Illuminance distribution of target imaging spot and detection model of missile guidance laser photoelectric detection system

BAOYI GUO*, ZHIYONG LEI, YAN WANG
School of Mechatronic Engineering, Xi'an Technological University, Xi'an, 710021, China

According to the detection mechanism of the missile guidance photoelectric detection system, combining the distribution function of the imaging spot of laser reflected by target surface, the experimental illuminance and the size of the photosensitive surface of photoelectric receiving detector, we study the illuminance distribution characteristics of the target imaging spot and set up the calculation model of illuminance distribution. Based on this model, we establish the output voltage signal function of the missile guidance laser photoelectric detection system, and then derive the calculation model of the signal-to-noise ratio of the system using the experimental illuminance, the thermal noise and the target radiation photon noise. Through experimental test and analysis, the results show that the target imaging spot energy at different detection distances is different, which makes the peak of the output voltage signal of the system significantly different. At the same time, with the increase of the detection distance, the laser echo energy decreases, and the peak of the output voltage signal of the system also decreases. In addition, we verify the illuminance distribution of target imaging spot under different detection distances.

(Received July 27, 2021; accepted November 24, 2021)

Keyword: Missile, Guidance, Laser, Photoelectric detection, Echo, Signal-to-noise ratio

1. Introduction

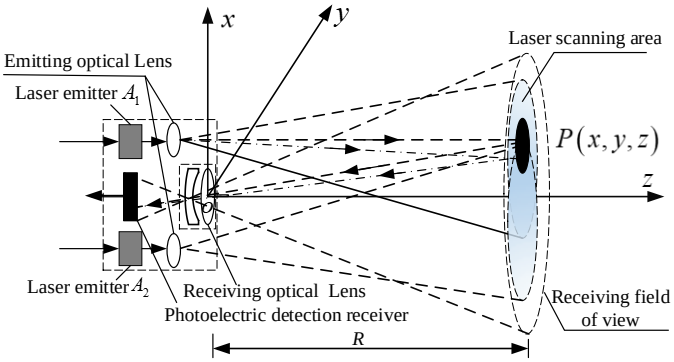
In the field of laser-guided weapon system, laser has the advantages of adjustable divergent beam, strong directivity, good monochromatism, high brightness, large emission power and far detection distance. It makes the way of laser guidance play a great role in the development of weapons, especially in the aspect of short-range detection and guidance of various laser fuzes and intelligent missiles [1-2]. The laser works in the optical band of electromagnetic wave, and its wavelength is very small. So, the geometrical parameters of the emitting and receiving field of view of the laser can be accurately controlled by using optical elements. For air-to-air and surface-to-air missiles [3-4], such as mortar bombs, cluster bombs, they are all require that the fuze has omnidirectional detection ability, which is usually achieved using multiple sets of laser emitters and receivers, that is, the fuze emitter and receiver are evenly arranged in the circumferential direction of the missile (usually 3-6 groups are required). The emitting optical system first collimates the laser beam of large divergence angle, and then, uses the cylindrical mirror, reflecting cone and optical wedge to expand the beam in the radial direction of the missile to form circumferential detection in 360° field of view [5-7]. However, due to the large emission field of view and the difference in the radiance illuminance of the surface of target in space, the detection ability of various guided missiles that adopts laser as the carrier has changed obviously. In addition, the detection ability of the laser fuze is insistent in different natural environments. How to improve the detection ability of the guided missiles is an important task in the development of guided weapon. There have been several researches on the missile guidance based on laser detection mechanism. For instance, the authors in [8] studied a projectile-target intersection algorithm for scanning six-quadrant laser detection system, proposed a mathematic model of the missile rotational velocity and analyzed the relative motion equation of projectile and target and the iterative decoupling algorithm. Bo Peng et al. [9] studied the laser circumferential scanning detection model of underwater targets, established the intersection equation of scanning beam and moving targets, and then simulated the laser scanning detection process of underwater target. Shanshan Chen et al. [10] studied the modeling of acquisition for ground target by using pulsed laser circumferential detection method, derived the analytical expression of pulsed laser echo signal for plane targets, and established the projectile-target intersection model of the laser circumferential detection system. However, all of them do not take into account the influence of the laser illuminance distribution and the target imaging spot illuminance distribution on detection performance of the system. In this paper, based on the illuminance distribution characteristics of the target imaging spot, we establish its illuminance distribution calculation model. By combining the environmental illuminance distribution function of the target location, we obtain the target imaging spot illuminance change law of the missile guidance laser photoelectric detection system, and give a calculation model of the target voltage signal output by the

