Research Article

Hui Tian*, Yanan Sun, Jinping Ni, and Fan Wang

# Analysis of the working mechanism and detection sensitivity of a flash detector

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**Abstract:** Flash detectors are mainly used to detect the brief light flashing when projectiles are launched or exploded in the air. They can output trigger pulse signals in real time to start a test instrument and carry out data collection. Because flash detectors cannot work reliably under strong background light radiation, this work studied the flash detector mechanism. The influence of background light radiance, lens aperture, and detection distance on the effective signal was analyzed, a mathematical model of detection sensitivity based on the background radiation brightness control was proposed, a mathematical formula of the detection distance of the flash detector was deduced, and the optimal working conditions were obtained. The researched model was verified by simulation analysis and actual test experiments, in the same external circumstances, the limit detection distance of the optimal aperture compared to the maximum aperture increased by 20%, and the effective signal voltage amplitude was twice the amplitude at the maximum aperture, and the results showed the correctness of the analysis. The proposed detection sensitivity model can be applied for a dynamic photoelectric detection instrument, which broadens its potential application in the engineering field.

**Keywords:** detection sensitivity, flash detector, long-distance brief light flashing

## 1 Introduction

The transient parameters that need to be measured when a projectile launched by a barrel weapon flies away from a muzzle or explodes in the air mainly include the distribution of the muzzle flow field, the flight attitude of the projectile in the semi confinement period, the impact pressure of the muzzle, the flight attitude in the air, and the three-dimensional coordinates of the explosion position [1]. These parameters are key technical indicators for evaluating the damage effectiveness of weapons with a large amount of test data and a short duration [2]. Due to the complex environment of the test site, dynamic test instruments, such as pulsed lasers, ultrahigh-speed cameras, pressure sensors, and light screen array sensors, are mainly used for measurement [3–5]. These instruments have limited data storage space, so it is necessary to start collecting the signal output by the sensor for a period of time after receiving a reliable trigger signal at a certain moment (such as the moment when the projectile is fired or the moment of an explosion in the air). For remote multipoint synchronous test experiments, test instruments at different locations also need to be triggered synchronously based on the same external signal. Therefore, a reliable and effective trigger signal is an important component to ensure the validity and accuracy of the test data [6,7].

There are three main methods for generating the trigger signal, including copper wire targets, acoustic detectors [8–10], and near-infrared detectors. In terms of the Copper wire target, the output trigger signal is generated by receiving the voltage change at the moment of disconnection of the copper wire, thus the method belongs to the contact measurement method, so it has poor security, and the signal transmission distance is short. For the acoustic wave detectors, the shock wave generated by the explosion of the projectile is detected by the use of a shock wave sensor, and a trigger signal is produced by the signal processing circuit. The detection distance is long but the detector is vulnerable to the wind, and it has poor reliability, besides, the speed of shock waves is slow, thus it has poor real-time performance. A near-infrared band flash detector can detect the flashing generated when an explosive is burned at the moment of projectile launch or when the projectile explodes in the air and outputs the trigger signal in real time based

* **Corresponding author: Hui Tian,** School of Optoelectronics Engineering, Xi'an Technological University, Xi'an 710021, China, e-mail: tianhui@xatu.edu.cn
**Yanan Sun, Jinping Ni, Fan Wang:** School of Optoelectronics Engineering, Xi'an Technological University, Xi'an 710021, China

on the principle of photoelectric conversion [11]. It has the advantages of a long detection distance, short response delay, and easy on-site installation, so it has been widely used in weapons testing [12,13].

During field tests, it has been found that a photoelectric detection chip, the core component of the flash detector, can be easily affected by ambient background light, especially when working in a strong light environment. The PIN-type silicon-based infrared photodetector is easily affected by sunlight radiation and enters a working state of light saturation [14], causing the detection sensitivity of the detector to be sharply reduced so that it cannot effectively detect a brief light flashing, and fail to work [15]. Solar-blind UV detector performed in the wavelengths between200–280 nm [16,17], which is not affected by natural ambient light, but the response time of such devices is generally in the millisecond range, and the effective detection distance is no more than 10 m. Besides, the effective detection of photosensitive area is no more than 5 mm × 5 mm, and it cannot be applied to weapons testing with long-range (more than 20 m) effective detection of transient flame, and there are few commercially available low-cost detectors.

