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Limit detection distance calculation method and detection performance in infrared detection system

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Due to the fact that detection performance of infrared detection target has problems of low capacity and capture rate, this paper studies detection distance calculation method of infrared detection target, according to characteristics of detecting light screen. Detection distance calculation model is deduced under different illuminate and target sizes, factors influencing detection distance are analyzed, and improving method is obtained; combining with infrared photoelectric detector characteristics and optical system parameters, limited detectable distance calculation method of infrared detection target is studied. Due to the relationship among response time, signal to noise ratio threshold and dark current of photoelectric detectors, limited detectable performance calculation function is set up, as well as variation rules among detection distance, optical system slit width, target radiation brightness and signal to noise ratio. By calculation and analysis, results show that under certain illuminate condition, when the target radiation brightness is stronger, detection range and capacity are stronger too; the higher SNR, the stronger the detection capacity.

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Keywords: Infrared light screen, The detection distance, Detection capacity, *SNR*

1. Introduction

For infrared detection light screen working in completely passive way, it has strong concealment, low altitude detection capacity and anti-jamming capacity when conducting detection to targets, which has been widely used in the field of military and civilian security projects [1-4]. Detecting screen can output pulse signals when targets pass through it, and can be used to measure flight speed of conventional weapons projectile in military field, and provide a trigger signal to high-speed photography for ballistic study [5-7]. Conventional detection screen uses the sky natural light as background, a thin fan-shaped detection area can be formed by a set of optical system in air, detection performance entirely depends on influence of sky brightness, and the screen cannot be used during night. This paper presents infrared detection screen formed by infrared lasers and optical system, which uses infrared laser as active light source and performance will not be affected by sky background brightness so that it can work all the time [8-9].

In the test of projectile flight speed by this infrared screen, when projectile is compared to a point, background of infrared light screen is narrow, and it can be seen as a single background. At present, what the big difference that actual performance and detection performance have is an important problem in infrared detection screen, and this difference lies primarily in infrared radiation of background using in detection screen, in the interference of infrared radiation, detection probability of infrared detection screen to target declines sharply in detection range, which causes a problem that target signals cannot be captured [10-11]. Therefore, the estimation of detection range for infrared light screen provides big assistance in development and application of infrared detection screen.

In general, detection range is an important index to measure infrared system detection performance. At present, domestic and foreign scholars have proposed several models on range estimation in infrared system. However, there is no specific calculation model of detection distance of infrared detection. Detection distance and limited detection distance calculation methods are studied in this paper.

2. Detection light screen principle of infrared detection screen

Infrared detection screen consists of infrared light source, lens and slit, filters, infrared photoelectric detectors and several other parts, as shown in Fig. 1. When projectile passes through the infrared light screen, infrared light reflected by projectile surface will be absorbed by photoelectric detectors in optical system. At this time, projectile target can be seen as a infrared point target, and infrared light screen can be seen as an infrared system.

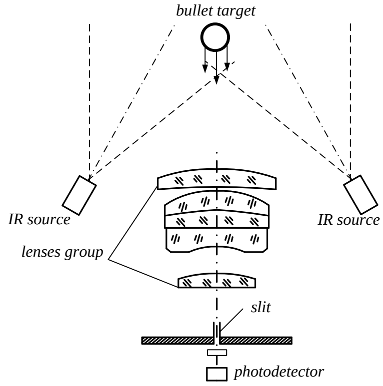


Fig. 1. Infrared detection screen optical path design

Slit forms a narrow detection area in the sky by lens, and its formation principle is shown in Fig. 2. The detection screens were built based on the principle of geometrical optics, especially the principle of parallel light, as shown in Fig. 3.