photoelectric detection receiving circuit. And then we establish the calculation model of the signal-to-noise ratio of the system. The model established in this paper does not use the traditional laser echo power calculation model, which is to directly obtain the laser echo power according to the laser emission power; while in this paper, we add the characteristics analysis of the illuminance distribution of the background environment at the detection position of the target and the illuminance distribution of the target imaging spot, and then obtain the calculation model of the voltage signal obtained by the conversion of the echo energy of the target reflected laser. This method more vividly characterizes the laser echo characteristics of the missile guidance laser photoelectric detection system.

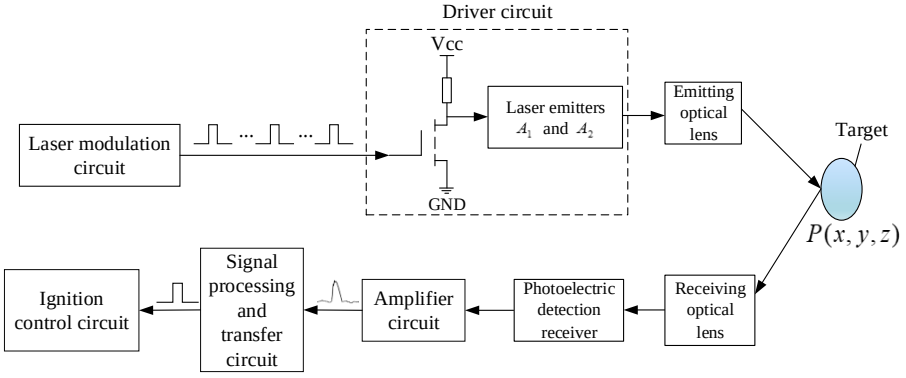
2. Echo signal modeling of missile guidance laser photoelectric detection system

2.1. Illuminance distribution of target imaging

According to the laser scanning detection mechanism of intelligent missile, the missile adopts the circumferential scanning detection mode. Based on this mode, the laser emitting device of missile periodically emits laser beams to form the detection area. If the target passes through the laser detection area, the echo energy of the laser reflected by the target is used as the basis to control the burst of missile [11-14]. The circumferential scanning detection mode of missile is mainly to obtain the laser energy reflected by target more reliably, and improve the guidance ability of the missile photoelectric detection. Fig. 1 is the detection principle of missile guidance laser photoelectric detection system. In Fig. 1(a), laser photoelectric detection module includes laser emitters A_1 and A_2, emitting optical lens, photoelectric detection receiver and receiving optical lens. The pulsed laser emitted by the laser emitters of A_1 and A_2 through the laser modulation circuit and the driver circuit. When the target passes through the laser scanning area, the laser energy reflected by the target enters the photoelectric detection receiver through the receiving optical lens to form a weak electrical signal, and the electrical signal is adjusted to a pulse signal by the signal processing module. When the pulse signal is greater than the threshold voltage set by the system, the system sends a detonation command to the ignition control circuit. The laser echo energy reflected by the target is related to the actual detection distance and angle of the missile-target intersection, etc. A single laser emitting and receiving optical path can form an independent detection system, while the missile itself has two laser emitting and receiving optical paths, then two different laser emission coverage areas are formed by two laser emitting optical paths at the detection distance of *R*. From the Fig. 1(a), we can find that there is an overlapping region at the two laser emission coverage areas. In the overlapping region, the laser energy is superimposed. Fig. 1(b) is the schematic diagram of the principle of the laser emitting module and photoelectric detection receiving module.