To address the above problems, a near-infrared band flash detector for the applications of weapons is analyzed. The research presented in this article is organized as follows: Section 2 introduced the working mechanism of a flash detector. In Section 3, the detection sensitivity model based on the adjustment of the aperture of lens contributions is proposed. In Section 4, the mathematical model of detection sensitivity for extreme detection distance is deduced. In Section 5, simulations and experiments are provided to validate the effectiveness of the method. Section 6 gives a conclusion of the proposed method and suggests some works in the future.

## 2 Analysis of the working mechanism of a flash detector

The instantaneous optical radiation energy generated when a projectile flies away from a muzzle or explodes in the air acts on the photoelectric detection chip inside a flash detector through the optical lens, and a weak current signal proportional to the light energy is received by the photodetector. The weak current signal is converted to a weak AC voltage signal, and the trigger pulse signal is finally output after amplification, filtering, and threshold triggering by the signal processing circuit. A photodiode is typically used as the core detection chip for the detection of the instantaneously changing optical signal.

The flash detector is mainly used in an outdoor environment. The photodiode receives the sky background light radiation in the normal state and the background light and the explosion flashing together through the optical lens to the photosensitive surface of the reverse-biased photodiode. When the photodiode works in a linear region, the output photocurrent has a good linear relationship with the received illuminance [18]. When the background radiation illuminance increases to a certain extent, the photodiode enters the saturation region, and its output photocurrent no longer increases with the increase in the illuminance, resulting in a photoelectric saturation effect [19]. In this case, the photodiode cannot respond to the received explosion flashing in time, resulting in the flash detector failing to work.

To ensure that the flash detector can respond effectively to the brief light flashing, it is necessary to adjust and change the lens aperture to ensure that the photodiode always works in the linear region. When the background light is strong, it is necessary to reduce the aperture of the lens in order to reduce the background light received by the photodiode, and adjust the photodiode from a saturated state to a linear working state [20]. However, a smaller lens aperture will weaken the radiant brightness of the flashing and reduce the detection sensitivity of the flash detector.

Figure 1 shows a schematic diagram of the working flow of the signal processing circuit of the flash detector. The photodiode receives both the explosion light and the background light. After the explosion light signal is amplified by AC, low-pass filtered and triggered by a threshold value, a trigger pulse signal is output; after the background light signal is amplified by DC and collected by voltage, the background light radiance voltage is displayed in real time through a digital tube, and the voltage value has a linear relationship with the radiance of the background light.

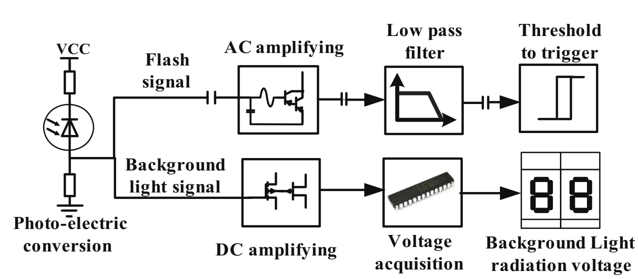



**Figure 1:** Workflow diagram of the signal processing circuit of the flash detector.

The output signal voltage amplitude of the flash detector caused by light radiation of the same energy is affected by the aperture of the detector lens and the detection distance, so the detection sensitivity of the flash detector can be described by the flashing signal voltage amplitude or the ultimate detection distance [21]. To effectively improve the detection sensitivity, the mathematical model of the detection sensitivity of the flash detector is proposed based on radiometry and photometry, and the aperture of the lens is adjusted according to the background light radiation brightness voltage, which effectively improves the ultimate detection distance of the flash detector.