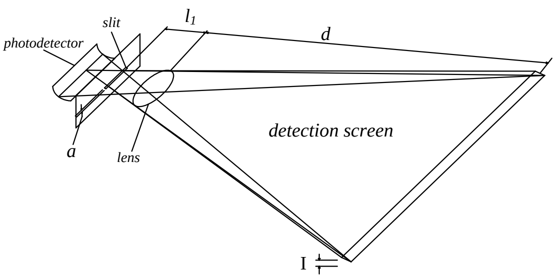


Fig. 2. The formation of infrared detection screen

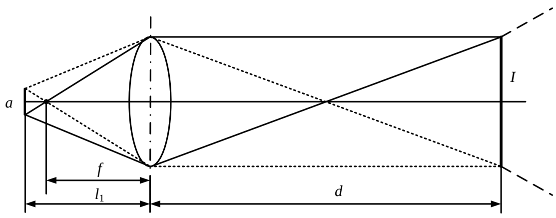


Fig. 3. The light path diagram of approximate parallel l ight screen

In Fig. 3, f is the focal length of the lens; a and b are the slit width and length; l_1 is the distance from lens to slit, which is the object distance in geometrical optics; I is the formation thickness of the screen, as well as the image location, its distance to the lens is d. Depending on thickness and width of the forming detection screen, together with the corresponding parameters of lens, the slit width a and location parameter l_1 are calculated [12-13]. Based on Newton Optical Formula, we can get the formulas as follows:

$$l_1 = \frac{d-f}{d \cdot f} \tag{1}$$

$$a = \frac{I}{d/f - 1} \tag{2}$$

In order to obtain higher response rate and precise detection screen position, thickness of the detection screen is generally designed to be thin. When it is towards sky background, detecting background is narrow, which can be treated as a single sky background.

3. Detection distance calculation model of infrared detection screen

When target infrared radiation received by infrared screen system in a certain distance can just meet the signal to noise ratio threshold, this distance is called operating distance of infrared detection screen. Since projectile target is regarded as infrared point, in addition, taking the effect of sky background IR noise into account, operating distance model based on noise equivalent irradiance (NEFD) is chosen to calculate the actual distance of infrared detection screen system [14-15].

Due to the angle of point target for infrared detection system is far less than the detection field, therefore, in addition to receiving a small amount of infrared radiation reflected by projectile, a part of background radiation will also be received.

Assume irradiance of infrared detection system received by target is:

$$E_t = \frac{q_t}{d^2} \cdot \tau_a \tag{3}$$

In equation (3), $q_t = R_t \cdot S_t$ is the radiation of target, R_t is the radiance brightness when target is illuminated by light source, s_t is the reflecting area of target, τ_a is the atmospheric transmittance, and d is the distance between target and detection system.

Because of the large field of view of infrared light screen, targets are impossible to fill the entire one, so a part of background radiation will go into detectors. Detecting screen background field of view can be seen as a single background, and at this time, radiation brightness of detection system coming from background radiation is obtained:

$$E_b = R_2(\varphi_d - \varphi_t) \cdot \tau_a \tag{4}$$

R_b is radiation brightness caused by background, $\varphi_t = S_t / d^2$ is the field of view of detection system center relative to target, φ_d is the detection field of view.

At this point, the total irradiance on detection systems is shown as follows.

$$E = E_t + E_b = [\frac{q_t}{d^2} + R_b(\varphi_d - \varphi_t)] \cdot \tau_a \tag{5}$$

When projectiles have not flown detection screen field of view, detection system fully towards the background, irradiance on the detection system is:

$$E_d = R_b \cdot \varphi_d \cdot \tau_a \tag{6}$$

So when projectile has passed through the detection screen, the changing irradiance is:

$$\Delta E = E - E_d = (\frac{q_t}{d^2} - R_b \cdot \varphi_t)\tau_a = \frac{R_t - R_b}{d^2} S_t \tau_a \tag{7}$$

NEFD of infrared detection system is:

$$A = \frac{\sqrt{S_d \cdot \Delta BW}}{S_o \cdot \tau_o \cdot D^*} \tag{8}$$

In equation (8), S_d is area of the detector, ΔBW is the equivalent noise bandwidth, S_o is the effective area of the optical system, τ_o is the optical system transmittance, and D^* is the detection rate.

