

MEASUREMENT METHOD FOR PROJECTILE VELOCITY IN VERTICAL TRAJECTORY BASED ON THREE PARALLEL LIGHT SCREENS

Linqiu Tan¹⁾, Ziyu Yang¹⁾, Yongjun Huang²⁾, Tao Dong¹⁾

1) School of Optoelectronic Engineering, Xi'an Technological University, Xi'an 710021, China
(✉ yangziyu@st.xatu.edu.cn)

2) Henan North Hongyang Machinery & Electronics Co., Ltd, Yuxi Industries Group Co., Ltd, Nanyang 474662, China

Abstract

To address the measurement limitations of traditional passive optoelectronic detection devices in testing the velocity of projectiles traveling along vertical trajectories, this paper proposes a velocity measurement method for projectiles with a vertical trajectory based on three parallel light screens. The proposed method addresses the limitations of the traditional uniform linear model which is restricted to calculating average velocity. By computing acceleration and instantaneous velocity along the vertical trajectory, it enhances measurement accuracy. Specifically, a velocity measurement model is developed for projectiles with vertical trajectories that incorporate deflection angle errors, gravitational effects and air resistance. These are key factors impacting the measurement accuracy of vertical trajectory velocity testing. Furthermore, numerical simulations are performed to analyse the characteristics of error variation. These results provide actionable guidance in practical measurement scenarios. Finally, field experiments are carried out to validate the feasibility of the proposed method and the applicability of the mathematical model. The results show that the velocity measurement relative error is no more than 0.18%. The proposed measurement method meets the requirements for testing the flight velocity of projectiles with vertical trajectories. It also provides a theoretical basis for research and technical implementation in related fields.

Keywords: photoelectric detection, velocity measurement, vertical trajectory, light screen array.

1. Introduction

Generally, accurately measuring the flight velocity of projectiles is essential for evaluating the performance of weapon systems, especially for vertical or high-angle trajectories which are typical of mortar shells. It also provides key scientific references for evaluating protective properties of protected object materials and optimizing equipment improvements [1–3]. These projectiles exhibit unique trajectory characteristics, typically involving flight phases with high elevation angles where the velocity vector maintains a significant vertical inclination. This poses a specific challenge for accurately measuring the velocity. Although traditional contact methods (*e.g.* foil/net targets) are intuitive, they suffer from poor safety (exacerbated by the high kinetic energy of projectiles with

a vertical trajectory), susceptibility to target deformation, low accuracy, and inefficiency [4, 5]. Therefore, non-contact measurement methods based on optical, acoustic, optoelectronic, and radar principles have emerged and gradually become mainstream [6–8].

Currently, several non-contact methods are employed, including optical vision-based systems, radar, acoustic arrays, line-array *charge-coupled devices* (CCDs), light screen array and so on. While optical methods (e.g. high-speed photography and photoelectric theodolites) offer high precision and repeatability [9], they require advanced processing and are limited by environmental conditions [10]. Radar provides high accuracy and all-weather capability but it struggles with small *radar cross-sections* (RCS) projectiles ($RCS \leq 0.1 \text{ m}^2$), limiting echo energy [11]. Acoustic arrays are compact and interference-resistant but, unfortunately, oblique trajectories reduce the signal-to-noise ratio and induce velocity errors [12]. Line-array CCDs perform well in real time with high precision. However, they require complex calibration and experience difficulties with the high-speed capture of weak signals, which reduces capture rates [13].

In particular, light screen arrays are widely adopted for projectile velocity measurement due to their high accuracy, high sensitivity, and stability. Specifically, they comprise active or passive optoelectronic detection devices forming geometrically arranged light screens. Typically, active systems require light screens perpendicular to the trajectory [14]. However, alignment deviations in vertical or high-angle trajectories introduce projection errors. Moreover, fixed light source supports limit the detection area usually $\leq 2 \text{ m} \times 2 \text{ m}$, restricting such devices mainly to indoor environments [15]. In contrast, passive optoelectronic detection devices use natural light as the background source to form large-area light screens, supporting the measurement of projectiles with various materials and calibres. Notably, elevation passive optoelectronic detection devices integrate an additional degree of mechanical freedom to accommodate high-angle trajectory tests within a specific range [16, 17]. While this effectively addresses the issue of non-perpendicular incidence by correcting the actual firing tilt angle, its typical configuration (usually involving two light screens arranged at a specific elevation) adopts an idealized model that yields the average velocity. Consequently, these methods are unable to fully account for significant velocity attenuation and trajectory deflection errors, especially as projectiles do not traverse the light screens vertically at a constant speed during high-angle trajectories [18]. Therefore, it is necessary to improve the measurement method to efficiently obtain projectile velocity in a vertical trajectory.

In this paper, a measurement method for projectile velocity in a vertical trajectory based on three parallel light screens is proposed. First, a measurement model for projectile velocity in a vertical trajectory is developed, considering deflection angle errors and projectile acceleration. Then, numerical simulation analyses are conducted to investigate the distribution characteristics of measurement errors influenced by parameters. Finally, a live-fire experiment is performed to validate the feasibility and applicability of the proposed method.

2. Methods

2.1. Measurement principle

The passive optoelectronic detection device is primarily comprised of an optical lens assembly, a slit diaphragm, and a photodetector [17]. The optical lens assembly collects natural light from the sky and projects it onto the slit diaphragm. The slit diaphragm restricts the field of view, forming a fan-shaped detection light screen, as shown in Fig. 1. The light screen expands in space and covers a specific detection area. When the projectile passes through the light screen, it blocks part of the incident light, causing a sudden drop in the light flux received by the photodetector. The

photodetector and the corresponding signal processing circuit convert these intensity changes into electrical signals. This calculates the moment of the projectile passing the detection light screen, and the projectile velocity can be obtained.

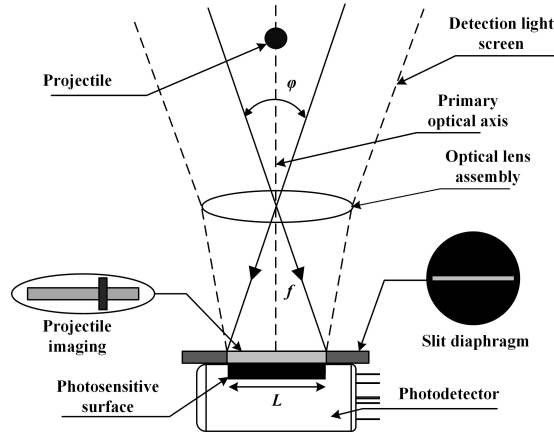


Fig. 1. Optical arrangement of a passive optoelectronic detection device.