## 3 Detection sensitivity model based on the lens aperture

When the flash detector detects a long-distance brief light flashing, the solid detection angle formed by the flashing to the detector $\Omega_t$ is much smaller than the maximum field of view formed by the detector $\Omega_s$, as shown in Figure 2. The light irradiance $E$ received by the photodiode located at the focal point of the image side of the optical lens is the superposition of the flashing irradiance and the background light irradiance, as shown in Eq. (1).

$$E = L_t \cdot \Omega_t + L_b(\Omega_s - \Omega_t), \tag{1}$$

where $L_t$ is the target brief light flashing radiance detected by the detector and $L_b$ is the radiance for the background light. According to the law of photoelectric conversion, the signal voltage output by the photodiode $v_t$ is shown in Eq. (2).

$$\begin{aligned} v_t &= E \cdot A_0 \cdot R_g \\ &= [L_t \cdot \Omega_t + L_b(\Omega_s - \Omega_t)] \cdot A_0 \cdot R_g, \end{aligned} \tag{2}$$

where $A_0$ is the pupil entrance area of the lens and $R_g$ is the voltage response magnification of the photodiode. When no brief light flashing is irradiated on the photodiode, the output signal voltage $v_b$ is only the brightness voltage of the background light, as shown in Eq. (3).

$$v_b = L_b \cdot \Omega_s \cdot A_0 \cdot R_g. \tag{3}$$

Therefore, the voltage amplitude of the brief light flashing signal output by the detection device $v_s$ is shown in Eq. (4).

$$v_s = v_t - v_b = (L_t - L_b) \cdot \Omega_t \cdot A_0 \cdot R_g. \tag{4}$$

In Eq. (4), when $L_t$ remains unchanged, the effective signal voltage amplitude increases as $L_b$ decreases. To reduce the influence of the background light on the brief light flashing, the lens aperture can be adjusted to reduce the radiance of the photodiode irradiated by the background light and increase the effective signal voltage amplitude. Eq. (5) represents the relationship between the solid angle $\Omega_t$, brief light flashing area $A_t$ and detection distance $R$. According to the corresponding relationship between the image surface illuminance and the lens aperture, the background light irradiance is converted into the expression for lens aperture number $F$ and $L_b$ by Eq. (6). The flashing light signal amplitude can be derived from Eq. (7) and obtained with Eqs. (4)–(6).

$$\Omega_t = \frac{A_t}{R^2}, \tag{5}$$

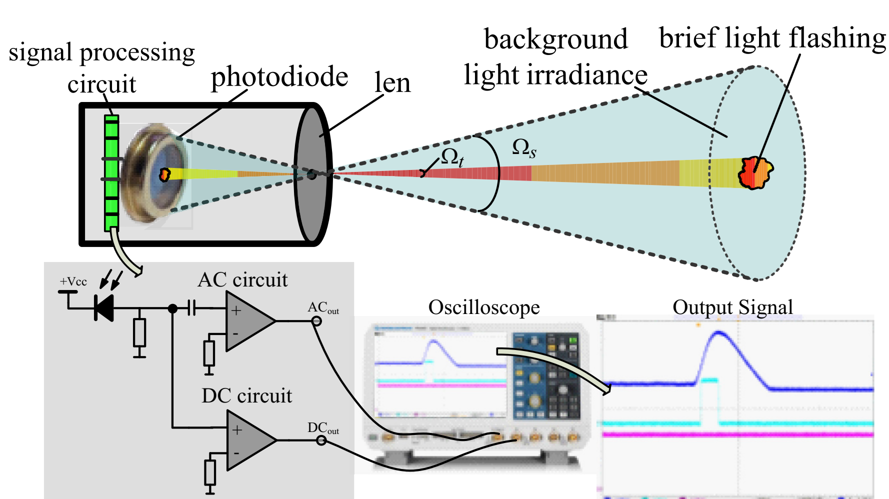



**Figure 2:** Schematic diagram of flash detector detection principle.

$$E = \frac{\pi \cdot L_b}{4F^2}, \quad (6)$$

$$v_s = \left(L_t \cdot \frac{A_t}{R^2} - \frac{\pi \cdot L_b}{4F^2}\right) \cdot A_0 \cdot R_g. \quad (7)$$