The signal to noise ratio is the ratio of irradiance difference to noise equivalent radiation, that is,

$$SNR = \frac{V_i}{V_d} = \frac{\Delta E}{A} \tag{9}$$

In equation (9), V_i is the input signal of outside system, V_d is the RMS value of detector noise making ΔE in equation (7) substituted in equation (9), and then the detection distance can be obtained by equation (10).

$$d = \sqrt{\frac{k(R_t - R_b)S_t\tau_a}{A\cdot(V_i/V_d)}} \tag{10}$$

k is the signal attenuation coefficient in formula (10), combining equation (8) with equation (10), then we can obtain this equation:

$$d = \sqrt{\frac{k(R_t - R_b)S_t\cdot S_o\cdot\tau_a\cdot\tau_o\cdot D^*}{(S_d\cdot\Delta BW)^{1/2}\cdot(V_i/V_d)}} \tag{11}$$

Equation (11) is the distance estimation model of infrared screen.

From the formula (10) and (11), we can see that there are two types of factors that influences the detection range of infrared detection target. The parameters of the numerator of the formula includes target radiation brightness R_t, the radiance brightness of the background R_b, echoing area of target S_t, the effective area of the optical system S_o, atmospheric transmissivity τ_a ,the transmittance of optical system τ_o ,specific detectivity of the detector D^*, the increasing of all which enhances the detection range; the parameters of the denominator of the formula includes the detector's area S_d ,effective noise bandwidth ΔBW , the SNR of detecting system(or V_i/V_d), the decreasing of which enhances the detection range. As to the design of opto-mechanical structure, the main factors to be taken into account is the effective area of the optical system S_o and the detector area S_d, S_o determines the selection of the lens, S_d is based on the slit size.

4. Limit detection capacity algorithm of infrared detection screen

Detection capacity of infrared detection optical system can be measured with signal to noise ratio, according to formula (9) and the system noise, and signal to noise ratio of infrared detection target can be defined as:

$$SNR = V/V_{noise} = N_s(\lambda)/\sqrt{N_s + N_d + N_b} \tag{12}$$

In infrared detection system, total noises contain target radiation photon noise n_1, background radiation photon noise n_2 and dark current noise n_3. When target reaches optical detection system, detection circuit goes up and down randomly, which produces the incident photon flow that is the formation of target radiation photon noise, $n_1 = (N_s)^{1/2}$. Dark current noise is white noise, which is a random process signal produced by hot produced carrier, and its equivalent electronic number n_3 is equal to square root of dark current electronic numbers $n_3 = (N_d)^{1/2}$. Background radiation noise is equal to photon numbers $n_2 = (N_b)^{1/2}$. So, total equivalent noise electronic numbers of photoelectric track system are obtained:

$$n_{noise} = \sqrt{n_1^{\ 2} + n_2^{\ 2} + n_3^{\ 2}} = \sqrt{N_s + N_d + N_b} \tag{13}$$

From equations (12) and (13), if *SNR* is big, it means detection performance and detection capacity are greater, assuming minimum detectable signal to noise ratio threshold of infrared detection target is $K_{\min}$. According to equation (13), inequalities (14) can be established.

$$N_s(\lambda) \ge (K_{\min}^{\ 2} + \sqrt{K_{\min}^{\ 2} + 4(N_d + N_b + N_s)K_{\min}^{\ 2}})/2 \tag{14}$$

The minimum detectable signal to noise ratio threshold $K_{\min}$ can be calculated by the root mean square value of noise, which is usually 1.2 times of systematic root mean square value of noise. If $K_{\min}$ is too larger, the detecting capability of the system would be lowered down; otherwise, the systematic noise would surpass $K_{\min}$, leading to instability of the detecting system.

In general, detection capability of infrared detection target is represented by magnitude, which is expressed by *m*, because of the relationship among magnitude, illumination and irradiance; illumination on optical system surface E_m is obtained.

$$E_m = E_0 \cdot 2.62^{-m} Lx \tag{15}$$

In equation (13), E_0 is the illumination values of zero magnitude, $E_0 = 2.65\times10^{-6} Lx$. Inequality (16) is needed to detect target information.

$$E_m = E_0 \cdot 2.62^{-m} Lx \geq \frac{2Mhc}{\lambda^*} \cdot \frac{K_{\min}^2 + \sqrt{K_{\min}^2 + 4(N_d + N_b + N_s)K_{\min}^2}}{t_0 \cdot \tau_0 \cdot \eta \cdot \pi D^2} \tag{16}$$

In equation (16), λ^* is the average detection wavelength of optical detection system, (usually $\lambda^* = 680\text{nm}$), η is the spectral quantum efficiency.

