*Imaging and Radiation Research (2022) Volume 5 Issue 1*
doi:10.24294/irr.v5i1.1741

## ORIGINAL RESEARCH ARTICLE

# Computational ghost imaging study based on incoherent light from blackbody radiation

**Guang Yang, Chunyu Sui, Tingting Jia, Zhandong Liu, Zongguo Li, Hongguo Li***

*School of Science, Tianjin University of Technology, Tianjin 300384, China. E-mail: lihongguo@tjut.edu.cn*

## ABSTRACT

In recent years, ghost imaging has made important progress in the field of remote sensing imaging. In order to promote the application of solar ghost imaging in this field, this paper studies the computational ghost imaging based on the incoherent light of blackbody radiation. Firstly, according to the intensity probability density function of blackbody radiation, the expression of contrast-to-noise ratio ($R_{CN}$) describing the quality of computational ghost imaging is obtained, and then the random speckle pattern simulating blackbody radiation is generated by computer with the idea of slice sampling, finally, a digital light projector is used to modulate and generate the random modulated light that simulates the blackbody radiation light source, and this light source is used to realize the computational ghost image of the reflective object in the experiment. The "ghost image" of the object under different measurement frame numbers is reconstructed, and the contrast-to-noise ratio describing the imaging quality is measured. The results show that the image quality is relatively good when the average intensity (gray) of the randomly modulated speckle is about 160. On the other hand, the contrast-to-noise ratio of the image gradually increases from 0.8795 to 1.241, 1.516, 1.755, 2.100 and 2.371 as the number of measurement frames increases from 2,000 to 4,000, 6,000, 8,000, 12,000 and 20,000, respectively. The experimental results are basically consistent with the theoretical analysis. The results are of great significance for the application of ghost imaging with incoherent light, such as sunlight, which is approximately regarded as blackbody radiation, in the field of remote imaging.

***Keywords:*** Speckle Imaging; Blackbody Radiation; Computational Ghost Imaging; Contrast-to-noise Ratio

**ARTICLE INFO**

Received: 27 November 2021
Accepted: 11 January 2022
Available online: 14 January 2022



## 1. Introduction

Ghost imaging, also known as correlation imaging, is different from the traditional image information of objects obtained through light field intensity distribution. It is a new type of optical imaging to obtain object image information through light field intensity correlation or intensity fluctuation correlation. The initial experiment of ghost imaging was realized by two-photon entangled light source. Later theories and experiments proved that it can also be realized by using thermal light source, that is, the thermal light source is divided into two beams with spatial correlation by using optical beam splitter. One beam is recorded by a barrel detector without spatial resolution after passing through the object (object beam) to be imaged, and the other beam is received by an area array detector with spatial resolution after free propagation for a certain distance, the image information of the object cannot be directly obtained from the signals recorded by the above single detector, but the image information of the object can be reconstructed by performing intensity or intensity fluctuation correlation measurement on the signals recorded by the above two detectors[1-9]. In 2008, Shapiro *et al.*[10] theoretically proposed computational ghost imaging. In this imaging scheme, only one path of object light is required in the experiment. The object light signal is measured in the barrel detector experiment, and the intensity distribution of the reference light is obtained through diffraction calculation. The image information of the object can be obtained by intensity correlation or fluctuation correlation between the object light signal and the intensity signal of the reference light path. Subsequently, Bromberg *et al.*[11] experimented to achieve computational ghost imaging. In 2013, Sun *et al.*[12] used the digital light projector to generate structured modulated light with binary distribution in experiments to realize the computational ghost imaging of three-dimensional objects, the breakthrough realized three-dimensional imaging technology based on ghost imaging technology. In recent years, the research results show that ghost imaging has important application prospects in remote imaging, remote sensing imaging, anti-turbulence, biomedical imaging, single pixel imaging and other fields[8]. Compared with entangled light sources, thermal light sources are easier to obtain. Among them, the solar light source which can be approximately regarded as blackbody radiation is the most easily obtained true thermal light source in nature. Theory and experiments show that ghost imaging can be realized by using true thermal light sources such as sunlight[5].

