

Article

Evaluation and Experiment of Flight Parameter Quality of the Plant Protection UAV Based on Laser Tracker

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Abstract: Research shows that the accurate acquisition of flight parameters of the plant protection UAV and accurate evaluation of flight parameter quality have great significance for improving the effect and precision of spraying. In order to further improve the accuracy of the flight parameter quality evaluation of the plant protection UAV, this study conducted an evaluation and experiment of the flight parameter quality of the plant protection UAV using a laser tracker. The experimental results showed that the current plant protection UAV used the average altitude and speed of the onboard sensors to determine whether it reached the preset flight operation parameters, but this interpretation method could not accurately reflect the actual flight situation. Laser trackers could obtain more accurate flight parameters, especially instantaneous flight parameters. Compared with the laser tracker, the flight trajectory, altitude, and speed of the UAV reflected by onboard sensors were erroneous and tended to be smooth and stable. This method can obtain more accurate flight parameters, improve the accuracy of the flight parameter quality evaluation of the plant protection UAV, and provide data support and a reference for the precision spraying and performance improvement of the plant protection UAV.

Keywords: plant protection UAV; flight parameter quality; laser tracker; accurate measurement



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1. Introduction

According to the 2020 China Plant Protection UAV Industry Development Report, the annual operating area of China's plant protection UAVs exceeded 66.67 million hm² [1,2]. Compared to 2019, a doubling of the annual operating area was achieved. With the increase in the operating area, the precision application technology of the plant protection UAV also has higher requirements.

In order to achieve precise application and improve the rate of utilization of droplets by the plant protection UAV [3–6], many scholars have conducted a series of explorations in terms of nozzle type [7,8], droplet size [9,10], spray pressure [11], etc. As the studies have progressed, the impact of the plant protection UAV flight parameters [12–15] on plant protection operation has become a hot research topic. Kirk et al. [16] studied the influence of nozzle orifice size, spray discharge angle, spray pressure, and aircraft flight speed on droplet drift. The experimental results show that aircraft flight speed was the dominating factor influencing atomization from most of the spray nozzle models. Chen et al. [17] conducted spraying experiments on a hybrid rice canopy with different flight parameters using a single-rotor electric unmanned helicopter. The relationship between the combination of operating parameters and the distribution of droplet deposition was

explored. Kharim et al. [18] found that the flight speed and spray volume of a low-altitude UAV had the greatest impact on droplet deposition density and uniformity in rice fields. Zhang et al. [19] found that the shape of citrus trees and the flight altitude of the UAV were important factors affecting droplet deposition. Tang et al. [20] proposed a prediction method to predict spray drift and deposition under complex conditions. They found that decreasing the flight altitude could improve droplet deposition, and increasing the flight altitude could reduce the deposition coefficient of variation. Our research group's previous studies [21] also found that flight altitude, flight speed, and the interaction between these two factors of an unmanned helicopter had a significant impact on the deposition concentration and uniformity.

Previous research on plant protection UAV spraying mainly focused on the influence of operational parameters on the spraying effect. It lacks an overall evaluation of the plant protection UAV flight parameter quality (flight altitude uniformity, speed uniformity, trajectory accuracy, etc.). However, the plant protection UAV flight parameter quality has an important impact on the spraying effect, and small changes in flight parameters can cause significant changes in droplet drift and deposition distribution [22]. Therefore, it is important to accurately evaluate the flight parameter quality of the plant protection UAV to improve the spraying effect. In recent years, some scholars have also conducted relevant studies on the evaluation of flight parameter quality using airborne sensors, such as GPS, RTK, and millimeter wave radar. Chen et al. [23] explored the relationship between the flight parameter quality and the spraying effect of the plant protection UAV to provide data support and guidance for the selection of the plant protection UAV and technical improvement. Jin et al. [24] studied the flight parameter accuracy, re-spray rate, leakage rate, droplet coverage, and effective pesticide utilization rate to provide a basis and reference for improving machine performance and field operation.

In summary, gaining accurate flight parameters of the plant protection UAV, especially for the flight altitude, flight speed, and flight trajectory, to achieve an accurate evaluation of the flight parameter quality has great significance for the accurate application of the plant protection UAV. Therefore, in order to further improve the accuracy of the flight parameter quality evaluation of the plant protection UAV, this study used a laser tracker to evaluate the quality of flight parameters, including flight trajectory, flight altitude, and flight speed, with an electric quadrotor plant protection UAV. It compared the experimental results with those obtained from the onboard sensors of the plant protection UAV. The main work of this research mainly involved:

- (1) Error analysis and calibration of the flight parameter measurement system of the plant protection UAV based on a laser tracker
- (2) Measurement system layout and flight parameter setting
- (3) Flight parameter quality evaluation index and evaluation method design
- (4) Data processing and evaluation after the experiments

It aimed to provide new ideas for the accurate evaluation of flight parameter quality for the plant protection UAV and a reference and guidance for the accurate spraying and performance improvement of the plant protection UAV.

2. Materials and Methods

The study was conducted at Jiangsu University, Zhenjiang City, Jiangsu Province (32°12'01" N; 119°30'45" E). As shown in Figure 1, the devices required for the evaluation and experiment of flight parameter quality were the electric quadrotor plant protection UAV and the Leica AT960-LR laser tracker measurement system. The parameters are shown in Table 1 [25]. The Leica AT960-LR laser tracker measurement system works with a Leica 38.1 mm target ball, which can measure a maximum distance of 160 m. According to the relevant literature [24] and standards (NY/T 3213-2018), the range of the Leica AT960-LR laser tracker measurement system meets the requirements of the flight parameter quality evaluation.

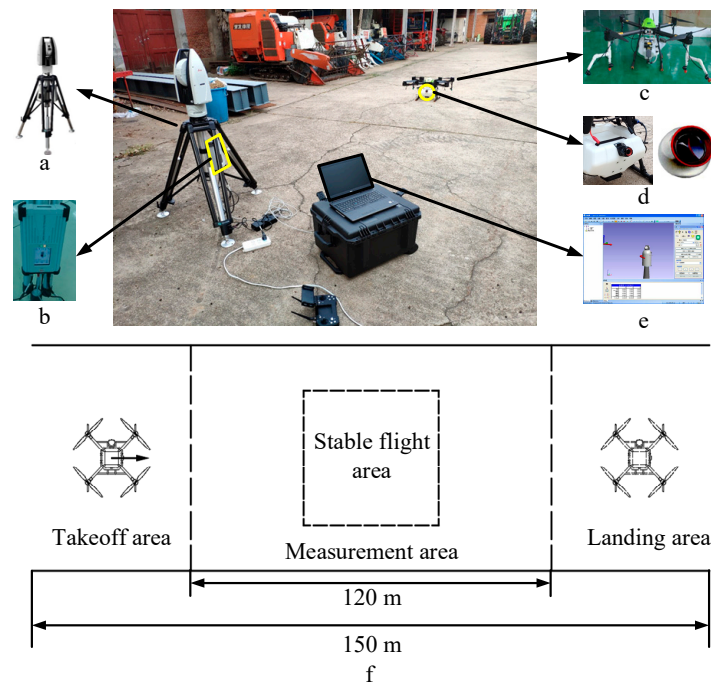


Figure 1. Experimental device and experiment area diagram: (a) Leica AT960-LR host and bracket, (b) controller, (c) UAV, (d) target ball, (e) host computer, (f) experiment area diagram.