Limit detection magnitude m of infrared detection target is set up.

$$m \leq 3.6 \cdot [-9.24 - \lg(\frac{4Mhc}{\lambda^*} \cdot \frac{K_{\min}^2 + \sqrt{K_{\min}^2 + 4(N_d + N_b + N_s)K_{\min}^2}}{t_0 \cdot \tau_0 \cdot \eta \cdot \pi D^2})] \tag{17}$$

In inequality (17), limit detection magnitude of infrared detection target system is related to signal to noise ratio threshold, dark current, background noise and optical system parameters. h is the Boltzmann constant, c is the light speed, D is the effective aperture diameter of optical lens, τ_0 is transparence rate, t_0 is the minimum time responded by photoelectric received devices, and M is the imaging area on photoelectric received detector surface.

5. Calculation and test analysis

5.1 Calculation and analysis of infrared detection target

When optical system, detectors, and detecting size of the target are determined, for equation (11), detection distance of infrared detection screen is related to radiation brightness of target R_t, radiation brightness of background R_b and the effective area S_o of optical system. For convenient simulation, other parameters can be normalized to k'. Equation (11) can be simplified.

$$d = \sqrt{k' \cdot (R_t - R_b) \cdot S_o} \tag{18}$$

When projection area of target (such as the caliber of projectile is 7.62mm) is much smaller than the probe's field of view, under the condition of lower detection height, radiation brightness R_b produced by background can be seen as a constant. When detection distance is short, R_b is relatively small so that it can be ignored. The effective area of the infrared light screen system is related to slit sizes, and it is converted into the slit area, as shown as follows.

$$S_o' = \alpha \cdot a \cdot b \tag{19}$$

b is length of slit. When the detection devices are confirmed, in order to obtain greater detection field of view, length of the slit should be equal to the length of detectors, so the slit length b is confirmed. Equation (18) can be further simplified.

$$d = \sqrt{k' \cdot \alpha \cdot R_t / a^{1/2}} \tag{20}$$

α is an equivalent coefficient in detection system. Assume diameter of the detection target is 7.62 mm, the length of slit is $b = 30mm$, and then relationship between detection distance, target radiation brightness and slit width is shown in Fig. 4.

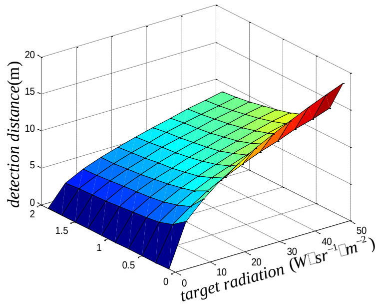


Fig. 4. The relationship among detection distance , target radiation brightness and slit width

In Fig. 4, detection distance increases with the decrement of slit width and with the increment of target radiation brightness, but it is not a linear relationship. For a determined slit width, when target radiation brightness increases, the detection distance also increases. As can be seen from the figure, when slit width is less, as, the detection distance significantly increases along with the increases of the target radiation brightness. Therefore, changing slit width can improve detection distance in designing detection systems.

When the background radiation brightness is high, the signal to noise ratio of the system will become big. In order to study the relationship between detection distance and signal-to-noise ratio of the system, other parameters in formula (11) are normalized to coefficient k'', and equation (11) can be simplified.

$$d = \sqrt{\frac{k'' \cdot R_t}{SNR}} \tag{21}$$

Conducting simulation to formula (18), results are shown in Fig. 5.