(a) Schematic diagram of laser scanning detection



(b) The principle of the laser emitting module and photoelectric detection receiving module

Fig. 1. The detection principle of missile guidance laser photoelectric detection system

When the target intersects with the missile at the detection distance of R, according to the rotating scanning mechanism of the missile, there is always a laser emission coverage area that can detect the target and form a reflection echo signal [15-16]. Because of the fast rotation velocity of the missile, the laser echo signal reflected by the target is a continuous signal with a certain time interval, and the peak of the echo signal energy is determined by the laser emission power and the reflectivity of the target [17-19]. In order to effectively evaluate the detection ability of the guided missiles, it is necessary to consider the parameters of each laser emitting and receiving optical path module [20-21]. In Fig. 1, the distance between the emitter and the receiver of each laser is *d*. When the detection distance is *R*, *d* is far less than *R*, which can be ignored in the calculation of the position of target. The center of receiving optical lens is regarded as the coordinate origin of system, and $oxyz$ is the coordinate system of the combination unit of laser emitter and receiver of the missile. *P* (*x*, *y*, *z*) is the relative position of the target to the missile. Based on the combined structure of laser emitter and receiver, this paper constructs the calculation model of laser echo energy and signal-to-noise ratio model of the system.

2.2. Illuminance distribution of target imaging spot in the missile-target intersection

According to Fig. 1, if the target is at any position of the entire field of view of the system, combining with the imaging basic principle of photoelectric detection receiver, the image formed by the target on the photosensitive surface of the photoelectric detection receiver is a diffuse spot imaging. The laser beam is reflected by target surface, so the area of the imaging spot is mainly determined by the cross-sectional area of the target surface. Based on the principle of optical imaging, the cross-sectional area of the target surface can be mapped out by the photoelectric detection receiver to reflect its dynamic changes, which forms the principle of laser circumferential scanning detection. The illuminance distribution of the ideal target image at any position $P(x, y, z)$ in the laser scanning area is *E* (*x*, *y*, *z*), and the point spread function of the optical system is $h(x, y, z)$, then the actual target imaging illuminance distribution *E'* (*x*, *y*, *z*) is given by Formula (1).

$$E'(x, y, z) = E(x, y, z) * h(x, y, z) \tag{1}$$

For the optical detection module in the missile guidance laser photoelectric detecting system, there is a certain distance between the target and the optical imaging system. Hence, it can be considered that the illuminance distribution of the target imaging is uniform. Then the target illuminance of $E_0(x, y, z)$ can obtain by:

$$E_0(x, y, z) = P / s_m \tag{2}$$

where *P* is the radiated power of the photoelectric detection receiver, s_m is the area of the imaging spot.

Assume that the geometric shape function of the target imaging spot on the photosensitive surface of the photoelectric detection receiver is $K(x, y, z)$, the illuminance of it can be expressed as:

$$E(x, y, z) = K(x, y, z) E(x, \tag{3}$$

The point-spread function $h(x, y, z)$ of the optical system is the inverse Fourier function of the optical transfer function, which is given by Formula (4).

$$h(x, y, z) = \pi a^2 \exp[-(\pi a^2 R^2)] \tag{4}$$

where *a* is the light spot radius reflected by the target on the photosensitive surface of the photoelectric detection receiver. By substituting (7) and (8) into (3), the actual illuminance distribution of the target imaging spot $E'(x, y, z)$ can be obtained.

The guidance mechanism of the missile is based on the effective laser echo energy reflected from target surface incidenting on the photoelectric detection receiver. Hence, the illuminance distribution of the target imaging spot determines the energy contributed by the target that can be detected by the photoelectric detection receiver.

3. Photovoltaic conversion calculation method of target signal

In order to evaluate the photoelectric detection ability of the guided missiles, based on the illuminance distribution function of the target imaging spot, assume that the environmental illuminance is $E_b(x, y, z)$, then the difference function of actual illuminance distribution between the target and background experiment is given by Formula (5).

$$\begin{aligned}\Delta H(x, y, z) = &[\overline{E}(x, y, z) - E_b(x, y, z)] \\ &\cdot K(x, y, z) * h(x, y, z)\end{aligned} \tag{5}$$

Through the photoelectric conversion relationship of the photoelectric detection receiver, the target signal voltage output by the photoelectric detection receiving circuit can be obtained by Formula (6).

$$V = A_v \int_{\lambda_1}^{\lambda_2} R_i(\lambda) \left(\iiint_{\Omega} \Delta H(x, y, z, d\lambda) dx dy dz \right) d\lambda \tag{6}$$

where λ_1 and λ_2 are the corresponding lower limit response wavelength and upper limit response wavelength

of the photoelectric detector receiver, Substituting (5) into (6), the target signal voltage is changed into Formula (7).

$$V = A_v \cdot \int_{\lambda_1}^{\lambda_2} R_i \frac{[\overline{E}(x,y,z) - E_b(x,y,z)]s_m \cdot \tau_0}{R^2} M d\lambda \quad (7)$$

where A_v is the total gain of the missile guidance laser photoelectric detection system, and R_i is the responsivity of the photoelectric detection receiver. *M* is expressed by Formula (8).

$$M = \iiint_{\Omega} K(x,y,z) * h(x,y,z) dxdydz \quad (8)$$

where Ω is the spatial region of missile-target intersection.