Table 1. Performance parameters of experimental device.

Device	Parameters	Values
Leica AT960-LR	Maximum measuring distance L (m)	160
	Distance accuracy AIFM ϵ_L ($\mu\text{m}\cdot\text{m}^{-1}$)	0.5
	Horizontal rotation angle θ_H ($^\circ$)	0 to 360
	Vertical rotation angle θ_V ($^\circ$)	−145 to +145
	Angle measurement accuracy ϵ_θ ($\mu\text{m}\cdot\text{m}^{-1}$)	$\pm 15 + 6$
	Maximum sampling frequency f (Hz)	1000
	Working temperature T ($^\circ\text{C}$)	0 to 40
UAV	Physical parameters	Self-weight (kg) Frame length (mm) Wingspan length (mm)
		8 1200 1980
	Flight parameters	Maximum takeoff weight (kg) Flight altitude (m) Flight speed ($\text{m}\cdot\text{s}^{-1}$)
		21.5 0 to 20 1.0 to 8.0
	Obstacle avoidance parameters	Obstacle avoidance mode Minimum obstacle diameter (mm) Maximum flight speed ($\text{m}\cdot\text{s}^{-1}$)
		Hold; Detour 30 3
	Spray parameters	Medicine box volume (L) Spray volume ($\text{L}\cdot\text{ha}^{-1}$) Nozzle type Spray span (m)
		10 12 to 18 Solid cone nozzle 3 to 5

As shown in Figure 2, when measuring UAV flight parameters, the laser tracker used the instrument's own coordinate system as the target coordinate system. The coordinate origin was at the center of the tracking head. The Z-axis was the normal direction of the horizontal dial. The zero-scale direction was established as the X-axis, and the Y-axis was determined by the right-hand rule. According to Formula (1), the three-dimensional coordinates of the UAV were calculated.

$$\begin{cases} x = L \sin \theta_V \cos \theta_H \\ y = L \sin \theta_V \sin \theta_H \\ z = L \cos \theta_V \end{cases} \quad (1)$$

where L is the spatial distance from laser tracker to target ball; θ_H is the horizontal angle; θ_V is the vertical angle; and x , y , and z are the projection distances of the target ball on the X , Y , and Z axes of the laser tracker, respectively.

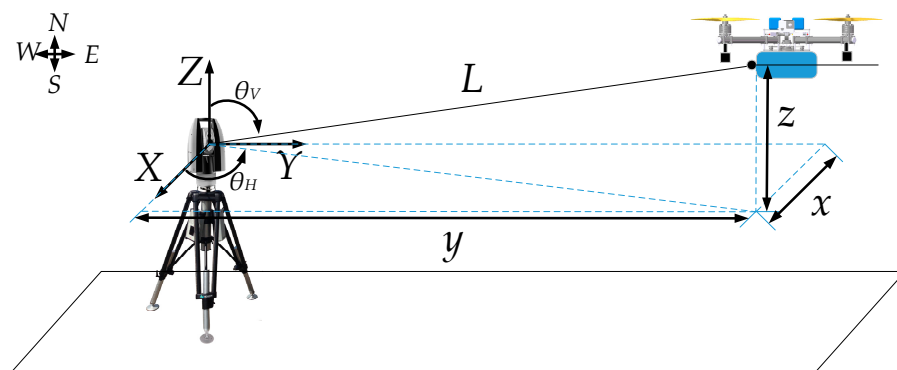


Figure 2. AT960 absolute laser tracker measurement principle and coordinate system.

Using a laser tracker to measure the flight parameters of the UAV and accurately analyze the error source to determine the error that can be compensated will have great significance for the calibration of the absolute laser tracker and the accurate acquisition of UAV flight parameters [25,26]. During the measurement process, the position, attitude, and speed of the UAV changed constantly, and the laser tracker was in a dynamic measurement state. Therefore, in this method, the measurement error of the laser tracker was mainly derived from the distance measurement error, angle measurement error, and laser incident angle error. According to the error propagation law, the following error formula were obtained.

$$\begin{cases} m_x^2 = \sin^2 \theta_V \times \cos^2 \theta_H \times m_L^2 + (\sin^2 \theta_V \times \sin^2 \theta_H + \cos^2 \theta_V \times \cos^2 \theta_H) \times \frac{L^2}{\rho^2} \times m_v \times m_H \\ m_y^2 = \sin^2 \theta_V \times \sin^2 \theta_H \times m_L^2 + (\sin^2 \theta_V \times \cos^2 \theta_H + \cos^2 \theta_V \times \sin^2 \theta_H) \times \frac{L^2}{\rho^2} \times m_v \times m_H \\ m_z^2 = \cos^2 \theta_V \times m_L^2 + \sin^2 \theta_V \times \frac{L^2}{\rho^2} \times m_v^2 \\ m_p^2 = m_x^2 + m_y^2 + m_z^2 = m_L^2 + \sin^2 \theta_V \times \frac{L^2}{\rho^2} \times m_v^2 + \frac{L^2}{\rho^2} \times m_v \times m_H \end{cases} \quad (2)$$

where m_H is the horizontal angle measurement error, and m_v is the vertical angle measurement error. In order to facilitate the analysis of measurement error, it is generally considered that $m_H = m_v$; m_L is the distance measurement error; ρ is the coefficient of the radian to the angle; and m_x , m_y , m_z , and m_p are the mean square error of the measuring points in the X , Y , and Z directions and the point position error, respectively.

From Formula (2), it is shown that before the experiment, the distance measurement error, angle measurement error, and laser incident angle error of the laser tracker needed to be calibrated. The AT960-LR laser tracker had a nominal distance measurement accuracy of $0.5 \mu\text{m} \cdot \text{m}^{-1}$ and an angle measurement accuracy of $\pm 15 + 6 \mu\text{m} \cdot \text{m}^{-1}$. Referring to the standard, JJF-1242-2010, the error calibration of the laser tracker was carried out using the laser tracker's own data and conducting repeated experiments.

