

## Research Article

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# Test influence of screen thickness on double-N six-light-screen sky screen target

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**Abstract:** In this article, a new method for processing trajectory parameter tests of flying targets with the geometric center of the screen as the response time of the detector is proposed. The superiority of this method over the conventional method for uniform thickness treatment is shown through the error and data analysis of the yaw angle, pitch angle, and flying speed. The relative distance between the test track and the real track shows the accuracy of the new method. The obvious statistical rules can be found for the errors of test parameters, which is conducive to the test research of random and violent vibrations of the target surface.

**Keywords:** flying target, yaw angle, pitch angle, running speed, sky screen target

## 1 Introduction

The flying target test plays an important role in aerospace [1,2], military matters [3,4], and other fields. The flying target test includes the inner orbit test, intermediate orbit test, and final orbit test, of which the intermediate orbit test is the most essential link of the flying test with the longest time and the most influenced by external factors. Flight trajectory and operating speed are the important factors of the intermediate orbit test, which can directly reflect the target fall attribute of the moving target. During the operating process, in addition to the interference of

gravity [5] and medium [6], the test method and parameter treatment method [7,8] have always been the focus of the research.

The diversity in light-screen targets contributes to the further optimization of the structure and accuracy. At present, many types of light-screen test models have been produced, such as light-screen targets with integrated transceiver [9], intelligent light-screen targets [10], and composite light-screen targets [11]. Sky screen targets are the passive light source test instrument that use natural light background to detect the flying target. In terms of the double-N six-light-screen sky screen target [12], the measurement of intensity of multitarget target fall and the operation vector can be actualized, and the test method is simple and reliable. After the test, the operating parameters [13] of the flying target can be obtained immediately.

At present, the data processing method of the six-light-screen sky screen target is not perfect. However, as the analysis method gradually deepened, the test accuracy is improved. The system has two typical processing approximations, that is, the thickness of each screen is considered to be uniform and the speed of the movement of the flying target is even between adjacent screens. Only by effectively solving these two approximation difficult problems can the trajectory parameters of the flying target be measured with high accuracy. This study aims to optimize the first approximation and proposes a hypothesis in accordance with the uniform increase of the screen thickness. The processing was conducted with the geometric center of the screen as the response time, and the method was verified through simulation, operation, and field experiment, providing the theoretical basis for achieving the test system of target fall with paperless targets.

## 2 Methodology

The test system of sky screen is to place a photoelectric detector directly below the trajectory of the flying target to be tested to form a detection screen with natural light as a background light source. The circuit corresponding

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to each detection sky screen will output an over-target signal to then obtain all analog signals of the flying target through signal data acquisition instrument. The corresponding time pulse signals will be obtained after processing. Finally, the position coordinates and speed of target fall will be calculated further by computer to transmit the data to the master computer terminal with test results displayed. The double-N six-light-screen sky screen target is composed of two three-light-screen target groups [13]. When the flying target passed through the double-N six-light-screen test system, six groups of pulse signals were generated, respectively, through the light screen and to calibrate the passing time, as shown in Figure 1.

When six passing moments  $t_1, t_2, t_3, t_4, t_5,$  and  $t_6$  were obtained from left to right, the test pitch angle  $\theta$ , the test azimuth angle  $\gamma$ , and the test speed  $v$  of the flying target could be derived, respectively, by using the principle of geometric optics:

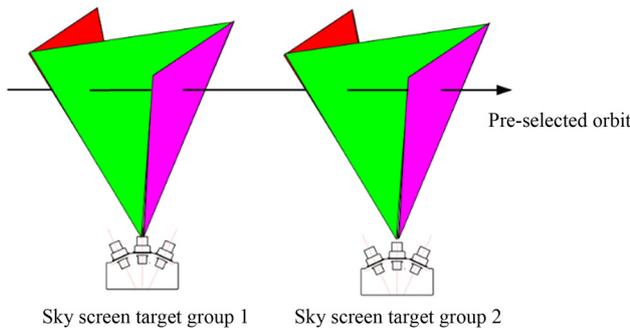
$$\theta = \arctan \left[ \frac{t_6 - t_4 - t_3 + t_1}{(t_6 + t_4 - t_3 - t_1) \tan \alpha} \cos \gamma \right] \quad (1)$$

$$\gamma = \arctan \left[ \frac{t_6 - t_3}{t_5 - t_2} \cot \beta (1 - \tan \alpha \tan \delta) - \cot \beta \right] \quad (2)$$

$$v = \frac{L \cos \alpha \cos \delta}{(t_6 - t_3) \cos \theta \cos \gamma \cos(\alpha + \delta)} \quad (3)$$

where  $\alpha$  referred to the angle between adjacent light screens at the pitch projection plane and  $\beta$  referred to the angle between adjacent light screens at the azimuth projection plane. There were four angles for each type of angle, and they were designed as equal symmetrical structures for the convenience of calculation.  $\delta$  referred to the angle between the preselected orbit of the flying target and the pitch plane, and  $L$  referred to the distance between two sky screen target groups.

