A GPU-based simulation system for infrared images of deep space targets

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Abstract

In study of deep space targets recognition, infrared images of deep space targets are needed for repeat testing and evaluating. Since the limitation of deep space flight experiments, it is difficult to obtain sufficient infrared images under different conditions. Infrared image simulation technology is brought up to solve this problem efficiently. The principle of deep space targets infrared imaging was studied. Based on the infrared sensor's optical properties, a hierarchical imaging model was built. The infrared camera and all the effects were simulated respectively, including motion trail of target and space objects, blurring, dispersion, blind elements, and noise. A mixed noise model was introduced by combining the random noise and Perling noise model. In the image simulating process, Graphic Processing Unit was used to produce noise image in real time. According to the reference photo of infrared sensors, infrared simulated images were evaluated using histogram distribution, the trend of intensity, and Signal to Noise Ratio, and the results show these images satisfied targets recognition algorithm.

Keywords: deep space targets, infrared optical properties, infrared imaging, graphic processing unit, Perling noise

1 Introduction

According to the infrared radiation characteristics of the target and the background, infrared image simulation technology produces infrared thermal image, this is very significant for the target tracking and recognition algorithm. The first principle model, proposed in 1988, considers infrared features of objects in different conditions, by solving equations to get radiation intensity distribution on the surface of the object [1]. But as solving the first principle model is very complicated and unpractical, a semi-empirical first principle model is proposed.

With the development of the infrared image simulation technology, the reality of infrared image becomes more and more strong. In 1996, in order to overcome the problem in lack of reality sense and measured infrared data, people rendered the scene and identified the target by the synthesis of real images and artificial images. In 2005, Gaussian proposed an infrared imaging simulator IRISIM, which can simulate the complete imaging process of the broadband and multispectral infrared imaging system, and evaluate the reliability of the simulation image [2].

Currently, the domestic research adopts the mature semi-empirical first principle model. In studying the effect of the infrared detector on imaging, domestic researchers have obtained certain achievements, including optical dispersion, detector noise, etc, and set up some models and methods [3]. Based on these models and methods, fully considering the influence of various infrared detectors imaging effect, this paper proposes the hierarchical model of imaging, and mixed noise model is established. The whole process implemented with the GPU, provides an effective way for the study of deep space target detection recognition algorithm.

2 Layered model for infrared detector imaging

Different from the traditional scanning detectors, the infrared staring detectors' imaging lack some factors such as blur, which is essential in the real world. To generate the final infrared image, the dispersion effect, blur, noise and blind pixel need to be added to the image.

Therefore, imaging can be layered in modelling, to simplify the modelling process. A complete infrared image can be divided into six layers. As shown in Figure 1.

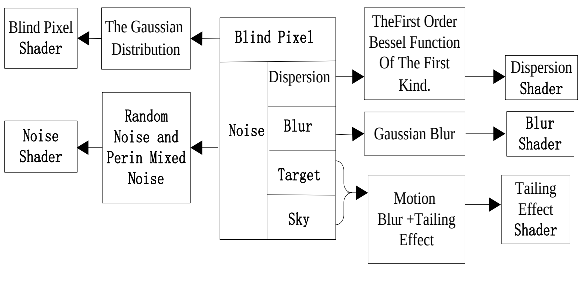

FIGURE 1 Layered model of infrared detector

The top is blind pixel, which will cover all the lower objects. The blind pixel conforms to the Gaussian distribution. The closer to the neutral, the lower the risk of producing blind pixel is. The blind pixel is achieved by blind pixel Shader. The blind pixel is divided into two branches, the relationship between which is not covered

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with each other, but for a certain pixel, the larger brightness value of two branches is obtained as the final brightness value. The left branch is noise. The noise of infrared image is simulated in the way of mixing random noise and Perling noise, and produced by the noise Shader. The right branch is top-down with four levels: blur, dispersion, target and stars. The dispersion phenomenon conforms to the trend of the first-order the first kind of Bessel function, which is implemented by blur Shader; blur phenomenon is simulated with Gaussian blur function, and implemented by blur Shader; Target and stars produce tailing effect, which is simulated by the motion blur algorithm and OpenGL camera Settings for the calculation of the interaction, and implemented by the tailing effect Shader.