2.1. Distance Measurement Error Calibration

As shown in Figure 3, the laser tracker distance measurement error calibration method and steps were as follows:

- (1) The laser was placed on the bracket, and the level was adjusted.

- (2) Eighteen collinear target ball base placement points, $S_1, S_2, S_3, \dots, S_{18}$, were set up. Additionally, the line between the base placement points coincided with the X-axis of the laser tracker to minimize the effects of horizontal and vertical angle errors. The distance between each base placement point was 1 m, the distance was determined by the distance information displayed by the host computer of the laser tracker, and the distance L_i was recorded as the standard value.
- (3) The target ball was placed on the base, the distance information of the host computer was recorded, the target ball was picked up and placed again in the same position, and the distance was recorded. The measurement was repeated three times at each base placement point, and the average distance S_i was recorded as the measured value.
- (4) The measurements were completed from S_1 to S_{18} in sequence, and continuous light was ensured throughout the measurement process; otherwise, all measurements were repeated. The error δ was calculated using the formula $\delta = |S_i - L_i|$.

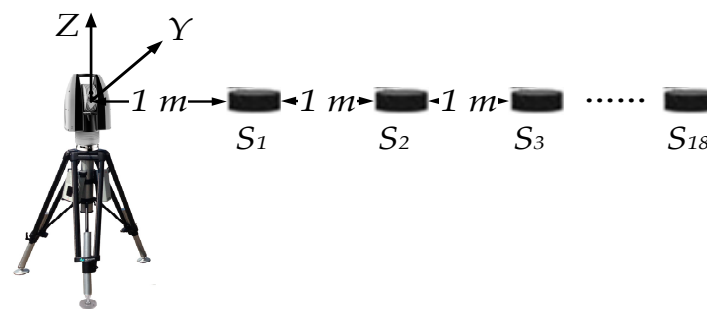


Figure 3. Schematic diagram of distance measurement error calibration.

2.2. Angle Measurement Calibration

As shown in Formula (2), the angle measurement error of the laser tracker was mainly the horizontal angle measurement error and the vertical angle measurement error. Usually, for the convenience of analysis, it is generally considered that the horizontal angle measurement error and the vertical angle measurement error are equal.

As shown in Figure 4, the methods and steps were as follows:

- (1) A horizontal guide rail was arranged within the measuring range of the laser tracker. The laser tracker was placed on the side of the guide rail and adjusted to the level. The specific placement method was as follows: the laser tracker was located on the vertical line of the guide rail, 5 m away from the guide rail, and the height was the same as the guide rail.
- (2) A total of 18 target ball base placement points, P_1 to P_{18} , were set up from the starting point to the endpoint of the guide rail. The distance between the placement points was 2 m. The coordinates of each placement point were measured with a laser tracker. The distance D_i between each placement point and the previous placement point was calculated as the standard value according to the formula $D_i = \sqrt{(X_i - X_{i-1})^2 + (Y_i - Y_{i-1})^2 + (Z_i - Z_{i-1})^2}$, where X_i , Y_i , and Z_i are the coordinates of the i th point.
- (3) The target ball was placed in sequence from P_1 to P_{18} again and was then placed three times at each placement point. The average coordinate was recorded to calculate the distance P_i from each placement point to the previous placement point as the measured value. The horizontal angle measurement error was calculated according to Formula (3).

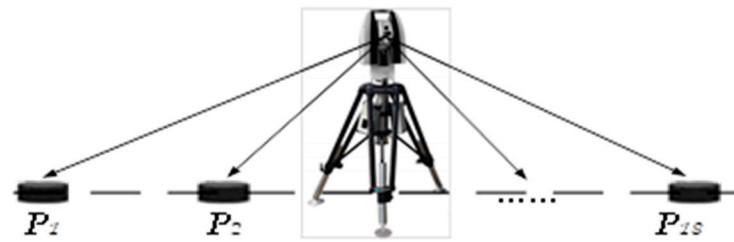


Figure 4. Schematic diagram of horizontal angle calibration.

$$\left\{ \begin{array}{l} P_i = \sqrt{(\bar{X}_i - \bar{X}_{i-1})^2 + (\bar{Y}_i - \bar{Y}_{i-1})^2 + (\bar{Z}_i - \bar{Z}_{i-1})^2} \\ \Delta_i = P_i - D_i \\ \sigma_{HZ}^i = \frac{\Delta_i}{P_i} \times \rho \\ \bar{\sigma}_{HZ} = \sqrt{\frac{\sum_{i=2}^n (\sigma_{HZ}^i)^2}{n-1}} \\ \sigma_0^i = \frac{15+6 \times P_i \times 10^{-3}}{P_i \times 10^3} \times \rho \end{array} \right. \quad (i = 2, 3 \dots n), \quad (3)$$

where $\bar{X}_i$, $\bar{Y}_i$, and $\bar{Z}_i$ are the average measurement coordinates of the i th point, mm; Δ_i is the error between the measured value and the standard value of the i th point, mm; σ_{HZ}^i is the angle measurement accuracy, " and σ_0^i is the angle nominal accuracy, ".

2.3. Laser Incident Angle Error Calibration

The laser tracker needs to work with the target ball for contact measurement. The angle of the laser beam into the target ball directly affects the measurement accuracy of the laser tracker. The target ball used in this study was the Leica 38.1 mm corner prism reflector with an incident angle range of $\pm 30^\circ$. As shown in Figure 5, the calibration method and steps to determine the error caused by the incident angle of the laser beam to the target ball on the measurement accuracy of the laser tracker were as follows.

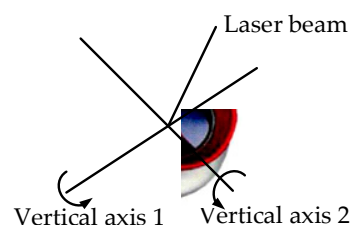


Figure 5. Schematic diagram of laser incident angle error calibration.

- (1) The target ball was placed on a fixed base, which was 5 m away from the tracker. The laser tracker and the target ball were placed on the same horizontal line to reduce the effect of angle measurement error.
- (2) The target ball was directed to the laser beam, and then the target ball was rotated around the laser beam in turn by 0° , 90° , 180° , and 270° . The measurement was repeated 3 times, and the measurement value displayed by the laser tracker host computer was recorded.
- (3) Within the incident range of the target ball, the target ball was rotated around 2 vertical axes with a rotation step of 10° . The measurement was repeated 3 times, and the measurement value was recorded.
- (4) The average value of the 3 repeated measurements in each axial was the observation value in that axial. The data obtained by rotating the target ball around the laser beam were fitted to obtain the center point of the target ball. Then, the error caused by the incident angle of the laser beam to the target ball on the measurement accuracy of

the laser tracker was obtained by the difference between the observed value and the center point of the target ball.