The lens aperture $A_0$ can be changed by adjusting the aperture number $F$. $L_t$ and $L_b$ will be decreased as $A_0$ decreases, but they decreased differently. The photosensitive area $A_d$ of the photodetector determines the optimal value of the lens aperture. Once $A_0$ is larger than $A_d$, the aperture mainly inhabits the background light radiation, and conversely, the aperture mainly inhabits the explosion flashing radiation.

## 4 Mathematical model of ultimate detection distance

The ultimate detection distance of the flash detector refers to the farthest distance that the flash detector can detect when the brightness of the explosion flashing is constant. At the test site, when the distance between the flash detector and the explosion point is greater than 20 m, it is considered to be the point target detection. Various factors affecting the detection sensitivity of the flash detector are analyzed according to the relevant theory of photometry and the law of photoelectric conversion. Combined with the theoretical model of the action distance of the point target detection system and the photoelectric detection mechanism, the detection distance formula of the flash detector is deduced. According to the law of photoelectric conversion, the specific detection rate of the photodiode used in the flash detector is deduced as $D^*$.

$$D^* = \frac{(A_d \cdot \Delta f)^{1/2} \cdot \left(\frac{v_s}{v_n}\right)}{P}, \quad (8)$$

where $\Delta f$ is the photodiode response frequency bandwidth, $v_n$ is the signal noise amplitude, and $P$ is the incident power radiated to the flash detector by the area $A_t$ of the brief light flashing, as shown in Eq. (9).

$$P = E \cdot A_0 = [L_t \cdot \Omega_t + L_b(\Omega_s - \Omega_t)] \cdot A_0. \quad (9)$$

A comprehensive analysis of various factors affecting the detection sensitivity of the flash detector, combined with Eqs. (5), (8), and (9), deduced the detection distance equation of the flash detector, as shown in Eq. (10).

$$R = \sqrt{\frac{(L_t - L_b) \cdot \cos\theta \cdot A_0 \cdot A_t \cdot D^*}{(A_d \cdot \Delta f)^{1/2} \cdot \left(\frac{v_s}{v_n}\right) - D^* \cdot L_b \cdot \alpha \cdot A_0}}, \quad (10)$$

where $\theta$ is the angle between the line connecting the brief light flashing point and the main point of the detector and the optical axis of the detector lens and $\alpha$ is the effective detection field of view of the flash detector. When detecting a long-distance brief light flashing, the detection angle $\theta$ is negligible, and the inherent detector parameters $A_0$, $A_d$, $\Delta f$, $D^*$, and $\alpha$ are fixed values. In terms of the determined $L_t$ and $L_b$, if $v_s > 5v_n$, the detector can generate a reliably triggered pulse signal, and the corresponding detection distance is the farthest detection distance of the flash detector under the corresponding background light radiance $R_{max}$.

By analyzing Eq. (10), we find that the main factor affecting the ultimate detection distance of the flash detector is the radiance of the background light. And the higher the value of $L_b$ is, the shorter the $R_{max}$ is. If the higher $L_b$ causes the photodiode to enter the saturation region, it can only be reduced by reducing $A_0$ to reduce the radiance of the background light and then make the photodiode work in the linear region. According to the flow chart of the signal processing circuit of the flash detector in Figure 1, the optimal lens aperture is selected according to the brightness voltage so that the flash detector can work in the optimal state, and the detection sensitivity of the flash detector can be effectively improved.