4. Calculation method of signal-to-noise ratio

The photoelectric detection ability of the guided missiles is generally expressed by the SNR [22-23], which is defined by Formula (9).

$$SNR = V / V_n \quad (9)$$

where V_n is the background noise signal voltage produced by the photoelectric detection receiver due to the influence of photon noise of target radiation n_1, photon noise of background radiation n_2 and dark current noise n_3. If $V_n > V$, the missile guidance laser photoelectric detection system cannot be able to recognize the target signal.

Assume that the incident photon stream generated by the random fluctuation of the detection circuit caused by the photon noise of target radiation is n_1, and $n_1 = (N_s)^{1/2}$. Dark current noise is a kind of white noise, which is a random process signal caused by the heat generation of the carrier. Its equivalent electron number n_2 is equal to the square root of the electron number of the dark current, and $n_2 = (N_d)^{1/2}$. The equivalent photon number of the background radiation noise is n_3, and $n_3 = (N_b)^{1/2}$. Then, the total equivalent noise electron number in the photoelectric detection receiver can be obtained by Formula (10).

$$N_n = \sqrt{n_1^2 + n_2^2 + n_3^2} = \sqrt{N_s + N_d + N_b} \quad (10)$$

Thus, the equivalent noise voltage of detection circuit output by the system is given by Formula (11).

$$V_n = \frac{1}{C} e \cdot N_n \cdot \kappa \cdot A_v \quad (11)$$

where κ is the total charge transfer efficiency, A_v' is the amplifier gain, *C* is the output equivalent capacitance, and *e* is the electron charge [24].

The *SNR* calculation function of missile guidance laser photoelectric detection system can be obtained by Formula (12).

$$SNR = \frac{C\int_{\lambda_1}^{\lambda_2} R_i \cdot Q(\iiint_{\Omega} K(x,y,z) * h(x,y,z) dxdydz) d\lambda}{e \cdot N_n \cdot \kappa \cdot A_v} \quad (12)$$

where $Q = \frac{[\overline{E}(x,y) - E_b(x,y)]S_t \cdot \tau_0}{R^2}$.

According to the basic principle of the missile guidance laser detection system and the illuminance distribution function of the target imaging spot in Fig. 1, the detection ability of the system is not only related to the laser emission power and the optical path of the system, but also related to the laser illuminance distribution on the target surface under the missile-target intersection. To improve the detection ability of the system, the model established in this paper introduces the analysis of the characteristics of the illuminance distribution of the target imaging spot, and then gives its illuminance distribution function. By using the illuminance distribution function of the target imaging spot, we derive the expression of the target voltage signal output by the photoelectric detection receiver, and construct the signal-to-noise ratio model of the system. The method proposed in this paper more scientifically describes the target echo energy of the missile guidance laser detection system, and provides help for the design of the missile guidance laser photoelectric detection system under uncertain missile-target intersection.

5. Experiment and analysis

According to the photoelectric detection mechanism of the guided missiles, the output voltage function of detection circuit and the calculation model of *SNR* are derived. We tested the fuze of the projectile, and the diameter of projectile is 76 *mm*. Based on the fuze parameters of the projectile, we carried out experimental tests. Assuming that the peak power of the emission pulse laser is about 38*W*, the field of view of the unit laser emitter is 18.4°, the emitted frequency of pulse laser is 3*KHz*, the field of view of the photoelectric detection receiver is 20.1°, the response wavelength range of the photoelectric detection receiver is 900 *nm* - 1100 *nm*, the size of the photosensitive surface is 1.5 *mm*×1.5 *mm*, the size of the optical lens aperture is 1:1.2; the transmittance of the optical lens τ_0 is 0.92, $N_d = 100e^-$, the charge transfer efficiency of the photoelectric detection receiver κ is 0.68, and the coefficient α in the point-spread