2.4. Flight Parameter Quality Evaluation Method

As shown in Table 2, the method combines the field operation of the plant protection UAV to design the UAV flight parameter combination. The UAV flight speed was 1–3 m/s, and the change step was 1 m/s. The flight altitude was 1–3 m, and the change step was 0.5 m. The flight speed and altitude were set at the ground station. The flight speed and trajectory from the onboard GPS and the flight altitude from the onboard millimeter wave (MMW) radar were used as the flight parameters from the onboard sensors, which were derived from the flight log. The parameters of the onboard GPS and MMW radar are shown in Table 3.

Table 2. Combination of flight parameters.

Combination Code	Altitude (m)	Speed (m·s ⁻¹)
h1.0s1	1.0	1
h1.0s2	1.0	2
h1.0s3	1.0	3
h1.5s1	1.5	1
h1.5s2	1.5	2
h1.5s3	1.5	3
h2.0s1	2.0	1
h2.0s2	2.0	2
h2.0s3	2.0	3
h2.5s1	2.5	1
h2.5s2	2.5	2
h2.5s3	2.5	3
h3.0s1	3.0	1
h3.0s2	3.0	2
h3.0s3	3.0	3

Table 3. Parameters of onboard GPS and MMW Radar.

Device	Parameters	Values
GPS (JS-AD56UB8)	Positioning accuracy (m)	2.5 (Without SBAS); 2 (SBAS)
	Sampling frequency (Hz)	10
	Receiver type	GPS; SBAS; QZSS; GLONASS; BDS
	Start time (s)	29 (Cold); 1 (Hot)
	Velocity accuracy (m·s ⁻¹)	0.1
MMW radar (Landing AG50)	Distance range (m)	0.5 to 50
	Distance accuracy (m)	0.1
	Angle range (°)	43 (Horizontal); 30 (Vertical)
	MMW frequency (GHz)	24 to 24.25
	Sampling frequency (Hz)	100

The position information measured by the Leica AT960-LR laser tracker used the tracker's own coordinate system as the target coordinate system, and the measurement data were given in the form of (x, y, z). The position information recorded by the UAV airborne sensor used the WGS84 coordinate system as the target coordinate system. The measurement data were given in the form of (*latitude, longitude*). As different coordinate systems were used, and the WGS84 coordinate system does not always accurately reflect the distance relationship between the positions, a unified coordinate system was based on the laser tracker's own coordinate system. Based on this, the flight parameters measured and quality evaluation methods of the plant protection UAV were as follows:

- (1) As shown in Figure 1, the flight altitude and speed accurate measurement experiment of the plant protection UAV was conducted at the Institute of Agricultural Equipment

- Engineering of Jiangsu University (32°12′01″ N; 119°30′45″ E). A rectangular area of 150 m × 10 m was selected in the east–west direction. Additionally, the area was divided into a takeoff area, a measurement area, and a landing area. The length of the measurement area was 120 m. The altitude of the plant protection UAV was determined by measuring the distance to the ground using an onboard MMV radar. In order to reduce the influence of terrain undulations on the measurement, a flat area of 25 m × 5 m in the measurement area was selected as the stable flight area. The evaluation of flight parameter quality was based on the stable flight data in this area.
- (2) The Leica AT960-LR laser tracker measurement system was placed on the west edge of the east–west central axis of the rectangular area, and the x, y direction of the tracker coordinate system coincided with the x, y direction of the UTM coordinate system. The height of the center of the tracking head of the laser tracker was measured from the ground as h_{ju} , and the GPS position information of the laser tracker was recorded. Data were converted to three-dimensional coordinates (x_{ju}, y_{ju}, h_{ju}) into the UTM coordinate system.
 - (3) The UAV was placed on the central axis of the rectangular area in the east–west direction, facing east and flying from west to east. The Leica 38.1 mm target ball was installed on the tail of the UAV 1 m away from the laser tracker.
 - (4) In order to avoid the measurement error caused by manual operation, this experiment used autonomous flight. The starting and ending points of the UAV route were set along the east–west central axis of the rectangular area. The distance between the two points was 150 m.
 - (5) After the UAV took off and stabilized hold at the starting point, the Leica AT960 measurement system started to record data. The UAV performed autonomous flight according to the flight parameters in Table 2. After the UAV reached the end point, the Leica AT960 measurement system stopped recording data. During the whole process, the laser light between the laser tracker and the target ball was kept constant; otherwise, the UAV was returned to the starting point, and the experiment was restarted.
 - (6) The high-precision position of the UAV from the laser tracker and the longitude, latitude, altitude, and speed of the UAV from the flight log were determined. Latitude, longitude, and altitude information was converted into three-dimensional coordinates (x_u, y_u, h_u) in the UTM coordinates. The position of the UAV relative to the laser tracker was calculated from the onboard sensor data obtained by $(x_u - x_{ju}, y_u - y_{ju}, h_u - h_{ju})$. The data (x_j, y_j, h_j) and $(x_u - x_{ju}, y_u - y_{ju}, h_u - h_{ju})$ were analyzed and processed.
 - (7) The flight trajectory, flight speed consistency and flight altitude consistency were used as evaluation indexes to evaluate the flight parameter quality of the plant protection UAV. Additionally, the consistency calculation was performed according to Formula (4).

$$\left\{ \begin{array}{l} \bar{X} = \frac{x_1 + x_2 + \dots + x_Z}{Z} = \frac{\sum x_i}{Z} \\ S = \sqrt{\frac{\sum (x_i - \bar{X})^2}{Z}} = \sqrt{\frac{\sum (x_i - \frac{\sum x}{Z})^2}{Z}} \\ CV = \frac{S}{\bar{X}} \times 100\% \\ V_j = \frac{\sum V_{ji}}{Z} = \frac{\sum [\sqrt{(x_{ji} - x_{ji-1})^2 + (y_{ji} - y_{ji-1})^2 + (z_{ji} - z_{ji-1})^2} \times f]}{Z} \end{array} \right. , \quad (4)$$

where $\bar{X}$ is the average value of a trait; S is the standard deviation of a trait; $x_1, x_2, \dots, x_m$ are the trait values of each sampling point; and Z is the sampling point. V_j is average flight speed measured by the Leica AT960 measurement system, m/s; V_{ji} is the instantaneous flight speed of a sampling point, m/s; x_{ji}, y_{ji} , and z_{ji} are three-dimensional coordinates of a sampling point relative to the Leica AT960 measurement system, mm; f is the sampling frequency of the Leica AT960 measurement system; and CV is the coefficient of variation of a trait, and the lower CV , the better the consistency.