In the treatment process of the test system, it is usually considered that the screen thickness is uniform with the median of the response pulse of the detector as the



**Figure 1:** Screen side view of double-N six-light-screen.

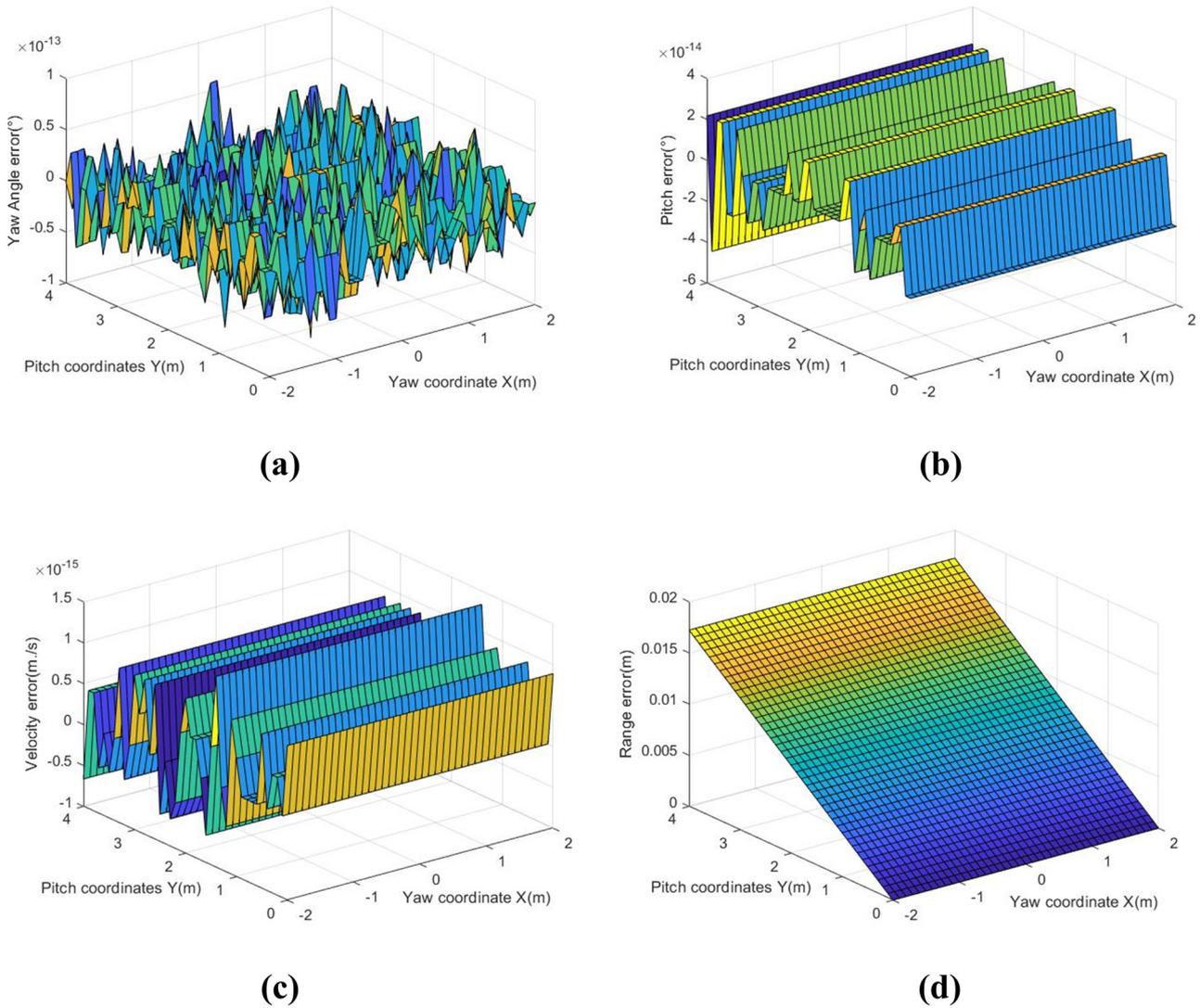
instantaneous value of the flying target passing through the screen. When the flying target passed through the first screen with normal incidence, the error analysis of the test parameters was conducted with the conventional treatment method, as shown in Figure 2.