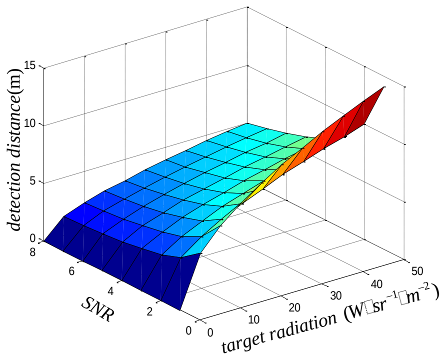


Fig. 5. The relationship between signal-to-noise ratio and detection distance

From Fig. 5, under a fixed SNR, detection distance of system increases with the increment of target radiation brightness. However, when the signal to noise ratio is larger, for a fixed target radiation brightness value, detection distance decreases on the contrary, because background radiation is large, which increases the input signal amplitude. Therefore, background radiation should be reduced in detection systems.

5.2 Limit capacity calculation and analysis of infrared detection target

Assuming photoelectric receiving detector of infrared detection target system is capable of sensing average wavelength with 680nm, when target is in the entire movement, transmittance of optical lens is $\tau_0 = 0.88$, optical lens aperture is $D = 250mm$, $N_d = 130e^-$, spectral quantum efficiency is $\eta = 0.81$ [16-17]. If the minimum signal to noise ratio threshold is $K_{\min} = 1.8$, $c = 3.0\times10^8 m/s$, $t_0 = 10^{-4} s$ and background illumination is 3x104cd/m2 in accordance with the formula (13) to (17), Fig. 6 shows the relationship between limit detection magnitudes and signal to noise ratio threshold of photoelectric detection system. Figure 7 shows the relation between limited detectable magnitude and dark current.

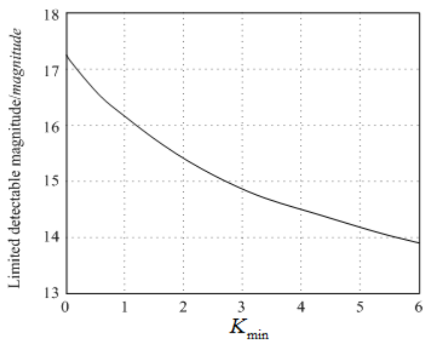


Fig. 6. The relation of Limited detectable magnitude and $K_{\min}$

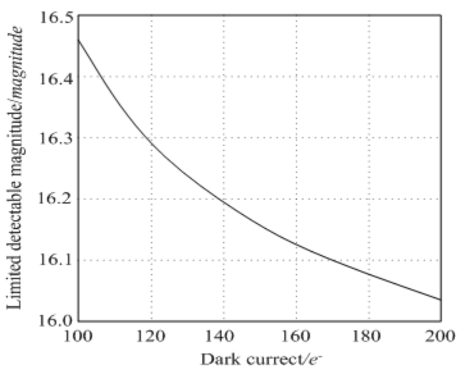


Fig. 7. The relation of Limited detectable magnitude and dark current

From Fig. 6, reducing signal to noise ratio threshold value can improve limited detectable magnitude of infrared detection target, which is conducive to target detection and distance, especially under strong light background environment condition, the higher signal to noise ratio, the better the detection performance. Under high signal to noise ratio conditions, low signal to noise ratio threshold can be selected. In Fig. 7, reducing dark current of infrared detection target system can increase its limited detectable magnitude to improve detection capacity。 However, curve changes in Fig. 7 changes dark current influences much less to limited detectable magnitude. When dark current changes from $100e^-$ to $160e^-$, limited detectable magnitude changes only 0.3. Therefore, in order to effectively improve limited detectable magnitude of infrared light screens, the signal to noise ratio threshold should be reduced as far as possible, as well as increase the effective aperture of the lens.

6. Test of detection distance

In order to verify the relation of detection distance and the slit width and target radiation brightness, the following experiment is designed. Standard lens with focus length of 50mm are used in infrared light screen optical system, the slit width designed to be 0.2mm. In order to avoid the effects of infrared radiation, we conduct experiments at night, and set infrared point light sources with adjustable radiation power at different heights above the lens. Oscilloscope is used to observe the output signal amplitude. When there are no point light sources, noise output voltage of detector is about 1V. Placing point light source at different heights, when the output signal amplitude is higher than the noise amplitude, detection distance can reach limit values, and then we measure the distance from infrared light to the lens surface, and the data is shown in Table 1.