3. Results and Discussion

3.1. Error Calibration Result

The error calibration experiment for the laser tracker measurement system and flight parameter quality evaluation was carried out according to the method mentioned above. The error calibration result of the Leica AT960-LR laser tracker measurement system is shown in Figure 6. The results show that within the distance range of the laser tracker distance measurement error calibration experiment, the maximum ranging error was $44.7 \mu\text{m}$, and the minimum ranging error was $4.6 \mu\text{m}$. According to the fitting formula between the ranging error and the measured distance, $\delta = 1.94L + 1.75$, the ranging error had a positive linear correlation with the measured distance. The average nominal angle measurement error was $2.77''$, and the actual measured average angle measurement error was $3.81''$, which exceeds the average nominal angle measurement error by 37.5%. The greater the incident angle of the laser beam, the greater the measurement error; the error distribution was symmetrical along the laser axis, and the maximum incident angle of the target ball could reach $27.1 \mu\text{m}$.

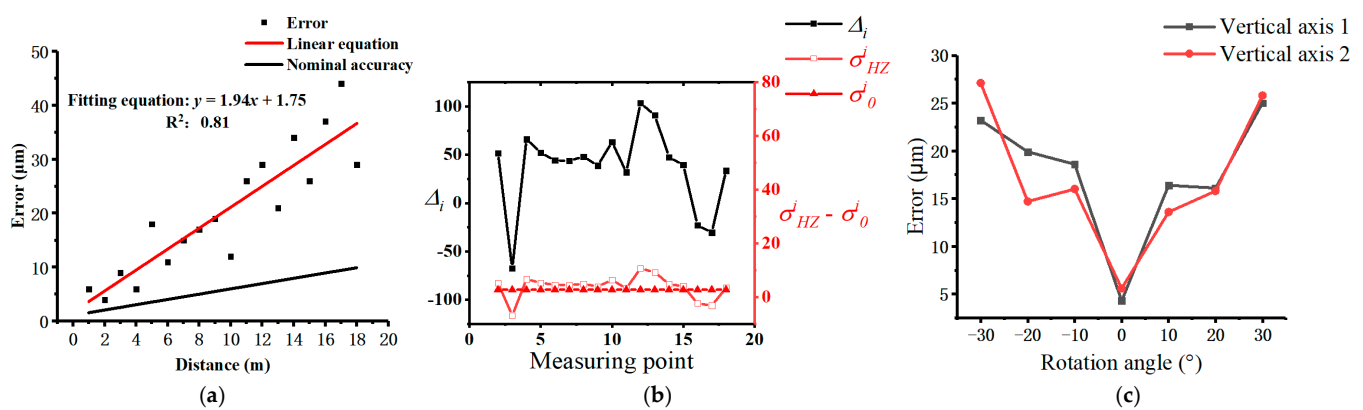


Figure 6. Error calibration results: (a) range measurement calibration, (b) angle measurement calibration, and (c) laser incident angle error calibration.

According to the error analysis and calibration results of the laser tracker, it is important that the target ball faces the laser tracker to reduce the measurement error caused by the incident angle. At the same time, the flight altitude and speed of UAV should not change greatly.

3.2. Flight Parameter Quality Evaluation Results

According to the method mentioned above, the experiment for the flight parameter quality evaluation of the plant protection UAV was carried out. The flight trajectory was drawn according to the position information of the UAV obtained by the onboard sensor and the Leica AT960-LR laser tracker measurement system, as shown in Figure 7.

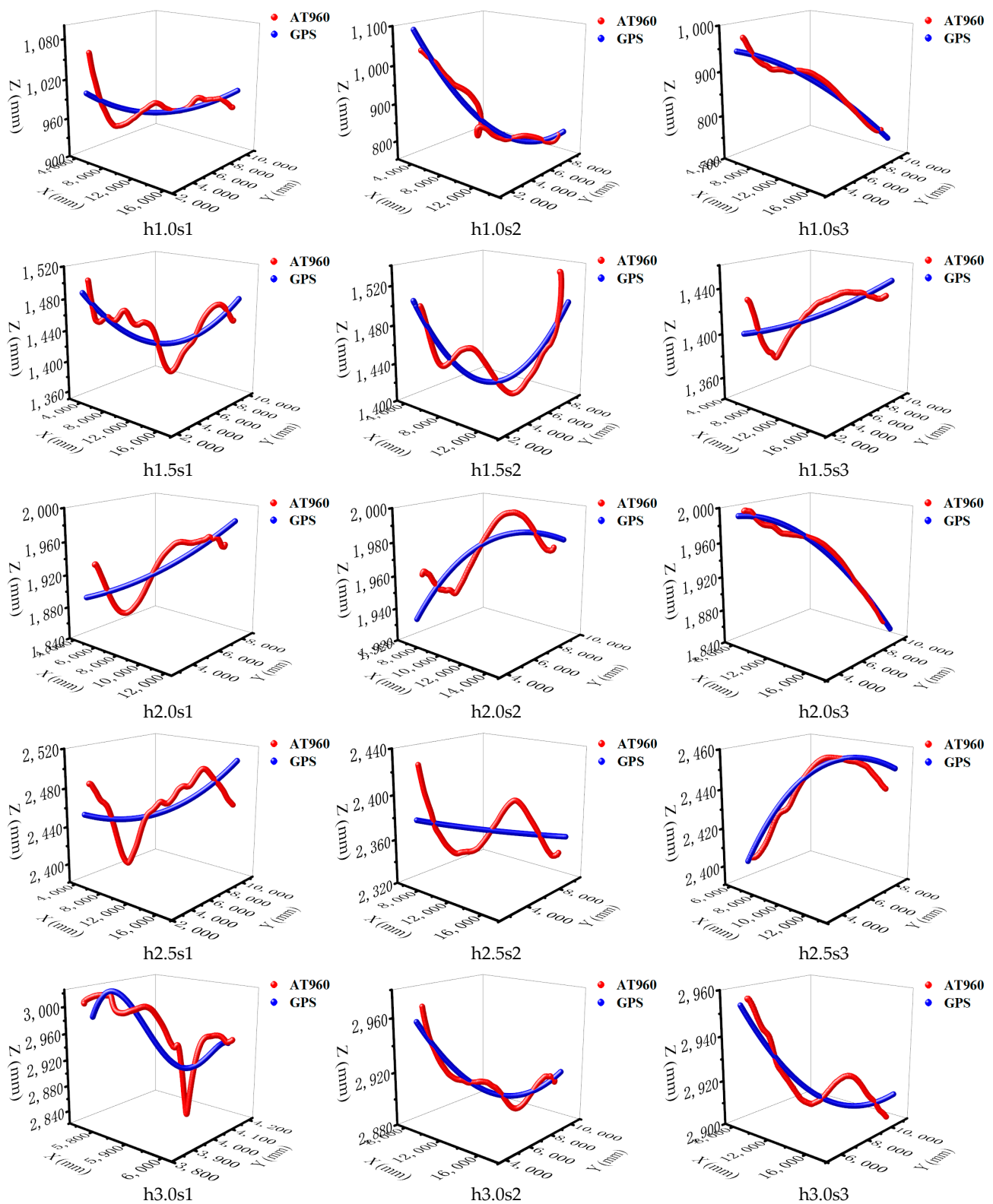


Figure 7. Flight trajectory.