Assuming that the length L of the photosensitive surface of the photodetector does not exceed the diameter of the imaging surface of the lens, the detection field of view φ is:

$$\varphi = 2 \arctan \frac{L}{2f}, \quad (1)$$

where f denotes the focal length of the optical lens. Generally, a shorter lens focal length yields a larger detection field of view for the passive optoelectronic detection device, but this reduces the system's effective aperture, consequently diminishing detection sensitivity. During vertical trajectory tests, the detection device is usually located at a significant distance from the projectile launch point (usually exceeding 5 m). This results in a larger area for the projectile to pass through the light screen, thereby reducing the requirement for a wide field of view while necessitating higher detection sensitivity. In order to ensure adequate sensitivity, a long focal length lens with a large effective aperture can be employed. Therefore, the Nikon AF-S Nikkor 85 mm f/1.4 G lens was selected with its focal length of 85 mm. The Chinese-made GD-24 phototube is chosen as the photodetector, with an effective photosensitive area of 20 mm × 30 mm, then according to (1), the field of view angle can be calculated to reach 20°. This parameter can meet the requirements for vertical trajectory velocity measurement.

According to the velocity measuring principle, a dual-light-screen system can measure the velocity of a projectile that passes through the light screen vertically and follows a uniform linear trajectory. However, for vertical trajectories, the combined effects of gravity and air resistance mean that the projectile does not traverse the two light screens at a constant velocity. Acceleration within a trajectory segment can be measured by recording at least three moments of projectile passage through the screens. Therefore, under the assumption that acceleration variation within a specific trajectory segment is negligible, using three parallel light screens allows the acceleration value of the projectile to be determined, and thus its velocity at any given time or position within that segment can be calculated.

Figure 2 illustrates the configuration of a vertical trajectory projectile velocity measurement system based on three parallel light screens. The power supply energizes three passive optoelectronic detection devices which form three parallel light screens. Notably, differences in screen thickness directly affect trigger signal correlation in a light-screen array system. Larger differences in thickness lead to difficulty in estimation for traditional correlation-based algorithms, resulting in degraded time interval estimation accuracy [19]. Therefore, the proposed method uses the mid-screen trigger mode. The moment when the bottom of the projectile reaches the midpoint of the light screen is defined as the trigger feature point, and the corresponding threshold is set to half of the peak level. Due to symmetrical structure of the light screen, the triggering time at the midpoint remains unaffected by variations in screen thickness. When the test projectile sequentially passes through three parallel light screens, the three photodetectors capture the variations in the optical signals and produce three electrical signals. These signals are processed by the projectile signal acquisition and processing unit to determine the moments at which the projectile passes through each light screen. Then, the acquired data is transmitted via a wireless network bridge or the network cable to the main control console, where these time values are integrated with an established mathematical model to calculate the projectile's flight velocity and interval acceleration. Furthermore, assuming acceleration remains constant over the measured segment of the trajectory, the acceleration data enables the velocity of the projectile to be determined at any point in time or position within the measured trajectory.

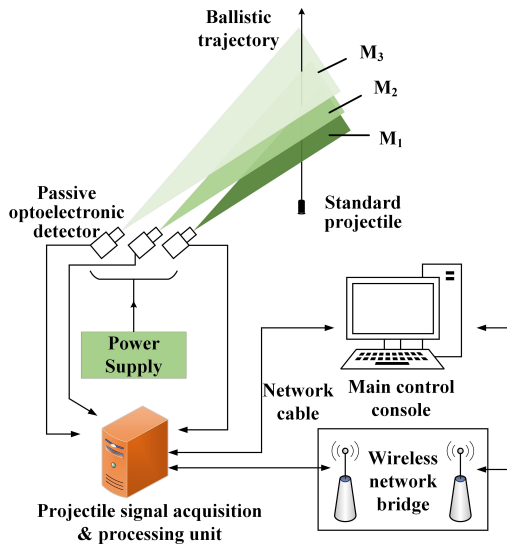


Fig. 2. Schematic diagram of a vertical trajectory projectile velocity measurement system based on three parallel light screens.

2.2. Measurement model

Figure 3 shows the coordinate system for the parallel three light screens in the YOZ plane. Since the screen spacing is relatively shorter compared to the entire trajectory during testing, the curvature of the trajectory within this detection range can be neglected and can be approximated as a straight line. The detection device closest to the projectile launch point, T_1 , is the starting

detection device; T_2 , the stopping detection device; and T_3 , the third detection device, is the one farthest away. A three-dimensional coordinate system is established with the starting point of the light screen for the T_2 detection device as the origin. The trajectory direction is defined as the Z-axis, with the projectile flight direction aligned positively along the Z-axis. The horizontal line connecting the projectile launch point and the passive optoelectronic detection devices defines the Y-axis. The X-axis and its direction are determined using the right-hand rule.

The distance from the starting detection device T_1 to the projectile launch point R is denoted as l' (referred to as the launch distance); the horizontal distance from T_1 to the stopping detection device T_2 is l_1 ; the distance from T_2 to the third detection device T_3 is l_2 . The angles between detection devices T_1 , T_2 , and T_3 relative to the Y-axis are σ_1 , σ_2 , and σ_3 , respectively. The light screens formed by detection devices T_1 , T_2 , and T_3 are denoted as M_1 , M_2 , and M_3 , respectively. The spacing of the ballistic trajectory between light screens M_1 and M_2 , M_2 and M_3 are S_1 and S_2 , respectively. The vertical height of the projectile when it reaches the first light screen M_1 from the launch point R is h . The positions of the three detection devices (T_1 , T_2 , and T_3) and the projectile launch point R lie on a straight line. Ideally, the distances between adjacent detection devices are equal, i.e., $l_1 = l_2$. Thus, the pitch angles of the three light screens are equal, i.e., $\sigma_1 = \sigma_2 = \sigma_3$, and the distances traversed by the projectile through each pair of adjacent parallel light screens are equal, i.e., $S_1 = S_2$. The projectile launch point R can be positioned anywhere along the Y-axis. S_1 and S_2 remain unchanged regardless of variations in l' , thus offering the advantage of flexible detection device placement.

