Air Alignment Method of Guided Projectile Based on INS/BDS

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Abstract. Initial alignment is a prerequisite for the work of INS and integrated navigation system. In order to solve the problem of rapid alignment of guided projectiles under high dynamic conditions, this paper proposes an air coarse alignment method based on kinematics constraints, and compensate for the influence of the earth's rotation. At the same time, this paper increases the pitch and yaw angle measurement information in the fine alignment process, thereby improving the speed and accuracy of air fine alignment. Simulation experiments show that after compensating for the influence of the earth's rotation, the roll angle alignment error is reduced by 1°. Compared with the traditional speed + position six-dimensional measurement fine alignment method, after adding pitch and yaw angle measurement information, The eastward speed error is reduced by 0.044 m/s, the northward speed error is reduced by 0.156 m/s, the sky speed error is reduced by 0.126 m/s, the eastward misalignment angle error is reduced by 2.1°, and the northward misalignment angle error is reduced by 0.7°, and the sky misalignment angle error is reduced by 0.86°.

Keywords: Air alignment · High dynamic · Kinematic constraints · Integrated navigation · Measurement

1 Introduction

Precision strike is the key pursuit of modern warfare. With the rapid development of information technology in the 21st century, the requirements for low-cost conventional ammunition have been guided and informatized to ensure the effectiveness and accuracy of firepower coverage in modern warfare. For guided projectile, the rotating systems can simplify the composition of the control system, reduce the impact of structural asymmetry, and improve the performance. Many countries have conducted in-depth research and application of guided projectile shells with rotating systems [1]. While the rotating systems brings many advantages, it also brings unique problems to the research of guided weapons in rotating systems. The first challenge is the high overload at the moment of launch (not less than 10000 g), and the requirements for high overload resistance are put forward for IMU (Inertial Measurement Unit) components. At the same time, due to the high spin, there are also high requirements for the measurement range of the gyro. Furthermore, the carrier spin will cause complex cone motion, which

W. Fu et al. (Eds.): ICMTEL 2021, LNICST 387, pp. 442–451, 2021.
https://doi.org/10.1007/978-3-030-82562-1_42

brings severe challenges to attitude measurement, especially roll angle measurement, which further affects the reliability and accuracy of navigation and guidance. Finally, due to the particularity of guided projectiles, the cost should also be considered [2–4]. The combination of inertial navigation system (INS) and Beidou global navigation satellite system (BDS) is an effective integrated navigation system, it uses the high-precision positioning information filtering algorithm of the BDS receiver to calibrate and compensate for the accumulated errors of the strapdown system, which improves the navigation accuracy and has been widely used.

Initial alignment is a prerequisite for the normal operation of INS. The accuracy and speed are two indicators for evaluating alignment effects [5]. The traditional initial alignment algorithm takes a long time to align and requires simple linear motion of the carrier [6]. Obviously, it cannot be used for the initial alignment of guided projectiles with weightlessness, high-speed spinning, and high-speed movement. Non-autonomous alignment is different from autonomous alignment. It needs to rely on external auxiliary equipment to provide reference information, such as GNSS (Global Navigation Satellite System), master-sub-inertial navigation transfer alignment system, magnetometer, etc. For guided projectiles, due to their limited size and short flight time, they are obviously not suitable for transfer alignment. On the other hand, due to its high-speed spin characteristics, the acquisition of the roll angle is the focus and difficulty of the current guided projectile alignment technology. The most commonly used method is to install a magnetometer on the projectile [7]. However, the attitude measurement method based on geomagnetic measurement technology has poor anti-interference ability and requires additional sensors [8]. Some scholars solve the problem of attitude calculation from the perspective of non-gyro inertial measurement methods, such as six accelerometers, eight accelerometers [9], but these methods require high accelerometer installation accuracy and angular velocity calculation accuracy, which will cause Real-time issues.

This paper proposes an air alignment method of guided projectile based on INS/BDS. The coarse alignment is completed by the method of rapid air alignment based on kinematics equations, and the influence of the earth's rotation on the coarse alignment is compensated. Then, on the basis of the traditional six-dimensional measurement precision alignment method, the pitch and yaw vector measurement information are added to construct an eight-dimensional measurement, thereby improving the accuracy and speed of the air precision alignment. At the same time, no additional sensors are used, which helps to save costs and control weight.