function $h(x, y, z)$ of the optical system is 0.42. Based on the spatial geometrical relationship of the target detected by the missile guidance laser photoelectric detection system, the target echo voltage of the photoelectric detection receiver is calculated by the quantitative calculation method under the condition of different detection distances. By comparing the relationship between the output peak voltage of the laser echo reflected by target and the average voltage of the inherent noise outputted by detection circuit, we analyze the *SNR* of the system in different environmental illuminances and different detection distances, which indicates the detection ability of the missile guidance laser photoelectric detection system. In order to represent the *SNR* of the system, the missile is taken as the center of the coordinate system and the target is placed at different positions on the oz axis. As shown in Fig. 2, P_1 and P_2 are two different positions. Two parallel planes $A_1A_2A_3A_4$ and $B_1B_2B_3B_4$ are formed based on points P_1 and P_2 respectively, and plane $A_1A_2A_3A_4$ and plane $B_1B_2B_3B_4$ are all parallel to the plane xoy. In the regions of plane $A_1A_2A_3A_4$ and plane $B_1B_2B_3B_4$, the position of the target is adjusted. The echo energy reflected by the target in the two plane areas is observed when the detection range are P_1=2.5 *m* and P_2=4.5 *m* respectively under different environmental illuminances. The cross-sectional area of the target is 240 *mm*×300 *mm*. The capture card is used to collect the target signal in this paper, and its capture frequency is 2*MHz*. Fig. 3 shows the echo signal at different planes orthogonal to oz axis. Fig. 3(a) is the pulse waveform of laser emitter A_1; Fig. 3(b) is the pulse waveform of laser emitter A_2; Fig. 3(c) is the target echo signal waveform.

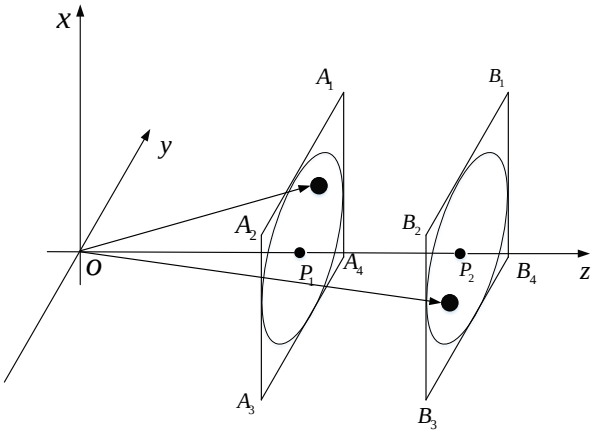
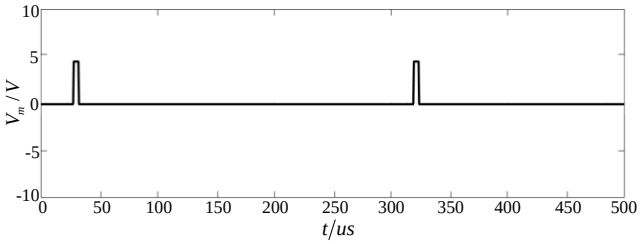
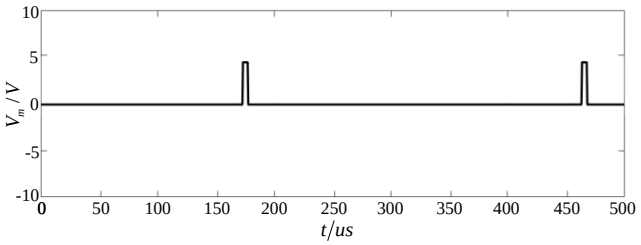


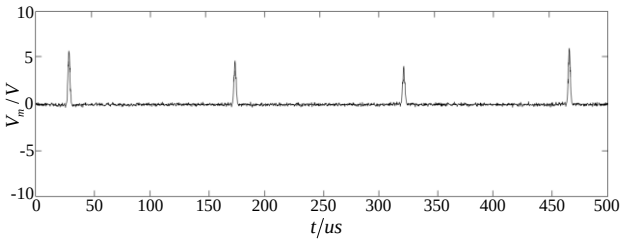
Fig. 2. Schematic diagram of target placement at different planes on the oz axis