The flight speed consistency and flight altitude consistency were also used as indicators of the quality evaluation of flight parameters. The consistency results are shown in Table 4, and the flight altitude and speed curves are shown in Figures 8 and 9.

Table 4. Consistency of flight speed and altitude.

Parameters	Average Altitude (mm)		Error from Set Altitude (%)		Average Speed (m·s ^{−1})		Error from Set Speed (%)		Altitude Consistency (%)		Speed Consistency (%)	
	AT960	Airborne Sensor	AT960	Airborne Sensor	AT960	Airborne Sensor	AT960	Airborne Sensor	AT960	Airborne Sensor	AT960	Airborne Sensor
h1.0s1	974.19	975.45	2.6	2.5	2.69	1.52	169.0	52.0	2.02	0.95	16.95	11.26
h1.0s2	868.39	868.93	13.2	13.1	3.01	2.35	50.5	17.5	8.99	8.34	15.57	2.37
h1.0s3	861.42	861.17	13.9	13.9	5.50	3.16	83.3	5.3	7.22	6.96	21.58	5.77
h1.5s1	1441.42	1439.39	5.9	6.1	2.58	1.04	158.0	4.0	1.82	1.16	27.10	13.17
h1.5s2	1450.88	1448.60	4.9	5.1	3.19	2.21	59.5	10.5	2.12	1.63	30.14	17.28
h1.5s3	1416.14	1416.04	8.4	8.4	5.59	2.98	86.3	0.7	1.30	0.92	16.19	4.73
h2.0s1	1930.57	1929.17	6.9	7.1	2.87	1.35	187.0	35.0	1.65	1.28	22.66	3.98
h2.0s2	1972.80	1972.38	2.7	2.8	4.60	2.08	130.0	4.0	0.82	0.71	24.12	2.47
h2.0s3	1940.41	1941.08	6.0	5.9	5.46	3.24	82.0	8.0	2.21	2.22	24.36	7.58
h2.5s1	2458.06	2458.75	4.2	4.1	2.65	1.31	165.0	31.0	1.09	0.57	25.00	14.37
h2.5s2	2362.02	2364.11	13.8	13.6	4.66	2.62	133.0	31.0	0.84	0.20	22.09	5.96
h2.5s3	2440.33	2444.44	6.0	5.6	5.53	2.56	84.3	14.7	0.62	0.54	26.33	5.49
h3.0s1	2950.64	2948.52	4.9	5.1	1.41	1.04	41.0	4.0	1.78	1.33	4.01	0.98
h3.0s2	2913.17	2913.87	8.7	8.6	4.52	2.48	126.0	24.0	0.53	0.48	25.97	1.19
h3.0s3	2919.64	2917.45	8.0	8.3	5.75	3.46	91.7	15.3	0.50	0.43	18.96	2.45

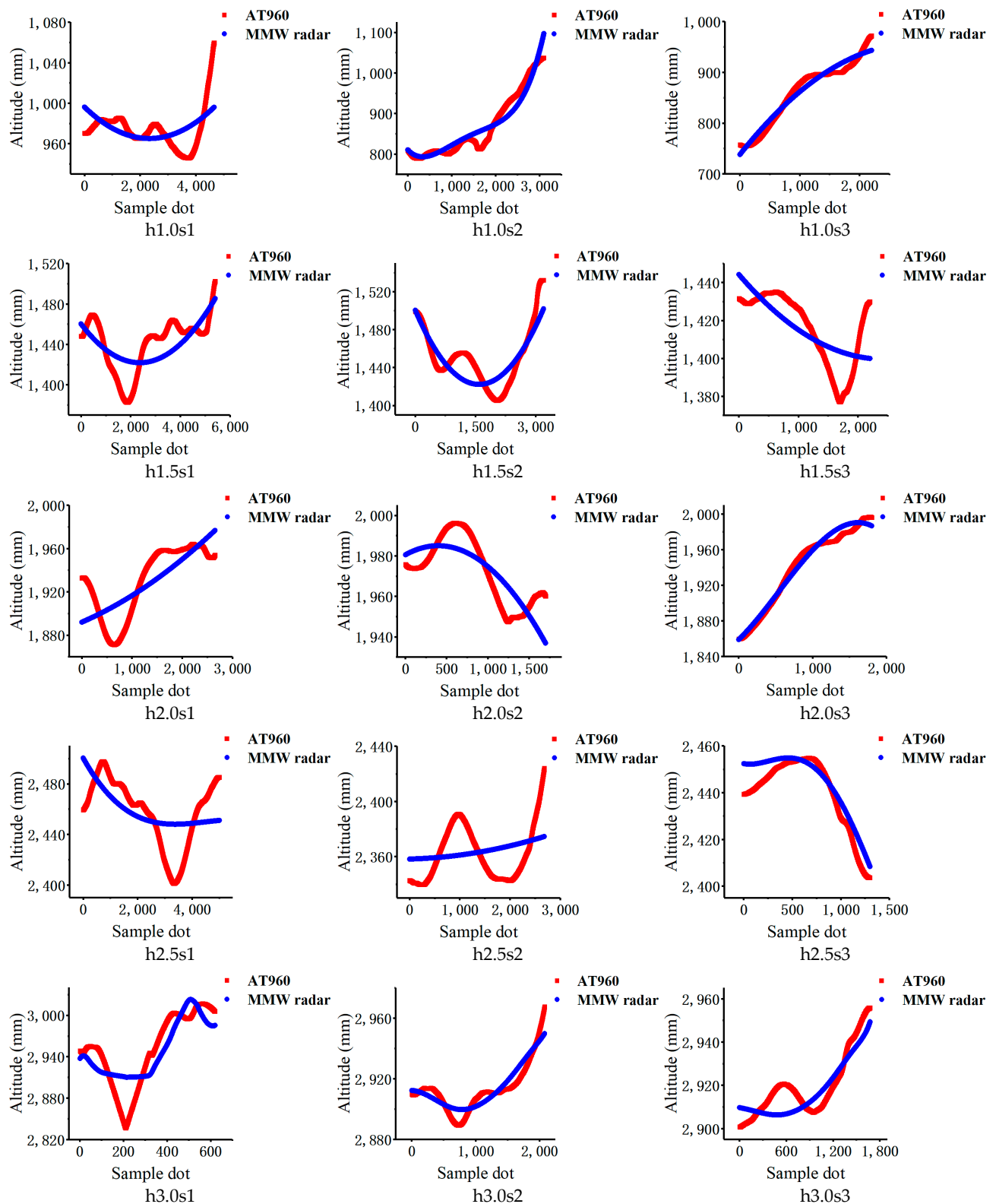


Figure 8. Flight altitude.

