can detect the temperature, humidity, air pressure and wind data at different altitudes in the vertical direction, as shown in Figure 1. Then, the multi-meteorological data are calculated by fitting polynomial method, and the meteorological data along the trajectory are obtained.
2.1. Detection of meteorological data of dropsonde

2.1.1. Principle of Warm and Wet Pressure. Using GPS digital electronic dropsonde, the sounding instrument can complete a series of tasks of meteorological data acquisition, processing and transmission. The temperature sensor adopts thermistor, which can effectively avoid the influence of long wave radiation on temperature measurement. Humidity sensor adopts humidity sensitive resistor, which can ensure good measurement accuracy, long-term stability and relatively small lag. The pressure is measured directly by a silicon single crystal empty cell pressure sensor.

2.1.2. Principle of wind measurement by GPS dropsonde. During the descent of the GPS sounder, the speed of the sounder descends approximately uniformly under the action of a parachute. When there are more than four effective satellites, the GPS system measures the distance between the satellite and the GPS receiver of the sounder by spread spectrum communication technology, and then calculates the three-dimensional coordinates of the sounder and the time at this moment. Then the actual wind speed and direction can be calculated by the following formula through the coordinates of the two adjacent points of the sounder relative to the base station during the descent process:

\[
\theta = \arctan \left( \frac{y_2 - y_1}{x_2 - x_1} \right) \tag{1}
\]

\[
v = \sqrt{\left( x_2 - x_1 \right)^2 + \left( y_2 - y_1 \right)^2} / t \tag{2}
\]

2.2. Acquisition of meteorological data along ballistic trajectory by fitting method

2.2.1. Least square fitting. With \( n+1 \) pairs of tabular data \((x_j, y_j)(j = 0, 1, 2, \cdots, n)\), the following equations are established using these data.

\[
\varphi(x) = a_0 + a_1 x + a_2 x^2 + \cdots + a_m x^m \tag{3}
\]

It is used to fit the given table function. When order \( m \) is determined, the polynomial can be determined by only finding \( a_0, a_1, a_2, \cdots, a_m \). \( a_0, a_1, a_2, \cdots, a_m \) is obtained by minimizing the sum of squares of residuals as the optimal criterion. According to the principle of finding the minimum value of multivariate function, the normal equation fitted by the least square method is finally obtained as follows.

\[
\begin{bmatrix}
\sum_{j=0}^{n} x_j & \sum_{j=0}^{n} x_j^2 & \cdots & \sum_{j=0}^{n} x_j^m \\
\vdots & \ddots & \vdots & \vdots \\
\sum_{j=0}^{n} x_j^m & \sum_{j=0}^{n} x_j^{m+1} & \cdots & \sum_{j=0}^{n} x_j^{m+n}
\end{bmatrix}
\begin{bmatrix}
a_0 \\
a_1 \\
\vdots \\
a_m
\end{bmatrix}
= 
\begin{bmatrix}
\sum_{j=0}^{n} y_j \\
\vdots \\
\sum_{j=0}^{n} x_j^{m} y_j
\end{bmatrix} \tag{4}
\]

By solving the above formula, \( m+1 \) polynomial coefficients \( a_0, a_1, a_2, \cdots, a_m \) can be obtained.

2.2.2. Acquisition of air temperature and pressure. Firstly, according to the temperature information measured by each dropsonde, the coefficient of fitting polynomial is calculated from the normalization equation (4), and the temperature fitting polynomial of each dropsonde detection point is obtained. Then the coordinates of any point on the ballistic trajectory are substituted into the temperature fitting polynomial to calculate the temperature of each point on the ballistic trajectory. Because quadratic polynomial has the advantages of high fitting accuracy and moderate calculation, we use quadratic polynomial to fit temperature polynomial. Firstly, the temperature data measured by
each dropsonde are fitted with \( N \) curves according to equation (6). The expression of the curve is as follows:

\[
\begin{align*}
T_1(y) &= a_{10} + a_{11}y + a_{12}y^2 \\
T_2(y) &= a_{20} + a_{21}y + a_{22}y^2 \\
&\quad \vdots \\
T_N(y) &= a_{N0} + a_{N1}y + a_{N2}y^2
\end{align*}
\]

In formula: \( T \) represents temperature and \( N \) is the number of dropsondes.

