Research on target infrared radiation characteristics and space target detection distance calculation method in photoelectricity detection system

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To improve the detection performance of the infrared detection system, optimize the structure of infrared detection system, this paper studies and analyzes the target surface radiation temperature, infrared radiation characteristics and space target detection distance. Based on the basic principle of the optical imaging detection system, the paper adopts the method of dividing the target into small units to establish a surface radiation temperature calculating model and set up the temperature radiation calculation function, and deduces the detection distance calculation function based on contrast and illuminance. By calculating and simulating, the results show the higher the target's reflectivity, the brighter the radiance of the target surface in the certain detection distance, and the output signal from photoelectric detector will enlarge.

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1. Introduction

The infrared radiation characteristics and detection distance are the core of the infrared radiation detection system, among these the infrared radiation characteristics of the target provides the devising theoretical basis for detection system, whereas the detection distance represents the detection capabilities of the detection system[1]. How to effectively extract the targeted information in the infrared optical imaging detecting system from the complex backgrounds is the core of the most optical detecting system, especially the detecting agencies with multi-infrared imaging detection system. Since the test results is only valid when each infrared detection system identify effectively the real targeted information[2-3]. Therefore, the study on how to calculate the space target surface temperature and the parameters of infrared radiation characteristics is an effective method of improving effectively the detection system performance. Especially with the development of infrared imaging detection technology, it was widely applied in the field of aviation, aerospace, weapons, coal mine, transportation etc. mainly due to the irreplaceable advantages (such as visible light image detecting system) that infrared detection can work well under complex environment and is not affected by the environmental illumination. However, infrared imaging detection system detects mainly based on the radiant heat of itself, for the same target from different background the effective detection distance depends on the radiation characteristics of target surface. To improve the detection performance of the infrared detection system, it is very necessary to set up the calculation model of target infrared radiation and detection distance

2. An equivalent calculation method of space target infrared radiant output signal

2.1 The infrared detection theory of space target

Fig.1 shows the light path schematic of space target in the infrared imaging system. The target radiation beam was from the field diaphragm to the aperture diaphragm and then was captured by the detector. d denotes the distance between field diaphragm and the aperture diaphragm. In order to restrain the stray light, the stray light diaphragm was added between the two diaphragms.

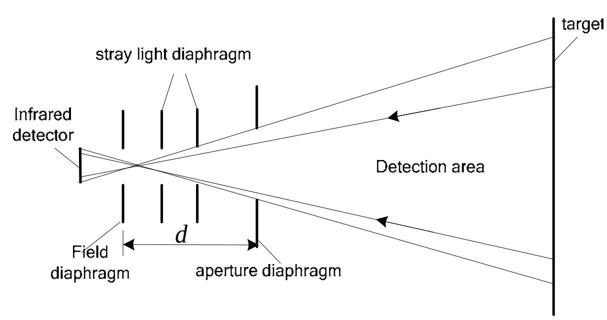

Fig.1. The light path schematic of space target in infrared imaging system.

To ensure that the radiation temperature information from the space target surface can completely go into the detector photosensitive surface, we set the field diaphragm as 24-32 mm, and the aperture diaphragm as 25-38 mm. The distance between the field diaphragm and the aperture diaphragm was 120-180 mm, while the size of detector photosensitive surface can select according to the practical need of detector field. When the target passing into the detection area, taking advantage of its motion state and environment conditions the target will map its surface temperature radiant energy to the infrared detector photosensitive surface by optical lens through the field diaphragm and the aperture diaphragm, next through the signal detector amplifying circuit and target detection signal recognition processing circuit, the dynamic information of space target which functioned in the detecting area will be detected.

2.2 The calculation for the infrared radiant surface temperature of the space target

According to the imaging principle of detection system, to calculate the infrared radiant energy of the target in the infrared imaging detection system, the surface of detecting target can be divided into $n \times m$ units. Then taking every bin as a radiant heat node, we can establish the equation. Next, exploiting the radiant energy super position of each unit on the target surface, we may calculate the whole target surface temperature function. Assuming the target as a cylinder, L is target length and r is target radius. Based on the imaging theory, the target imaging area on the detector is the expanded area of target semicircular; it can be shown by Fig.2. The whole radiant energy of space target on the infrared detector photosensitive surface is determined by $n \times m$ units.