It could be seen that the yaw angle error processed with uniform thickness in the two-dimensional target surface coordinates was within the range of  $\pm 1 \times 10^{-13}$  degrees, and the fluctuation uniformity was relatively stable. The pitch angle error was not affected by the yaw coordinates, but as the pitch coordinates increased, the pitch angle error tended to increase as a whole. In addition, the fluctuation range of pitch coordinates within 4 m was within  $\pm 4 \times 10^{-14}$  degrees. Both the speed error and the relative distance error were not affected by the yaw coordinates, and the speed error increased slightly with the increase of pitch coordinates. In addition, the fluctuation center of the overall error was  $5 \times 10^{-16}$  m/s, and the regularity of fluctuation was relatively poor. The relative distance error was directly proportional to the pitch angle coordinates, which was obviously undesirable in the relatively high flight test area. If the screen system was applied to the highly variable environment, such as mountains and oceans, it would bring certain troubles to the flight trajectory test.

When the flying target passed through the first screen with oblique incidence, the same conventional method for pulse median treatment was used to analyze the error for the test parameters, as shown in Figure 3.

It was obvious that the errors of each parameter of oblique incidence were much larger than those of normal incidence, and the fluctuation range was wider. As the pitch angle increased, the yaw angle error would also increase, and the influence of the yaw direction on the yaw angle error was more significant. In addition, the yaw direction had a weak influence on the pitch angle error; however, the larger the pitch angle, the larger the pitch angle error. When the pitch angle was zero, which was referred to as a normal incidence, the pitch angle error was relatively small, which was consistent with the law reflected in Figure 2(b). The influence degree of the yaw direction on the speed error was similar to that of the pitch direction, both experiencing the same increase and decrease of value in small range. The degree of the yaw direction had no obvious influence on the relative distance error, but as the pitch angle increased, the relative distance error would also significantly increase. In addition, the error fluctuation slope slowly increased. During the analysis of the flight trajectory, the pitch angle factor should be prioritized in the error compensation.

In accordance with the simulated result, it could be seen that the errors of the measured data were not stable



**Figure 2:** Parameter error of uniform thickness in normal incidence: (a) error between the yaw angle and set true value, (b) error between pitch angle and set true value, (c) error between the speed and set true value, and (d) error between the relative distance and set true value.