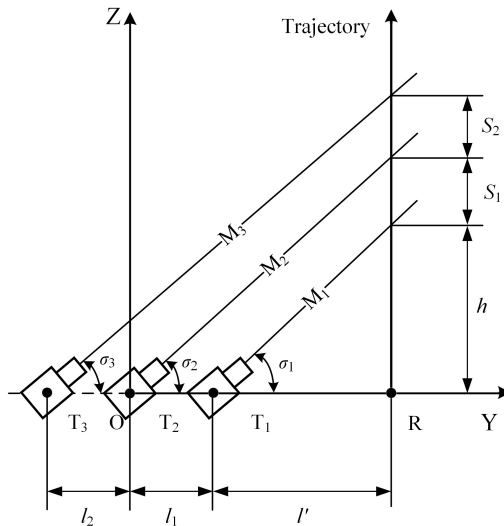


Fig. 3. Schematic diagram of the projection of three parallel light screens on the YOZ plane.

2.2.1. Ideal conditions

Barrel weapons, which typically refers to firearms that employ direct aiming, exhibit high projectile velocities and stable trajectories within their effective range. Under ideal conditions, their trajectories can be approximated as uniform linear motion [20]. The projectile is assumed to be fired vertically, with precise light screen angles and minimal (negligible) effects from air resistance and gravity. In this scenario, velocity can be measured using just two passive optoelectronic detection devices (the starting detection device T_1 and the stopping detection device T_2).

T_1 and T_2 form two parallel light screens, M_1 and M_2 . The angle between each light screen and the Y-axis is $\sigma_1 = \sigma_2 = \sigma$. The moments at which the projectile passes sequentially through the two light screens are t_1 and t_2 . From geometric relationships, the vertical distance traversed by the projectile between the two light screens is:

$$S_1 = l_1 \cdot \tan \sigma. \quad (2)$$

According to the velocity measuring principle, the projectile velocity v is:

$$v = \frac{S_1}{t}, \quad (3)$$

where t is the time interval taken by the projectile to pass through the two light screens M_1 and M_2 , i.e., $t = t_2 - t_1$. Substituting (2) into (3) yields the flight velocity v of the projectile under ideal conditions as:

$$v = \frac{l_1 \cdot \tan \sigma}{t_2 - t_1}. \quad (4)$$

2.2.2. Considering angle error conditions

In practical testing, if the projectile trajectory is not perfectly perpendicular to the horizontal plane (Fig. 4), the screen spacing S_1 will vary with the trajectory deflection angle. Correcting S_1 is critical for enhancing the measurement accuracy of velocity.

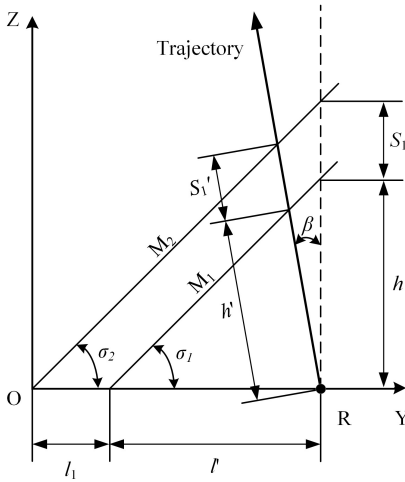


Fig. 4. Schematic diagram of the deflection angle β of the trajectory on the yoz plane.

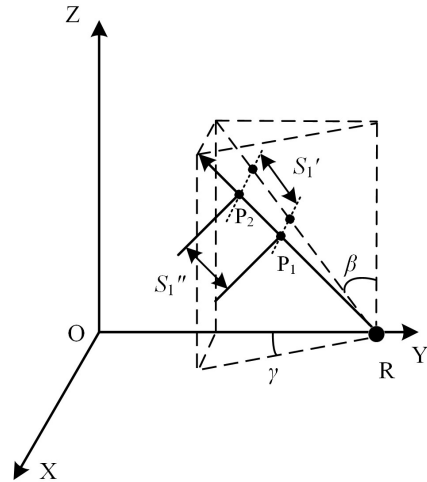


Fig. 5. Geometric relationship diagram for screen spacing with trajectory deviation angles.

Assuming the projectile trajectory forms a deflection angle β only on the YOZ plane, the screen spacing on the YOZ plane is S'_1 (Fig. 4). If the deflection angle β of the projectile trajectory on the YOZ plane and γ on the XOY plane are considered simultaneously, the screen spacing will be S''_1 (Fig. 5). In Fig. 5, P_1 and P_2 are the points at which the trajectory intersects the two light screens M_1 and M_2 .

From the geometric relationships shown in Fig. 4, it can be seen that:

$$\begin{cases} h = l' \cdot \tan \sigma_1 \\ h + S_1 = (l_1 + l') \cdot \tan \sigma_2. \end{cases} \quad (5)$$

Then S_1 can be given by (6):

$$S_1 = (l_1 + l') \tan \sigma_2 - l' \cdot \tan \sigma_1. \quad (6)$$

According to the Law of Sines:

$$\frac{h}{\sin\left(\frac{\pi}{2} - \beta + \sigma_1\right)} = \frac{h'}{\sin\left(\frac{\pi}{2} - \sigma_1\right)}, \quad (7)$$

where h' is the straight-line distance from the launch point to the point where the trajectory intersects with the screen M_1 . It can be obtained by (8):

$$h' = \frac{h \cdot \sin\left(\frac{\pi}{2} - \sigma_1\right)}{\sin\left(\frac{\pi}{2} - \beta + \sigma_1\right)}. \quad (8)$$

Similarly,

$$\frac{h + S_1}{\sin\left(\frac{\pi}{2} - \beta + \sigma_2\right)} = \frac{h' + S'_1}{\sin\left(\frac{\pi}{2} - \sigma_2\right)}, \quad (9)$$

and S'_1 can be given by (10):

$$S'_1 = \frac{(h + S_1) \cdot \sin\left(\frac{\pi}{2} - \sigma_2\right)}{\sin\left(\frac{\pi}{2} - \beta + \sigma_2\right)} - h'. \quad (10)$$