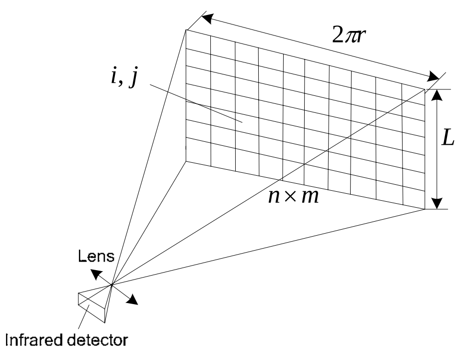

Fig.2. A optical schematic of the target expanded area equivalent radiation image.

Suppose, i and j refers to the (i , j) node on the target surface, according to the law of energy conservation, the node heat balance equation for every node is obtained by formula (1).

$$Q_1 + Q_2 + Q_3 + Q_4 + Q_5 + Q_6 - Q_7 = m_{ij} \cdot c \frac{dT_{ij}(t)}{dt} \quad (1)$$

In (1), from Q_1 to Q_7 designates respectively the received solar radiant energy by unit (i , j), the ground reflection solar radiant energy, the heat conduction from the adjacent unit, the heat conduction from target inside, the acquired radiant energy from air friction, as well as the energy loss caused by heat radiation m_{ij} is the quality of unit, and c stands for the nodes ratio heat capacity[4].

Q_1 stands for the received solar radiation energy of the unit (i , j), its expression is

$$Q_1 = \alpha_r E_0 \tau_0 \phi_{ij} \Delta S \quad (2)$$

In (2), α_r refers to the solar radiation absorption ratio on the target surface. E_0 is the solar radiation constant. τ_0 is the atmospheric transmittance ratio. ϕ_{ij} stands for the direction factor of received solar radiation from the unit. (i , j).

Q_2 refers to the received radiant energy of the unit (i , j) from ground reflection, its expression is

$$Q_2 = \rho_E \alpha_r E_0 \eta \varphi_{2ij} \Delta S \quad (3)$$

In (3), ρ_E is the reflectivity of the earth surface. $\rho_E = 0.35$, φ_{2ij} refers to the ratio of solar radiation from earth reflection arrived at every unit which is called solar radiation view factor of earth reflection[5].

Q_3 refers to the ground radiation energy received by the unit (i , j),its expression is

$$Q_3 = \alpha_r E_{io} \varphi_{3ij} \Delta S \quad (4)$$

In (4), E_{io} refers to the infrared radiation density of the earth, $E_{io} = 220W / m^2$. φ_{3il} is the ratio of infrared radiation leaving the earth arrived at the unit (i , j), which is called earth radiation view factor[6].

Q_4 is the sum of heat conduction from the unit (i , j) which receives the heat conduction from adjacent units, its expression is

$$Q_4 = \sum_{i'j'} \frac{k_c A_{i'j'ij} [T_{i'j'}(t) - T_{ij}(t)]}{L_{i'j'ij}} \quad (5)$$

In (5), $A_{i'j'ij}$ refers to the conduction area of the unit (i' , j') and the unit (i , j). $L_{i'j'ij}$ is the range between the unit (i' , j')and the unit (i , j). k_c stands for the coefficient of conduction of target's material. $T_{i'j'}(t)$ is the temperature of unit (i' , j') at "t" moment. $T_{kl}(t)$ stands for the temperature of unit (i , j) at t moment.

Q_5 refers to conduction heat which is received inside by the unit (i , j), the expression is

$$Q_5 = \frac{k_c[T_c - T_{ij}(t)]\Delta S}{\delta} \quad (6)$$

In (6), q_w stands for the heat flux of target surface.

Q_6 refers to the energy obtained by the unit (i , j) through aerodynamic heat when the target in high speed motion. The expression is

$$Q_6 = q_w \Delta S \quad (7)$$

In (7), Q_7 refers to the energy loss caused by heat radiation, its expression is

$$Q_7 = \varepsilon_g \sigma T_{ij}^{\ 4}(t)\Delta S \quad (8)$$

In (8), ε_g is the emissivity rate of target surface, σ is the *Bolzmann* constant.

If plugging the equation (2)~(8) into equation (1),we can get the radiation energy of the detecting target's unit (i , j). The equation (1) only refers to the radiation energy of the unit (i , j). The radiation energy of whole target can be figured out according to the total detecting target area in detection field.