In order to promote the application of solar ghost imaging in remote imaging and other fields, different from the traditional use of light field impulse response function and light field coherence theory, in this paper, the contrast-to-noise ratio of imaging is obtained by analyzing the light field statistical correlation and the intensity probability density function describing the blackbody radiation. Integrating the slice sampling idea, the digital optical projector is used to generate the random modulated light simulating the blackbody radiation, so as to realize the computational ghost imaging based on the incoherent light of the blackbody radiation, and the variation law of the imaging contrast-to-noise ratio with the number of measured frames and other factors is experimentally studied.

# 2. Basic principles

## 2.1 Contrast-to-noise ratio expression of computational ghost imaging

Suppose that the blackbody radiation light generated by modulation is received by a barrel detector without spatial resolution after passing through the reflected object, and the intensity distribution of the reference light is calculated. Finally, the intensity fluctuation correlation measurement is carried out between the intensity signal of the barrel detector measured in the experiment and the corresponding reference light intensity calculated, that is, the computational ghost imaging is realized. The intensity fluctuation correlation function of ghost imaging is described as[13]:

$$G(x)=\frac{1}{N}\sum_{n=1}^{N} I_0^{(n)} I^{(n)}(x)-\frac{1}{N^2}\sum_{n=1}^{N} I_0^{(n)} \sum_{n=1}^{N} I^{(n)}(x) \tag{1}$$

Where, $N$ is the total number of measurements (total frames), $n$ represents the $n$-th measurement, $I_0^{(n)}$ and $I^{(n)}(x)$ is the intensity value measured by the barrel detector and the intensity distribution of the corresponding speckle pattern for the $n$-th measurement respectively, and the relationship between the two is:

$$I_o^{(n)}=\sum_{x} I^{(n)}(x) O(x) \tag{2}$$

Where, $O(x)$ is the reflectance function of the reflective black-and-white binary object, namely:

$$O(x)=\begin{Bmatrix} R_1, white \\ R_2, black \end{Bmatrix} \tag{3}$$

Where $R_1$ and $R_2$ represent the reflectance of white area and black area respectively.

The contrast-to-noise ratio ($R_{CN}$) is used to characterize the imaging quality of ghost imaging, which is defined as[13-15]:

$$R_{CN}=\frac{\langle G(x_{R_1})\rangle-\langle G(x_{R_2})\rangle}{\sqrt{\Delta^2 G(x_{R_1})+\Delta^2 G(x_{R_2})}} \tag{4}$$

Where, $\langle G(x_{R_1})\rangle$ is the average value of the intensity fluctuation correlation function corresponding to the white area of the object, $\langle G(x_{R_2})\rangle$ is the average value of the intensity fluctuation function corresponding to the black area of the object, and the corresponding variance is expressed as $\Delta^2 G(x) = \langle G^2(x)\rangle - \langle G(x)\rangle^2$, the numerator in formula (4) represents the contrast of the associated image, and the denominator represents the noise of the image.

Considering the statistical properties of thermotical fluctuations, a general expression describing the contrast-to-noise ratio of computational ghost image can be obtained[15]:

$$R_{CN} = (R_1 - R_2)\sqrt{\frac{N-1}{2(T_1R_1^2 + T_2R_2^2) + (R_1^2 + R_2^2)[(1-1/N)(\gamma_1/\sigma_1)^4 - 2 + 3/N]}} \tag{5}$$

Where, $T_1$ and $T_2$ are the number of speckle within the white area and black area of the reflective object (the ratio of the total area of the corresponding area of the object to the area of a single speckle), $\sigma_I^2 = \langle I^2\rangle - \langle I\rangle^2$ and $\gamma_I^4 = \langle (I - \langle I\rangle)^4$ represent the variance and kurtosis of the blackbody radiation intensity, respectively.