Substituting equations (5), (6) and (8) into equation (10) yields equation (11) as follows:

$$S'_1 = \frac{(l_1 + l') \cdot \sin \sigma_2}{\cos(\beta - \sigma_2)} - \frac{l' \cdot \sin \sigma_1}{\cos(\beta - \sigma_1)}. \quad (11)$$

From the geometric relationships in Fig. 5, we obtain:

$$S''_1 = \frac{S'_1}{\cos \gamma}. \quad (12)$$

Substituting (11) into (12) yields the corrected screen spacing S''_1 as follows:

$$S''_1 = \frac{(l_1 + l') \cdot \sin \sigma_2}{\cos(\beta - \sigma_2) \cdot \cos \gamma} - \frac{l' \cdot \sin \sigma_1}{\cos(\beta - \sigma_1) \cdot \cos \gamma}. \quad (13)$$

Substituting (13) into (3) yields the corrected flight velocity of the projectile as:

$$v = \frac{(l_1 + l') \cdot \sin \sigma_2}{(t_2 - t_1) \cdot \cos(\beta - \sigma_2) \cdot \cos \gamma} - \frac{l' \cdot \sin \sigma_1}{(t_2 - t_1) \cdot \cos(\beta - \sigma_1) \cdot \cos \gamma}. \quad (14)$$

2.2.3. Considering the effects of gravity and resistance

During flight, projectiles are subject to the effects of gravity and air resistance. Along a vertical trajectory, the accelerations caused by gravity and air resistance act in the same direction, which is opposite to the trajectory of the projectile. Compared to horizontal or elevation trajectories, velocity attenuation is considerably more pronounced for projectiles on a vertical path. Therefore, it is crucial to consider the impact of acceleration on velocity measurement accuracy.

For standard projectiles, the trajectory coefficient can be found in relevant publicly available technical documentation [21], and the air resistance acceleration can be calculated using drag coefficient tables. However, it is impossible to determine values such as the trajectory coefficient for projectiles still in the research and development phase (especially non-rotationally symmetric bodies) through this approach. This renders them unsuitable for existing drag coefficient tables. For this, an additional light screen T_3 is proposed for the ideal vertical trajectory model to enable acceleration measurement. This approach allows for determination of the velocity of the projectile at any given moment or position within the studied trajectory range, as shown in Fig. 3.

When the projectile passes sequentially through three light screens M_1 , M_2 , and M_3 , the respective over-screen moments are t_1 , t_2 , and t_3 . Assuming that the projectile undergoes uniformly decelerated linear motion within this detection zone, the average velocity in this zone can be considered as the velocity at the mid-time instant. Then the velocity v_{1m} of the projectile at the intermediate moment t_{1m} between passing through light screens M_1 and M_2 can be calculated as follows:

$$v_{1m} = \frac{S_1}{t_2 - t_1}, \quad (15)$$

$$t_{1m} = t_1 + \frac{t_2 - t_1}{2}. \quad (16)$$

Similarly, the average velocity of the projectile passing through the light screens M_2 and M_3 is $v_{2m} = S_2 / (t_3 - t_2)$, and the intermediate moment is $t_{2m} = t_2 + (t_3 - t_2) / 2$.

Then, the acceleration of the projectile traveling along its trajectory is:

$$\alpha = \frac{\Delta v}{\Delta t} = \frac{v_{2m} - v_{1m}}{t_{2m} - t_{1m}} = \frac{2 [S_2 (t_2 - t_1) - S_1 (t_3 - t_2)]}{(t_3 - t_2) (t_3 - t_1) (t_2 - t_1)}. \quad (17)$$

For ideal conditions, S_1 and S_2 can be derived from (2):

$$\begin{cases} S_1 = l_1 \cdot \tan \sigma \\ S_2 = l_2 \cdot \tan \sigma \end{cases} \quad (18)$$

Considering the angle errors, the corrected S_1 and S_2 can be obtained from (13) as:

$$\begin{cases} S_1'' = \frac{(l_1 + l') \cdot \sin \sigma_2}{\cos(\beta - \sigma_2) \cdot \cos \gamma} - \frac{l' \cdot \sin \sigma_1}{\cos(\beta - \sigma_1) \cdot \cos \gamma} \\ S_2'' = \frac{(l_2 + l_1 + l') \sin \sigma_3}{\cos(\beta - \sigma_3) \cdot \cos \gamma} - \frac{(l_1 + l') \sin \sigma_2}{\cos(\beta - \sigma_2) \cdot \cos \gamma} \end{cases} \quad (19)$$

Substituting equation (18) or (19) into (17) yields the acceleration α of the projectile under different conditions. Assuming acceleration remains constant over a segment of the trajectory, the velocity at a given moment is:

$$v_\alpha = v_1 + \alpha t_\alpha, \quad (20)$$

where v_1 is the velocity of the projectile when it passes through the light screen M_1 . Assuming the moment t_1 is the starting point ($t_1 = 0$), then $v_1 = v_{1m} - \sigma \cdot t_{1m}$. According to (20), the velocity v_α at any given time t_α can be calculated.

Furthermore, assuming the intersection point of the light screen M_1 and the trajectory is the starting point, the corresponding time t_α at any position along the trajectory can be calculated using the distance S and acceleration α , as shown in (21):

$$S = v_1 t_\alpha + \frac{1}{2} \alpha t_\alpha^2. \quad (21)$$

Subsequently, by substituting the calculated t_α into (20), the velocity at any given position along the trajectory can be derived.

3. Results and discussion

3.1. Theoretical error analysis

This section conducts a theoretical simulation analysis of the measurement error distribution characteristics based on the proposed measurement model. Differentiating (3) yields the velocity error equation as:

$$\frac{\Delta v}{v} = \frac{\Delta S_1}{S_1} + \frac{\Delta t}{t}, \quad (22)$$

where $\Delta S_1/S_1$ is the relative error in the measured screen spacing, $\Delta t/t$ is the relative time error and the over-screen moment error Δt is determined by the quantization accuracy of the 1 MHz sampling system, with $\Delta t = 1 \mu s$.