In (1), Q_1, Q_2, Q_3, Q_5, Q_4 and Q_8 are irrelevant to $T_{ij}(t)$, while Q_6, Q_7 and Q_9 are a function of $T_{ij}(t)$. And there are high order term $T_{il}^4(t)$ and differential term $\frac{dT_{il}(t)}{dt}$ [7]. To reduce the process of calculation, we can simplify the equation as following:

Firstly, transfer the differential to the backward difference operators

$$\frac{dT_{il}(t)}{dt} = \frac{T_{il}(t) - T_{il}(t - \Delta t)}{\Delta t} \quad (9)$$

Next, transfer the high order term to first degree,

$$T_{ij}^{\ 4}(t) = 4T_{ij}^{\ 3}(t - \Delta t)T_{ij}(t) - 3T_{ij}^{\ 4}(t - \Delta t) \quad (10)$$

From (1), (9) and (10), it's knowable that for any unit of target, given the temperature values $T_{ij}(t - \Delta t)$ at $t - \Delta t$ moment, we can figure out the temperature value $T_{ij}(t)$ at t moment by recursion, and finally get the temperature values of each unit at every moment.

Based on Fig.2, the total area of target surface can be gain formula (11).

$$\mathrm{S} = n \times m \times \Delta \mathrm{S} \quad (11)$$

If the flying targets are not cylinder but arbitrary shape, the calculation method is the same. We also divide the flying target into $n \times m$ units to gain target surface radiation temperature.

If the flying targets has some angle when it passing through detection area, the total area of target surface area has some change. Supposed, θ is the angle that flying targets passing through detection area and vertical motion direction, the total area of target surface can be gain formula (12).

$$\mathrm{S} = n \times m \times \Delta \mathrm{S} \times \cos\theta \quad (12)$$

So, the surface radiation temperature will be decided by formula (12).

After obtaining the temperature distribution of target surface through the model above, we can figure out the M_λ , namely Spectral radiant exitance of target surface in the detection field based on the *Planck's* law[8-10].

$$M_\lambda(\lambda) = \int_{\lambda_1}^{\lambda_2} \varepsilon \frac{c_1}{\lambda^5 (e^{c_2/\lambda T} - 1)} d\lambda \quad (13)$$

In (13), λ refers to the radiation wavelength (um), c_1 and c_2 are the radiation constant, ε is the radiation coefficient of target's material. In practice, we mainly focus on obtaining the flying target from the infrared detection system of sky-screen. Therefore, when we study the infrared radiation characteristics of target, it's essential to consider the in target process of radiation energy within sensitive spectral range of infrared detector. The radiant radiance of target is $I(T, \lambda)$, it's expression is

$$I(T, \lambda) = \frac{\varepsilon}{\pi} A_1 \int_{\lambda_1}^{\lambda_2} \frac{c_1}{\lambda^5 (e^{c_2/\lambda T} - 1)} d\lambda \quad (14)$$

In (14), λ_1 and λ_2 refers respectively to the upper and lower waveband, and A_1 is the target's radiation area. On the radiant radiance of known target, provided that the active radiation flux received by infrared photoelectric imaging detector is $\Phi(\lambda)$, we can get the following expression

$$\Phi(\lambda) = \frac{A_1 A_2}{R^2} \int_{\lambda_1}^{\lambda_2} I(T, \lambda) d\lambda \quad (15)$$

In (15), A_2 stands for the target area detected by the detector receiver device, R refers the distance between detector and the flying target.

According to the target in the infrared detection system, the V_p is output signal from photoelectric detector can be calculated by expression (15)[11].

$$V_p = \int_{\lambda}^{\lambda+\Delta\lambda} RSR(\lambda)\Phi(\lambda)d\lambda = \frac{\pi}{2}(\frac{D}{f})^2 hc^2\tau_0 A\eta \cdot \int_{\lambda}^{\lambda+\Delta\lambda} RSR(\lambda)\varepsilon_\lambda \tau_\lambda \frac{1}{\lambda^5 \exp(hc/\lambda KT)-1} d\lambda \quad (16)$$

In (16), λ refers to response infrared wavelength of the detector, δ is the increasing factor of wavelength, k is the temperature coefficient constant, A is photosensitive area of photoelectric detector, D is the entrance pupil aperture in optical system, η is the modulation coefficient, τ_λ is the spectral transmittance in optical system, $RSR(\lambda)$ is the spectral responsivity, T is target surface radiation temperature, ε_λ is the radiation coefficient of target's material under wavelength λ [12] . If we want to improve the output signal from photoelectric detector, we must choose high $RSR(\lambda)$ and large aperture optical lens to design detection system.