## 5 Simulation and experiment

Based on the above theoretical analysis, combined with Eq. (7), the flash detector is simulated and calculated under different lens apertures, and the variation law of the output effective signal voltage amplitude with the background light radiation brightness voltage and the action distance is simulated, as shown in Figure 3. Figure 3(a)–(c) shows the corresponding voltage amplitudes of the output flashing signal when the lens aperture $F$ is 1.4, 4, and 11, respectively. The voltage amplitudes of the output effective signal in the three conditions gradually decrease with the increase in the detection distance and gradually decrease with the increase in the voltage value of the background light brightness.

Comparing $F = 1.4$ and $F = 4$, reducing the aperture of the lens mainly suppresses the brightness of the background light and has little effect on the radiant brightness of the flashing. When $F = 11$, the aperture of the lens is smaller, and the effective signal amplitude is not affected by the background light radiant brightness voltage. Figure 3(d) shows the corresponding relationship between the output

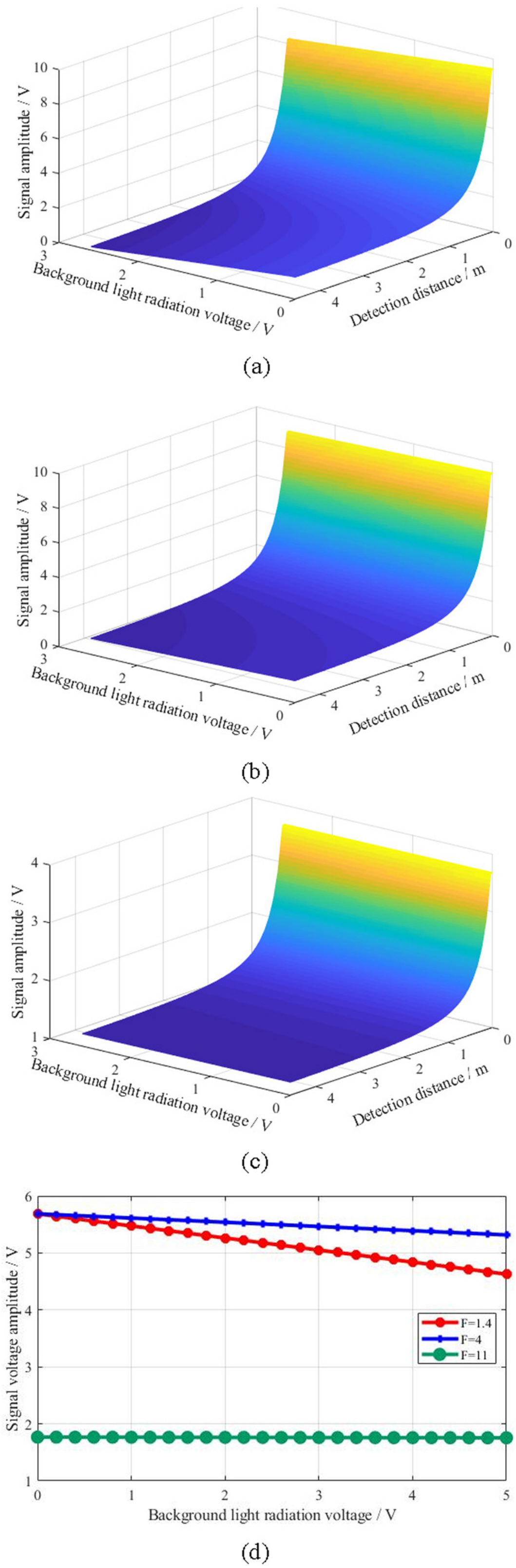



**Figure 3:** Detection sensitivity model of different lens apertures: (a) detection sensitivity model of $F = 1.4$, (b) detection sensitivity model of $F = 4$, (c) detection sensitivity model of $F = 11$, and (d) signal amplitude corresponding to different apertures in the same detection range.

signal amplitude and the background light radiant brightness voltage under three different apertures when the effective detection distance is 10 m, while $F = 1.4$ the output signal amplitude is greatly affected by the brightness of the background light. When $F = 11$, the overall signal amplitude is low; when $F = 4$, the effective signal amplitude is high, and the influence of the background light brightness is weak, it is an ideal working state.