2 Air Alignment Method of Guided Projectile

2.1 Air Coarse Alignment Algorithm Based on Kinematics Equations

Firstly, the coordinate systems should be defined: Inertial coordinate system $OX_iY_iZ_i$. Navigation coordinate system (ENU) $OX_nY_nZ_n$. Projectile coordinate system $OX_bY_bZ_b$, The Y_b axis is the rotation axis of the guided projectile, the X_b axis is the horizontal axis, and the Z_b axis is the sky axis. Ballistic coordinate system $OX_2Y_2Z_2$, The Y_2 axis is the ballistic pointing axis. The relationship of each coordinate system is shown in Fig. 1. It is stipulated that the yaw angle is 0° when pointing north, and it is positive from north to west.

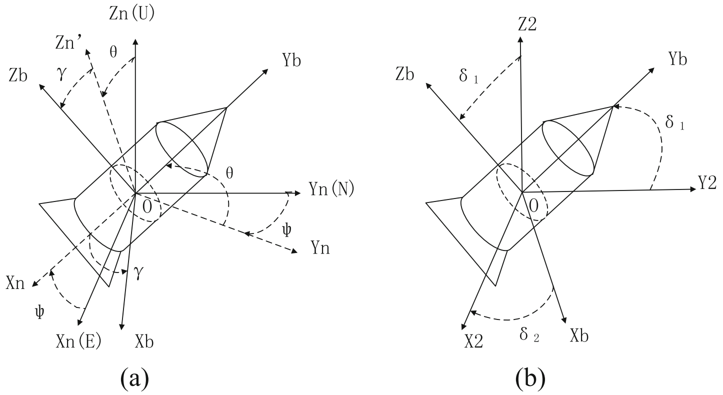


Fig. 1. (a) shows the relationship between navigation coordinate system and projectile coordinate system; (b) shows the relationship between ballistic coordinate system and projectile coordinate system

After the guided projectile is launched and before the satellite receiver is powered on, the guided projectile will be in a complex angular motion state due to the initial disturbance. At this time, the trajectory of the projectile can only be roughly predicted by the ballistic parameters. While the BDS receiver receives the navigation information, according to the component of the velocity measurement value in the navigation coordinate system, the ballistic inclination and the ballistic deflection of the guided projectile can be calculated.

$$\theta_a = \arctan \frac{v_u}{\sqrt{v_e^2 + v_n^2}} \tag{1}$$

$$\psi_2 = -\arctan \frac{v_e}{v_n} \tag{2}$$

v_e, v_n, v_u respectively represent the eastward speed, northward speed, and skyward speed in the satellite navigation results.

According to the theory of external ballistics, the following relationship exists between the projectile coordinate system and the ballistic coordinate system:

$$\psi \approx \psi_2 + \delta_1; \theta \approx \theta_a + \delta_2 \tag{3}$$

At the same time, during the ascent of the guided projectile flight, the angle of attack caused by the initial disturbance will rapidly decay to a small amount in a short time, so the following approximation can be used:

$$\psi \approx \psi_2; \theta \approx \theta_a \tag{4}$$

According to the theory of external ballistics, the kinematic equation of the projectile body rotating around the center of mass is:

$$\begin{cases} \dot{\theta} = \frac{d\theta}{dt} = \omega_{nbz}^b \sin\gamma + \omega_{nbx}^b \cos\gamma \\ \dot{\gamma} = \frac{d\gamma}{dt} = \omega_{nby}^b - (\omega_{nbz}^b \cos\gamma - \omega_{nbx}^b \sin\gamma)\tan\theta \\ \dot{\psi} = \frac{d\psi}{dt} = (\omega_{nbx}^b \sin\gamma - \omega_{nbz}^b \cos\gamma)/\cos\theta \end{cases} \tag{5}$$

In the formula, $\dot{\theta}$, $\dot{\gamma}$, $\dot{\psi}$ represents the pitch rate, roll rate, and yaw rate of the rotating projectile; ω_{nbx}^{b}, ω_{nby}^{b}, ω_{nbz}^{b} respectively represents the sensitive angular rate of the projectile coordinate system relative to the three-axis navigation coordinate system; The first two formulas of (5) can be solved:

$$\begin{cases} \sin\gamma = \frac{\omega_{nbz}^{b}\dot{\theta}-\omega_{nbx}^{b}\dot{\psi}\cos\theta}{\dot{\theta}^2+(\dot{\psi}\cos\theta)^2} \\ \cos\gamma = \frac{\omega_{nbx}^{b}\dot{\theta}+\omega_{nbz}^{b}\dot{\psi}\cos\theta}{\dot{\theta}^2+(\dot{\psi}\cos\theta)^2} \end{cases} \tag{6}$$

