Optical setup for evaluating image quality of thermal imaging lenses working in the spectral region of 8÷12 µm

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ABSTRACT

In this paper, we demonstrate a homemade setup and an image processing algorithm to evaluate the image quality of optical systems working in the spectral region of 8-12 µm. The working principle of our approach relies on measuring the line spread function (LSF) and the modulation transfer function (MTF). All components in the setup are carefully designed and manufactured, and we strictly follow quality control to limit measurement errors. The setup can determine the LSF and MTF of a thermal imaging lens with a focal length of f' ≤ 500 mm and pupil diameter D ≤ 100 mm. A number of objective samples have been studied using our setup, and the experimental results indicate that our setup can work reliably with high accuracy.

Keywords: PSF; LSF; ESF spread functions; MTF modulation transfer function; Infrared collimator; Infrared microscope objective.

1. INTRODUCTION

Evaluating the image quality of conventional optical systems, especially thermal imaging systems, is always an essential task because it helps answer the question of whether the optical system meets the specifications and technical requirements. For thermal imaging systems operating in the infrared spectral region, their functional components have different characteristics compared to visible optical systems thus it requires unique fabrication technologies. Therefore, equipment to evaluate their quality must be reliable and high quality. Currently, this device is mainly manufactured by famous brands in the world, such as METS (Ci-system), IR-COL (Hgh), Image Master (Trioptics), DT100 (Inframet), etc. In addition, this equipment is costly, and most of them only evaluate the image quality of the entire thermal imaging system (including the optical components and the sensor) and not the optical components alone. Therefore, when the thermal imaging system is not qualified, it will be challenging to determine the responsible module.

Solving the above problem is an urgent requirement in the current situation, especially in Vietnam, there is no equipment to evaluate the quality of thermal imaging systems operating in the 8-12 µm spectral region. As a result, this work proposes an efficient method and builds a device model and a processing algorithm to evaluate the image quality of a thermal imaging system to ensure reliability and high applicability.

2. METHODS OF MEASURING LSF, MTF AND DESIGN, MANUFACTURE OF COMPONENTS OF THE MEASURING SETUP

2.1. Methods of measuring LSF, MTF

In general, the image quality of a thermal imaging system can be characterized by the line spread function (LSF). From that, it is possible to calculate the modulation transfer function (MTF) by Fourier transform LSF [1-3]. The MTF measurement method is a standard used to evaluate the ability of the system to transmit a quality signal or not. In fact, the signal, when passing through a system, is transformed according to certain rules so that the received signal is not exactly the same as the input signal. The transformation rule is called the MTF of the system. The quality of the optical system can be determined based on the MTF graph.

The diagram of the LSF measurement method is shown in figure 1. A radiation source (1) illuminates light to a narrow slit (2). After passing through the slit, the radiation beam is collimated by a collimator (3). Then, the radiation beam goes through a testing system (4) and forms an image on the image plane (5). The size of the obtained image is usually very small, equivalent to the size of a few pixels on a thermal image sensor (7), so typical sensors cannot record the energy distribution of this image directly. Therefore, it is necessary to use a microscope objective (6) to magnify the image so that the sensor can fully record the characteristic information and evaluate the image quality of the optical system. After obtaining the slit image, we can determine the LSF and MTF of the system by using an image processing algorithm.

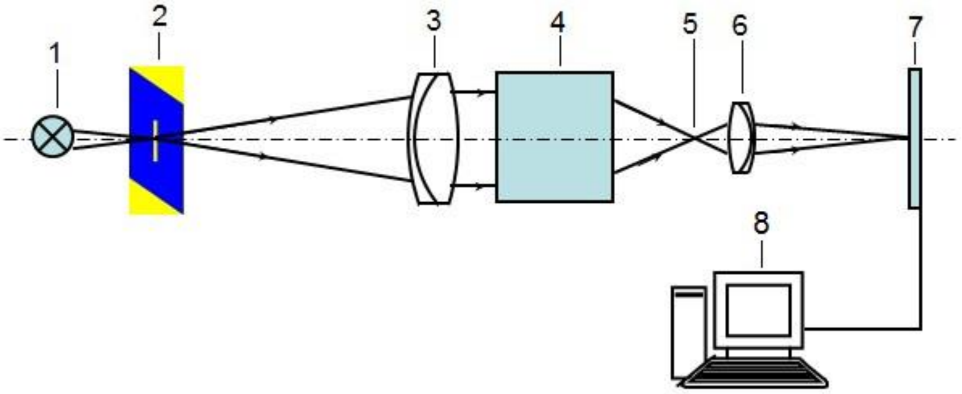


Figure 1. *Diagram of the measurement setup for determining the LSF.*
1. Radiation source; 2. Slit; 3. Collimator; 4. Objective to be tested;
5. Image plane of the tested objective; 6. Microscope objective; 7. Sensor; 8. Computer.