The effective detection field angle of the flash detector developed by the project team is 10°, and the photodiode is a Hamamatsu S3590-08, in which the sensitive area is 10 mm × 10 mm. The technical performance parameters of the photodiode are brought into Eq. (10) to simulate the corresponding relationship between the ultimate detection distance of the flash detector and the number of apertures of different lenses $F$ (1.4, 2, 2.8, 4, 5.6, 8, 11, 16), as shown in Figure 4. As the aperture of the lens gradually decreases, $R_{\text{max}}$ increases and then decreases. When $F = 4$, the ultimate detection distance is the largest; at this time the size of $A_0$ and $A_d$ are comparable, and the lens can effectively suppress the radiance of the background light without greatly attenuating the radiance of the brief light flashing.

To verify the detection sensitivity model of the flash detector, tests were carried out. Ten L12170 infrared LEDs from the Hamamatsu Company are connected in parallel to form a brief light flashing source, and the luminous field of the light source is aligned with the flash detector. The peak emission wavelength of this type of LED is 870 nm, and the radiation flux is 80 mW. Under the control of the signal source, the synchronous output duration of LEDs is a 200 μs pulse flashing, simulating a brief light flashing. The distance between the flashing source and the flash detector is 20 m, and the background light radiation brightness measured by the luminance meter

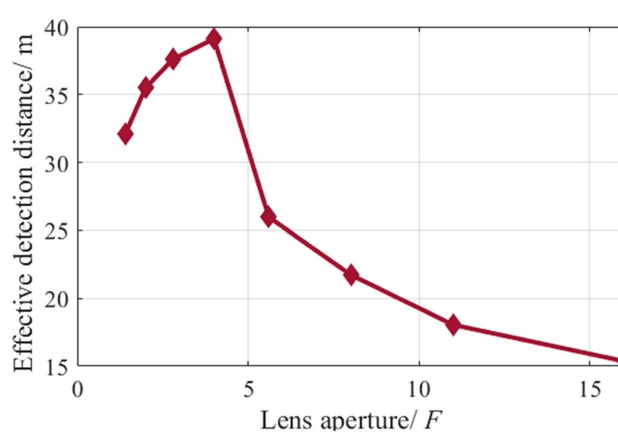



**Figure 4:** Relationship between the ultimate detection distance and brightness.

during the test is 7,500 cd/m$^2$. By changing the $F$ value, the background light radiation brightness entering the photodiode is changed, and the corresponding background light radiation brightness voltage value and the effective signal amplitude of the pulse light signal are changed. Table 1 shows the effective signal voltage amplitude under different $F$ values, and the effective signal voltage amplitude at the optimal aperture $F$ = 4 is twice the amplitude at the maximum aperture $F$ = 1.4. Figure 5(a) shows the corresponding data curve, Figure 5(b) shows the signal waveforms detected by the oscilloscope when $F$ = 2.8, where CH1 is the analog signal output by the flash detector, CH2 is the trigger pulse signal, CH3 is the background light radiation brightness voltage level, and Figure 5(c) shows the schematic diagram of flash detection.

To verify the ultimate detection distance model, the brief light flashing source is used, and the output analog signal amplitudes of the flash detector under different lens apertures are measured. Since the noise amplitude of the flash detector is less than 0.3 V, the trigger pulse signal threshold is set to 1.5 V to ensure the reliability of the output trigger signal. The distance between the brief light flashing source and the detector is gradually increased. When the trigger pulse signal is just no longer output, the corresponding distance is the ultimate detection distance of the flash detector. Table 2 shows the ultimate detection distance under different apertures during actual measurement, and the limit detection distance of the optimal aperture $F$ = 4 compared to the maximum aperture $F$ = 1.4 is increased by 20%. Figure 6(a) shows the corresponding signal waveform when $F$ = 4 under a detection distance of 41.1 m. The flash detector can reliably output the trigger pulse signal, where CH1 is the analog signal output by the flash detector and CH2 is the corresponding trigger pulse signal. Figure 6(b) shows the signal waveform when $F$ = 4 under a detection distance of 41.6 m, and it cannot output the trigger pulse signal.