Thus, we can gain the ratio of electrical output signal in different wavelength by formula (17).

$$R_{12} = \frac{\int_{\lambda_1}^{\lambda_1+\Delta\lambda} RSR(\lambda)\varepsilon_\lambda \tau_\lambda \frac{1}{\lambda^5 \exp(hc/\lambda kT)-1} d\lambda}{\int_{\lambda_2}^{\lambda_2+\Delta\lambda} RSR(\lambda)\varepsilon_\lambda \tau_\lambda \frac{1}{\lambda^5 \exp(hc/\lambda kT)-1} d\lambda} \quad (17)$$

In (17), $\Delta\lambda$ refers to the synchronous increment of the waveband λ_1 and λ_2, R_{12} is the ratio of electrical output signal in different wavelength. We can use formula (16) to calculate the output signal of photoelectric detector, and calculate target surface radiation temperature by using formula (1).

3. The detection distance calculation method

According to the equivalent calculating method of infrared output signal in infrared detection field, we can get the radiation energy and detecting output signal under certain illumination conditions, as well as the calculation model of equivalent radiation area for the space target. In order to identify effectively the target signal of infrared detecting system, it's essential to establish the calculation model of detection distance in the infrared detecting system from the contrast. Based on the definition of contrast modulation, the definition of contrast C_M can be expressed by formula (18).

$$C_M = \frac{E_{\max} - E_{\min}}{E_{\max} + E_{\min}} = \frac{E_t}{E_t + 2(E_b + E_0)} \quad (18)$$

In (18), E_t refers to the target's irradiance on the infrared detector's photosensitive surface. E_b designates the irradiance of background light on the infrared detector's photosensitive surface. E_0 stands for the radiated irradiance of detecting imaging lens on the infrared detector's photosensitive surface[13-14].

$$E_t = \frac{M_\lambda(\lambda)\tau_0\tau_1}{4} \cdot \left|\frac{D}{f}\right|^2 \quad (19)$$

$$E_b = \frac{\tau_0\tau_1}{4} \cdot L_b \cdot \left|\frac{D}{f}\right|^2 \quad (20)$$

$$E_b = \frac{1}{4} \cdot M_{\lambda 0} \cdot \left|\frac{D}{f}\right|^2 \quad (21)$$

Here, $M_{\lambda 0} = \varepsilon_0 \cdot M_\lambda(\lambda)$, ε_0 designates lens transmittance. Therefore, formula (17) can be transferred into

$$C_M = \frac{M_\lambda(\lambda)\tau_0\tau_1}{M_\lambda(\lambda)\tau_0\tau_1 + 2(\tau_0 \cdot \tau_1 \cdot L_b + M_{\lambda 0})} \quad (22)$$

In (22), L_b is background luminance, the detection distance of infrared detection system was designated as R , its expression is

$$R = f \cdot \sqrt{\frac{M_\lambda(\lambda)\cdot\tau\cdot\tau_0}{2(M_{\lambda 0} + \pi\tau_0 L_b)}\left|\frac{A}{A_m}\right| \cdot \left|\frac{1-C_M}{C_M}\right|} \quad (23)$$

In (23), A_m refers to the imaging radiation area mapped on the infrared detector photosensitive surface by the target's effective radiation area in the space detecting field. So, based on the parameter such as background illumination of infrared detection system, radiance of target, modulation contrast etc, we can figure out effectively the target's surface temperature, output signal intensity and efficient detection range of infrared detection system.

4. Calculation and analysis

According to the infrared detection theory and the calculation method mentioned above, we adopt the qualitative analysis for the temperature field characteristics of space target surface. Let's make the following assumptions: the target is within the observable spectrum range beyond the atmosphere, the solar irradiance is

$570\times10^{-4}W/cm^{-2}$, the aperture of detection receiver optical lens is 18 mm, the lens transmittance of optical system is 0.85, the infrared wavelength is from 650 nm to 1400 nm, the detection receiving field of view of the infrared photoelectric detector is 38°, the light-sensing surface area of the received infrared detector is $16\text{mm}\times12.5\text{mm}$, the responsivity of the detector is $3082V\cdot m^2/J$, the detected dark current noise is $12000e^-/s$, the spectral responsivity called $RSR(\lambda)$ is 0.56A/W, the irradiance of the target from the earth is $697\times10^{-4}W/cm^{-2}$[15].