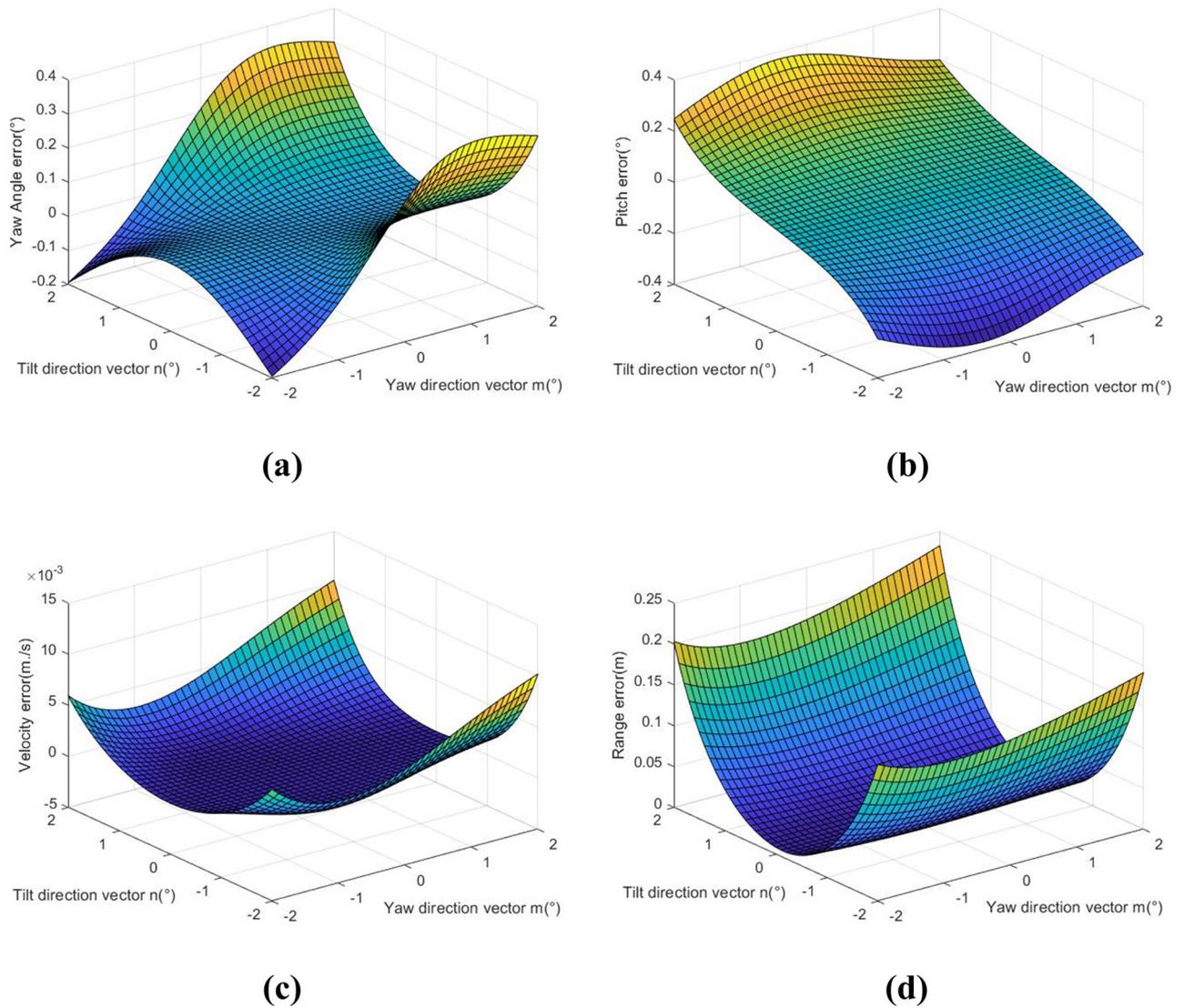
regardless of normal incidence or oblique incidence. Especially the influence of pitch coordinates on the test errors was more obvious, which was one of the reasons why the target fall error of the flying target might reach several centimeters. It could be seen that although the responsive time to the pulse was rather short, the selection of the effective instantaneous value in the interval was very important.

### 3 Experimental procedures

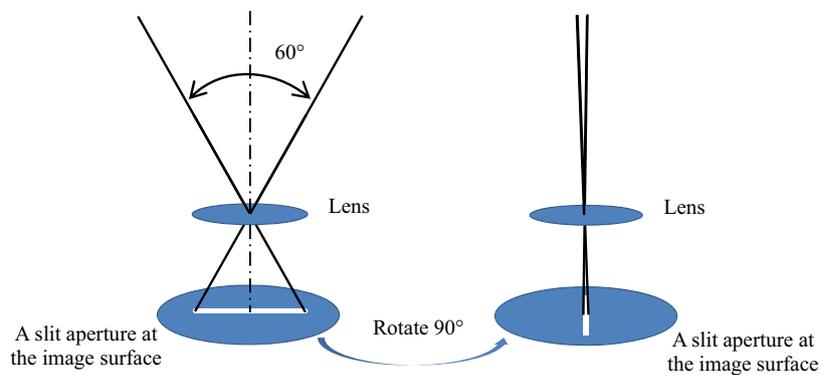
In the actual test process, Nikon lenses with focal length of 24 mm were adopted for the optical lenses of system.

The slit aperture and the photoelectric detector were 30 mm in length. A detection field angle of  $60^\circ$  was formed jointly by the optical lenses and the slit aperture. Affected by the width of the aperture slit, there was a certain thickness for the cross section of the field, and it increased with the growth of the height, as shown in Figure 4.

If the thickness changes of the screen were considered and the installation of the sky screen target groups were not in the same plane, the treatment of test response time with the pulse center would be further discussed. A bold assumption was made here. When the edge diffraction and scattering phenomena were ignored, the geometric center surface of each screen should be taken as the response time of the test. Then, the data was



**Figure 3:** Parameter error of uniform thickness in oblique incidence: (a) error between the yaw angle and set true value, (b) error between pitch angle and set true value, (c) error between the speed and set true value, and (d) error between the relative distance and set true value.