## 2.2 Expression for the contrast-to-noise ratio of computational ghost image based on incoherent light radiated by blackbody

According to the probability density function of blackbody radiation intensity, the expression of intensity contrast-to-noise ratio can be obtained. The intensity distribution of blackbody radiation is analyzed in rectangular coordinate system. In the equilibrium state, the blackbody radiation is spontaneous radiation incoherent light which is thermal light. Therefore, the probability density function of the intensity distribution of blackbody radiation in three directions of the rectangular $I_x$, $I_y$, $I_z$ coordinate system is the negative exponential distribution of thermal light, which meets[15]:

$$P_i(I_i) = \frac{1}{\langle I_i\rangle} e^{-I_i/\langle I_i\rangle}, (i = x, y, z) \tag{6}$$

In the equilibrium state, the intensities in the three directions of blackbody radiation are independent of each other, but the total light intensity can be equal to:

$$I = I_x + I_y + I_z \tag{7}$$

The expected value of strength meets:

$$\langle I_x\rangle = \langle I_y\rangle = \langle I_z\rangle = \frac{1}{3}\langle I\rangle \tag{8}$$

Then the probability density function of the total intensity of blackbody radiation is:

$$\mathrm{P(I)} = \iiint_0^\infty dI_x dI_y dI_z P_x(I_x) P_y(I_y) P_z(I_z) \cdot \delta(I - I_x - I_y - I_z) \tag{9}$$

Considering equations (6) and (8), simplifying the above formula, the probability density function of the total intensity of blackbody radiation can finally be written as:

$$\begin{aligned}\mathrm{P(I)} &= \frac{27}{\langle I\rangle^3}\int_0^I dI_x e^{-3I_x/\langle I\rangle} \cdot \int_0^{I-I_x} dI_y e^{-3I_y/\langle I\rangle} e^{-3(I-I_x-I_y)/\langle I\rangle} \\ &= \frac{27}{2}\frac{I^2}{\langle I\rangle^3} e^{-3I/\langle I\rangle}\end{aligned} \tag{10}$$

From equation (10), it is easy to obtain any $n$-order moment of blackbody radiation intensity:

$$\langle I^n\rangle = \int_0^\infty I^n p(I) dI = \frac{(n+2)!}{2}\left(\frac{\langle I\rangle}{3}\right)^n \tag{11}$$

For the convenience of expression, set $\mu_n = \langle I^n\rangle$, the variance and kurtosis of the fluctuation of blackbody radiation intensity can be further calculated according to equation (11), which are, respectively:

$$\sigma_I^2 = \mu_2 - \mu_1^2 = \frac{1}{3}\mu_1^2 \tag{12}$$

$$\gamma_I^4 = \mu_4 + 6\mu_2\mu_1^2 - 4\mu_3\mu_1 - 3\mu_1^4 = \frac{5}{9}\mu_1^4 \tag{13}$$

Substituting equations (12) and (13) into equation (5), the expression of contrast-to-noise ratio describing the quality of reflective ghost imaging based on blackbody radiation can be obtained as follows:

$$R_{CN} = (R_1 - R_2)\sqrt{\frac{N-1}{2(T_1R_1^2 + T_2R_2^2) + (R_1^2 + R_2^2)(3 - 2/N)}} \tag{14}$$

It can be seen from equation (14) that the contrast-to-noise ratio of computational ghost imaging based on blackbody radiation is positively correlated with the total measurement times, that is, as the total number of measurements (total number of frames) increases, the contrast-to-noise ratio of the imaging increases. In addition, it is also related to factors such as the reflectivity of the object.

# 3. Experimental verification

In order to verify the above theoretical results, the digital optical projector is used as a spatial light modulator to generate the simulated random modulated light whose intensity probability density conforms to the blackbody radiation, and then the random modulated light is used as a light source to realize the computational ghost imaging experiment.

## 3.1 Generation of randomly modulated light with intensity probability density function conforming to blackbody radiation

For the distribution of intensity probability density function that is typical, such as negative exponential, binary, poisson and other distributions, the corresponding function is directly called by the program language to generate the corresponding random speckle pattern, while the probability distribution of blackbody radiation intensity represented by equation (10) is not typical and cannot be directly generated. In this paper, a slice sampling based on Markov chain Monte Carlo algorithm proposed by Neal in 2003[16] is used to generate randomly modulated optical speckle according to the intensity probability density function of blackbody radiation. The basic idea is as follows: sample from the intensity probability density function of blackbody radiation $u = P(I)$, first initialize, arbitrarily select the intensity $I_0$ and step size $W$ and then repeat the following steps: (1) fix $I_i$, and uniformly sample on the $[0, P(I_i)]$ interval; (2) fix $u_i$, uniformly sampling on the slice of the interval $I_i$ where the function value is greater than $u_i$. After repeating the above steps, the joint distribution is the joint distribution of $\{I_i, u_i\}$ is obtained, and finally $\{I_i\}$ is extracted from it. Based on the above algorithm, a distribution satisfying the probability density function of blackbody radiation is obtained, as shown in **Figure 1**. The blue histogram represents the probability of random number generated, and the red curve is a curve drawn directly according to the probability density function of blackbody radiation. The results show that this algorithm is effective in generating random modulated light of blackbody radiation.

