Research on detection capability calculation model of photoelectric sensor in near sea surface optical detection system

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To improve the photoelectric detection capability of optical detection system in near sea surface, this paper set up a photoelectric detection capability model based on solar irradiance and target characteristic, analyzed its optical detection principle and influence factors, researched the target reflection characteristics, the noise characteristics and detection method to calculate the distance in photoelectric sensor detection system. According to the characteristics of solar radiation, the reflection characteristics of the target and the noise characteristics of photoelectric detection system, this paper derived the expression of the maximum detection distance, studied the relationship among the background illumination, aperture of optical system, the effective reflection area and maximum detection distance, concluded and analyzed the changing curves among the aperture of optical system, the light incidence angle and the maximum detection distance, and the changing curves among *SNR* threshold, the light incidence angle and the maximum detection distance. Through experiments, the results show the established calculation model of the maximum detection distance and analysis method were correct and scientific.

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1. Introduction

With the widely usage of the shipboard photoelectric sensing equipments in surface forces and the diversification of naval combat mission, the detection of space target in near sea surface is becoming more and more important[1]. In the shipboard photoelectric sensor system, the photoelectric detection system is an important part of space-based guard system for space targets, such as the precise detection for target, precise positioning and tracking, and the information capture of target. Because of the environmental characteristics in near sea surface, the detection capability of photoelectric sensor detection system is not satisfactory [2]. The detection performance is affected by many factors, such as the scattering from background light of sea surface, the parameters of photoelectric detection sensor in optical system and the responsiveness of the photoelectric sensor, etc. [3-5], especially the influence from the sea clutter in sea surface, which causes serious degradation on performance of the photoelectric sensor for remote target in near sea surface [6]. Currently, the relevant research is mainly focusing on the analysis of optical turbulence and aerosols, and the influence of the natural phenomena happened on the sea surface, such as refraction and diffraction, and the analysis on performance of photoelectric equipment. This article builds a mathematical model of the maximum of detection distance based on the reflection characteristics of visible light for space targets and the noise characteristics of system, researches the quantitative relationship between the maximum of detection distance and the influence factors by numerical simulation method, and obtains the changing curve between the maximum of detection distance and influence factors. Through experiment, the established mathematical model is verified, and a method to improve the detection distance is proposed.

2. The detection principle for space target in near sea surface of photoelectric detection system

The detection principle of photoelectric detection system in near sea surface is shown in Figure 1. The target receives the solar radiation, and then reflects part of the

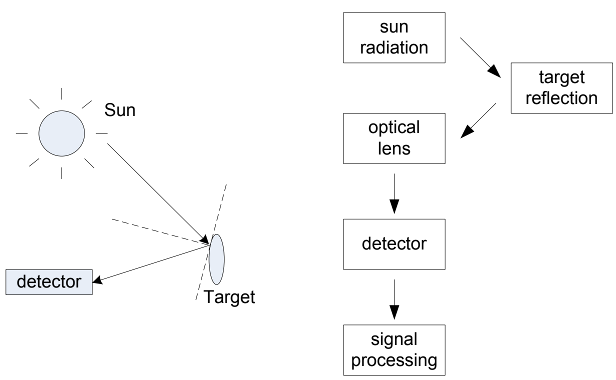

Fig. 1. The detection schematic diagram of photoelectric detection system on space target

receiving solar radiation energy, which enters the photoelectric sensor through an optical lens; the photoelectric sensor converts the receiving light energy into an electrical signal. The detection for space target is achieved through the analysis of the electrical signal.

The radiant energy from the sun is spread in space which makes all or part area of space target to be illuminated. The reflection echo carrying the brightness information of target enters the detection system after transmission in space for a distance. When the photoelectric sensor receives the reflection echo, the light energy is converted into electrical energy, which forms the electrical signals. Then the detection mission for space target is completed via analysis of the receiving electrical signals.

When other parameters of detection system have been certain, in order to improve detection performance of photoelectric detection system in sea surface, it is need to increase the reflection area from space target, at the same time, to reduce the influence of background light. Choose optical device with high filter coefficient and photoelectric receiving device with high responsivity to design receiving detection system. When filter coefficient is high, the received effective reflection energy was stronger. At the same time, the usage of detector with high responsivity can effectively receive reflection energy of moving target with high speed. In addition, when the detection circuit is designed, it is possible to reduce the inherent noise signal, so that the *SNR* of detection system can be effectively improved which can effectively improve detection performance.