It can be derived from (6):

$$\tan\gamma = \frac{\omega_{nbz}^{b}\dot{\theta} - \omega_{nbx}^{b}\dot{\psi}\cos\theta}{\omega_{nbx}^{b}\dot{\theta} + \omega_{nbz}^{b}\dot{\psi}\cos\theta} \tag{7}$$

For a well-designed projectile, the yaw angular rate after launching can be ignored, so (7) can be simplified to:

$$\tan\gamma \approx \frac{\omega_{nbz}^{b}}{\omega_{nbx}^{b}} \tag{8}$$

According to the characteristics of the guided projectile in the trajectory of the projectile during the ascent period of flight:

$$\dot{\theta} \approx \frac{\omega_{nbz}^{b}}{\sin\gamma} \approx \frac{\omega_{nbx}^{b}}{\cos\gamma} < 0 \tag{9}$$

If the definition of the roll angle is [–180°,180°], the unique solution of the roll angle can be obtained by combining (8) and (9), as shown in Table 1.

Table 1. Roll angle value range judgment table

$\tan\gamma$	ω_{nbz}^{b}	ω_{nbx}^{b}	$\sin\gamma$	$\cos\gamma$	Numerical interval	The value of γ
≥ 0	≥ 0	>0	≤ 0	<0	[–180°, –90°)	$\lvert\gamma\rvert$–180°
	≥ 0	$=0$	– 90°			
	≤ 0	<0	≥ 0	>0	[0°, 90°)	$\lvert\gamma\rvert$
≤ 0	≥ 0	<0	≤ 0	>0	(–90°, 0°]	– $\lvert\gamma\rvert$
	<0	$=0$	90°			
	≤ 0	>0	≥ 0	<0	(–90°, 180°]	180°–$\lvert\gamma\rvert$

On the other hand, by inertial navigation theory:

$$\omega_{nb}^{b} = \omega_{ib}^{b} - C_n^b\omega_{in}^{n} \tag{10}$$

Among them, ω_{ib}^{b} is the output value of strapdown gyroscope, and is determined by Eq. (11):

$$\omega_{in}^{n} = \omega_{ie}^{n} + \omega_{en}^{n} = \begin{bmatrix} -\frac{v_n}{R_M} \\ \omega_{ie}\cos L + \frac{v_e}{R_N} \\ \omega_{ie}\sin L + \frac{v_e}{R_N}\tan L \end{bmatrix} \tag{11}$$

v_e, v_n, v_u represents the easterly speed, northerly speed, and celestial speed in the satellite navigation results respectively; ω_{ie} represents the earth's rotation rate, which is a constant value; L is the latitude information in the position; R_M, R_N is the earth's curvature radius.

Expand formula (10) in terms of components:

$$\begin{bmatrix} \omega_{nbx}^{b} \\ \omega_{nby}^{b} \\ \omega_{nbz}^{b} \end{bmatrix} = \begin{bmatrix} \omega_{ibx}^{b} \\ \omega_{iby}^{b} \\ \omega_{ibz}^{b} \end{bmatrix} - C_n^b \begin{bmatrix} \omega_{inx}^{n} \\ \omega_{iny}^{n} \\ \omega_{inz}^{n} \end{bmatrix} \tag{12}$$

Where C_n^b is the attitude transfer matrix. Expand it and calculate it to get:

$$\begin{aligned} \omega_{nbx}^{b} &= \omega_{ibx}^{b} - [(\cos\gamma\cos\psi + \sin\gamma\sin\psi\sin\theta)\omega_{inx}^{n} \\ &+(-\cos\gamma\sin\psi + \sin\gamma\cos\psi\sin\theta)\omega_{iny}^{n} + (-\sin\gamma\cos\theta)\omega_{inz}^{n}] \end{aligned} \tag{13}$$

$$\begin{aligned} \omega_{nbz}^{b} &= \omega_{ibz}^{b} - [(\sin\gamma\cos\psi - \cos\gamma\sin\psi\sin\theta)\omega_{inx}^{n} \\ &+(-\sin\gamma\sin\psi - \cos\gamma\cos\psi\sin\theta)\omega_{iny}^{n} + (\cos\gamma\cos\theta)\omega_{inz}^{n}] \end{aligned} \tag{14}$$

Substituting (13) and (14) into (8), the formula that compensates for the influence of the earth's rotation can be obtained:

$$\sin\gamma \cdot \omega_{ibx}^{b} = \cos\gamma \cdot \omega_{ibz}^{b} + M \tag{15}$$

Where:

$$M = \sin\psi\sin\theta \cdot \omega_{inx}^{n} + \cos\psi\sin\theta \cdot \omega_{iny}^{n} - \cos\theta \cdot \omega_{inz}^{n}$$

Equation (15) is the formula for quickly obtaining the compensated roll angle.