Therefore, in order to develop a device to evaluate the image quality of a thermal imaging system, we have to design and establish a system operating in the infrared spectrum together with investigating image processing algorithms to determine LSF, MTF. From there, it is possible to assess the quality of the optical system quickly and accurately.

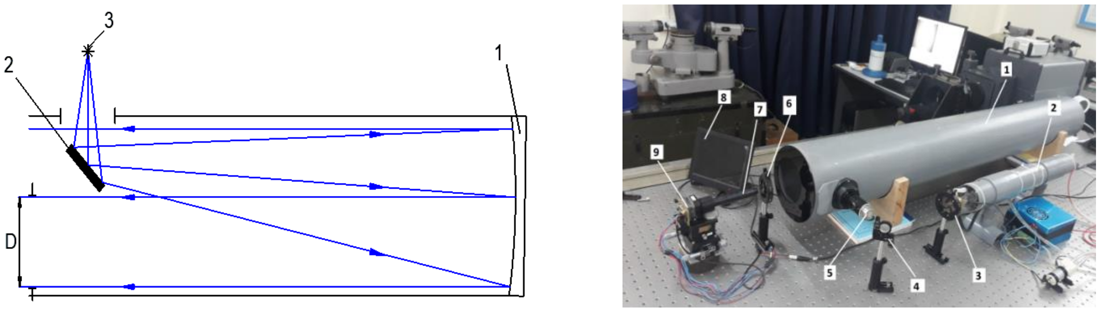
2.2. Design, manufacture of components of the measuring setup

The optical setup includes a radiation source which is a black body, a small slit serving as a sample, a collimator, a tested objective, a microscope objective working in the infrared spectral region, and a sensor. However, the collimator and microscope objective is not commercially available. As a result, we have to design and manufacture them ourselves.

2.2.1. Infrared collimator

The infrared collimator is one of the most critical components in an optical testing system, so it must have a high quality. The function of the collimator is to produce a standard target at infinity. In other words, the wavefront of the radiation beam coming out of the collimator is a plane wavefront with an error of less than λ/10 [4, 5].

Information on the design, manufacture, and operation of the infrared collimator has been published at a prestigious scientific conference [6]. The basic parameters include focal length f' = 1510 mm and the diameter of output beam D = 100 mm (figure 2a). The testing result shows that the collimator can perform well (figure 2b) with wavefront aberration at 10.6 µm PV = 0.044λ (≈λ/20) and RMS = 0.066λ, meeting the optical testing requirements.



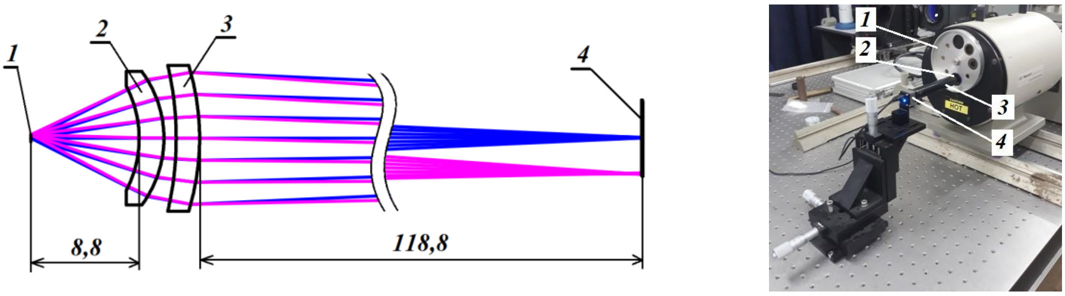
a) Principle diagram of the measuring setup.
1. Main mirror; 2. Secondary mirror;
3. Radiation source.

b) Optical image of the actual setup.
1. Collimator; 2. Radiation source;
3. Beam expansion system; 4. Mirror;
5. Sample; 6. Objective to be tested;
7. Microscope; 8. Computer; 9. Sensor.