Suppose that the target of infrared imaging detector system is a cylinder, its length is 1240 mm, the atmospheric transmittance is 0.78, the absorptive of solar radiance on the target surface is 0.67, the spectral transmittance of optical system is 0.88; based on (1) to (10), we can figure out that the reflectivity of surface's material is 0.63, 0.72, and 0.88. The relationship between reflectivity and the variation of target radius can reflect the radiation temperature curve of the target surface, as is shown in Fig. 3. The curve A refers to the reflected surface temperature under the reflectivity of surface's material is 0.63. The curve B refers to the reflected surface temperature under the reflectivity of surface's material is 0.72. The curve C refers to the reflected surface temperature under the reflectivity of surface's material is 0.88. From Fig.3, we can see that: with the same target radius, the target's reflectivity is proportional to its surface temperature. For the target made from the same material which has the same reflectivity, the larger the target radius, the higher temperature of target's surface obtained by the detection system. Therefore, for the target's material with the same reflectivity, we can amplify the optical aperture of optical field of view and improve the transmitting energy as much as possible and then converge the energy on the diaphragm field in order to improve the reflectivity of target and eventually improve the detection performance of the system effectively.

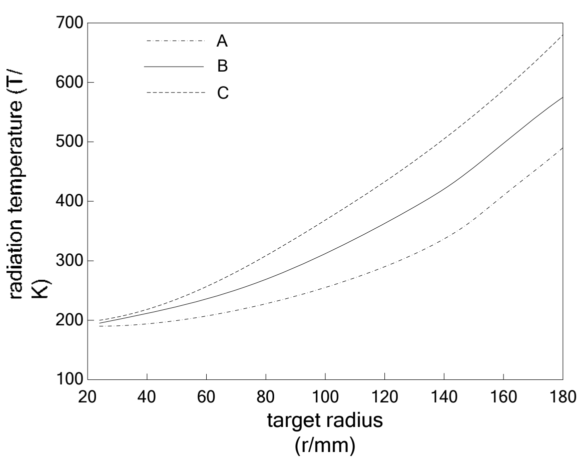

Fig.3. Target reflected radiation temperature curve under different target radius.

Under the known condition, combining with the Equation (22), assuming the optical lens *f* is 35mm, we discusses the surface radiation temperature characteristics, which is obtained by target detection distance and the detection system, Fig. 4 is target reflected radiation temperature curve under different detection distance. From Fig. 4 it's obvious that the detection distance of target is inversely proportional to the surface radiation temperature of target in the same optical aperture diaphragm and detection circuit, the further the detection distance, the less the radiation temperature energy, if the detection distance more than 40m, the surface radiation temperature of target will than less 100K. The result shows the higher the target's reflectivity, the brighter the radiance of the target surface in the certain detection distance, at the same time, if the entrance pupil aperture enlarge in optical system, the detection distance also enlarge under the same target. So, we may choose large aperture optical lens to design detection system to improve detection performance based on formula (16) .

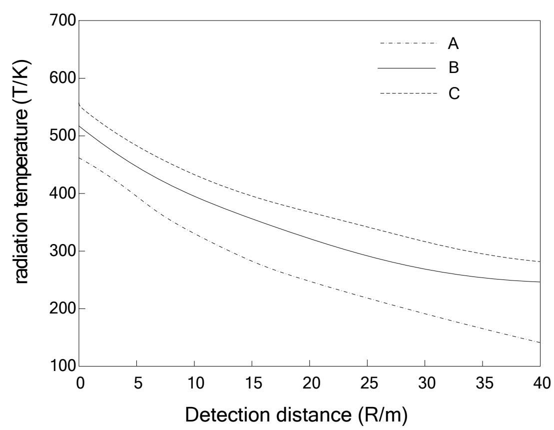

Fig. 4. Target reflected radiation temperature curve under different detection distance.