Since the roll angle is defined as [–180°, 180°], formula (15) is used in the specific calculation:

If $\omega_{ibx}^{b} \le 0$: $\sin\gamma \cdot \omega_{ibx}^{b} = \cos\gamma \cdot \omega_{ibz}^{b} + M$.

Else if $\omega_{ibx}^{b} > 0$: $\sin\gamma \cdot \omega_{ibx}^{b} = \cos\gamma \cdot \omega_{ibz}^{b} - M$.

After the roll angle is finally calculated, the determination of the roll angle range is consistent with Table 1.

At this time, the attitude angle, speed, and position information required by the coarse alignment of the guided projectile can be obtained.

2.2 Air Fine Alignment Algorithm Added Pitch and Yaw Measurement

Traditional air fine alignment methods mostly use six-dimensional measurement to construct the measurement equation:

$$Z = \begin{bmatrix} r_{GNSS} - r_{INS} \\ v_{GNSS} - v_{INS} \end{bmatrix} = HX + V \tag{16}$$

In the formula, r_{GNSS} represents the three-dimensional position vector output by the GNSS system; r_{INS} represents the three-dimensional position vector output by the INS system; v_{GNSS} represents the three-dimensional velocity vector output by the GNSS, v_{INS} represents the three-dimensional velocity vector output by the INS; $H = \begin{bmatrix} I_{6\times 6} & 0_{6\times 9} \end{bmatrix}$ is the measurement matrix; V is the quantity Measure noise; Z is the measured value; X is the 15-dimensional state quantity.

Due to the characteristics of fast rotation speed, fast movement speed, and relatively fixed ballistic trajectory of guided projectiles, the yaw and pitch information derived from GNSS speed is considered to construct an eight-dimensional measurement matrix. At the same time, because the fifteen-dimensional state quantity contains the system misalignment angle, not the attitude angle error, it is necessary to build the relationship between the attitude angle error and the system misalignment angle:

$$\begin{bmatrix} \delta\psi \\ \delta\theta \\ \delta\gamma \end{bmatrix} = \begin{bmatrix} -\tan\theta\sin\psi & \tan\theta\cos\psi & -1 \\ -\cos\psi & -\sin\psi & 0 \\ \sin\psi/\cos\theta & -\cos\psi/\cos\theta & 0 \end{bmatrix} \begin{bmatrix} \varphi_E \\ \varphi_N \\ \varphi_U \end{bmatrix} \tag{17}$$

Take the first two rows of the matrix in the above formula:

$$C_{2\times 3} = \begin{bmatrix} -\tan\theta\sin\psi & \tan\theta\cos\psi & -1 \\ -\cos\psi & -\sin\psi & 0 \end{bmatrix} \tag{18}$$

Then the new measurement matrix is:

$$H_{8\times 15} = \begin{bmatrix} C_{2\times 3} & 0_{2\times 6} & 0_{2\times 6} \\ 0_{6\times 3} & I_{6\times 6} & 0_{6\times 6} \end{bmatrix} \tag{19}$$

On this basis, an 8-dimensional measurement equation can be constructed:

$$Z = \begin{bmatrix} \delta\psi \\ \delta\theta \\ \delta r \\ \delta v \end{bmatrix} = \begin{bmatrix} \psi_{GNSS} - \psi_{INS} \\ \theta_{GNSS} - \theta_{INS} \\ r_{GNSS} - r_{INS} \\ v_{GNSS} - v_{INS} \end{bmatrix} \tag{20}$$

3 Experimental and Comparative Analysis

Firstly, this paper sets the ballistic parameters: the simulation step is 0.001 s, the ballistic duration is 180 s; the initial longitude of the carrier is 114°, the initial latitude of the carrier is 30°, the initial height of the carrier is 5 m; the initial velocity of the carrier is