By substituting the \( Y \)-axis coordinate of the arbitrary point \( R(x_0, y_0) \) of ballistic trajectory into equation (5), a series of corresponding relations between \( x \) and \( T \) are obtained. Then the series of data are fitted into quadratic polynomials, and the expression of temperature curve at \( y_0 \) altitude is obtained.

\[
T(x) = a_0 + a_1x + a_2x^2 \quad (y = y_0)
\]

Then the \( X \)-axis coordinate of the arbitrary point \( R(x_0, y_0) \) of the trajectory is substituted into (6), and the temperature of the arbitrary point \( R \) is calculated.

\[
T_R = a_0 + a_{x0} + a_{x2}x_0^2 \quad (y = y_0)
\]

The acquisition of air pressure is similar to that of temperature, so there is no further discussion here.

2.2.3. Wind Acquisition. Unlike the acquisition of temperature, wind is a vector unit, which has both size and direction. Therefore, it is necessary to decompose the vector of wind into scalars on \( X \)-axis and \( Z \)-axis. If the angle between wind and \( X \)-axis is \( \theta \), then the wind on \( X \)-axis and \( Z \)-axis is respectively:

\[
\begin{align*}
W_X &= W \cos \theta \\
W_Z &= W \sin \theta
\end{align*}
\]

Secondly, the quadratic polynomial fitting of the wind on \( X \)-axis and \( Y \)-axis is carried out, and the results are as follows:

\[
\begin{align*}
W_{X1}(y) &= a_{10} + a_{11}y + a_{12}y^2 \\
W_{X2}(y) &= a_{20} + a_{21}y + a_{22}y^2 \\
&\quad \vdots \\
W_{XN}(y) &= a_{N0} + a_{N1}y + a_{N2}y^2 \\
W_{Z1}(y) &= a_{10} + a_{11}y + a_{12}y^2 \\
W_{Z2}(y) &= a_{20} + a_{21}y + a_{22}y^2 \\
&\quad \vdots \\
W_{ZN}(y) &= a_{N0} + a_{N1}y + a_{N2}y^2
\end{align*}
\]

In formula: \( W_X \) means vertical wind, \( W_Z \) means crosswind and \( N \) means the number of dropsondes.

By substituting \( Y \)-axis coordinates of arbitrary point \( R(x_0, y_0) \) of ballistic trajectory into equation (9) and equation (10), a series of corresponding relations between \( x \) and \( W_X \) and \( W_Z \) are obtained.
Then the series of points are fitted into quadratic polynomials, and the expressions of longitudinal and cross-wind curves of arbitrary point $R$ of ballistic trajectory are obtained:

$$
\begin{align*}
W_x(x) &= a_0 + a_1 x + a_2 x^2 \\
W_y(x) &= a_0 + a_1 x + a_2 x^2
\end{align*}
$$

(11)

By substituting the X-axis coordinate of arbitrary point $R(x_0, y_0)$ into formula (11), the longitudinal $W_x(x_0, y_0)$ and cross wind $W_z(x_0, y_0)$ of arbitrary point $R$ in ballistic trajectory are calculated. Finally, the wind speed of arbitrary point $R$ is obtained according to the formula of synthesis operation.

$$
W_R = \sqrt{W_x^2(x_0, y_0) + W_z^2(x_0, y_0)}
$$

(12)

Since the wind direction at any point in the trajectory can come from any direction, different quadrants of the wind speed $R(W_{R_x}, W_{R_z})$ at any point in the plane coordinate system can be obtained according to different formulas. If $R(W_{R_x}, W_{R_z})$ is in the first quadrant, as shown in Figure 2, then it is calculated by formula (13) and other analogies.

$$
\theta = \arcsin \frac{W_{R_z}}{W_R}
$$

(13)

If $R(W_{R_x}, W_{R_z})$ is in the second and third quadrants, it is calculated according to formula (14).

$$
\theta = 180 - \arcsin \frac{W_{R_z}}{W_R}
$$

(14)

If $R(W_{R_x}, W_{R_z})$ is in the fourth quadrant, it is calculated by formula (15).

$$
\theta = 360 + \arcsin \frac{W_{R_z}}{W_R}
$$

(15)

3. Calculating Ballistic Elements by Using Meteorological Data along Ballistic Trajectory
Taking a certain type of artillery as the research object, the firing accuracy of artillery firing using meteorological bulletin and meteorological data along ballistic trajectory is analyzed. The results of shooting distance and sideslip are calculated at different angles of fire and different charge numbers.