Based on formula (13) and (14), and the known conditions, for the same optical system parameters and the detector with different infrared wave length, the relationship between wavelength and target surface and target surface radiation energy is as shown in Fig. 5. We analyze it within the wave range of 600 nm ~1400 nm . It shows that there is not a proportionality between the two factors above, nor is there an inversely proportionality between the wavelength and the target surface radiation temperature. The results show when the wave band within a short range, the variation of radiation of target radiation on the photoelectric detector becomes evident. The peak range of this wave band is among 800 nm ~900 nm approximately. All of this shows that the radiation of space target responds sensitively to the wave band in the above range. The highest radiation temperature obtained by the detector is up to 570k. In Fig. 5, B and C refers to the two target material with different reflectivity. The reflectivity of target material produces less effect on the radiation temperature of target surface.

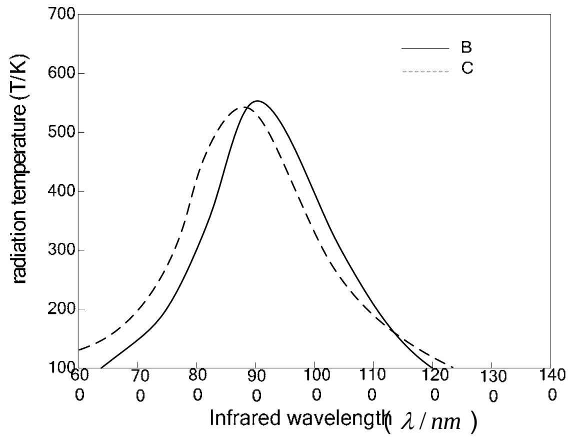

Fig.5 Target reflected radiation temperature curve under different infrared wavelength.

Based on above theory, as well as the known conditions in Fig.3, we discuss the function of detection distance and output signal amplitude. As is shown in Fig. 6, the detection distance is in inverse proportion to output signal amplitude. The further the detection distance, the less the output signals amplitude and the distribution of output signal amplitude approaches the exponential decay trend. When we expand the optical aperture diaphragm, the output signal amplitude increases correspondingly. K_1 and K_2 is two kinds aperture diaphragm, the value of them are respectively 28 mm and 32 mm. In order to improve the detection distance of detection system, the optical lens, aperture and the wavelength of detector should be taken into account.

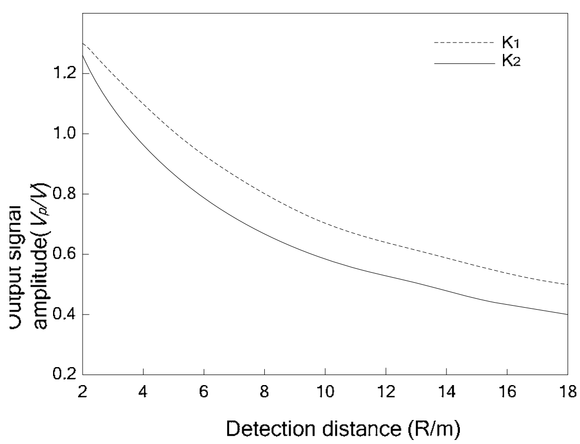

Fig. 6. The relation between output signal amplitude and detection distance.

From the above analysis, the space target surface temperature is related to optical structure parameters of detection system and to the spectral wavelength etc. while the detection distance is related to the dimension of target surface, to the surface temperature, to the reflectivity etc. To improve detection performance of infrared detection system, it's essential to take all these into account, such as the optical structure parameters, the choice of photoelectric detector in detection circuit etc, only in this way can the performance (such as sensitivity) of the infrared detection system be improved greatly.

4. Conclusions

Based on the basic theory of infrared optical imaging detection system, this paper studies the calculation method of the thermal radiation energy on the target surface, and establishes its calculation model. By adopting the method of transferring the differential into the backward difference operators , we reduces the calculation amount of higher order functions and obtains the radiation energy of each unit on the target surface. According to the total area of space target in detection field, we also deduce the output signal equation of infrared detector. The paper discusses the target irradiance and the irradiance of background light on the infrared detector photosensitive surface, as well as the contribution to detection system from the detection imaging lens radiation's irradiance on the infrared detector photosensitive surface, and establishes the calculation function of contrast and detection distance. By calculating and analyzing, it is obvious that the brighter the irradiance of the target on the infrared detector photosensitive surface, the higher the contrast, the further the detection distance. The calculation in this paper provides the theory analysis and practical foundation for the specific design of the infrared detection system, and also provides the modification basis for improving the detection performance of the system.

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