1500 m/s; The initial roll angle of the carrier is 0°, the initial yaw angle of the carrier is –90° (true north is 0°, and the west by north is positive), and the initial pitch angle of the carrier is 45°; The weight of the shell is 18 kg, and the shell diameter is 0.065 m; The air density is 1.29 kg/m^2, the air resistance coefficient is 0.0789; the initial roll angular rate is 126 rad/s. Secondly, this paper sets IMU error: 20 deg/h for gyroscope zero offset, 1000 ug/h for accelerometer zero offset, angle random walk 5 deg/sqrt(h), speed random walk 10 ug/sqrt(Hz), and set BDS position error to [5 m, 5 m, 5 m], the speed error is [1 m/s, 1 m/s, 1 m/s].

3.1 Experiment and Comparison of Air Coarse Alignment Methods

In order to verify the air coarse alignment method of guided projectiles based on kinematic equations proposed in this paper, this article first uses the guided projectile trajectory generator to generate ideal gyroscope and accelerometer data. Then this paper adds the corresponding error according to the actual situation. The trajectory parameters of the trajectory generator are used as true values for comparison.

Figure 2 shows the pitch and yaw errors of the guided projectile. It can be seen that the pitch angle error is less than 5*10$^{\wedge-4}$ rad, and the yaw angle error is less than 10$^{\wedge-3}$ rad.

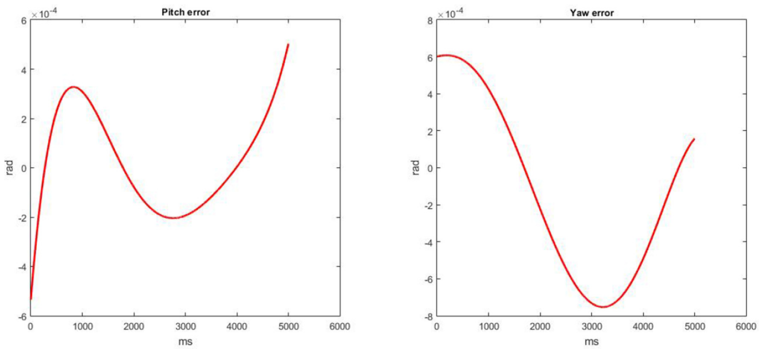
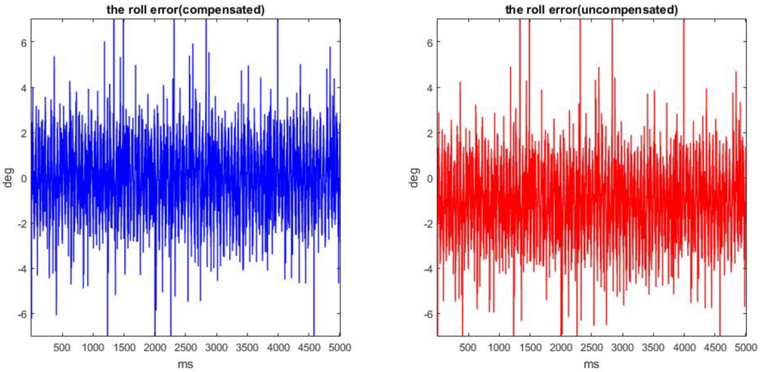


Fig. 2. Pitch and yaw error of coarse alignment

Figure 3(a) shows the alignment error of the roll angle after compensating for the influence of the earth's rotation. Figure 3(b) shows the alignment error of the roll angle when the influence of the earth's rotation is not compensated. It shows that if the effect of the earth's rotation is not compensated, the roll angle alignment result would have a drift of more than 1°.

3.2 Experiment and Comparison of Air Fine Alignment Methods

Figure 4 shows the air fine alignment error of eight-dimensional measurement. The first subfigure shows the east misalignment angle and the north misalignment angle. It can be shown that the east misalignment angle is less than 1.38° and the north misalignment



(a) (b)

Fig. 3. Roll error of coarse alignment

angle is less than 0.55°. The second subfigure shows the sky misalignment angle is less than 1.4°. In the third subfigure, it can be shown that the speed errors are less than 0.5 m/s. The last subfigure shows the position errors are less than 2 m.