**Table 1:** Effective signal voltage amplitude under different lens aperture $F$ values

| Lens aperture $F$ | Background light radiance voltage (V) | Effective signal voltage amplitude (V) |
|---|---|---|
| 1.4 | 4.6 | 3.8 |
| 2 | 3.2 | 5.6 |
| 2.8 | 1.8 | 7.5 |
| 4 | 1.4 | 9.4 |
| 5.6 | 0.8 | 5 |
| 8 | 0.6 | 3 |
| 11 | 0.4 | 2 |
| 16 | 0.25 | 0.9 |

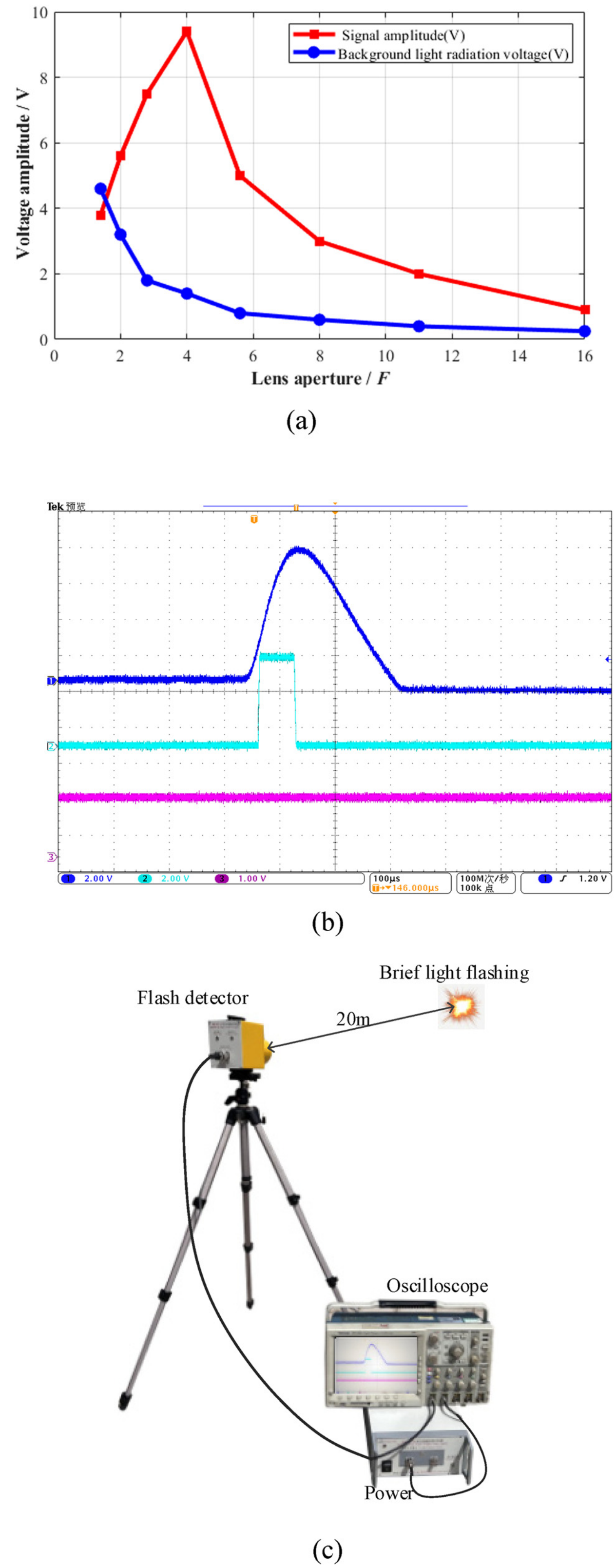
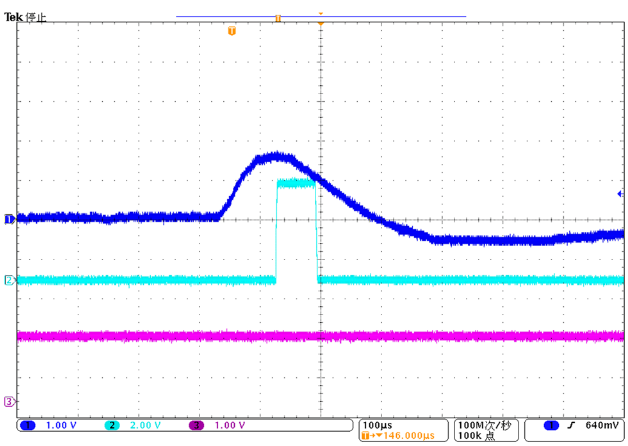