***Figure 2.** Schematic diagram and optical image of the actual setup.*

2.2.2. Microscope objective

The microscope objective is an essential component in the optical measuring system. It magnifies the diffraction trace many times to allow the sensor to fully record the image's characteristic information produced by the tested object. To be used in testing optical testing systems, the microscope must have good quality with wavefront aberration of less than λ/10.



a) Diagram of the microscope objective.
1. Radiation source; 2. Aplanat lens;
3. Standard lens; 4. Sensor.

b) Image of the setup used for testing
the infrared microscope.
1. Black body; 2. Small hole;
3. Microscope; 4. Sensor.

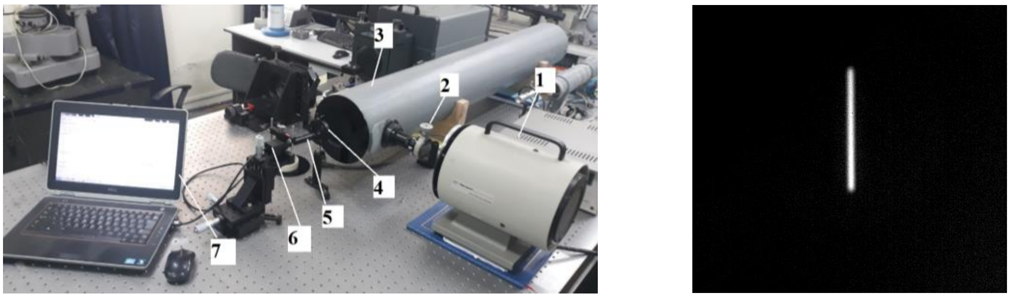
***Figure 3.** Diagram of the optical system and the setup for testing performance of the microscope objective.*

The microscope objective's design, manufacture, and testing have been published at a prestigious scientific conference [7]. It consists of two components: an aplanat lens and a standard lens (figure 3a). The such arrangement reduces the aperture and eliminates aberrations while creating the actual image displayed on the sensor. An experimental study shows that the microscope objective works well (figure 3b). The wavefront aberration of the lenses is less than λ/10; magnification $\beta \approx 10^x$, meeting the optical testing requirements.

3. IMAGE PROCESSING ALGORITHMS AND LSF, MTF MEASUREMENT RESULTS

3.1. Image processing algorithm of the thermal image system

With the components that have been designed and manufactured above, we proceed to arrange the measuring setup as shown in figure 4a. It can be seen that a clear image of the slit (sample) is obtained on the sensor (figure 4b). The radiant energy is distributed concentratedly in the center of the slit and is gradually reduced near the edges due to signal attenuation caused by the noise of the system. The current image quality is not sufficient for determining LSF. It is, therefore, necessary to have an image processing algorithm to make the LSF and MTF measurement results more accurate.



a) Optical setup of the measuring LSF system. 1. Black body; 2. Sample; 3. Collimator; 4. Objective to be tested; 5. Microscope; 6. Sensor; 7. Computer.

b) The image of the sample.

***Figure 4.** System operation test model and the image of the sample.*

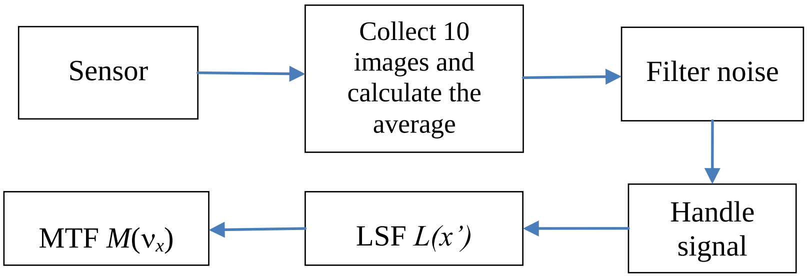


***Figure 5.** The process of processing LSF and MTF measurement results.*

The process of processing LSF and MTF measurement results are shown in figure 5. Firstly, the sensor takes 10 images of the sample and averages the corresponding pixels over these 10 images to get a final image that looks like figure 4b. The purpose of this step is to increase the signal/noise ratio, then the quality of the received useful signal will increase compared to the case of taking only a single image of the sample.