3. The solar irradiance characteristics and target reflection characteristics

3.1 The radiation characteristics of sun for detection target

The space target dose not shine by itself, and the light energy received by the photoelectric sensor mainly comes from the reflective sunlight, which means radiation of target comes from the solar radiation. It is shown in Figure 2. $\vec{n}$ is the normal direction of the target surface, and the angle between the incident sunlight and the normal direction is α and $\alpha \in (-\pi/2,\ \pi/2)$, and β stands for the angle between the line C, which is the connection line from the photoelectric sensor to the center of the target, and the normal direction $\vec{n}$ and $\beta \in (-\pi/2,\ \pi/2)$. Assumed the solar spectral irradiance is $E(\lambda)$, and the irradiated area is A_1, then the solar radiation received by the target is :

$$dF = \int \cos\alpha A_1 E(\lambda) d\lambda \qquad (1)$$

In (1), α is the angle between the incident sunlight and the normal direction, which shown in Fig 2.

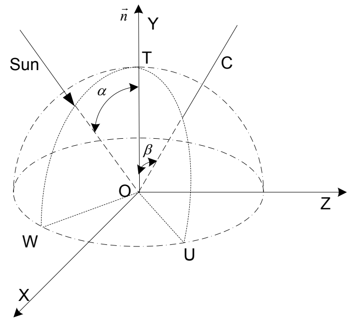

Fig. 2 Schematic diagram of the sunlight on the target

3.2 Reflection characteristics of the target

Due to the difference of wrapping material, the permittivity and the roughness on surface of the targets, different targets exhibit different reflection characteristics. Assumed average reflectivity from the target surface is ρ, and then the reflective luminous flux of the target is [8]:

$$d\Phi = \int \rho \cos\alpha A_1 E(\lambda) d\lambda \qquad (2)$$

When the effective reflection area of space target is A_2, and β stands for the angle between the line *C* and the normal direction $\vec{n}$, the irradiance, when the distance between target and photoelectric sensor is *R*, is:

$$E = \frac{\rho E_0 A_1 A_2 \cos\alpha \cos\beta}{\pi R^2} \qquad (3)$$

In (3), E_0 is the background illumination.

Then at the pupil on optical lens of the photoelectric sensor, the light energy of the signal reflected from space target is [9]:

$$E_{NL} = \frac{\zeta \rho \kappa E_0 A_1 A_2 A_3 \cos\alpha \cos\beta}{\pi R^2} \qquad (4)$$

In (4), ζ stands for the attenuation factor of the light energy when the light is interfered via the refraction, scattering and sea clutter in near sea surface in communication process. κ is the transmittance of the optical system, A_3 is the pupil area of the optical system, $A_3 = \pi (d/2)^2$, *d* is the effective aperture of the optical system. Based on (4), in order to enhance the light energy of the signal reflected from space target, the effective reflection area of space target should be increased which is also that the caliber of target should be increased, and then the energy obtained by the photoelectric sensor increases. And the increase on the size of aperture in optical system also can enhance the receiving light energy of the signal reflected from space target. Then, the detection capability can be improved.

The responsive photon number from surface element ΔA_{ij} of the photoelectric sensor is:

$$N_F = \frac{\ell \gamma \Delta t E_{NL}}{(hc/\vec{\lambda})\tau} \qquad (5)$$

In (5), ℓ is the responsivity of the photoelectric sensor, γ is the average quantum efficiency, and Δt is the minimum of detection time when the photoelectric sensor has output signal, $\vec{\lambda}$ is the average wavelength, τ is the ratio of the area of imaging flare to the area of photosensitive surface of photoelectric sensor. Under the condition of the certain illuminance and detection distance, when the caliber of target increases, the reflective energy of target will enhance. According to the formula (5), the radiant energy received by photoelectric sensor enlarges, then the amplitude of output from photoelectric sensor will increase, the value of *SNR* will advance, which will cause the enhancement of the detection capability.