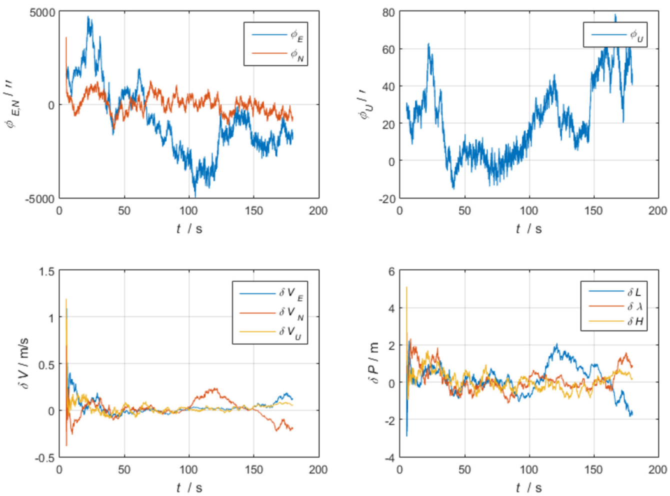


Fig. 4. Air fine alignment error of eight-dimensional measurement

Figure 5 shows the air fine alignment error of six-dimensional measurement. Compared with the Fig. 4, The first subfigure shows that the east misalignment angle can reach 5.56° in maximum and the north misalignment angle can reach 2.78° in maximum which are. The second subfigure shows that the sky misalignment angle can reach 3.33° which is 2 times larger than the sky misalignment angle in Fig. 4. In the third subfigure, it can be shown that the speed errors are less than 1 m/s. The last subfigure shows the position errors are less than 2 m.

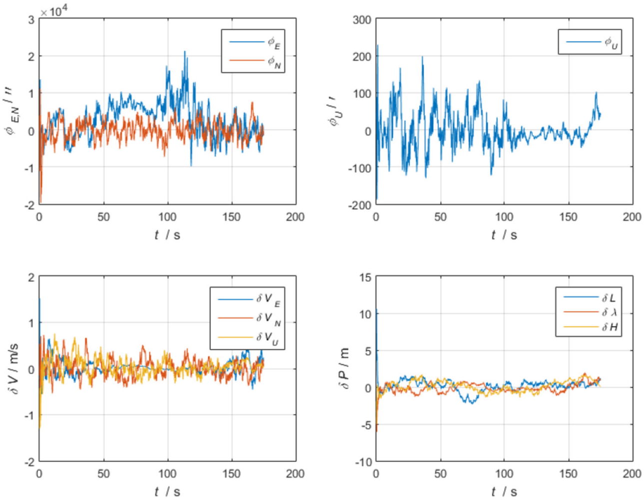


Fig. 5. Air fine alignment error of traditional six-dimensional measurement

Table 2 shows the comparison of the two methods' RMSE error.

Table 2. Comparison table of air fine alignment errors of the two methods

RMSE	Six-dimensional	Eight-dimensional
Eastward position error (m)	0.81	0.66
Northward position error (m)	0.80	0.57
Sky position error (m)	0.6	0.53
Eastward velocity error (m/s)	0.14	0.096
Northward velocity error (m/s)	0.24	0.084
Sky velocity error (m/s)	0.18	0.054
Eastward misalignment angle (°)	2.48	0.38
Northward misalignment angle (°)	0.85	0.14
Sky misalignment angle (°)	1.14	0.28

It can be seen that after adding the pitch and yaw measurement information, The eastward speed error is reduced by 0.044 m/s, the northward speed error is reduced by 0.156 m/s, and the sky speed error is reduced by 0.126 m/s; The eastward misalignment angle error is reduced by 2.1°, the northward misalignment angle error is reduced by 0.7°, and the sky misalignment angle error is reduced by 0.86°.

4 Conclusion

In order to achieve rapid air alignment of guided projectiles, this paper proposes an air coarse alignment algorithm based on kinematics equations and an air fine alignment algorithm which adds pitch and yaw angle measurement information. When the guided projectile receives the BDS signal, it first obtains the speed and position information of the guided projectile at this time, and calculates the yaw angle and pitch angle from the speed information. Then, combined with the above information and the kinematics equation of the guided projectile, the roll angle can be obtained. Simulation experiment shows that the compensated air coarse alignment algorithm reduces the error by 1° compared with the uncompensated algorithm. After finishing the air coarse alignment, on the basis of the traditional six-dimensional measurement information in the air fine alignment method, this paper adds pitch and yaw measurement information. Simulation experiment shows that the speed error and misalignment error of the new air fine alignment are significantly reduced, and the convergence speed is also significantly faster.

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