According to the error propagation theory [22–24] and (13) for the corrected screen spacing S_1'' , the screen spacing error is:

$$\begin{aligned} (\Delta S_1'')^2 = & \left(\frac{\partial S_1''}{\partial l_1} \right)^2 (\Delta l_1)^2 + \left(\frac{\partial S_1''}{\partial l'} \right)^2 (\Delta l')^2 + \left(\frac{\partial S_1''}{\partial \sigma_1} \right)^2 (\Delta \sigma_1)^2 \\ & + \left(\frac{\partial S_1''}{\partial \sigma_2} \right)^2 (\Delta \sigma_2)^2 + \left(\frac{\partial S_1''}{\partial \beta} \right)^2 (\Delta \beta)^2 + \left(\frac{\partial S_1''}{\partial \gamma} \right)^2 (\Delta \gamma)^2, \end{aligned} \quad (23)$$

where Δl_1 is the error of the horizontal distance between the detection devices T_1 and T_2 , $\Delta l'$ is the launch distance error, $\Delta \sigma_1$ and $\Delta \sigma_2$ are the light screen pitch angle errors of M_1 and M_2 , respectively, $\Delta \beta$ and $\Delta \gamma$ are the trajectory deflection angle errors. The errors $\Delta \sigma_1$ and $\Delta \sigma_2$ are combined from the detection device arrangement error and the optical calibration deviation, with $\Delta \sigma_1 = \Delta \sigma_2 = 0.02^\circ$. The errors $\Delta \beta$ and $\Delta \gamma$ originate from the maximum deviation of the sighting system, with $\Delta \beta = \Delta \gamma = 0.02^\circ$. The errors Δl_1 and $\Delta l'$ originate from the measurement errors of the steel tape measure, with $\Delta l_1 = \Delta l' = 0.5$ mm.

Assuming the light screen pitch angles are $\sigma_1 = \sigma_2 = 45^\circ$ and the deviation angles of the trajectory are $\beta = \gamma = 0^\circ$, typically, the muzzle velocity of mortars ranges from 60 to 500 m/s. Therefore, the projectile velocity is set to 500 m/s. If the launch distance l' is preset to 10 m, 20 m, and 30 m, respectively, the variations of relative velocity error versus the horizontal distance l_1 between the adjacent detection devices T_1 and T_2 will be shown in Fig. 6. Clearly, the relative velocity error decreases as l_1 increases. As l_1 increases, the curve flattens, meaning the relative velocity error becomes less sensitive to changes in the horizontal distance between the detection devices. Furthermore, the smaller the launch distance l' , the smaller the relative velocity measurement error. If the horizontal distance l_1 is at least 7.36 m and the projectile launch point distance l' is 10, 20, or 30 m, the relative velocity errors will remain within 0.2%, 0.33%, and 0.46%, respectively.

The following simulation values are set: projectile launch distance $l' = 10$ m, horizontal distance between the adjacent detection devices $l_1 = 7.5$ m, and projectile velocity $v = 500$ m/s.

Assuming the pitch angles σ_1 and σ_2 of the light screen vary synchronously within a range of 10° to 80° ($\sigma_1 = \sigma_2 = \sigma$) and the trajectory deflection angle is $\gamma = 0^\circ$, the variations of relative velocity error versus light screen pitch angle σ at the trajectory deflection angle of $\beta = 0^\circ$ and $\beta = 10^\circ$, respectively, are shown in Fig. 7. It can be seen that the minimum relative velocity error of 0.2% will occur if the light screen pitch angle σ approaches 45° at $\beta = 0^\circ$. However, the minimum error of 0.167% occurs at σ approaching 50° for $\beta = 10^\circ$. Furthermore, the velocity measurement error will remain below 0.2% if σ ranges from 32.1° to 68° at $\beta = 10^\circ$.

Figure 7 depicts the scenario where both light screens change simultaneously with equal pitch angles ($\sigma_1 = \sigma_2 = \sigma$). However, in actual measurements, situations may arise where the pitch angles of the two light screens are unequal ($\sigma_1 \neq \sigma_2$). Figure 8 shows the relative velocity errors as a function of one light screen pitch angle at the other light screen pitch angle of 45° . It can be seen that the relative velocity error will decrease as σ_2 increases at $\sigma_1 = 45^\circ$ if σ_2 varies from 42° to 48° , as shown in Fig. 8(a). Conversely, the relative velocity error increases as σ_1 increases at $\sigma_2 = 45^\circ$, as shown in Fig. 8(b). However, the conclusion remains consistent. If the non-parallelism of the two light screens increases the screen spacing, the relative speed error will decrease. However, if the non-parallelism reduces the screen spacing, the relative error will increase. This conclusion can provide guidance for the placement of detection devices. Additionally, consistent with the findings presented in Fig. 7, the relative velocity error at $\beta = 10^\circ$ is smaller than that at $\beta = 0^\circ$, indicating that the velocity measurement error for vertical trajectories is greater than that for trajectories launched at angles of 80° relative to the horizontal plane.

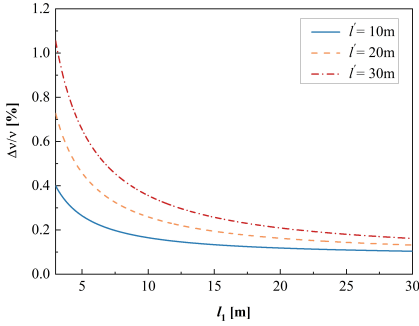


Fig. 6. Distribution characteristics curves of relative velocity error versus horizontal distance between the detection devices l_1 .

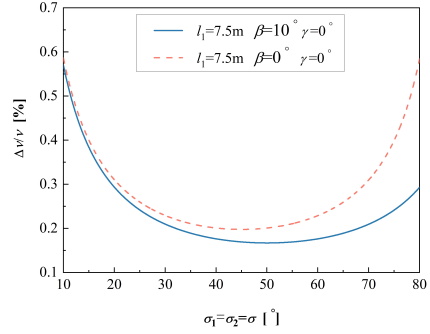


Fig. 7. Distribution characteristics curves of relative velocity error versus light screen pitch angle σ .