**Figure 4:** Schematic of the field thickness of detected by the sky screen target.

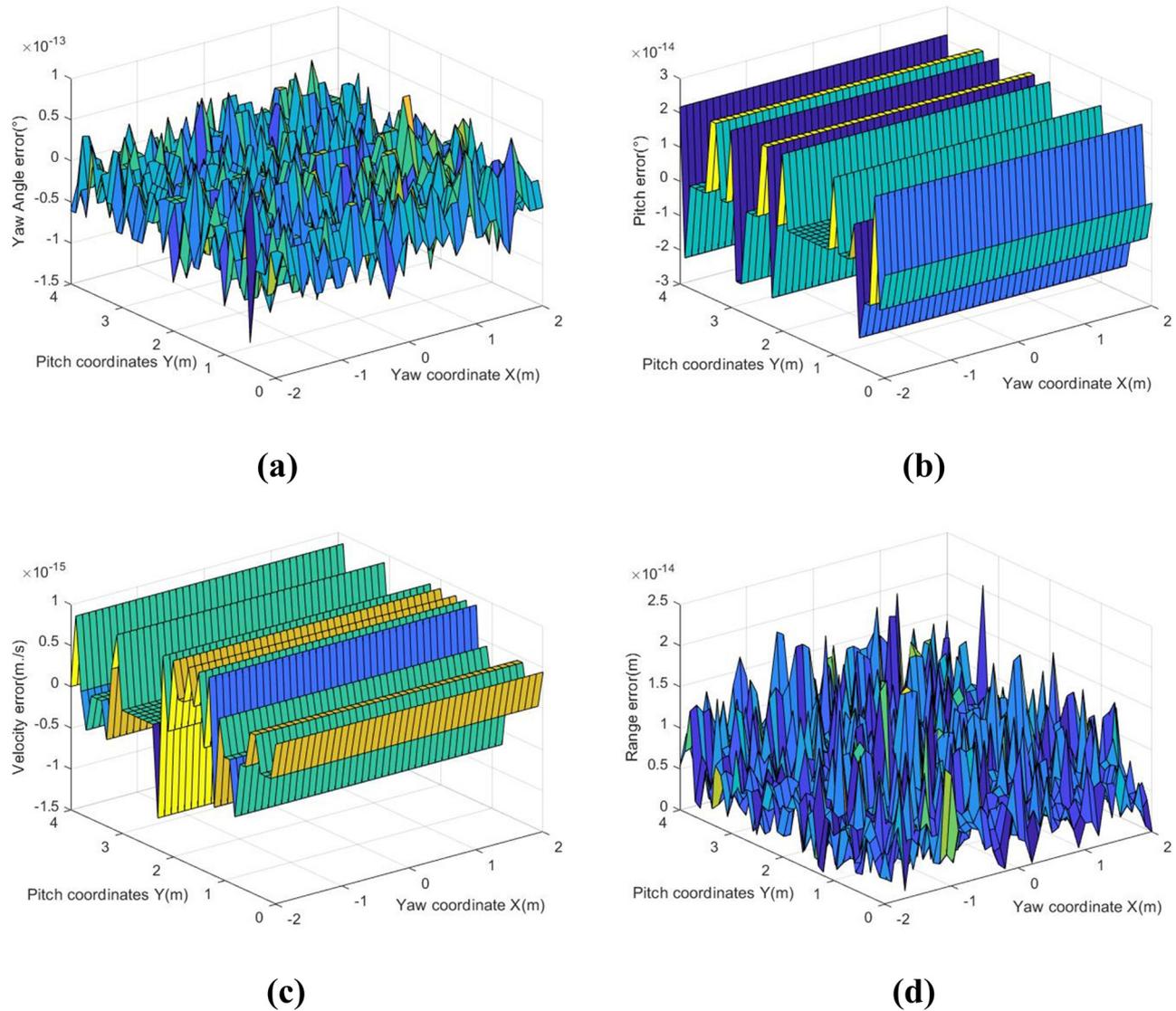
traversed in the forward and backward time regions with the pulse center, and the orbit parameters of the simulation test were compared with the set orbit parameters. The smaller the average error, the better the test effect.

In the system, the front and rear screens and geometric center screens of the six light screens could form 18 screen structures, respectively, and the respective equations of planes were established for analysis. When the flying target passed through the first screen with normal incidence, the simulated analysis was conducted for the test parameter errors after traversal operation, as shown in Figure 5.