4. The noise characteristics of the detection system and the calculation of the maximum of detection distance

4.1 The noise characteristics of the detection system

When the photoelectric sensor detects the target in near sea surface, the noise mainly comes from the noise of photoelectric sensor, the background noise during detecting, the photon noise, and the inherent noise of the driving circuit etc. [10-11]. According to the definition of noise, the total noise of the detection system can be expressed as:

$$N_Z = \sqrt{N_F + N_A + N_H} \tag{6}$$

In (6), N_F is the photon number produced by the target radiation, N_A is the photon number generated by the dark current, N_H is the photon number generated by the background noise in near sea surface, N_F is the shot noise which also is known as the photon noise radiated by the target, which generated by the random fluctuations of the incident photon flow, and it is belongs to a white noise. N_A, which is a kind of noise from dark current, is mainly generated by a random vibration due to the thermal motion of charge carriers. N_A is also a white noise and follows the Poisson distribution [12]. The background noise during detecting is caused by the random fluctuations of the photon arrival rate, and the N_H, background noise, is mainly caused by the photon number generated by the stray light of the background.

4.2 The calculation of the maximum detection distance

Signal-noise ratio (*SNR*) is a measure index of the system's detection capability, and generally using electronic number as a unit to define the *SNR* [13]. According to the calculation of the system noise, the *SNR* of system can be drawn as follows:

$$SNR = \frac{N_e}{N_{noise}} = \frac{N_F}{\sqrt{N_F + N_A + N_H}} \tag{7}$$

In (7), N_e is the receiving photon number within a certain period of time, N_{noise} is the photon number generated by total noise of system during the same time. According to (7), when other parameters of detection system have been certain, in order to improve the *SNR* of detection system, it is need to increase effective reflection area, namely, to increase the corresponding A_2. The size of aperture in optical system can be increased to improve the *SNR*. And choose optical device with high filter coefficient and photoelectric receiving device with high responsivity to design receiving detection system. When filter coefficient is high, which can reduce the impact from noise and the received effective echo energy was stronger. At the same time, the use of high responsivity detector can effectively receive echo energy of moving target with high speed. In addition, when the detection circuit is designed, it is possible to reduce the inherent noise signal, so that the *SNR* of detection system can be effectively improved.

In order that the target can be detected, which means that target signal can be extracted from noise signals, the *SNR* of system, when target is detected in near sea surface, must be greater than or equal to the *SNR* threshold T_Y. The *SNR* threshold is determined by detection probability and false alarm probability [14], so, the minimum of photon number generated by the target radiation should meet:

$$N_{F\min} = \frac{T_Y^2 + \sqrt{4T_Y^2(N_A + N_H) - T_Y^4}}{2} \tag{8}$$

According to the (5) and (8), the light energy $E_{NL_{\min}}$ at the entrance pupil can be obtained:

$$E_{NL\min} = \frac{\tau(hc/\vec{\lambda})(T_Y^2 + \sqrt{4T_Y^2(N_A + N_H) - T_Y^4})}{2\ell\gamma\Delta t} \tag{9}$$

According to the (4) and (9), the maximum of detection distance is as follows:

$$R_{\max} = \sqrt{\frac{\zeta\rho\kappa\ell\gamma\Delta t\vec{\lambda}d^2 E_0 A_1 A_2 \cos\alpha\cos\beta}{2N_{F\min}\tau hc}} \tag{10}$$

Based on formula (10), the maximum of detection distance is related with the effective reflection area of the target, aperture, the background luminance, the minimum of detection time when the detector has output signal and the incident angle of light, etc. [15]. When the effective reflection area of the target becomes larger, the target energy received by detector increases, the maximum of detection distance is enlarged when other parameters never changed. When the aperture of the optical system is increased, the contrast of detection system is augmented and the maximum of detection distance is improved. When the value of the background luminance is bigger, the contrast of signal is smaller, which is not conducive to improve the detection distance. In order to improve the detection distance of detection system, detection system should work under the appropriate background luminance conditions. If the background luminance is strong, the effective echo energy of target will weaken, detection distance will reduce. When the background luminance is weak, the difference between the reflective echo energy from target and the energy from background light will become large, which is conducive to improve the detection distance. In conclusion, based on these parameters such as background illumination of detection system, the effective reflection area of the target, effective aperture etc., and the maximum of detection distance of detection system can be figured out effectively.