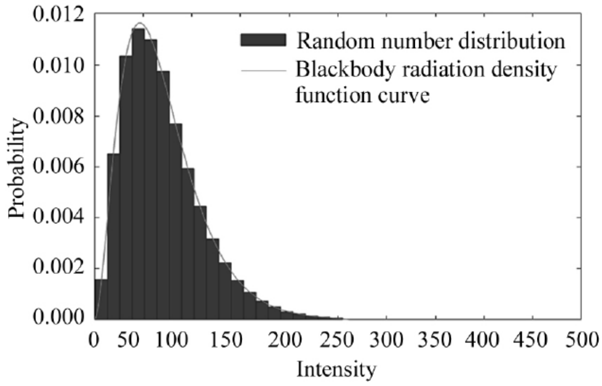


**Figure 1.** Probability distribution of random number in line with blackbody radiation.

## 3.2 Experiment on computational ghost imaging based on incoherent light radiated by blackbody

The schematic diagram of the experimental device of computational ghost imaging based on the incoherent light radiated by blackbody is shown in **Figure 2**, and the corresponding physical diagram of the experimental device is given in **Figure 3**. The random speckle pattern of simulated blackbody radiation generated by the above algorithm is sent to the digital optical projector (Sony, VPL-EX254) through the program to form random modulated light. After 70 cm transmission, the random modulated light irradiates a reflective black-and-white object ("TUT" with a size of 16 cm × 8 cm, white characters on black background), and a photodetector (a photocell without spatial resolution to the object is a barrel detector) is placed 60 cm away from the object to record the modulated light diffusely reflected by the object, and then the signal recorded by the detector is input to the computer through the data acquisition card (DAQ card, national instruments, iDAQ-NI-USB6009, with a sampling rate of 48 kS/s) to acquire the corresponding "barrel detection data", finally, the "bucket detection data" of the hidden object information is correlated with the corresponding modulated speckle pattern according to formula (1) to reconstruct the image information of the object, that is, to realize the computational ghost imaging. In the experiment, the modulated speckle pattern were delivered to the digital optical projector by the control computer at a rate of 360 pieces/min, the number of speckle in the white area and black area of the object is $T_1$ = 712 and $T_2$ = 4,899, respectively, and the reflectance of the white area and black area of the object is about $R_1$ = 0.84 and $R_2$ = 0.15, respectively. The computational ghost imaging results were measured when the total number of frames was 2,000, 4,000, 6,000, 8,000, 12,000 and 20,000, respectively.