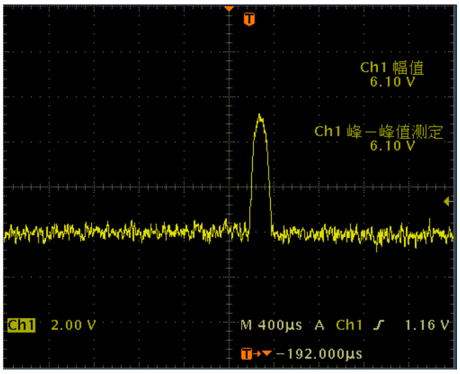
Table 1. Corresponding detection distance of different radiation brightness

No.	Point-source ($W\cdot sr^{-1}m^{-2}$)	Distance (m)	Amplitude (V/V)
1	10	1.5	1.2
2	20	2.2	1.1
3	30	2.7	1.2
4	40	3	1.1
5	50	3.45	1.2

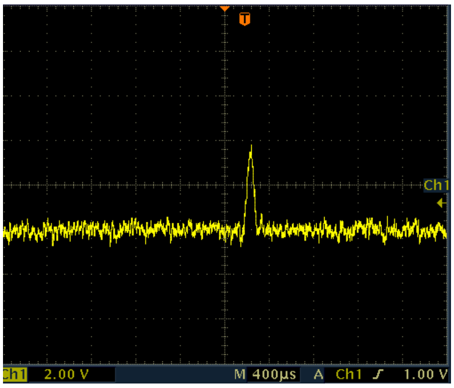
From Table 1, for a fixed slit width, the detection distance of infrared detection light screen increases with the increment of the radiance brightness. When reaching the limit, output signal of detection circuit will be overwhelmed by noise.

Placing the radiation brightness value with 20 $W \cdot sr^{-1} m^2$ point light source at different distances above the lens, oscilloscope is used to observe the output voltage, and the data is shown in Table 2. At the moment of placing light source in a distance of 0.5 meters and 0.8 meters above the lens, detector output waveforms are respectively shown in Fig. 8.

From Table 2, when the radiance brightness of point light source is a definite value, with the distance from point light to the lens surface increasing, amplitude of the detector output signal continues to drop. Therefore, in practical application, radiation energy of air attenuation and optical system can not be ignored. In addition, in practical applications, radiation brightness reflected by projectile target should be improved to increase radiation power, thereby enhancing the detection distance of infrared light screen.



(a) detector output waveform at the moment of placing light source above the lens 0.5 meters



（b）detector output waveform at the moment of placing light source above the lens 0.8 meters

Fig. 8. Detector output waveform at the moment of placing light source above the lens 0.5 meters and 0.8 meters,

Table 2. The relation of detection distance and amplitude of output signal voltage under fixed radiation

No.	Distance (m)	Amplitude (V/)
1	0.5	6
2	0.8	4.8
3	1.2	3.2
4	1.5	2.3
5	2	1.5

7. Conclusions

An infrared detection screen system consists of slits, optical system. Infrared light source is presented in this paper, and calculation method of detection distance is deduced aiming at point target under single background. Through numerical simulation, relation of detection distance, slit width and target radiation brightness are obtained. Under a certain condition of target radiation brightness and signal to noise ratio, increasing slit width can improve detection distance of infrared light screen; the changing rule among detection distance, signal to noise ratio and target radiation brightness are obtained. When target radiation brightness is determined, background radiation should be inhibited, or signal to noise ratio of system will increase, which can decrease detection distance. According to the concept of limited magnitude and optical design of infrared light screens, calculation functions of limited detection capacity are analyzed and deduced, and detailed analysis process and results are shown. Calculation method proposed in this paper provides theoretical basis and practical design factors for new infrared light screen designing, and provides scientific analysis of improving the detection performance. In addition, calculation methods in this paper are also suitable for device of photoelectric detecting system, and it has a very high research value.

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