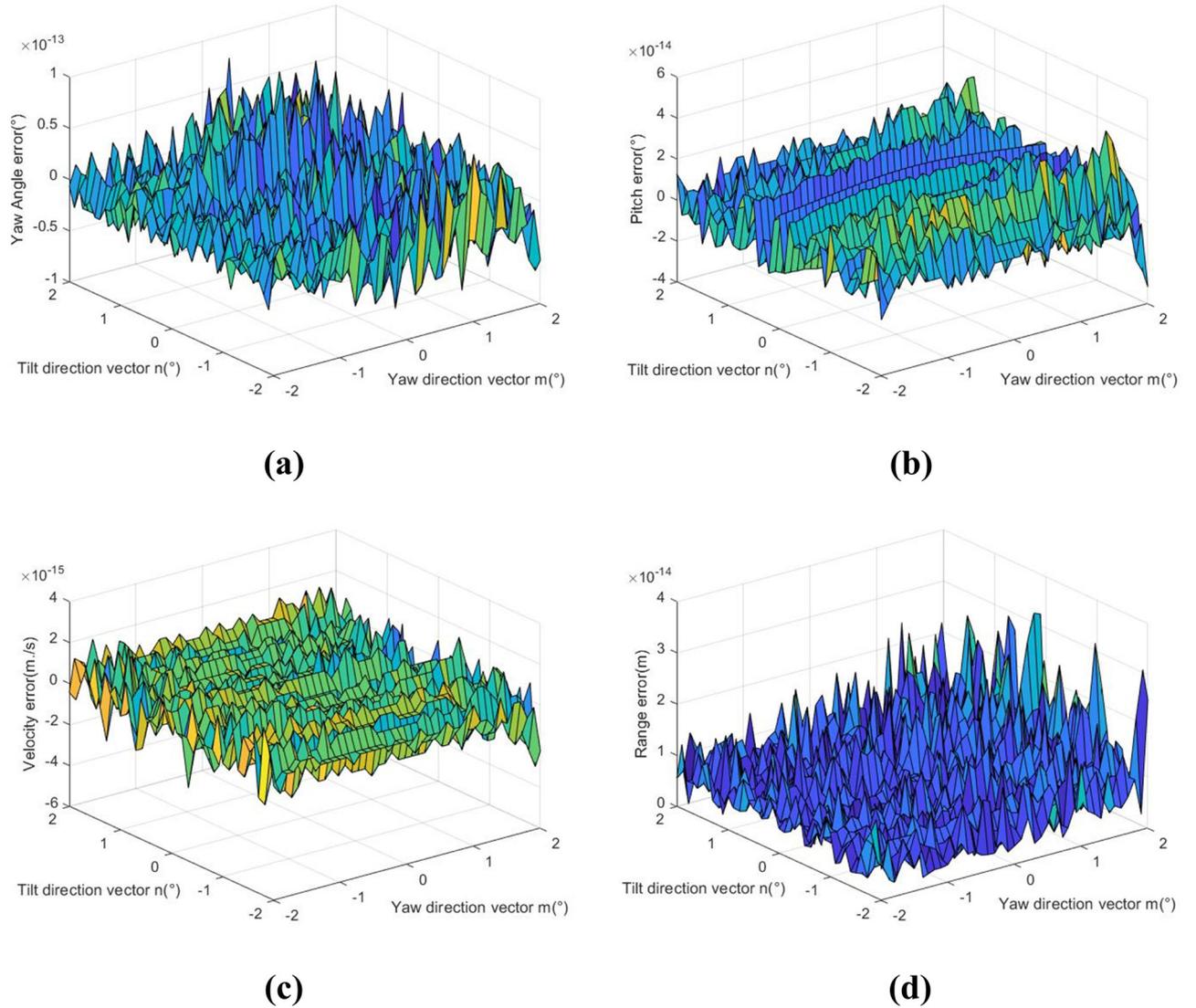
It could be seen from the above figures that the test parameters involving the changes of the screen thickness were much smoother than the error fluctuation of uniform thickness approximation. The overall error fluctuation

of the yaw angle was within the range of  $\pm 0.5 \times 10^{-13}$  degrees, and the overall fluctuation was more balanced. The pitch angle error and the speed error were still mainly affected by the pitch coordinates, but when compared with the uniform thickness, the error fluctuation range did not increase. The pitch angle error was near  $\pm 2 \times 10^{-16}$  degrees, and the center of the overall speed error was 0 m/s with the approximation fluctuation within the range of  $\pm 1 \times 10^{-15}$  m/s. The fluctuation of the relative distance error was within  $2 \times 10^{-14}$  m, which was several orders of magnitude better than the uniform thickness. In addition, it showed typical statistical distribution characteristics, which is conducive to the later data compensation analysis.