**Figure 5:** Correspondence between the signal amplitude and the lens aperture: (a) data curve of the light radiance and the effective signal, (b) signal waveform when $F$ = 2.8, and (c) schematic diagram of flash detection.

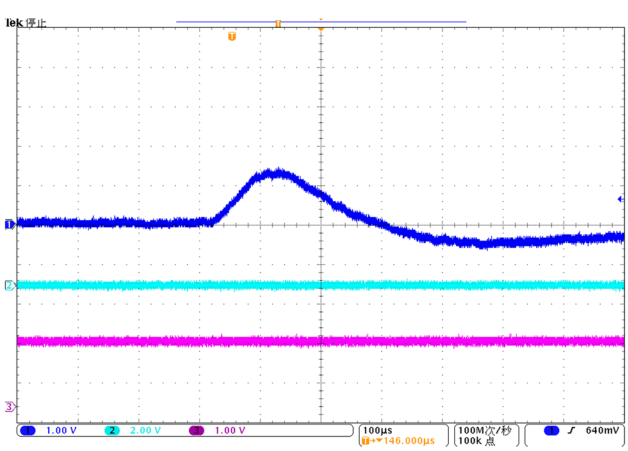
**Table 2:** Ultimate detection distance under different lens apertures $F$

| Lens aperture $F$ | Signal noise amplitude (V) | Ultimate detection distance (m) |
|---|---|---|
| 1.4 | 0.32 | 32.6 |
| 2 | 0.30 | 35.5 |
| 2.8 | 0.26 | 37.2 |
| 4 | 0.25 | 41.1 |
| 5.6 | 0.22 | 31.3 |
| 8 | 0.22 | 24.5 |
| 11 | 0.22 | 17.5 |
| 16 | 0.22 | 12.1 |

By analyzing the experimental data, the variation law of the flashing signal amplitude is found to be consistent with the proposed model. When the radiant brightness of the background light is higher, by setting the aperture of the lens to an appropriate value, the amplitude of the flashing signal can be effectively improved and the ultimate detection distance of the flash detector can be increased.




(a)




(b)

**Figure 6:** Correspondence between the signal amplitude and the lens aperture: (a) data curve of the light radiance and the effective signal and (b) signal waveform when $F = 2.8$.

## 6 Conclusion

The flash detector studied in this work is mainly used to detect long-distance brief light flashing. To address the problem of trigger failure under the condition of strong background light radiation, the influencing factors of detection sensitivity are studied, and a detection sensitivity mathematics model based on the influence of the background light radiation brightness is constructed. Then, a mathematical expression of flashing signal amplitude and action distance is deduced. The optimal working state of the detector under different background light radiance conditions is determined, which can effectively improve the ultimate operating distance of the trigger. Simulation analysis and experimental verification of the researched measurement model in different states show the correctness of the research method. The results showed that in the same external circumstances, the limit detection distance of the optimal aperture compared to the maximum aperture increased by 20%, and the effective signal voltage amplitude is twice the amplitude at the maximum aperture.

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