3 Simulation of infrared characteristics for deep space target

Due to the difficulty of the deep space target intercept test in the reality, which spends high cost and a lot of manpower, the way of simulation experiment is adopted.

3.1 THE TARGET TEMPERATURE FIELD CALCULATION WITH FINITE VOLUME METHOD

Deep space target temperature directly determines the target radiation condition. Target surface temperature is affected by many factors. To study the influencing factors, a deep space target surface thermal equilibrium relation is established and the equation is solved. Therefore, the target surface element temperature and the target surface temperature field distribution is obtained.

The system mainly uses the finite volume method [4] for target temperature field calculation. The basic idea of finite volume method is a series of grid in the calculation area, which does not overlap with each other, is divided, and each grid point is surrounded by a control volume. Each control volume of the differential equation is integrated, and then a set of discrete equations are obtained. The biggest advantage of the finite volume method is that even in the condition of coarse grid; the accurate integral conservation is also shown.

The main source of external thermal radiation that the target in the deep space environment received is as follows:

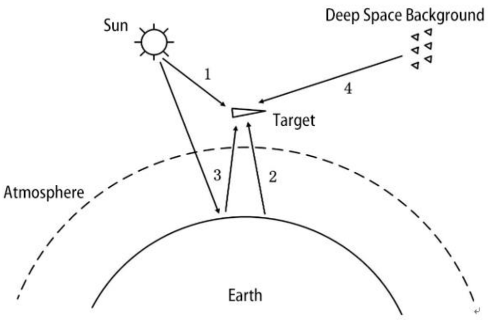


FIGURE 2 Thermal environment of the deep-space targets among them

Among them:

1 is the direct radiation from sun to target Q_{sun}, 2 is the radiation from earth to target Q_{earth}, 3is the reflection of the sun from the earth radiation Q_{ErefS}, 4 is the deep space background radiation Q_{space}.

When a target surface unit receives the radiation and is regarded as the research object, it also exchanges the heat source $Q_{exchange}$ with the nearby unit and internal heat source Q_{inside} of heat. Target surface unit, at the same time, under the influence of various thermal itself, also radiate heat energy, remember to Q_{self}. All of them are factors that make effects on the change of the target surface internal energy Q_{tempr}. The thermal balance equation is established by selecting a binning on targets.

Because deep space background in addition to the sun and the earth's makes little effect on the target radiation Q_{space}, it will be ignored and a balance Equation is obtained:

$$Q_{self} + Q_{tempr} = Q_{sun} + Q_{earth} + Q_{ErefS} + Q_{exchange} + Q_{inside}. \quad (1)$$

Then, balance Equation is established for each binning. As there is T4 factors in the thermal factors of binning, the difference method [5] is used in the linearization of equations, and solution is obtained according to the linear equations. There are many methods of solving linear equations. The methods often used are: Jacobi iteration method, the fourth-order Runge-Kutta method and Gauss-Seidel iterative method. Gauss-Seidel iterative method is used in the system, to calculate the temperature field distribution on the surface of the target on every moment.

3.2 TARGET RADIATION CALCULATION

From the perspective of deep space detector on target, the radiation it receives is related with energy and radiation on the surface of the target, the target reflection, and the target distance, detecting angle and so on. Thus these factors will be analysed.