(a) The pulse waveform of laser emitter A_1



(b) The pulse waveform of laser emitter A_2



(c) The target echo signal waveform

Fig. 3. The echo signal at the position of P_1=2.5m

When the detection distance is 2.5*m*, the experimental illuminance in plane $A_1A_2A_3A_4$ is represented as $E_b(x, y, 2.5)$, the target illuminance is represented as $E_0(x, y, 2.5)$, then the target imaging illuminance distribution obtained by the photoelectric detection receiver is determined by $E'(x, y, 2.5)$. The laser energy reflected by target received by photoelectric detection receiver be determined by Formula (11). Under the condition that the peak power of pulse laser is 38*W*, the environmental illuminance is 2.0×10^3 *cd*/m^2. Table 1 shows the average values of the echo peak signal V and the noise signal V_n captured by photoelectric detection system when the center of target at eight different positions in plane $A_1A_2A_3A_4$. The unit of coordinate is meter and the unit of voltage signal is volt.

Table 1. The echo voltage test data under the environmental illuminance of $2.0\times10^3 cd/m^2$

No.	x/m	y/m	V/mV	V_n/mV
1	-0.525	0.232	2108	460
2	-0.411	0.097	4685	497
3	-0.267	0.037	4655	478
4	-0.117	-0.004	4651	469
5	0.068	0.007	4854	488
6	0.206	0.091	4634	472
7	0.416	0.037	4628	491
8	0.513	-0.079	2148	466

When the experimental illuminance is changed to $4.2\times10^3 cd/m^2$, Table 2 shows the average values of the echo peak signal V and noise signal V_n captured by the system at eight different positions.

Table 2. The echo voltage test data under the environmental illuminance of $4.2\times10^3 cd/m^2$

No.	x/m	y/m	V/mV	V_n/mV
1	-0.531	-0.106	2280	559
2	-0.426	0.151	4892	593
3	-0.285	-0.049	4496	526
4	-0.072	0.106	4758	545
5	0.095	0.019	4665	533
6	0.266	-0.055	4962	579
7	0.044	0.007	4372	530
8	0.524	-0.085	2412	588

According to the test data in Tables 1 and 2, the average *SNR* of the system is calculated to be 8.43 and 7.41, respectively. It indicates that the change of environmental illuminance affects the SNR of the system. When the environmental illuminance is $2.0\times10^3 cd/m^2$, the average value of the background noise is less than $478mV$. However, when the environmental illuminance increases to $4.2\times10^3 cd/m^2$, the average value of background noise is close to $557mV$. Under the condition of constant laser emission power, the increase of environmental illuminance has a certain impact on the performance of the system. Meanwhile, it can be seen that when the target position deviates from the center of the detection area, the peak voltage output by the photoelectric detection receiver has a slight decrease. The main reason is that there is an angle of θ between the target position and the center of the missile, and $\theta=\arctan\sqrt{x^2+y^2}/oP_1$. Hence, the echo energy at coordinate of $P(x,y,2.5)$ is $1/\cos^4\theta$ times that of at the central position. In the effective emitted laser field and photoelectric receiving field, the target can reflect a certain echo energy. The distribution of the echo energy at the position of P_1=2.5m is shown in Fig. 4.

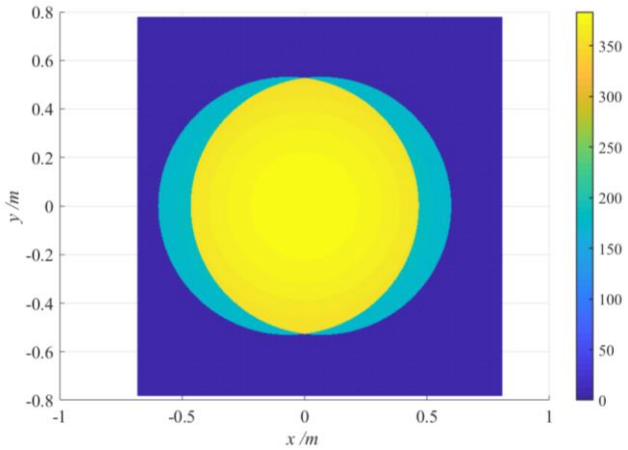


Fig. 4. The distribution of echo energy at the position of P_1=2.5m (color online)

When the detection distance is 4.5m, the environmental illuminance in plane $B_1B_2B_3B_4$ is represented as $E_b(x,y,4.5)$, and the target illuminance is represented as $E_0(x,y,4.5)$, then the target imaging illuminance distribution obtained by the photoelectric detection receiver is determined by $E'(x,y,4.5)$. When the environmental illuminance is $2.5\times10^3 cd/m^2$ and $4.8\times10^3 cd/m^2$, respectively. Eight different position points are sampled. The average values of the echo peak signal V and the noise signal V_n is shown in Tables 3 and 4.