However, the signal quality is still affected by noise signals, which are mainly round spots that have high frequencies. Therefore, for better image quality, a low-pass filter with the aim of blocking high-frequency signals must be used. The principle of this method is to multiply the image matrix by a 3x3 filter matrix [8]. Multiplying the image with the filter matrix is like sliding the filter matrix by row on the image and multiplying by each region of the image, then adding these results, we get the value of the central pixel (figure 6).

The input matrix I is multiplied by the filter matrix to form the output matrix O. After going through this step, the output image will be smoother, and the quality is greatly improved after filtering the noise.

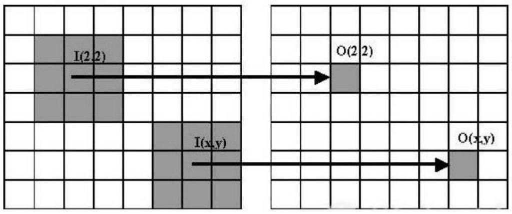


***Figure 6.** Description of noise filtering method.*

Then, using a line to cut perpendicular to the image of the sample, we will get the LSF. The graph of the LSF shows the highest intensity in the center of the slit and gradually decreases on both sides. In addition, this LSF is magnified 10 times by the microscope objective. Therefore, in the data processing step, the LSF at the sensor must be scaled down 10 times (corresponding to a pixel size of 1.7 µm), and converted to LSF at the image plane of the objective to be examined. This conversion is done by the relationship between the input and output signal as follows [9]:

$$V_{out} = c_1 \Phi_{in}^{\gamma} + c_2$$

In which: V_{out}: Output signal; Φ_{in}: Input signal; γ: Gamma correction; c_1: Constant, $c_1 = 1$; c_2: Offset value (used to limit the effect of noise).

So:

$$\left(V_{out} - c_2\right) = c_1 \Phi_{in}^{\gamma}$$

In fact, in this case:

$$V_{out} = LSF_{cambien} \quad and \quad \Phi_{in} = LSF_{HTQH}$$

Therefore:

$$\left(LSF_{cambien} - c_2\right) = \left(LSF_{HTQH}\right)^{\gamma}$$

Here: γ = 0.7 (according to manufacturer's announcement);

$LSF_{cambien}$: LSF at the sensor;

LSF_{HTQH}: LSF at the image plane;

c_2 has a value proportional to the average value of the entire signal of the image.

So:

$$LSF_{HTQH} = \left(LSF_{cambien} - c_2\right)^{\frac{1}{\gamma}} = \left(LSF_{cambien} - c_2\right)^{\frac{1}{0.7}} = \left(LSF_{cambien} - c_2\right)^{1.4}$$

From this equation, the MTF was determined by the Fourier transform of the LSF_{HTQH}:

$$MTF = \left| F\left[\mathrm{LSF}_{HTQH} \right] \right|$$

3.2. Results and discussion

To test the performance of the setup, we selected two thermal imaging objective samples that had parameters of LSF, MTF functions. Then, we carried out the measurement and compared the measured results with LSF and MTF provided by the manufacturer. The basic parameters of the two objective lenses are shown in table 1:

Table 1. *Basic parameters of infrared objectives.*

	Objective sample 1	Objective sample 2
Focal length	19 mm	100 mm
F-number	F1.25	F1.0
Manufacturer	Flir	Wavelength Opto-electronic

Objective sample 1, manufactured by Flir, is the objective taken from the thermal imaging device for inspection. However, the manufacturer only announced the specific parameters of the thermal imaging device, not the LSF and MTF parameters of the thermal imaging objective. To test the quality of this objective, we obtained its diffraction pattern. Experimental results in figure 7 show a circular light spot with energy intensity concentrated in the center and decreasing towards the outside, corresponding to the diffraction theory [10]. Thus, the objective is very well eliminated aberrations, and machining errors are small. As a result, the LSF and MTF can be calculated according to the diffraction limit, and they are considered to be almost the same as the actual LSF, and MTF of the objective. Therefore, although the manufacturer does not publish the LSF, MTF of the objective, we can use theoretical LSF, MTF to compare with the LSF, MTF measured through our setup and from which we will be able to evaluate the quality as well as the reliability of our optical setup.