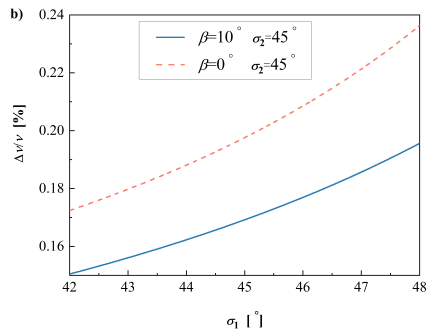
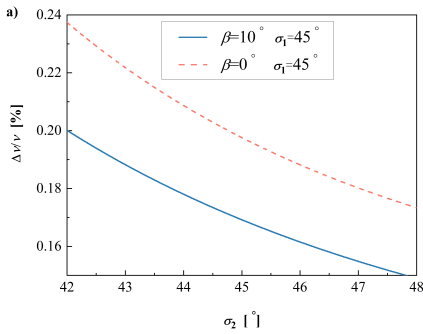


Fig. 8. Relative velocity errors as a function of (a) σ_2 at $\sigma_1 = 45^\circ$, (b) σ_1 at $\sigma_2 = 45^\circ$.

Based on the simulation conditions mentioned previously, the light screen pitch angles are set to $\sigma_1 = \sigma_2 = 45^\circ$ and the trajectory deflection angle γ is set to 0° . The trajectory deflection angle β on the YOZ plane is defined as positive in the counterclockwise rotation direction. Figure 9 shows the variation of the velocity relative error at β ranging from -40° to 100° . It can be seen that the relative velocity error decreases initially and then increases as β increases. If β approaches 87° (approaching a horizontal trajectory), the relative velocity measurement error will reach its minimum value of 0.04%. To achieve the relative velocity measurement error within 0.2%, the β angle must exceed -0.7° . In practical velocity measurement tests, for example, the elevation angle of the mortar barrel ranges from 40° to 85° and the β angle is typically preset between 5° and 50° . This results in the relative velocity measurement error ranges from 0.1% to 0.18%.

The trajectory deflection angle γ on the XOY plane will be supposed as positive if it rotates counterclockwise. Based on the previously mentioned simulation conditions, the distribution characteristics curves of relative velocity error versus trajectory deviation angle γ for different β values are shown in Fig. 10. The relative velocity errors remain nearly constant of γ from -10° to 10° . This indicates that γ has a negligible influence on relative velocity error, far smaller than the effect of β . Figure 10 also presents a detailed enlargement of the relative velocity error curve as a function of γ at $\beta = 10^\circ$. The relative velocity error is minimal at $\gamma = 0^\circ$. As γ varies from 0° to 10° or -10° , the relative velocity error increases by merely 0.00003%. Therefore, the influence of γ on the relative velocity error can be ignored if it varies from -10° to 10° .

The simulation results indicate that the relative velocity error of the measurement system will be smaller if the horizontal distance between the detection devices is larger and the launch distance is smaller. The horizontal distance between the detection devices l_1 must exceed 7.36 m to ensure that the relative velocity measurement error does not exceed 0.2% with $l' = 10$ m, $\beta = \gamma = 0^\circ$, $v = 500$ m/s, $\sigma_1 = \sigma_2 = \sigma = 45^\circ$, $\Delta\beta = \Delta\gamma = 0.02^\circ$, $\Delta l' = 0.5$ mm, and $\Delta t = 1$ μ s. The minimum relative velocity error of 0.2% will occur if the light screen pitch angle σ approaches 45° with $l_1 = 7.5$ m and all other parameters remain the same. In mortar projectile velocity measurement tests, the β angle is typically preset to values between 5° and 50° , yielding a relative velocity error range of 0.1% to 0.18%. The minimum relative velocity error of 0.1% is achieved at $\beta = 50^\circ$. The effect of the trajectory deviation angle γ on relative velocity error can be neglected within the range of -10° to 10° . However, during actual detection device placement, efforts should be made to approach 0° , where relative velocity error is minimized.

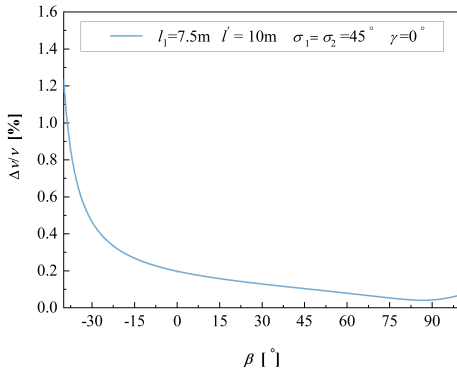


Fig. 9. Distribution characteristics curve of relative velocity error versus trajectory deviation angle β .

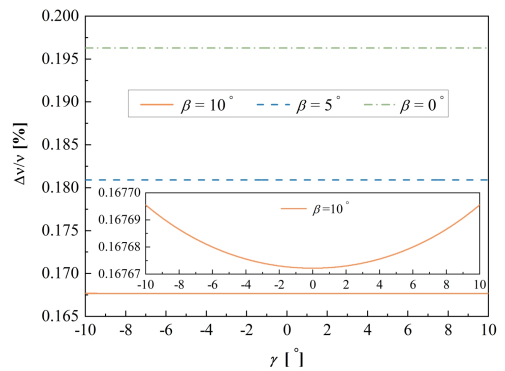


Fig. 10. Distribution characteristics curves of relative velocity error versus trajectory deviation angle γ for different β values.

3.2. Live-fire experiment

To validate the accuracy of the proposed measurement model, a live-fire experiment is conducted. Figure 11 shows the layout of the experimental field. Three light screens are arranged in parallel at pitch angles of 45° relative to the horizontal plane. To verify the accuracy of the velocity measurement, an additional T_4 detection device is placed behind the T_3 detection device. All four detection devices are horizontally aligned at a 45° pitch angle and spaced at equal horizontal intervals. Thirty 60 mm calibre conventional mortar projectiles are fired at an angle ω of 80° relative to the horizontal plane.

The fixed projectile launch point is positioned 10 m horizontally from the T_1 detection device (*i.e.*, $l' = 10$ m). The horizontal distances between two adjacent detection devices were $l_1 = l_2 = l_3 = 7.5$ m. The emission point of the collimating laser device on the detection device T_4 was designated as the coordinate origin. Four over-screen moments of the projectile, t_1, t_2, t_3 , and t_4 , can be obtained by four passive optoelectronic detection devices and the corresponding signal acquisition and processing unit.