3.2.1 The radiation factor of itself

The radiation of target unit is related with the temperature of the unit. When the temperature of the target is high, the radiation increases. When the temperature reduces, the radiation will be reduced accordingly. Since infrared radiation of the target is distributed at different wavelengths, it only needs to study the radiation of observed wavelengths. With an optical variable to describe the target, using Planck's law to describe the spectral distribution of blackbody radiation E_λ:

$$E_\lambda = \frac{c_i \lambda^{-5}}{\exp(\frac{c_2}{\lambda T}) - 1}, \quad (2)$$

among them: T is temperature; λ is wavelength; c_1 is the first radiation constant, value is 3.742×10-6 W m2; c_2 is the second radiation constant, value is 1.4388×10-2 m K.

With the integration of the infrared sensors from floor to ceiling, effective radiation flux for sensor of the target unit itself outward radiation can be obtained:

$$E_{Self} = \int_{\lambda_1}^{\lambda_2} \varepsilon_\lambda E_\lambda d_\lambda \,, \tag{3}$$

where λ_1 is infrared wavelength floor; λ_2 is infrared wavelengths ceiling; ε_λ is the surface spectral emissivity of target unit.

3.2.2 Reflection radiation factors

The calculation of target unit reflection from the external radiation is complicated. The direct radiation of the sun on the target Q_{sun}, the radiation of the earth on the target Q_{earth}, the sun radiation from the reflection of the earth Q_{ErefS}, and the radiate on from the other units Q_{others} .At the same time the effective receiving band range of the detector is also taken into account. The target unit calculating formula for the reflection of radiation is:

$$E_{reflect} = \rho_s K_s \left(Q_{sun} + Q_{ErefS}\right) + \rho_l K_e (Q_{ErefS} + Q_{others}) \,, \tag{4}$$

among them: ρ_s is the reflectivity of the target unit to the infrared solar radiation; ρ_l is the reflectivity of the target unit to the infrared earth radiation; K_s is the proportion of the total radiant energy from solar radiation in the infrared radiation of the detector; K_e is the proportion of the total radiant energy from earth radiation in the infrared radiation of the detector.

3.2.3 Detector factor

Detector receives the radiation flux associated with the target and the radiation flux, also with the environment, and the target distance and Angle. That is:

$$H = \sum_{i=1}^{N} \mu_i A_i E_{Mi} \,, \tag{5}$$

among them: N is the total number of factors, μ_i is the pupil coefficient of unit normal and the angel of the detector; E_{Mi} is the radiation flux of target unit, the value is:

$$E_{Mi} = E_{self} + E_{reflect} \tag{6}$$

Using optical device to focus infrared energy of objects in the scene's on the infrared detector, and then transforming infrared data from each detector element into standard video formats, they can be displayed on the standard video detector, or recorded on videotape. As a result that the infrared detector is heat rather than light, they can be used all-day long.

4 Infrared image simulation based on GPU

4.1 INFRARED DETECTOR IMAGING

Temperature change rate of the object is reflected in the image grayscale change rate. When the temperature of the object changes, the imaging grayscale of warhead target and decoy change over time, then we can obtain the grayscale time series and grayscale change rate.

4.2 INFRARED IMAGING EFFECTS

4.2.1 Tailing

In the real world, the infrared detector exposure is not instantaneous, this will result in that images it captured have tailing phenomenon. In addition, as interceptors constantly do orbit adjustment and attitude adjustment, Astronomical do back and forth motion relative to the infrared detector, this also produces tailing phenomenon.

To simulate tailing phenomenon, there are two approaches as follows:

1) Directly tailing phenomenon is seen as Motion blur to deal with. This method is simple, in each frame captured image, apply motion blur algorithm to target point to achieve the trailing effect. As shown below:

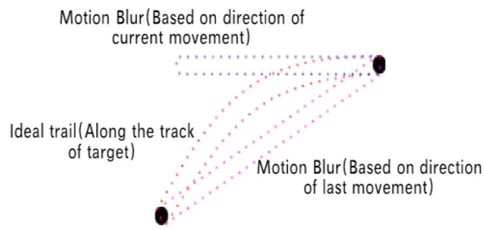


FIGURE 3a Tailing simulated by Motion blur

2) Set the camera so as not to remove the previous frame image when drawing the next frame image. This approach is slightly more complicated. Firstly several intermediate frames need to be inserted between each two frames. Provided frame A_1, A_2, A_3 are inserted between the original frame A and frame B. When rendering frame A_1, frame is not output to the screen, instead is output to a separate frame buffer to store until A_2, A_3 and B rendering are completed, then the image in the frame buffer is displayed on the screen. As shown below:

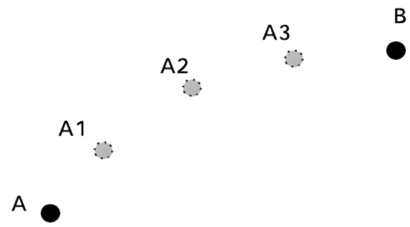


FIGURE 3b Tailing simulated by camera features

We combine the above two methods, namely firstly use Method 2 to insert intermediate frames, and each frame image output to the frame buffer, while use Method 1 to do motion blur for each frame image. This guarantees that the images were real enough.

4.2.2 Blur

Blur mainly refers to the Gaussian blur. Noticing that images outputted by the computer simulation are too sharp, but in real life there is always some blur exciting in the edges of the image captured by camera. In order to simulate this phenomenon, we need to apply a slight Gaussian blur to the image, so that the edge of objects in the image is slightly soft, close to the effect of the real world.

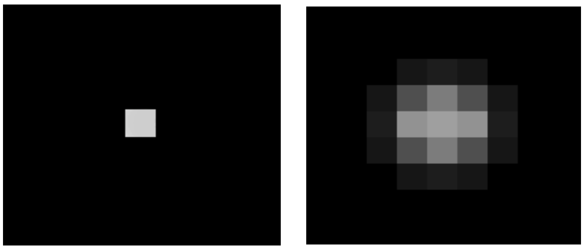
Gaussian blur uses probability density function of normal distribution to calculate the weight of the surrounding pixels, which is defined as follows:

$$f(x) = \frac{1}{\sqrt{2\pi\sigma}} \exp\left(-\frac{(x-u)^2}{2\sigma^2}\right). \tag{7}$$

We use the standard normal function to generate natural effect, when $\mu = 0$, $\sigma = 1$ this is probability density function of standard normal distribution as follows:

$$f(x) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{x^2}{2}\right). \tag{8}$$

Point target in infrared image before and after joining blur is displayed as follows:



a) before adding blur b) after adding blur

FIGURE 4 Blur effect

4.2.3 Dispersion

In the background of deep space, the main impact on the size of dispersion circle is the diffraction and aberrations. Aberrations can be weakened as much as possible by improving the optical system. But the diffraction phenomenon is the inevitable result of the spread of radiation, cannot eliminate.

Optical instruments generally use circular aperture [6], for dispersion energy of circular aperture diffraction calculation Equation is:

$$I(\omega) = |U(\omega)| = I_0 \left[\frac{2J_1(k\alpha\omega)}{k\alpha\omega}\right]^2, \tag{9}$$

where I_0 is the centre intensity of dispersion circle, $k = 2\pi / \lambda$ is wavelength constant, α is the diameter of incident aperture, ω is the angle, $J_1(\ )$ is the first order the first kind of Bessel function.

Assuming the radius of incident aperture is α , the radius of reflector is $\varepsilon\alpha$, the diffraction energy distribution is:

$$I(\omega) = |U(\omega)| = \frac{I_0}{(1-\varepsilon^2)^2} \times \left\{\frac{2J_1(k\alpha\omega)}{k\alpha\omega} - \varepsilon^2 \left[\frac{2J_1(k \in \alpha\omega)}{k \in \alpha\omega}\right]\right\}^2. \tag{10}$$