When the flying target passed through the first screen with oblique incidence, the simulated analysis for the test



**Figure 5:** Parameter error of nonuniform thickness in normal incidence: (a) error between the yaw angle and set true value, (b) error between pitch angle and set true value, (c) error between the speed and set true value, and (d) error between the relative distance and set true value.



**Figure 6:** Parameter error of nonuniform thickness in oblique incidence: (a) error between the yaw angle and set true value, (b) error between pitch angle and set true value, (c) error between the speed and set true value, and (d) error between the relative distance and set true value.

**Table 1:** Data statistics of field tests

S/N	$t_2/\mu\text{s}$	$t_3/\mu\text{s}$	$t_4/\mu\text{s}$	$t_5/\mu\text{s}$	$t_6/\mu\text{s}$	$x_B$	$y_B$	$x_{PC}$	$y_{PC}$	$v/\text{ms}^{-1}$	$\theta/^\circ$	$\gamma/^\circ$
1	2.811	4.79	24.914	27.668	29.406	162	-110	152.9	692	145.6	-0.6	0.2
2	1.542	4.818	25.794	27.117	29.812	-198	-218	-220.1	579.7	142.1	-1.8	0.7
3	1.158	5.951	24.633	26.263	31.025	-448	206	-488.1	1023.4	145	1.4	0.9
4	3.206	5.765	25.104	28.643	31.378	140	180	125.4	986.8	142.1	1.5	0.1
5	2.553	3.977	26.53	29.415	30.426	301	-233	293.7	564.1	136.2	-0.1	1.6
6	1.854	3.137	24.714	26.584	28.008	69	-277	58.4	518	145.5	0.5	-0.5
7	2.177	6.024	28.118	30.845	34.083	-27	23	-50.2	823.5	128.4	0.1	2.2
8	1.114	6.006	27.31	29.289	33.805	-292	125	-330.3	936.9	130.9	1.4	2.4
9	2.825	7.19	28.17	31.444	35.773	-122	255	-138.1	1061	127	1.2	0.7
10	0.039	4.378	25.731	26.235	29.869	-411	-182	-456.3	615.6	140.9	-0.4	2.5

index	mid_	mid	Δmid	t	
i1	44	0	0.00000001	-0.00000001	0.00000440
i2	1	0.000039	0.00003900	0.00000000	0.00003910
i3	-41	0.004378	0.00437801	-0.00000001	0.00437390
i4	41	0.025731	0.02573105	-0.00000005	0.02573510
i5	1	0.026235	0.02623501	-0.00000001	0.02623510
i6	-36	0.029869	0.02986904	-0.00000004	0.02986540

Figure 7: Operation interface of experimental data traversal.

parameter errors after traversal operation was conducted, as shown in Figure 6.

As can be seen from the above figures, the error fluctuation of all parameters was much more stable than the range of the uniform thickness treatment method, achieving significant improvement in the overall error. In addition, the yaw coordinates and pitch coordinates would not cause fluctuations in the parameter error. The fluctuation of the yaw angle error was within the range of  $\pm 0.8 \times 10^{-13}$  degrees, and the center of the pitch angle error was  $0.5 \times 10^{-14}$  degrees with the fluctuation within the range of  $\pm 2.5 \times 10^{-14}$  degrees. The error fluctuation of two angles involving the screen thickness was about  $10^{14}$  times higher than the error fluctuation with uniform thickness. The fluctuation of the speed error was within the range of  $\pm 2 \times 10^{-15}$  m/s with improvement of about  $10^{13}$  times. The small increase next to  $2 \times 10^{-14}$  m occurs for the relative distance error with the increase of yaw coordinates and pitch coordinates. In the test heights of the common flying targets, the relative distance error did not exceed  $4 \times 10^{-14}$  m. In the test environment with

inconspicuous height changes, the appropriate mean value could be selected for analyzing and processing the flight trajectory.

To verify the simulation result, sunny days were selected to conduct the experiment in the outfield. The distance between two sky screen groups was arranged to be 3,600 mm, and the height difference of vertical target groups was  $\Delta H = 10$  mm. Ten groups of test parameters were calibrated and processed, respectively, as shown in Table 1.