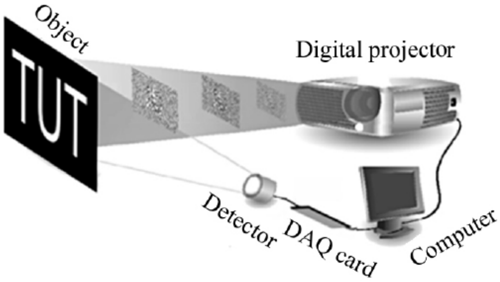


**Figure 2.** Schematic diagram of computational ghost imaging.

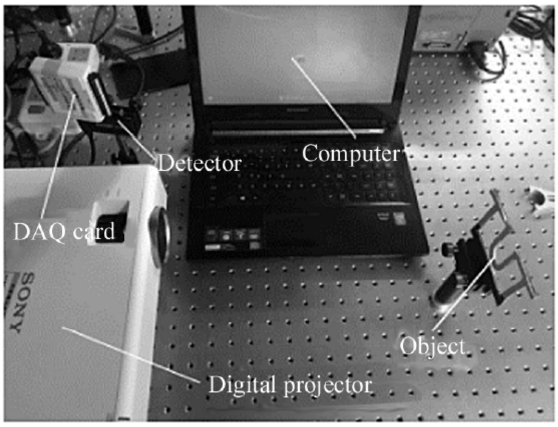


**Figure 3.** Actual picture of experimental device for computational ghost imaging.

## 4. Result analysis and discussion

Using the above experimental device, firstly, when other conditions remain unchanged, the average intensity gray value of the speckle pattern pre-generated by the computer is 160, and the imaging quality is good. Then, the computational ghost image based on blackbody radiation is experimentally studied, and the ghost image of black-and-white reflective objects is obtained. **Figure 4a–f** shows the computational ghost image results under the conditions that the total number of frames measured is 2,000, 4,000, 6,000, 8,000, 12,000 and 20,000 respectively. According to the experimental results, the contrast-to-noise ratios of the corresponding object images in **Figure 4a–f** are about 0.8795, 1.241, 1.516, 1.755, 2.100 and 2.371, respectively. Therefore, with the increase of the total number of measurement frames, the contrast-to-noise ratio of the object image becomes larger, that is, the imaging quality becomes better. In order to further compare with the theoretical results, **Figure 5** shows the variation of the contrast-to-noise ratio of the object image with the total number of measured frames. The star-shaped points in the figure represent the experimental results of the contrast-to-noise ratio, and the curve is the theoretical curve drawn according to equation (14) and the relevant parameters of the object. It can also be seen from **Figure 5** that with the increase of the total number of measurement frames, the contrast-to-noise ratio of the object image gradually increases, and the experimental results are basically

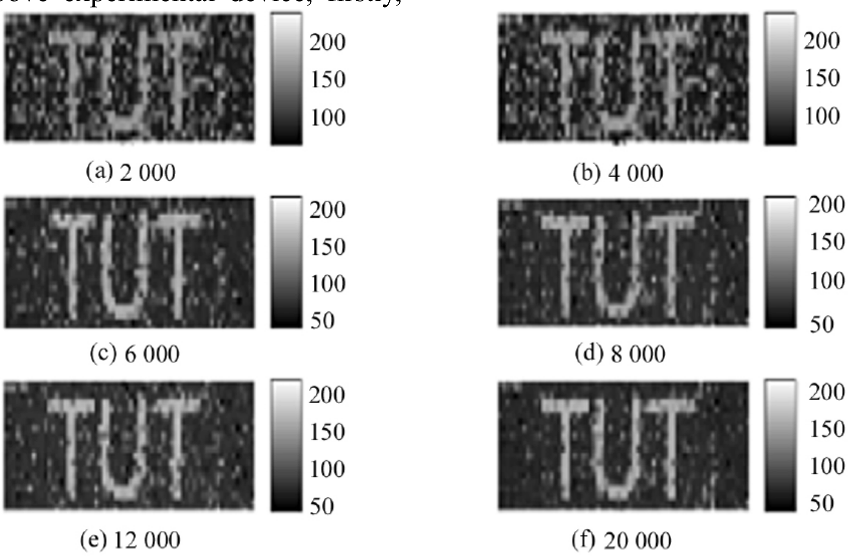


**Figure 4.** Ghost images of object obtained under the condition that the number of frames is 2,000, 4,000, 6,000, 8,000, 12,000, 20,000 respectively.

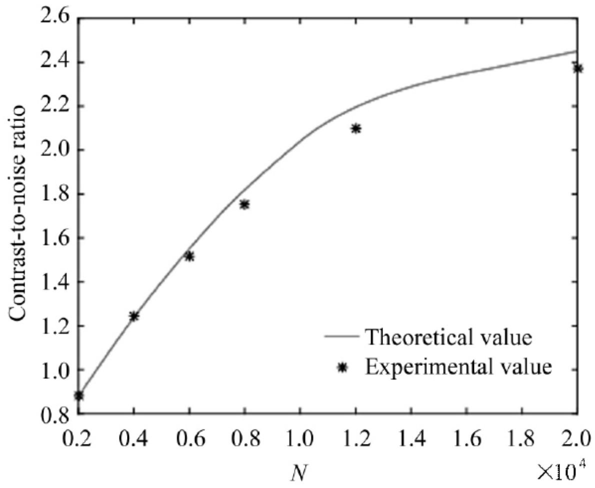


**Figure 5.** The contrast-to-noise ratio of computational ghost image changes with the total number of measurement frames.

consistent with the theory. It can be seen that, in practical applications, the imaging quality can be improved by increasing the number of measurement frames. The contrast-to-noise ratio of the image obtained from the experiment deviates slightly from the theoretical value, which may be caused by the noise such as ambient background stray light in the experiment.