The second factor impacting dispersion circle is aberration. In the simulation, we can simply use uniform optical defocus to simulate the impact caused by aberration by adding defocus coefficient μ in the above function. For reflection system can be written as:

$$I(\omega) = |U(\omega)| = \frac{I_0\mu^2}{(1-\varepsilon^2)^2} \times \left\{\frac{2J_1(k\alpha\mu\omega)}{k\alpha\mu\omega} - \varepsilon^2 \left[\frac{2J_1(k \in \alpha\mu\omega)}{k \in \alpha\mu\omega}\right]\right\}^2. \tag{11}$$

This can reflect the diffusion phenomena caused by aberration without changing the basic distribution of the diffraction. The implementation of dispersion phenomenon is estimated and simplified in the system, Dispersion effect as shown below:

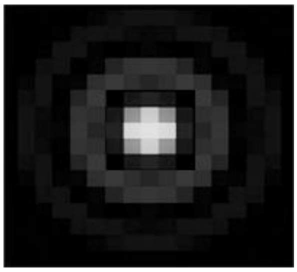


FIGURE 5 Dispersion effect

4.2.4 Blind pixel

Blind pixel is also known as failure, including death pixel and overheating pixel. Performance on the infrared image, death pixel is a black spot for all time, while overheating pixel is white dot forever. According to the project demand, system just simulate white dot.

Central area of infrared detectors undertakes main task of recording the target position. Therefore, blind pixels of central area are less and obey the Gaussian distribution, namely the closer from the centre, the smaller odds of blind pixel. However, the peripheral blind pixels are more and obey uniform distribution. Blind dollar rate for the entire focal plane is about 0.1%.

4.2.5 Noise

Noise can be divided into two parts to simulate. One part is the white noise shown in the uniform distribution. The other part use Perling to simulate the lower image noise of "piece" light and dark areas. Then the brightness values of the upper is remapped around 1.0, and superpose the brightness values of the lower image again to get close to the true noise pattern.

1) Random Noise

The upper noise is easier, regarded as the effects of white noise. Then the white noise has nothing to do with the frequency, and is even distributed on the whole infrared image. The brightness range of your white noise is set as the maximum and the minimum brightness, and the two values are between 0 and 1. The implementation only needs to produce the brightness value of the image between the maximum value and the minimum value with the random number generator.

Because generation of the noise is accomplished in the GPU Shader language and Shader does not directly provide random noise function, this system uses the following hash function to generate pseudo random numbers:

```
float rand(vec2 seed){
return fract(sin(dot(seed.xy, vec2(12.9898,78.233))) * 43758.5453);
}
```

When called, the x, y coordinates of points on the image are introduced to the function as a seed vector, to get the brightness values of point. Then we obtain the more-random image.

2) Perling noise

It needs to use Perling noise function to generate the lower noise. Perling noise is mainly used to simulate real objects, to replace the general random number generator to produce hard and rough result.

Ken Perling proposed a simple method of one-dimension noise function in 1985, called as classical Perling noise. It can be generalized to the two-dimensional case. The implementation steps are as follows:

1) A value and a gradient is specified for all integers (x, y) coordinates, and the space is divided into many squares;

2) In the plane, to coordinate for integer points, the value specified for it is set as a value of a point; for points inside square, we make the interpolation with four vertices values and gradient in squares.

For example, for point (x, y), i and j are integers which x and y are respectively made down. The square four vertices are: (i, j), $(i+1, j)$, $(i+1, j+1)$, $(i, j+1)$ .Make $u = x - i$, $v = y - j$, and then the contribution of the four vertices to the point (x, y) can be achieved with the dot product in the gradient $(g_{00}, g_{10}, g_{11}, g_{01})$ and (x, y) point and the direction of the four vertices $((u,v),(u-1,v),(u-1,v-1),(u,v-1))$. But in the case of two-dimension interpolation is more complex, and the number of interpolation grows as the growth of the dimension exponential growth.

In order to simplify the calculation and use the hardware implementation easier, Ken Perling improved his method in 2001 and the improved noise is called Simplex noise. The algorithm of Simplex noise effectively reduces the number of interpolation.