Midpoint meteorological bulletin is omitted due to confidentiality. The meteorological data along the trajectory are shown in Table 1.
Table 1. Along-trajectory meteorological data.

| Height (m) | Air temperature (°C) | Pressure (hPa) | Wind speed (m/s) | Wind direction (°) | Height (m) | Air temperature (°C) | Pressure (hPa) | Wind speed (m/s) | Wind direction (°) |
|------------|-----------------------|----------------|------------------|-------------------|------------|-----------------------|----------------|------------------|------------------|
| 107        | 24.7                  | 1033.4         | 13.0             | 295.8             | 4950       | -34.4                 | 1028.4         | 11.6             | 91.7             |
| 235        | 22.9                  | 1026.8         | 12.3             | 225.4             | 4742       | -31.2                 | 1022.5         | 11.0             | 81.6             |
| 378        | 20.7                  | 1018.9         | 11.4             | 164.4             | 4535       | -28.3                 | 1015.8         | 10.5             | 71.8             |
| 532        | 18.2                  | 1010.0         | 9.7              | 115.9             | 4357       | -26.2                 | 1006.8         | 10.1             | 65.0             |
| 695        | 15.6                  | 1000.4         | 8.2              | 80.1              | 4180       | -24.2                 | 999.0          | 9.9              | 70.3             |
| 857        | 12.9                  | 991.1          | 9.0              | 56.9              | 3910       | -21.4                 | 990.8          | 8.9              | 82.7             |
| 1010       | 10.5                  | 982.5          | 9.9              | 43.7              | 3746       | -19.8                 | 982.0          | 9.8              | 87.7             |
| 1185       | 7.9                   | 973.1          | 10.8             | 36.2              | 3590       | -18.3                 | 973.9          | 9.8              | 92.5             |
| 1305       | 6.2                   | 967.0          | 11.9             | 45.7              | 3437       | -16.8                 | 966.5          | 7.9              | 82.1             |
| 1478       | 3.8                   | 958.5          | 11.0             | 54.5              | 3285       | -15.4                 | 958.5          | 9.0              | 71.2             |
| 1610       | 2.1                   | 952.4          | 9.8              | 38.5              | 3127       | -13.9                 | 952.0          | 10.1             | 79.8             |
| 1775       | 0.1                   | 945.2          | 10.2             | 43.5              | 2965       | -12.4                 | 944.8          | 9.2              | 67.8             |
| 1937       | -1.9                  | 938.5          | 10.5             | 59.1              | 2770       | -10.5                 | 938.0          | 10.3             | 74.4             |
| 2090       | -3.6                  | 932.5          | 11.4             | 54.6              | 2615       | -9.0                  | 930.4          | 10.4             | 70.9             |
| 2245       | -5.3                  | 926.7          | 10.8             | 60.0              | 2464       | -7.5                  | 925.0          | 11.4             | 66.9             |
| 2416       | -7.0                  | 902.5          | 11.2             | 75.5              | 2290       | -5.8                  | 918.8          | 10.5             | 61.5             |
| 2580       | -8.7                  | 914.8          | 10.5             | 90.1              | 2145       | -4.2                  | 913.6          | 9.5              | 56.6             |
| 2765       | -10.5                 | 908.6          | 9.9              | 74.3              | 1950       | -2.5                  | 908.4          | 10.5             | 49.6             |
| 2974       | -12.5                 | 901.8          | 10.1             | 77.9              | 1784       | -0.1                  | 902.4          | 9.7              | 43.7             |
| 3155       | -14.2                 | 896.0          | 10.5             | 82.1              | 1620       | 1.9                   | 896.9          | 8.5              | 38.8             |
| 3327       | -15.8                 | 890.6          | 11.5             | 71.5              | 1479       | 3.8                   | 891.9          | 9.0              | 35.7             |
| 3510       | -17.5                 | 884.9          | 10.8             | 75.3              | 1315       | 6.0                   | 887.1          | 9.7              | 34.5             |
| 3705       | -19.4                 | 878.9          | 11.4             | 80.7              | 1170       | 8.1                   | 882.4          | 11.5             | 36.6             |
| 3884       | -21.1                 | 873.5          | 11.1             | 92.7              | 1020       | 10.4                  | 877.7          | 10.6             | 43.0             |
| 4010       | -22.4                 | 869.8          | 10.4             | 98.5              | 862        | 12.9                  | 872.7          | 11.9             | 56.4             |
| 4273       | -25.2                 | 862.1          | 9.4              | 85.1              | 720        | 15.2                  | 864.8          | 12.2             | 75.8             |
| 4450       | -27.3                 | 857.1          | 10.4             | 87.8              | 586        | 17.3                  | 859.7          | 12.9             | 102.4            |
| 4648       | -29.8                 | 851.6          | 9.4              | 81.6              | 432        | 19.8                  | 854.7          | 10.5             | 145.5            |
| 4820       | -32.3                 | 847.0          | 10.8             | 93.6              | 314        | 21.7                  | 849.0          | 13.0             | 189.6            |
| 5010       | -35.5                 | 842.0          | 11.7             | 85.8              | 206        | 23.3                  | 843.6          | 13.5             | 240.0            |