So far, the theoretical results of contrast-to-noise ratio obtained from the intensity probability density function and the statistical properties of blackbody radiation are verified. The results are of great significance for the application of ghost imaging to long-range imaging, especially for ghost imaging based on sunlight and other sources that can be regarded as blackbody radiation sources or computational ghost imaging.

## 5. Conclusion

In this paper, computational ghost imaging based on incoherent light emitted by blackbody is studied theoretically and experimentally. Different from the commonly used light field coherence theory, from a statistical point of view, a general expression of the contrast-to- noise ratio of the computational ghost image describing the reflective black-and-white binary object is given. Then, based on the probability density function of the total intensity of blackbody radiation, the expression of the contrast-to-noise ratio characterizing the computational ghost image based on the incoherent light of blackbody radiation is obtained. Then, the idea of slice sampling is fused to generate random speckle consistent with blackbody radiation, the digital light projector is used as the spatial light modulator to modulate the random modulated light. Finally, the experimental verification is carried out by using the computational ghost imaging experimental device. It shows that with the increase of the total number of measurement frames, the contrast-to-noise ratio of the reflected object image gradually increases, that is, the imaging quality gradually improves. The research results are of great significance for ghost imaging applications which can be regarded as blackbody radiation sources based on sunlight.


## Acknowledgements

This work was supported by the National Natural Science Foundation of China (11604243) and the Tianjin Natural Science Foundation of China (16JCQNJC01600).


## Conflict of interest

The authors declared no conflict of interest.

## References


1. Pittman TB, Shih YH, Strekalov DV, *et al.* Optical imaging by means of two-photon quantum entanglement. Physical Review A 1995; 52(5): R3429.
2. Valencia A, Scarcelli G, D'Angelo M, *et al.* Two-photon imaging with thermal light. Physical Review Letters 2005; 94(6): 063601.
3. Ferri F, Magatti D, Gatti A, *et al.* High-resolution ghost image and ghost diffraction experiments with thermal light. Physical Review Letters 2005; 94(18): 183602.
4. Zhang D, Zhai Y, Wu L, *et al.* Correlated two-photon imaging with true thermal light. Optics Letters 2005; 30(18): 2354–2356.
5. Cao D, Xiong J, Zhang S, *et al.* Enhancing visibility and resolution in *N*th-order intensity correlation of thermal light. Applied Physics Letters 2008; 92(20): 201102.
6. Gao C, Wang X, Cai H, *et al.* Influence of random phase modulation on the imaging quality of computational ghost imaging. Chinese Physics B 2019; 28(2): 020201.
7. Wu H, Wu W, Chen M, *et al.* Computational ghost imaging with 4-step iterative rank minimization. Physics Letters A 2021; 394: 127199.
8. Zhang D, Yin R, Wang T, *et al.* Ghost imaging with bucket detection and point detection. Optics Communications 2018; 412: 146–149.
9. Huang J, Shi D, Meng W, *et al.* Spectral encoded computational ghost imaging. Optics Communica-

tions 2020; 474: 126105.

10. Shapiro JH. Computational ghost imaging. Physical Review A 2008; 78(6): 061802.
11. Bromberg Y, Katz O, Silberberg Y. Ghost imaging with a single detector. Physical Review A 2009; 79(5): 053840.
12. Sun B, Edgar M P, Bowman R, *et al.* 3D computational imaging with single-pixel detectors. Science 2013; 340(6134): 844–847.
13. Zerom P, Shi Z, O'Sullivan MN, *et al.* Thermal ghost imaging with averaged speckle patterns. Physical Review A 2012; 86(6): 063817.
14. Chan KWC, O'Sullivan MN, Boyd RW. High-order thermal ghost imaging. Optics Letters 2009; 34(21): 3343–3345.
15. Chan KWC, O'Sullivan MN, Boyd RW. Optimization of thermal ghost imaging: High-order correlations vs. background subtraction. Optics Express 2010; 18(6): 5562–5573.
16. Neal RM. Slice sampling. The Annals of Statistics 2003; 31(3): 705–767.