Table 3. The echo voltage test data under the environmental illuminance of $2.5\times10^3 cd/m^2$

No.	x/m	y/m	V/mV	V_n/mV
1	-1.009	0.297	790	472
2	-0.925	0.165	896	522
3	-0.589	0.078	1833	514
4	-0.214	0.192	1813	496
5	0.205	-0.005	1970	539
6	0.781	-0.221	1618	471
7	0.802	0.066	1728	503
8	1.039	-0.035	887	530

Table 4. The echo voltage test data under the environmental illuminance of $4.8\times10^3 cd/m^2$

No.	x/m	y/m	V/mV	V_n/mV
1	-0.997	-0.32	965	647
2	-0.814	-0.095	1936	632
3	-0.55	0.402	1785	568
4	-0.247	0.087	2080	638
5	0.028	-0.011	1858	577
6	0.349	0.282	1906	599
7	0.493	-0.152	2007	655
8	0.985	-0.05	923	603

According to the test data in Tables 3 and 4, the average *SNR* of the system is calculated to be 2.85 and 2.74, respectively. It indicates that the *SNR* of the system decreases with the increase of detection distance. Therefore, when the detection performance of guided-missile decreases, the detection sensitivity also decreases. Fig. 5 shows the echo energy distribution at the position of P_2=4.5*m*.

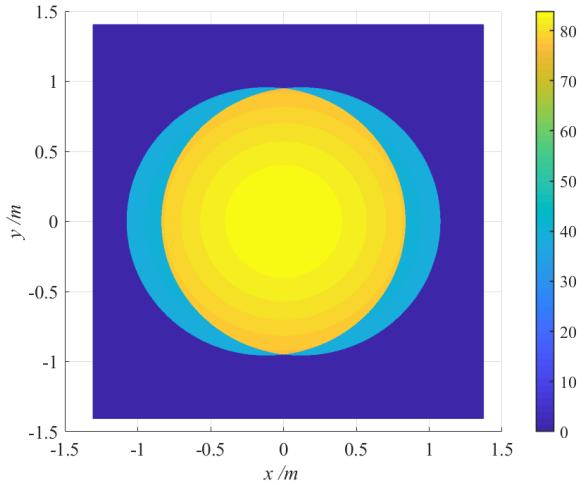


Fig. 5. The distribution of the echo energy at the position of P_2 *=4.5m (color online)*

According to Tables 1-4 and Figs. 5-6, under the same detection distance, the average signal-to-noise ratio of the system decreases with the increase of environmental illuminance; the reason is that the increase in the environmental illuminance leads to the increase of the target signal voltage output by the photoelectric detection receiving circuit. However, the noise voltage signal generated by the background noise will increase more widely, which will eventually lead to a decrease in the average signal-to-noise ratio of the system. At the same time, under the same environmental illuminance, the average signal-to-noise ratio of the system decreases with the increase of the detection distance; for a target at different detection distances, the size of the imaging spot is different. When the detection distance is larger, the area of the imaging spot also is larger, and the target illuminance is smaller, then the weaker the energy of the average unit. Hence, the reflected energy for the same target is lower, and the target signal voltage output by the photoelectric detector receiving circuit is lower. Eventually, the lower the signal-to-noise ratio of the system. Above conclusions are basically consistent with the *SNR* model of the system established in this paper, which further verifies the correctness and scientific of the established *SNR* model.