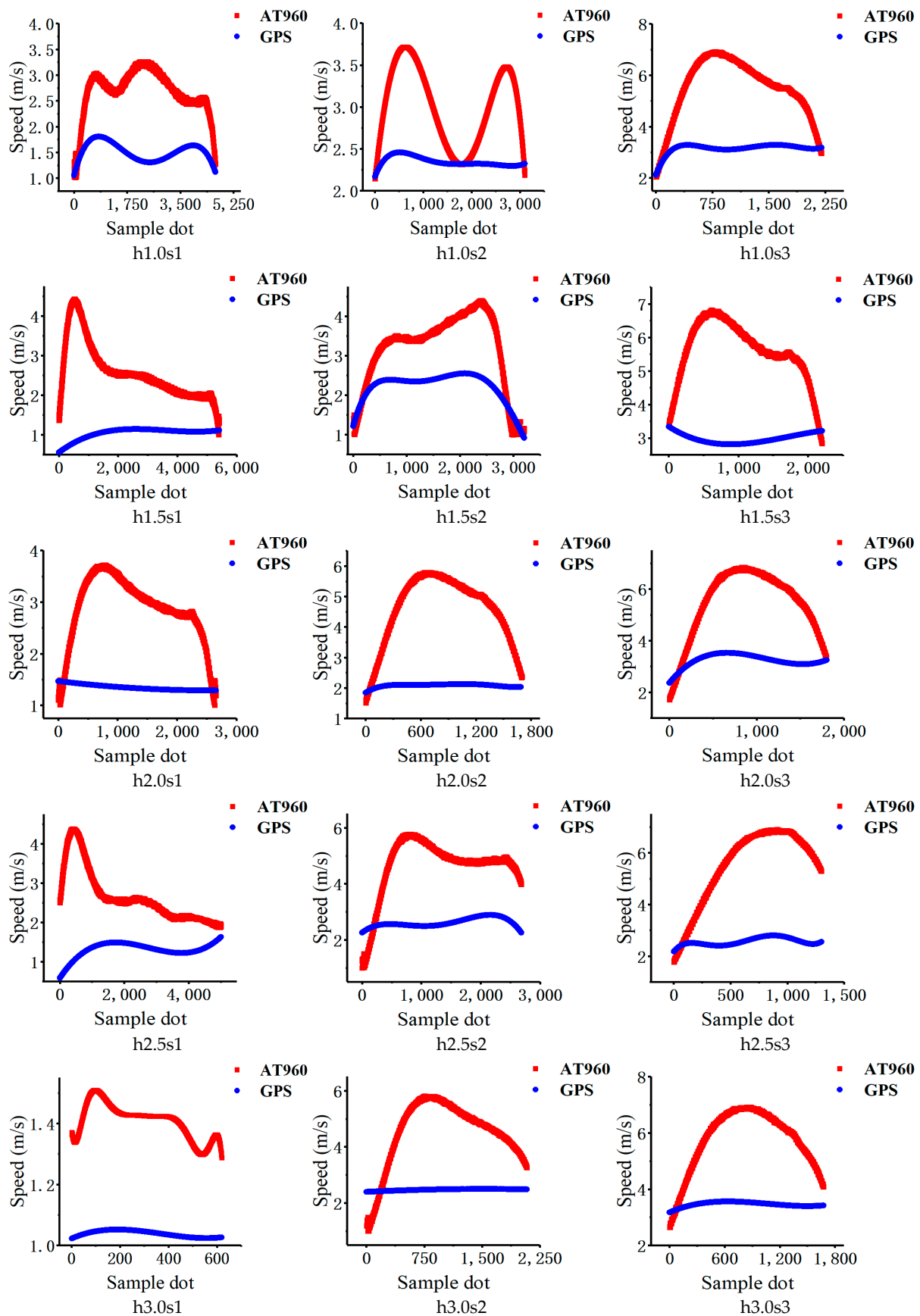


Figure 9. Flight speed.

- (1) It is shown in Figure 7 that the flight trajectory of the UAV reflected by the onboard sensor was relatively smooth, while the high-precision flight trajectory obtained by the laser tracker fluctuated greatly, especially for the flight altitude. Further analysis based on Table 4 and Figure 8 shows that the error between the average altitude and the set value obtained by the onboard sensor and laser tracker was less than 15%, and the error range was concentrated in the 5%–8% range. The deviation between the instantaneous flight altitude and the set altitude was relatively large. When the set flight altitude and speed were 1 m and 3 m/s, respectively, the maximum deviation between the altitude measured by the laser tracker and the set value was 245 mm. And at the same flight altitude and speed, the deviation between the altitude measured by onboard sensors and the set value was also the largest, which was 262 mm.
- (2) According to the analysis of the altitude consistency index reflecting the actual flight altitude stability, the altitude consistency measured by onboard sensors was the best when the set flight altitude and speed were 2.5 m and 2.0 m/s, respectively, which was 0.20%. The worst was 8.34% when the set flight altitude and speed were 1.0 m and 2.0 m/s, respectively. The results of the laser tracker, which had higher accuracy and were closer to reality, were as follows: the altitude consistency was the best when the flight altitude was 3.0 m and the flight speed was 3.0 m/s, which was 0.50%; the worst was 8.99% when the flight altitude was 1.0 m and the flight speed was 2.0 m/s. Comparing the altitude consistency between the laser tracker and the onboard sensor under the same flight parameters, when the flight altitude and speed were set at 2.0 m and 3.0 m/s, respectively, the deviation was the smallest, at 0.45%. When the flight altitude and speed were set at 2.5 m and 2.5 m/s, respectively, the deviation was the largest, at 76.19%. In the whole experiment, the average deviation of the altitude consistency was 24.95%.
- (3) According to Table 4 and Figure 9, the flight speed curve obtained by the onboard sensors was relatively stable without significant fluctuation, while the high-precision flight speed obtained by the laser tracker fluctuated greatly. The maximum error between the average flight speed measured by onboard sensors and the set value was 52%, the minimum error was 0.7%, and the error was concentrated at 15%. The maximum error between the average flight speed measured by the laser tracker and the set value was 187%, and the minimum error was 41%.
- (4) From the analysis of the speed consistency index, which reflects the actual flight speed stability, the speed consistency measured by onboard sensors was the best when the flight altitude was 3.0 m and the flight speed was 1.0 m/s, which was 0.98%. The worst speed consistency measured by onboard sensors was 17.28% when the flight altitude and speed were 1.5 m and 2.0 m/s, respectively. The speed consistency measured by the laser tracker was the best when the flight altitude was 3.0 m and the flight speed was 1.0 m/s, which was 4.01%; when the flight altitude was 1.5 m and the flight speed was 2.0 m/s, the speed consistency measured by the laser tracker was the worst, at 30.14%. Comparing the speed consistency between the laser tracker and onboard sensor under the same flight parameters, it can be seen that when the flight altitude and speed were set to 1.0 m and 1.0 m/s, respectively, the deviation between the two was the smallest, at 33.57%; when the flight altitude and speed were set to 3.0 m and 2.0 m/s, respectively, the deviation between the two was the largest, at 95.42%; in the whole experiment, the average deviation of the speed consistency between the two was 70.02%.
- (5) The experimental results show that the current plant protection UAV used the average altitude and speed of onboard sensors to determine whether to reach the set values of operational flight parameters. However, by comparing the real-time data of the laser tracker, it was found that the consistency of flight altitude and speed measured by the onboard sensors was erroneous and tended to stabilize. The flight altitude and speed of the plant protection UAV during operation changed constantly and showed a large deviation from the set value. With regard to the flight speed, there was a huge