Surface temperature: 299.6K  Ground Pressure: 1039.3mm  Ground Wind Speed: 13.5m/s  altitude of Meteorological Station: 54m

In theory, the meteorological data along the trajectory can more truly reflect the real meteorological conditions of the whole trajectory. Therefore, the shooting distance and sideslip calculated by the meteorological data along the trajectory are taken as accurate values, and the deviation of shooting distance and sideslip calculated by the meteorological bulletin at the midpoint of the trajectory is analyzed. Through the trajectory element calculation software, the calculation results of shooting distance and sideslip at different charge numbers and angles are shown in Table 2 (Table 4-Table 7 is outlined).

Table 2. Contrast of shooting distance and deviation of full charge under various meter scales.

| Firing angle $\theta_c$ (mil) | Range of fire $X_c (m)$ | Side deviation $Z_c (m)$ |
|------------------------------|-------------------------|-------------------------|
| Meteorological Bulletin $X_{c1}$ | Along-trajectory meteorological data $X_{c2}$ | Absolute deviation $|X_{c2} - X_{c1}|$ | Meteorological Bulletin $X_{c1}$ | Along-trajectory meteorological data $X_{c2}$ | Absolute deviation $|X_{c2} - X_{c1}|$ |
| 417                          | 14163                   | 14094                   | 69                    | 152                    | 138                    | 14                      |
| 583                          | 16052                   | 15922                   | 130                   | 218                    | 208                    | 10                      |
| 750                          | 16806                   | 16606                   | 200                   | 277                    | 263                    | 14                      |
Table 3. Contrast of shooting distance and deviation of No.1 charge under various meter scales.

| Firing angle \( \theta_c (\text{mil}) \) | Range of fire \( X_c (m) \) | Side deviation \( Z_c (m) \) |
|------------------------------------------|----------------------------|-----------------------------|
| Meteorological Bulletin \( X_{c1} \) | Along-trajectory meteorological data \( X_{c2} \) | Absolute deviation \( |X_{c2} - X_{c1}| \) | Meteorological Bulletin \( X_{c1} \) | Along-trajectory meteorological data \( X_{c2} \) | Absolute deviation \( |X_{c2} - X_{c1}| \) |
| 417 | 12994 | 12954 | 40 | 113 | 114 | 1 |
| 583 | 14835 | 14751 | 84 | 178 | 176 | 2 |
| 750 | 15585 | 15398 | 187 | 231 | 237 | 6 |

It can be seen from tables 2 and 3 that:

1. There are deviations in shooting distance and sideslip calculated by means of midpoint meteorological bulletin and meteorological data along the trajectory, and the deviation is large, reaching 200 meters at the maximum. Especially when the range is large and the trajectory is high, the high-altitude wind varies greatly and the deviation is large. It shows that it is necessary to use meteorological data along ballistic to ensure artillery firing.

2. The deviation of shooting distance and sideslip calculated by means of midpoint meteorological bulletin and meteorological data along the trajectory fluctuates greatly, which indicates that the meteorological conditions in ballistic airspace vary greatly with the increase of shooting distance. The meteorological data along the trajectory detected by UAV can reflect the changes of meteorological conditions along the trajectory more truthfully.

3. The overall trend of the deviation of shooting distance and sideslip calculated by ballistic midpoint meteorological bulletin and along ballistic meteorological data increases with the increase of shooting range. However, even when shooting distance is small, there are still large deviations, which indicates that the approximate calculation and adjustment error of meteorological data in the process of compiling meteorological bulletin is large and can not be neglected.

4. Conclusion

Based on the analysis of the influence of meteorological data on artillery firing accuracy, a method of acquiring meteorological data along ballistic trajectory by UAV is proposed, and the firing accuracy of artillery firing using meteorological bulletin and meteorological data along ballistic trajectory is analyzed. It is concluded that the use of meteorological data along the trajectory for artillery firing can improve firing accuracy and has good military benefits.

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