The passing time of the first screen was arranged to be 0, and  $x_B$  and  $y_B$  referred to horizontal and vertical coordinates of paper targets. In addition,  $x_{PC}$ ,  $y_{PC}$ ,  $v$ ,  $\theta$ , and  $\gamma$ , respectively, refer to horizontal and vertical coordinates, speed, pitch angle, and azimuth angle processed with pulse median. Traversal operation was conducted for each group of passing time to seek the minimum relative distance between the simulated running orbit and the experimental orbit. The operation interface is shown in Figure 7.

Traversal processing was conducted for ten groups of data from the experiment to obtain the optimal target flying speed  $v_2$ , the pitch angle  $\theta_2$ , and the azimuth angle  $\gamma_2$ . The operating trajectory fitted by this group of parameter values coincides with the operating trajectory with the geometric center surface of each screen as the response time, indicating that the previous conjecture is reasonable. To better observe the degree of improvement of the test accuracy, statistics was conducted for the data difference, as shown in Table 2.

Where,  $\Delta x$  and  $\Delta y$  referred to the difference values between horizontal and vertical coordinates processed with the pulse median and horizontal and vertical coordinates of paper targets.  $\Delta x'$  and  $\Delta y'$  referred to the difference values between horizontal and vertical coordinates with optimal processing of traversal and horizontal and vertical coordinates of paper targets.  $\Delta v$ ,  $\Delta \theta$ , and  $\Delta \gamma$ , respectively, referred to the difference values of the speed, the pitch angle, and the azimuth angle of the two processing

Table 2: Data statistics of traversal operation processing

S/N	$x_{PC2}$	$y_{PC2}$	$v_2/\text{ms}^{-1}$	$\theta_2/^\circ$	$\gamma_2/^\circ$	$\Delta x$	$\Delta x'$	$\Delta y$	$\Delta y'$	$\Delta v/\text{ms}^{-1}$	$\Delta \theta/^\circ$	$\Delta \gamma/^\circ$
1	159	459.5	146.1	-0.68	0.39	9.1	3	-802	-569.5	0.5	-0.08	0.19
2	-218.1	353.2	142.62	-1.91	0.77	22.1	20.1	-797.7	-571.2	0.52	-0.11	0.07
3	-480.9	782.4	145.55	1.27	0.96	40.1	32.9	-817.4	-576.4	0.55	-0.13	0.06
4	132.2	745.3	142.65	1.39	0.26	14.6	7.8	-806.8	-565.3	0.55	-0.11	0.16
5	295.4	329.8	136.67	-0.2	1.72	7.3	5.6	-797.1	-562.8	0.47	-0.1	0.12
6	66.2	280.2	145.98	0.35	-0.36	10.6	2.8	-795	-557.2	0.48	-0.15	0.14
7	-43.6	589.8	128.88	-0.02	2.37	23.2	16.6	-800.5	-566.8	0.48	-0.12	0.17
8	-318.2	697.2	131.41	1.23	2.51	38.3	26.2	-811.9	-572.2	0.51	-0.17	0.11
9	-137.7	822.7	127.45	1.09	0.84	16.1	15.7	-806	-567.7	0.45	-0.11	0.14
10	-441.2	382.7	141.43	-0.56	2.58	45.3	30.2	-797.6	-564.7	0.53	-0.16	0.08

methods. As can be seen from the above table, the coordinate data with the geometric center of the screen as the response time was obviously closer to the data of paper targets, and the experiment was in line with the theoretical analysis. Therefore, there is a reason to believe that the data in the last three columns of Table 2, to some extent, reflect the optimization range of the processing method with the geometric center of the screen as the response time compared with the processing method of pulse median.

## 4 Conclusion

If the thickness of the screen surface is considered and the geometric center of each screen is used to define the response time of the flying target trajectory, the accuracy of the processing results of the yaw angle, the pitch angle, and speed is significantly improved compared with the case of uniform thickness. In addition, the fluctuation range of the parameter errors significantly decreased, showing good probability statistics. The relative distance error between the measured trajectory and the true value can also directly reflect the test superiority with the screen thickness considered. In this article, the traversal operation method was adopted to conduct data analysis, and the theoretical result was verified through the field experiment data. The high consistency of the results was maintained. The processing method can effectively improve the speed of the flying target and the test accuracy of the running trajectory, providing effective theoretical basis and feasible means for the dynamic test system.

The parameter errors were observed from the perspective of the statistical law, and the test parameter processing method with the screen thickness considered can be applied to the situations where the heights and angles of target fall targets are variables, providing effective processing methods for the dynamic target surface test under complex environment such as strong vibration and oceans.

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