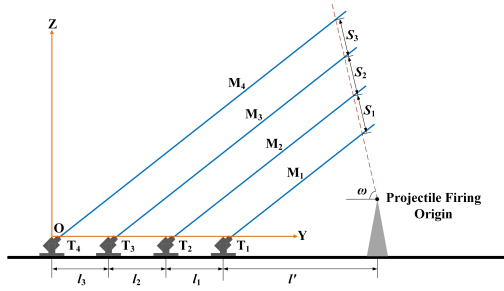


Fig. 11. Schematic diagram of the test site layout.

The light screen detection zone is relatively smaller compared to the trajectory of the projectile. Assuming the acceleration remains constant within the measured interval of the trajectory, the average velocity in the detection zone can be considered as the velocity at the mid-time instant. Similar to equations (15) and (16), the velocity v_{3m} of the projectile at the intermediate moment t_{3m} ($t_{3m} = t_3 + (t_4 - t_3)/2$) when it passes between light screens M_3 and M_4 is $v_{3m} = S_3/(t_4 - t_3)$.

From (17), the acceleration α of the projectile can be determined. Thus, the velocity $v_{3\alpha}$ of the projectile at the mid-moment t_{3m} will be given by:

$$v_{3\alpha} = v_{1m} + \alpha \cdot (t_{3m} - t_{1m}). \quad (24)$$

The relative velocity error of the acceleration measurement model is

$$\delta_\alpha = \frac{v_{3\alpha} - v_{3m}}{v_{3m}} \times 100\% \quad (25)$$

In the regular setup with two screens, the velocity is calculated by assuming that the projectile moves at a constant velocity between the two screens. The velocity of the projectile passing between light screens M_3 and M_4 at the mid-moment t_{3m} is considered to be v_{1m} . The relative error between v_{1m} and the actually measured value v_{3m} as

$$\delta_m = \frac{v_{1m} - v_{3m}}{v_{3m}} \times 100\%. \quad (26)$$

The relative error curves are illustrated in Fig. 12. It contains the error values calculated by (25) and (26). The δ_m curve represents the relative errors obtained using the regular two light screens (without acceleration correction), and δ_α represents the errors gained using the proposed three parallel light screens (acceleration-corrected model). It can be seen from Fig. 12 that the absolute value of δ_α obtained from the acceleration measurement model does not exceed 0.18%, which is significantly smaller than the relative error δ_m without acceleration correction. This demonstrates that the acceleration-corrected velocities from the proposed method more closely match the actual projectile velocity, thus validating the critical role of acceleration parameters in vertical trajectory models. The experimental results confirm the effectiveness of the proposed method in high-angle scenarios compared to the regular method.

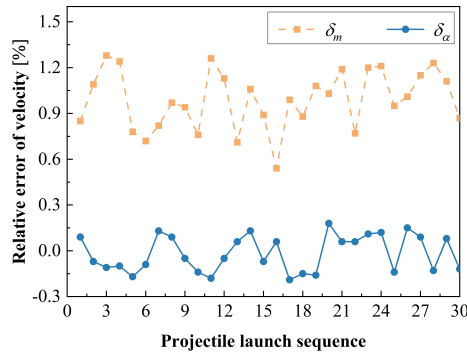


Fig. 12. Relative error curves for velocity measurement.

4. Conclusions

The paper proposes a measurement method for projectile velocity in a vertical trajectory based on three parallel light screens. Systematic measurement models are developed for ideal conditions, angle error considered scenarios, and projectile velocity attenuation situations. By quantifying the acceleration of the projectile, its velocity can be accurately determined at any position along the trajectory within the measured trajectory range. Through comprehensive analysis and simulation, the optimal parameters for detection device placement are identified, and measurement errors are validated via live-fire tests. Experimental results indicate that the velocity measurement relative error remains $\leq 0.18\%$, fulfilling the precision requirements for vertical trajectory projectile velocity assessments. This approach enables high accurate measurements of projectile velocities in the vertical trajectory.

Future research could investigate the effects of aerodynamic-motion coupling under complex conditions, such as firing from unstable platforms (*e.g.*, ships or airborne artillery), crosswind and muzzle gas disturbances, and projectile rotation, by establishing a multi-degree-of-freedom trajectory model. Furthermore, incorporating a broader range of error sources, such as projectile shape, mass distribution and variations in wind speed and direction, could refine the velocity correction methodology more effectively.

Acknowledgements

This work was supported by the Natural Science Basic Research Plan of Shaanxi Province (2024JC-YBMS-478).

References

- [1] Wu, S., Sikdar, P., & Bhat, G. S. (2022). Recent progress in developing ballistic and anti-impact materials: Nanotechnology and main approaches. *Defence Technology*, 21, 33–61. <https://doi.org/10.1016/j.dt.2022.06.007>
- [2] Das, N., & Nanthagopalan, P. (2024). Ballistic impact resistance of ultra-high-performance concrete (UHPC): A comprehensive experimental investigation and parametric analysis. *International Journal of Impact Engineering*, 187, 104912. <https://doi.org/10.1016/j.ijimpeng.2024.104912>
- [3] Liang, C., Shen, Q., Deng, Z., Li, H., & Liang, D. (2024). An improved particle filtering projectile trajectory estimation algorithm fusing velocity information. *Measurement*, 241, 115749. <https://doi.org/10.1016/j.measurement.2024.115749>
- [4] Widayaka, P. D., Kusuma, H., & Attamimi, M. (2019). Automatic shooting scoring system based on image processing. *Journal of Physics Conference Series*, 1201(1), 012047. <https://doi.org/10.1088/1742-6596/1201/1/012047>
- [5] Liu, P., Chen, Y., Kong, S., Wang, H., Fu, S., & Wang, J. (2023). Overlapping bullet hole detection based on Improved watershed algorithm. In *2023 8th International Conference on Signal and Image Processing (ICSIP)* (pp. 136–140). <https://doi.org/10.1109/icsip57908.2023.10271043>
- [6] Chen, D., Deng, C., Yang, Z., Shen, L., & Han, J. (2024). Accuracy calibration of the multi-light screen measurement system using array optical signal. *Measurement Science and Technology*, 35(9), 095008. <https://doi.org/10.1088/1361-6501/ad5197>
- [7] Smagowski, P., & Kaniewski, P. (2025). Algorithm for estimating ballistic object trajectories using an electro-optical tracking system. *Metrology and Measurement Systems*, Vol. 32 (2025) No. 2, pp. 1–14. <https://doi.org/10.24425/mms.2025.154667>
- [8] Mudgal, D. N., & Bhatnagar, N. (2024). Design, fabrication, and calibration of an IR-based ballistic chronograph. *IEEE Transactions on Instrumentation and Measurement*, 74, 1–7. <https://doi.org/10.1109/tim.2024.3493894>
- [9] Zhou, J., & Kong, D. (2023). Research on a measurement method for spatio-temporal distribution of fragments based on a high-speed camera network. *Measurement Science and Technology*, 34(10), 105406. <https://doi.org/10.1088/1361-6501/ace735>
- [10] Hou, Y., Di, C., Li, Y., Zhang, J., & Peng, P. (2021). Error analysis of projectile attitude measurement by high-speed camera. *Journal of Physics Conference Series*, 2033(1), 012170. <https://doi.org/10.1088/1742-6596/2033/1/012170>
- [11] Gilson, L., Imad, A., Rabet, L., Van Roey, J., & Gallant, J. (2020). Real-time measurement of projectile velocity in a ballistic fabric with a high-frequency Doppler radar. *Experimental Mechanics*, 61(3), 533–547. <https://doi.org/10.1007/s11340-020-00676-4>
- [12] Xing, H., Yang, X., Ji, X., & Wu, H. (2020). A fusion algorithm of passive sound source localization based on the two-plane four-element cross array. *Review of Scientific Instruments*, 91(3), 034901. <https://doi.org/10.1063/1.5080761>
- [13] Dong, T., Gao, F., Chen, D., & Yang, J. (2020). Recognition method of the dual-objective in a linear array CCD-based improved photoelectric measurement system using two lasers with different wavelengths. *Optik*, 217, 164857. <https://doi.org/10.1016/j.ijleo.2020.164857>