As mentioned above, the two-dimensional classic Perling noise makes that the two-dimensional space is filled with a square, using four vertices used with three interpolations, and Simplex noise makes that the two-dimensional space is filled with an equilateral triangle, using three vertices with interpolation.

4.3 INFRARED IMAGE GENERATION BASED ON GPU

We use GPU programming, specifically Shader programming for image simulation. The Shader can't save intermediate results in memory, we can use a technology known as the "render to texture" (RTT), to save the intermediate results rendered in a certain extent, and used to image transmission in the multiple Shader.

Concrete implementation steps are shown in the Figure 6 below:

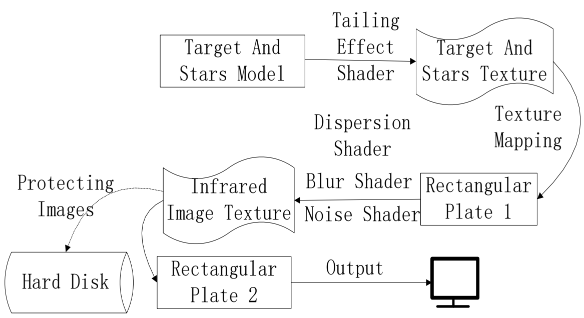


FIGURE 6 Implementation steps based on Shader

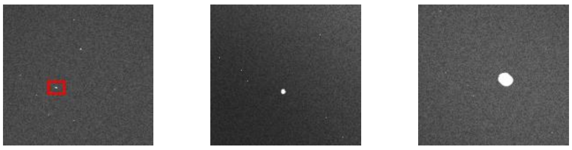
Because in the middle dispersion and blur effect needs to be based on the current coordinate view around the point, and the dispersion is to check a certain distance from the current point on the existence of a target. If any, the current point assignment is set; Blur is according to the brightness of the points around and reset the brightness of the current point. So we need to save target and star to join the tail effect to a texture, that it is convenience to check dispersion and blur query Shader. And noise Shader does not need to use the result of a step, so the noise Shader does not introduce another texture.

We can notice that a system is a requirement to save and read infrared image, or store it in hard disk, or sent to the network, so the above is the two nodes "infrared image texture" and "rectangle plate 2". If there are not the two nodes, the infrared image directly output to the screen, and cannot be read.

5 Simulation results evaluation

5.1 SIMULATED PICTURES OF INFRARED TARGETS

The following figures show the real-time infrared simulation images (the original image is too big, the picture is cropped):



a) The 100th frame b) The 800th frame c) The 900th frame

FIGURE 7 Simulation of infrared images

These pictures show the change of the target in infrared image after the start of the simulation. Target is getting closer, and the target point is also growing. Noticed that the tiny white spot in the background is blind pixel, the noise also can be clearly seen.

5.2 THE EVALUATION OF INFRARED IMAGE

In the literature [7], it gives a deep space infrared background image by a certain type of infrared detector:

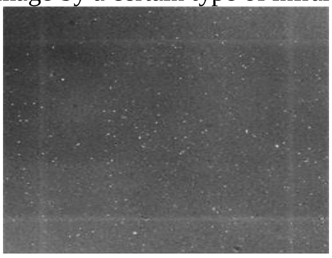


FIGURE 8 Real images of infrared detector

Considering the final goal of the system is target recognition, the infrared image generated by our system should meet an indicator, which is suitable for an ideal target recognition algorithm. We can assess simulated images based on it. As shown in Figure 8, using infrared background image as a reference image, compare it with the simulation image, thereby assess the simulation results.

1) The assessment about characteristics of histogram distribution.