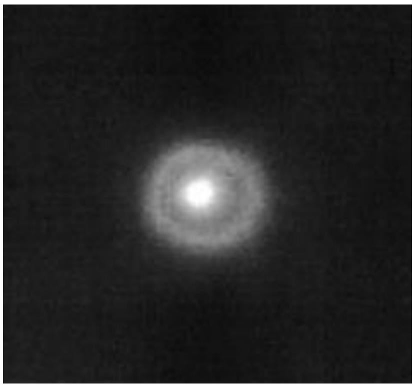
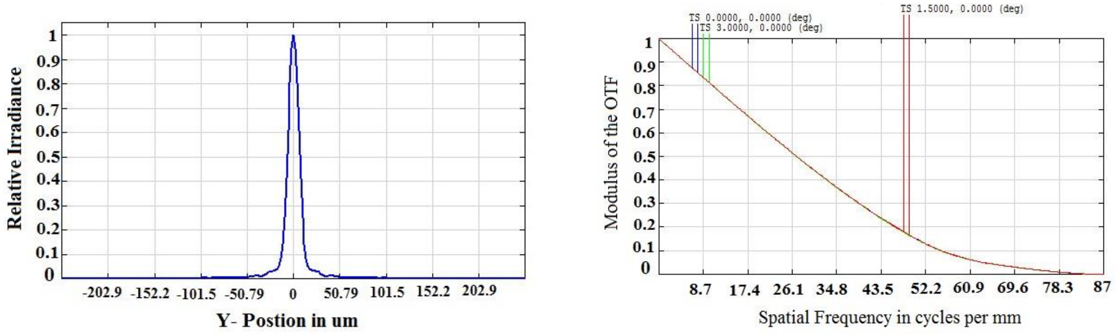


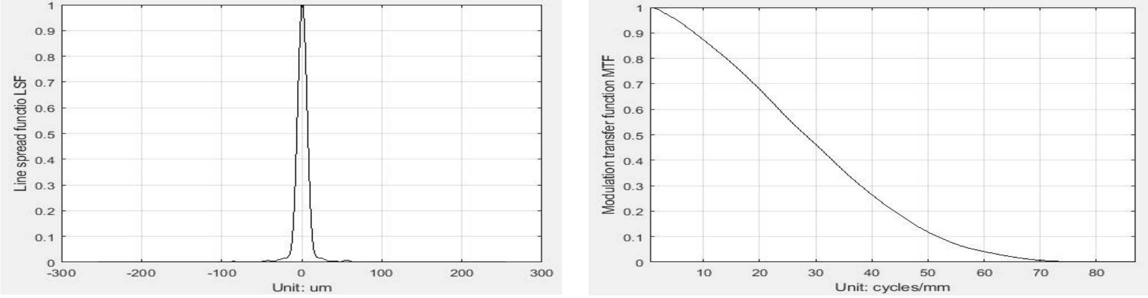
Figure 7. *Image of a small hole with a diameter of 10 µm.*

- The function LSF, MTF are calculated according to the diffraction limit and are performed on Zemax optical software. The calculated LSF and MTF are shown in figure 8a and figure 8b.

- LSF, MTF measured through the setup are shown in figure 8c and figure 8d:



a) Theoretical LSF. *b) Theoretical MTF.*



c) Experimental LSF. *d) Experimental MTF.*

Figure 8. *The theoretical and experimental LSF and MTF.*

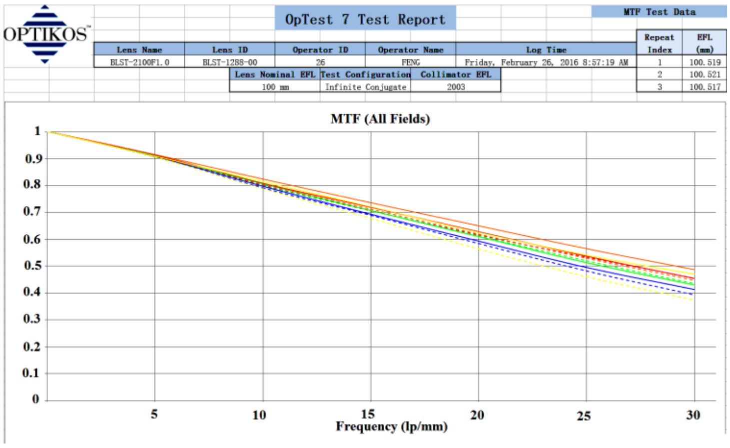
When comparing the theoretical and experimental results, it can be seen that the LSF functions have relatively similar shapes. The energy distribution clearly shows the structure of one maximum in the center with high intensity and gradually decreases to the sides. Regarding the MTF, the experimental MTF values are relatively close to the theoretical MTF (table 2).