5. The detection capability analysis of photoelectric sensor detection system

The analysis on detection capability of system is equal to analyze the maximum of detection distance. From the above analyses, the maximum of detection distance is influenced by the transmittance of the optical system, the effective aperture of the optical system, the incident angle of sunlight, the response rate of the photodetector, the average quantum efficiency and the value of *SNR* threshold, etc. [16-17].

Assumed the average reflectance of the target surface is 0.65, the irradiated area of the target is 0.83m^2, the effective reflection area of the target is 0.69m^2, $\alpha = \beta$, the effective aperture of the optical system is 0.1m, the transmittance of the optical system is 0.78, the average wavelength is 0.65μm, the average quantum efficiency is 0.7, the minimum of detection time is 100ms, the response rate of the photodetector is 0.83, the value of *SNR* threshold is 2.5, the value of τ is 1.0×10^{-3}, the photon number generated by dark current is 20s^{-1}, the photon number generated by the background noise in near sea surface is 220s^{-1}, According to (10), we analyze the relationship among the maximum of detection distance, the effective aperture of optical system and the value of *SNR* threshold of detector.

5.1 The influence of the aperture on the detection ability of system

The choice on the size of aperture is restrained mutually by two factors, on the one side, the bigger the aperture is, the ability for the system to collect light energy is the stronger and the sensitivity of the system is better. For this aspect analysis, when the size of aperture is big, the detection result is better. However, in fact, the saturation of detector will lead to a decrease on contrast with the increase on the size of aperture. So, it is essential to choose a reasonable size of aperture in optical system. According to (10), the relationship between the maximum of detection distance *R* and the size of aperture in optical system *d* at different incident angles, it is shown as follows Figure 3.

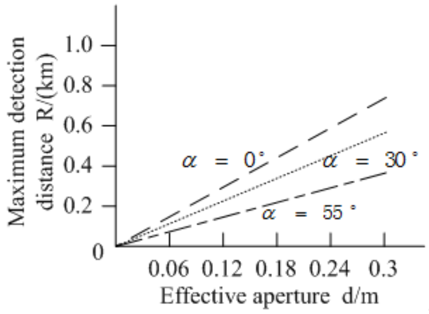

Fig.3 The relationship among maximum of detection distance, relative aperture and incident angles

It can be seen from Figure 3, when the incident angle is constant, the *R* increases linearly as the increase of *d*. When *d* is constant, the maximum of detection distance is inversely proportional to the incident angle. When *d* is very small, the maximum of detection distance does not change obviously at different incident angles. But when *d* is greater than 0.18m, the maximum of detection distance reduces obviously as the increase of the incident angles. Therefore, increasing the size of aperture in optical system can improve effectively the detection capability of the detection system, but the detection distance can be susceptible from the incident sunlight direction.

5.2 The influence of the value of *SNR* threshold on detection ability of system

For the photoelectric sensor detection system in near sea surface, the higher the value of *SNR* is, the stronger the detection capability of the system is. The *SNR* threshold is an important index for signal detection. In order to quantitatively research the maximum of detection distance varies with the *SNR* threshold, the simulation study is conducted via changing different value of *SNR* threshold. It is shown in Figure 4, when the *SNR* threshold is constant, the maximum of detection distance *R* is inversely proportional to the incident angle α. When the incident angle α is constant, the maximum of detection distance decreases with the increase of the value of *SNR* threshold T_y. When the value of *SNR* threshold is less than 2.5, the maximum of detection distance gets a sharp decrease with the increase of the value of SNR threshold. When the value of *SNR* threshold is greater than 2.5, the maximum of detection distance changes slightly with the increase of the value of *SNR* threshold, while the change of the incident angles impacts the maximum of detection distance little. With the change of incident angles, at the same detection distance, the luminous flux will reduce, and the output will reduce which can result in the decrease of *SNR*. When the target enters the detection field out of the vertical, in order to detect the space target, the value of *SNR* threshold can correspondingly reduce which can make the detection sensitivity to amplify and then the detection distance can be increased.