- [14] Gao, J., & Zhang, X. (2023). An information recognition and time extraction method of tracking a flying target with a sky screen sensor based on wavelet modulus maxima theory. *Mathematics*, 11(18), 3936. <https://doi.org/10.3390/math11183936>
- [15] Geng, D., Chen, L., Hou, Z., Zhang, X., & Wei, X. (2024). The laser screen imaging measurement system based on arrayed fibers. *Optics and Lasers in Engineering*, 183, 108551. <https://doi.org/10.1016/j.optlaseng.2024.108551>
- [16] Liu, S. (2016). *Experimental Exterior Ballistics*. Beijing, China: Beijing Institute of Technology Press (in Chinese)
- [17] Li, H., Ni, J., Yang, X., & Dong, Q. (2022). Test influence of screen thickness on double-N six-light-screen sky screen target. *Open Physics*, 20(1), 1–8. <https://doi.org/10.1515/phys-2022-0010>
- [18] Wang, J., Sun, H., Chen, D., Huang, Y., Dong, T., Li, H., Shen, L., & Yang, Z. (2024). Photoelectric sensor array-based measurement method for the key motion parameters of the small flying object considering non-uniform curve trajectory. *Sensor Review*, 45(1), 65–73. <https://doi.org/10.1108/sr-08-2024-0682>
- [19] Chen, D., & Ni, J. (2017). Pulse compression-based improvement on the estimation accuracy of time interval between two trigger signals in light screen array. *Optik*, 158, 675–683. <https://doi.org/10.1016/j.ijleo.2017.12.177>
- [20] Paulter, N. G. (2023). Measurement uncertainty of bullet velocities that are acquired with light screens and a waveform recorder. *Journal of Testing and Evaluation*, 51(6), 4567–4574. <https://doi.org/10.1520/jte20230061>
- [21] Kim, S., & Kim, J. (2020). Optimal design of a coil gun projectile by analyzing the drag coefficient and electromagnetic force on the projectile. *Journal of Mechanical Science and Technology*, 34(7), 2903–2911. <https://doi.org/10.1007/s12206-020-0622-5>
- [22] Dong, T., Li, S., Chen, D., & Yang, Z. (2023). Measurement method for the flight parameters of a small flying object using a multi-dimensional LED detection array. *Photonics*, 10(12), 1313. <https://doi.org/10.3390/photonics10121313>
- [23] Ngeljaratan, L., & Moustafa, M. A. (2021). Uncertainty and accuracy of vision-based tracking concerning stereophotogrammetry and noise-floor tests. *Metrology and Measurement Systems*, Vol. 29 (2022) No. 1, pp. 75–92. <https://doi.org/10.24425/mms.2022.140028>
- [24] Liu, X., Xia, Y., & Rui, X. (2023). Uncertainty evaluation of multilateration-based geometric error measurement considering the repeatability of positioning of the machine tool. *Metrology and Measurement Systems*, Vol. 30 (2023) No. 1, pp. 49–63. <https://doi.org/10.24425/mms.2023.144864>



Linqiu Tan received her B.Sc. degree and M.Sc. degree in instruments science and technology, and her Ph.D. degree in mechanical engineering from Xi'an University of Technology, in 2005, 2008 and 2016, respectively. Since 2016, she has been a teacher at the School of Optoelectronic Engineering, Xi'an Technological University. Her research interests include photoelectric detection, embedded technology as well as lidar. Currently, she is involved in photoelectric detection instrument and photoelectric

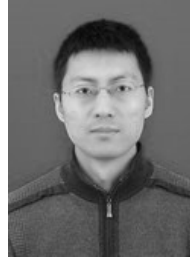
test technology for shooting ranges.



Ziyu Yang obtained her B.Sc. and M.Sc. degree in measurement and control technology and instruments and ordnance engineering from Xi'an Technological University, respectively. She is currently pursuing a Ph.D. degree in optical engineering at Xi'an Technological University.



Yongjun Huang obtained his B.Sc. degree from the Xi'an Technological University North Institute of Information Engineering in 2022 and his M.Sc. degree from Xi'an Technological University in 2025. He is currently an engineer at Henan North Hongyang Machinery & Electronics Co., Ltd.



Tao Dong obtained his B.Sc. and M.Sc. degrees from Xi'an Technological University respectively in 2003, 2006, and received his Ph.D. degree in mechatronic engineering from Xi'an University of Technology in 2015. He is currently a teacher of the Photoelectric Testing Technology Institute of the School of Optoelectronic Engineering of Xi'an Technological University, mainly studying design of optical machine structure for photoelectric detection instrument and photoelectric test technology for shooting ranges.