Table 2. *Compare the experimental MTF and the theoretical MTF.*

MTF \ Spatial Frequency	10	20	30	50	70	84
$MTF_{theoretical}$	0.78	0.6	0.44	0.15	0.01	0
$MTF_{experimental}$	0.87	0.67	0.46	0.14	0.01	0
%	11.5	11.7	4.5	6.7	0	0

The measured contrast is only higher than the theoretical one at the first part of the curve and corresponds to the low frequency range ($\nu_x \leq 20$ lp/mm). This is because the working range of the sensor is not enough to receive low signals. This issue will be investigated in future work. However, with the current results, the measuring setup is still suitable for testing the lenses of military thermal imaging equipment. Because these devices are often used for distant observation, the target then has a small angular size, so the high frequency range will be more important.

The second objective sample was manufactured by Wavelength Opto-electronic. The MTF published by the manufacturer and the MTF measured through our setup are plotted in figures 9a and 9b. It can be seen that the measured MTF is consistent with the provided MTF from the shape to the value of the corresponding points on the graph. However, similar to the above case, the measured contrast is slightly higher than the manufacturer's announcement in the first part of the curve because the sensor is not sensitive enough to receive a low signal.



OpTest 7 Test Report

Lens Name	Lens ID	Operator ID	Operator Name	Log Time
BLST-2100F1.0	BLST-1288-00	26	FENG	Friday, February 26, 2016 8:57:19 AM

Lens Nominal EFL	Test Configuration	Collimator EFL
100 mm	Infinite Conjugate	2003

MTF Test Data

Repeat Index	EFL (mm)
1	100.519
2	100.521
3	100.517

a) MTF as announced by the manufacturer.

b) Experimental MTF.

Figure 9. *MTF as announced by the manufacturer and experimental MTF.*

Based on the consistency between the measured LSF, MTF, and theoretical/published LSF, MTF of some thermal imaging objectives, we can conclude that our measuring setup is highly suitable for use in testing thermal imaging optical systems.

4. CONCLUSIONS

We have demonstrated an optical measuring setup that can measure the LSF and MTF of a thermal imaging system. Several setup components, including the collimator and microscope objective, are designed and manufactured with good quality. In addition, we have successfully developed image processing algorithms and mathematical transformations scientifically and straightforwardly to improve the image quality from which we can get accurate LSF and MTF. The experimental results show that measured LSF and MTF of several thermal objectives are nearly the same as theoretical/provided LSF and MTF. This finding indicates that our measuring system is reliable. This is the first measuring setup in Vietnam that is capable of evaluating the image quality of the thermal imaging system, which is very helpful for the research and development of domestic thermal imaging systems.

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TÓM TẮT

Xây dựng mô hình thiết bị đánh giá chất lượng ảnh của hệ thống quang học ảnh nhiệt làm việc trong vùng phổ 8-12 μm

Trong bài báo này, chúng tôi trình bày việc xây dựng một mô hình thiết bị và thuật toán xử lý ảnh để đánh giá chất lượng ảnh của hệ thống quang học ảnh nhiệt làm việc trong vùng phổ 8-12μm trên cơ sở phương pháp đo hàm tán xạ đường LSF và hàm truyền điều biến MTF. Tất cả các thành phần trong mô hình thiết bị được thiết kế, chế tạo và kiểm soát chất lượng chặt chẽ để hạn chế sai số đo. Mô hình thiết bị cho phép xác định hàm LSF và MTF của ống kính ảnh nhiệt với tiêu cự f’ ≤ 500 mm; đường kính đồng tử D ≤ 100 mm. Các kết quả đo đạc thực nghiệm được tiến hành với một số mẫu vật kính đã khẳng định khả năng làm việc và độ tin cậy của mô hình thiết bị.

Từ khóa: Hàm tán xạ PSF; LSF; ESF; Hàm truyền điều biến MTF; Ống chuẩn trực hồng ngoại; Vật kính hiển vi hồng ngoại.