difference between the speed measured by the laser tracker and the set value. Based on the experimental results, the possible reasons for this situation are as follows.

First, because of the different sampling frequencies of the onboard sensors and laser tracker, the measured data were different. In this study, the sampling frequencies of the onboard sensors were as follows: GPS: 10 Hz, MMW: 100 Hz, and laser tracker: 1000 Hz. The laser tracker records more data at the same time. The onboard sensor with a low sampling frequency loses some data, and the lower sampling frequency smooths and filters the data.

Second, according to the GPS positioning principle, the GPS is not sensitive to speed changes in the vertical direction. The speed output from the GPS is mainly in the horizontal direction, and the plant protection UAV judges whether the flight speed reaches the set value according to the GPS speed. The laser tracker calculates the flight speed by measuring the 3D coordinates of the plant protection UAV, which has high accuracy in both the horizontal and vertical directions. During the flight of the plant protection UAV, there is a certain degree of vertical fluctuation. The GPS can only measure the horizontal speed and does not measure the vertical speed. However, the laser tracker can measure both horizontal and vertical speeds. As a result, there is a large discrepancy between the flight speed measured by the laser tracker and the set value.

Third, the control algorithm of the plant protection UAV was based on the average value of onboard sensors over a certain period of time to determine whether the flight parameter reached their set values. In addition, the flight data may be filtered and smoothed in the control algorithm.

Due to a combination of these reasons, the flight parameters fed back to the plant protection UAV, and the operator showed that the set values were met. However, the more accurate flight parameters measured by the laser tracker were different from the set values. Especially for the flight speed, a huge difference was observed between the speed measured by the laser tracker and the set value.

The experimental results show that only using the data from onboard sensors to evaluate the flight parameter quality has a large error with real flight conditions. According to this research, by introducing the AT960-LR laser tracker, which is independent of the plant protection UAV, the flight trajectory, altitude, and speed of the plant protection UAV can be accurately obtained. The accuracy of the quality evaluation of flight parameters can be further improved. This study may provide new ideas for the accurate evaluation of the flight parameter quality of plant protection UAVs and provide reference and guidance for accurate spraying and performance improvement of plant protection UAVs through accurate flight parameter quality evaluation.

4. Conclusions

In order to achieve the accurate flight parameter quality evaluation of the plant protection UAV, this study used flight trajectory, flight altitude consistency, and flight speed consistency as evaluation indexes. The quality evaluation and experiment of flight parameters based on an absolute laser tracker were carried out.

- (1) According to the experimental results, the current plant protection UAV used the average altitude and speed of the onboard sensors to judge whether the flight operation parameters reached the set values. Compared with the Leica AT960-LR absolute laser tracker, the flight trajectory, altitude consistency, and speed consistency output from the onboard sensors were erroneous, with a tendency to become smoother and more stable. This may be due to the fact that the onboard sensor sampling frequency (GPS: 10 Hz, MMW: 100 Hz) is lower than that of the laser tracker sampling frequency (1000 Hz) or that the data are filtered and smoothed by the control algorithm of the plant protection UAV. This shows that only using the data from onboard sensors to evaluate the flight parameter quality cannot accurately reflect real flight conditions. The real-time data of the onboard sensor and laser tracker indicate that the flight altitude and speed of the plant protection UAV change constantly during the operation

process, and the deviation between the real-time data and the set value was large. Particularly in the flight speed, the deviation between the real-time data measured by the laser tracker and the set value was large, the maximum error was 187%, and the minimum error was 41%.

- (2) The maximum difference between the average flight altitude measured by onboard sensors and the laser tracker was only 4.11 mm. However, there was a large gap between the two in flight altitude consistency. The best flight altitude consistency measured by onboard sensors was 0.20%, and the worst was 8.34%. The best flight altitude consistency measured by the laser tracker was 0.50%, and the worst was 8.99%. Under the same flight parameters, the minimum deviation of flight altitude consistency measured by onboard sensors and the laser tracker was 0.45%, the maximum deviation was 76.19%, and the average deviation was 24.95%.
- (3) The best flight speed consistency measured by onboard sensors was 0.98%, and the worst was 17.28%. The best flight speed consistency measured by the laser tracker was 4.01%, and the worst was 30.14%. Under the same flight parameters, the minimum deviation of flight speed consistency measured by the onboard sensors and laser tracker was 33.57%, the maximum deviation was 95.42%, and the average deviation was 70.02%.
- (4) The experimental results show that only using the data from onboard sensors to evaluate flight parameter quality causes a large error in real flight conditions. This article utilized the high accuracy of the laser tracker to accurately obtain the flight trajectory, altitude, and speed of the plant protection UAV, which can further improve the accuracy of flight parameter quality evaluation. It aimed to provide new ideas for the accurate evaluation of the flight parameter quality of the plant protection UAV and provide data support and guidance for accurate spraying and performance improvement of the plant protection UAV through accurate flight parameter quality evaluation.

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