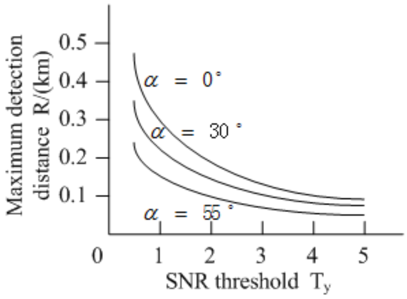

Fig.4 The relationship among maximum of detection distance, SNR threshold and incident angles

From Figure 4, when the value of *SNR* threshold is 0.5, the maximum of detection distance can all exceed 0.2km with different incident angles. However, when the range of the value of *SNR* threshold is between 0.5 and 2, the maximum of detection distance only can reach 0.1km. Thus, within a certain distance, proper reducing the value of *SNR* threshold can obviously improve the detection capability of the system.

6. Experiments and analysis

To check the detection capability of the photoelectric sensor optical system in near sea surface, a photoelectric sensor detection system platform was established according to the solar radiation characteristic of the target, the reflection properties and the noise characteristics. Considering to the computing formula of the maximum detection range, a high-speed acquisition card in a different sea background illumination was used to collect output analog signals from the photoelectric sensor under different distances and to take comparative analysis between analog signal amplitude of the output signal and the amplitude of the noise inherent. Usually the pulse signal of the dynamic target was obtained commonly by using comparing-conversion-processing methods in the detection circuit of the analog output signal, which can be used to measure whether there was a target in photoelectric detection sensor system. It was often to use more than a certain value of threshold voltage as the critical state of the signal converting in comparing-conversion-processing circuit, and this value of threshold voltage should be greater than the maximum amplitude of the currently background inherent noise in the circuit. According to this recognition principle, an experiment was taken in the sea surface for a simulated target.

The size of the simulated target was 2.7m × 0.8m, the optical lens was 85-125mm, the relative aperture was 1:2.8, and when the detection distance were 500m and 1000m, the dynamic experiment was accomplished. When the range of background illumination was between 1.0 × 10^3cd/m^2 and 8.0 × 10^3cd/m^2, the target signal was collected. The relation between the normal of the reflective surface and the optical axis of the optical detection system was parallel. Table 1 showed the output signal and the inherent noise signal of the photoelectric sensor under different illumination conditions in the distance 500m and 1000m.

Table 1 Output signal and inherent noise signal when relative aperture is 1:2.8 under different illumination conditions

Num	illumination conditions (E/cd·m^{-2})	500m detect distance(R/m)		1000m detect distance (R/m)	
		Output signal with target (V/mV)	Inherent noise (V/mV)	output signal with target (V/mV)	Inherent noise (V/mV)
1	1.0×10^3	5103	902	4594	919
2	2.0×10^3	5508	913	4688	956
3	3.0×10^3	5589	901	4676	915
4	3.5×10^3	5603	1023	4808	997
5	4.2×10^3	5621	1012	4801	1180
6	4.8×10^3	5619	1100	4753	1079
7	5.2×10^3	5593	1637	4920	1638
8	6.5×10^3	5624	2032	5024	2026
9	7.0×10^3	5645	2346	5055	2340
10	7.5×10^3	5638	2894	5008	2883
11	8.0×10^3	5595	2987	5284	2996

In Table 1, under the same condition of detection distance, the amplitude of the output target signal was increased gradually with the increase of the background illumination as well as an obvious change in the inherent noise. When the background noise was less than3.0×10^3 cd/m^2, the target output signal amplitude changed obviously, while the inherent noise almost unchanged. With the definition of *SNR*, at 3.0×10^3 cd/m^2 background illumination conditions, most part of the value of *SNR* were greater than 5.4. However, when background illumination conditions was greater than 3.0×10^3 cd/m^2 or less than 4.8×10^3 cd/m^2, the value of *SNR* was close to 5.4. The phenomenon indicated that the contrast was distinct with the $1\times10^3 \sim 4.8\times10^3$ cd/m^2 background illumination, the detection ability of photoelectric sensor detection system was relatively stable, and the detection capabilities was improved. In addition, when the distance increases, under the same background illumination conditions, the inherent noise signal of photoelectric sensor detection system was almost constant, but the output signal of the target slightly decreased, and when the distance was increased. For the same target, the increase of the distance meant the decrease of effective area from imaging to the photoelectric sensor photosensitive surface. At the same photoelectric sensor detection system, the decrease of effective area resulted in the attenuated intensity of the target output signal, which substantially coincided with the above theoretical analysis of the definition of *SNR* and formula (10). When background illumination was greater than 4.8×10^3 cd/m^2, the amplitude of output signal did not change obviously, but the inherent noise signal had an obvious increase. Under the strong background illumination conditions, the influence on stray light of photoelectric detection system made the photoelectric sensor to detect more spurious signals. According to the principle of superposition, stray light of photoelectric detection system was superimpose, the output of inherent noise signal increases, and it was easy to drown useful target signal in the background signal, which resulted that it was hard to recognize the real target signal for photoelectric sensor detection system. Therefore, detection performance of the detection system was relatively poor under strong background illumination. In order to eliminate the influence of the strong background illumination, there was a need to use the filter technology to eliminate the influence, which improved the detection capability of photoelectric sensor detection system.