6. Conclusions

Based on the detection mechanism of the missile guidance laser photoelectric detection system, and combined with the distribution function of the target imaging spot, the environmental illuminance and the size of the photosensitive surface of photoelectric detection receiver, the illuminance distribution of the target imaging spot is studied and the output voltage signal function of the system is established; According to the definition of *SNR*, the calculation model of *SNR* for missile guidance laser photoelectric detection system is constructed. Through the parameters design of the missile guidance laser photoelectric detection system, the echo energy obtained by the system at two different detection distances is given, and the echo energy distribution of the target in different positions at the same detection distance is analyzed. Then, the relationship between the peak signal output by the system and the environmental illuminance is studied. The results show that when the center of the missile is orthogonal to the center of the target, laser echo energy reflected by target is the strongest; and the target echo energy is reduced with the increase of the detection distance. The fuze with single detection system has inherent weaknesses, and the laser fuze is sensitive to the interference of light, rain and snow. Therefore, in the harsh battlefield environment, by combining the laser fuze with the radio fuze, the capacitance fuze, the electrostatic fuze and the magnetic fuze, it can be realized to complete the reliable detection and identification of targets in the harsh battlefield environment through the fusion technology of detection information and the conversion technology between different fuze systems. The theoretical calculation model and method of detection performance proposed in this paper provide a basis for the improvement of the missile guidance laser photoelectric detection system under uncertain missile-target intersection.

Acknowledgments

This work has been supported by Project of the National Natural Science Foundation of China (No. 62001365).

References

[1] Kaibin Zong, Chenglong Zhang, Zhimin Zhuo, Modern Defence Technology **48**(3), 49 (2020).
[2] Wei Xiong, Menghu Che, Computer Measurement and Control **27**(11), 252 (2019).
[3] He Zhang, Hongxia Li, Libo Ding, Bingting Zha**,** Infrared and Laser Engineering **49**(4), 9 (2020).
[4] Fan He, Xiaofang Xie, Tao Sun, Ship Electronic Engineering **40**(7), 1 (2020).
[5] Ruping Zou, Shichao Chen, Yun Chen, Jianling Zhang, Acta Armamentarii **42**(1), 1 (2021).
[6] Hao Yang, Xiaobin Xu, Minzhou Luo, Qinyang Qu, Optik **199**, 163335 (2019).
[7] Bulent Ozkan, Mustafa Kemal Ozgoren, Gokmen Mahmutyazicioglu, Turkish Journal of Electrical Engineering and Computer Sciences **25**(5), 3591 (2017).

[8] Yuan Li, Yanhua Li, Luo Li, Haichao Guo, Yanmei Zhang, Acta Armamentarii **36**(11), 2073 (2015).
[9] Bo Peng, Kun Zhong, Hui Zhao, Zhongyun Li, Infrared and Laser Engineering **48**(12), 135 (2019).
[10] Shanshan Chen, He Zhang, Xiaobin Xu, Infrared and Laser Engineering **47**(2), 113 (2018).
[11] Tiebao Zhang, Guie Li, Laser Journal **41**(2), 181 (2020).
[12] Yingluo Zhang, Yingmin Wang, Aiping Huang, Xin Hu, Optoelectronics Letters **16**(2), 137 (2020).
[13] Wei Zhang, Yuzhao Li, Zhesi Wang, Yan Liu, Infrared and Laser Engineering **49**(4), 58 (2020).
[14] Xiang Zheng, Baiqin Zhao, Acta Optica Sinica **37**(5), 289 (2017).
[15] Hanshan Li, Xiaoyue Sang, Xiaoqian Zhang, Keding Yan, IEEE Access **7**, 135732 (2019).
[16] Yanming Shao, Shuang Wang, Xin Wang, Zongmei Chen, Yue Yu, Laser and Infrared **50**(3), 285 (2020).
[17] Yaqing Li, Liguo Wang, Lei Gong, Qian Wang, Optik **225**, 165861(2021).
[18] Eun-San Kim, Journal of the Korean Physical Society **70**(1), 53 (2017).
[19] Hanshan Li, Xiaoqian Zhang, Wang Miao, IEEE Sensors Journal **19**(22), 10443 (2019).
[20] Xiaobin Xu, He Zhang, Minzhou Luo, Zhiying Tan, Infrared Physics and Technology **96**, 330 (2019).
[21] Shanshan Chen, He Zhang, Xiaobin Xu, Optik **179**, 305 (2019).
[22] Hanshan Li, Xiaoqian Zhang, Xuewei Zhang, IEEE Transactions on Instrumentation and Measurement **70**, 1001308 (2021).
[23] Shuai Li, Huayan Sun, Yanzhong Zhao, Journal of Ordnance Equipment Engineering **39**(3), 178 (2018).
[24] Yanran Li, Mingyong Liu, Optoelectron. Adv. Mat. **10**(5), 336 (2016).

*Corresponding author: baoyiguo1980@sina.com