What target recognition algorithm first need to do is eliminating noise in the background. However, filtering background noise is related to the histogram of images. The histogram of referential image as shown below:

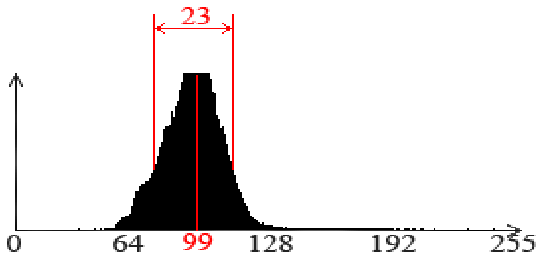


FIGURE 9 Histogram of real deep space infrared background image

The luminance values of reference image is trapezoidal distribution, middle value is 99. Among the pixels, whose luminance value is more than the half of middle value, the difference between max luminance value and min luminance value (hereinafter referred to as "the width of the ladder") is 23.

Histogram distribution of simulation image is as follows:

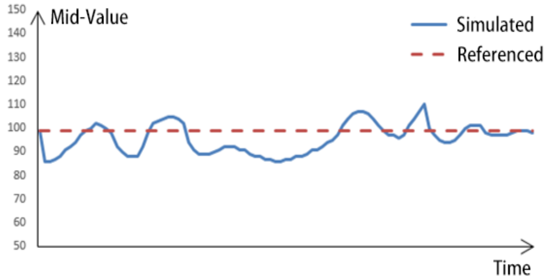


FIGURE 10 Comparison of middle value

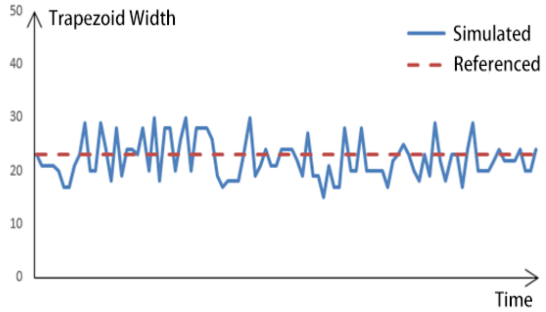


FIGURE 11 Comparison of trapezoidal width

In the simulation image, the histogram changes along with the noise. But the change is always kept within a certain range. The middle value of the simulation image has always been in the vicinity of 99, the maximum deviation is -13.13%, average deviation is -3.43%. The standard deviation of the difference was 0.05; Keystone width of simulated image is always around 23. The maximum deviation is -34.78%, average deviation is -3.52.%, the standard deviation of the difference was 0.13. The histogram distribution of simulation image is close to reference image, we can consider that the simulation image truthfully reflects the infrared image.

2) SNR evaluation of infrared images

In this experiment, we assume the point target is a pixel, and the luminance value is 255. We have a random sample of ten in a series of simulation images to compare with the real image, SNR of real images is 27.74 dB and SNR of simulation image is shown as below:

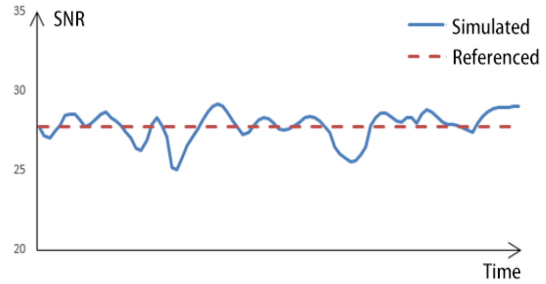


FIGURE 12 Comparison of SNR

The SNR of simulated image fluctuated around 27.74dB, the maximum deviation is -9.73%, average deviation is 0.27%, the standard deviation of the difference was 0.02. The SNR of simulated image is close to the reference image, and we can consider that the simulated image is close to real infrared image.

6 Conclusions

In this paper, according to the imaging principle of infrared detectors, we set up a hierarchical imaging model and give a method for simulation of targets, stars, blur, dispersion, blind pixel, as well as noise. The modelling of noise is discussed in detail. We implementation this method based on GPU to generate more realistic infrared images. According to reference image of an infrared detector, the histogram trend of infrared simulation images, and the signal to noise ratio were evaluated. Simulation results verify the modelling method and show these images satisfied targets recognition algorithm.

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