In order to improve the detection performance of detection system in near see surface under different illumination conditions, the optical lens could be replaced with a greater size of optical aperture, the relative aperture is 1:1.8. When the experimental conditions was same as the experimental conditions of Table 1, the obtained output signal and inherent noise signal from detector could be seen in Table 2.

Table 2 The output signal and inherent noise signal when relative aperture is 1:1.8 under different illumination conditions

Num	background illumination (E/cd·m^{-2})	500m detection distance(R/m)		1000m detection distance(R/m)	
		Output signal with target (V/mV)	Inherent noise (V/mV)	output signal with target (V/mV)	Inherent noise (V/mV)
1	1.0×10^3	5263	920	4698	914
2	2.0×10^3	5642	919	4823	922
3	3.0×10^3	5699	929	4999	919
4	3.5×10^3	5703	1004	4936	998
5	4.2×10^3	5685	1129	4848	1098
6	4.8×10^3	5712	1079	5033	1165

It could be seen in Table 2, the inherent noise would increase as the increase on the size of aperture, but the increase on amplitude of the output signal was more obvious, which meant that the size of aperture increased, the detection distance also increased. Therefore, the theoretical calculated result of the relationship between the size of aperture and the maximum of detection distance accorded with the simulation results.

From Table 1 and Table 2, at low background illumination conditions, the detection performance of detection system was stable, while the background illumination was more than 4.8×10^3 cd·m^{-2}, the output of inherent noise signal was increased. In order to eliminate the effect of strong background luminance, the spectral filter was added in the receiving optics lens. This detection system had selected a filter whose filter factor is 0.62. Due to the difference of background spectral characteristics, when the parameters of the photoelectric detection system had been certain, the appropriate spectral filtering method was chosen according to the characteristics of the different background luminance spectrum. Table 3 showed the test data under strong background illumination condition after added spectral filter when the detection distance was 500m.

Table 3 The output signal and inherent noise signal after the detection system add filter

Num	background illumination (E/cd·m^{-2})	output signal with target (V/mV)	Inherent noise (V/mV)
1	6.5×10^3	4239	779
2	7.2×10^3	4220	798
3	7.8×10^3	4318	809
4	8.0×10^3	4296	783
5	8.2×10^3	4299	795

It could be seen from Table 3, the filter technology reduced the influence on the stray light of the detection system, the amplitude of inherent noise obviously reduced, and the value of *SNR* was close to 5.3, which indicated that filter measure could effectively eliminate the influence on stray light of photoelectric detection system, and the detection capability of the photoelectric sensor detection system had been obviously improved.

7. Conclusions

This paper researched the detection capability of system via using the maximum of detection distance as an indicator, established a mathematical model on maximum of detection distance of system based on the reflection characteristics for visible light of the target and the noise characteristics of system, analyzed the quantitative relationship among maximum of detection distance and the size of aperture in optical system, the direction of incidence of sunlight, and value of *SNR* threshold through the numerical simulation, obtained the variation relationship among the maximum of detection distance and each influencing factor. Many experimental data were collected from tests of different observation conditions. During the experiment, five groups of test data were obtained and analyzed via changing the background illumination, the size of aperture in optical system and the observation distance. Under strong background illumination conditions, the detection performance of the detection system was poor. In order to improve the detection performance of the detection system, a filter was added to the test, it can be seen from the test data that the filter eliminates the impact form the strong background illumination. Through the analysis on different parameters, an approach which can improve the detection capability of the photoelectric sensor detection system was proposed, which provided a theoretical basis for the design of a photoelectric detection system in near sea surface and a prediction on performance of a system.

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