

DESIGN AND FABRICATION OF THE THERMAL IMAGING SYSTEM FOR TANK SIGHTS

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Abstract

This study reports the first successful design and fabrication of a thermal imaging sight for tank artillery in Vietnam, utilizing an uncooled detector operating in the long-wave infrared (LWIR) spectrum. The objective lens, consisting of only three spherical elements with a focal length of 100 mm, was evaluated using the modulation transfer function (MTF). The system achieved MTF values approximately 0.5 at a spatial frequency of 30 cycles per millimeter (cycles/mm), approaching the diffraction limit. Measurements of the minimum resolvable temperature difference (MRTD) demonstrate that the sighting system is capable of detecting tank-sized targets at ranges exceeding 2 kilometers.

Keywords: Thermal objective; thermal imaging system; tank sights; MRTD.

1. Introduction

Thermal imaging systems operating in long-wave infrared (LWIR) spectrum play a critical role in military applications. Two main types of infrared detectors are used: cooled and uncooled [1]. While cooled detectors offer superior sensitivity, uncooled detectors are widely adopted due to their compact size, ease of operation, and low cost. Current trends in system development emphasize miniaturization and extended detection range, requiring higher resolution from both detectors and optical components [2]. To meet these demands, aspherical and diffractive optics have been employed to enhance image quality while maintaining compact system size [3]-[5]. However, such approaches pose significant challenges in developing countries, where restrictions on importing cooled detectors and limited access to precision manufacturing technologies for aspherical and diffractive surfaces hinder implementation. As a result, uncooled detectors combined with spherical optics remain a preferred solution. The major drawback of spherical optics is the need for a larger number of lenses, leading to increased system size, weight, and cost [6]. Reducing lens count while maintaining optical performance remains a key design challenge.

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In this paper, the authors demonstrate for the first time in Vietnam the feasibility of designing and manufacturing a lens that uses only three spherical elements, using with an uncooled detector (Tau 2 - Flir) for target recognition of a tank at a distance over 2 km. The issue of evaluating the modulation transfer function (MTF) quality of the lens and measuring the minimum resolvable temperature difference (MRTD) to assess the working distance of the device has been carried out, demonstrating good quality [3].

2. Design

The subject of this study is to design a thermal imaging camera capable of recognizing a tank target at a distance of 2000 meters. The system is based on the FLIR Tau 2 thermal core, which serves as the primary sensor module. The key specifications of the Tau 2 detector used in the design are summarized in Tab. 1. This sensor is commercially available at a reasonable cost and offers characteristics suitable for long range detection applications.

Tab. 1. Parameter of sensor Tau 2 from Flir [7]

| Parameters | Value |
|--------------------|---|
| Spectral band | 7.5 - 13.5 μm |
| Type of detector | Vox Microbolometer |
| Pixel size | 17 μm |
| Sensitivity (NETD) | < 50 mK |
| Resolution | 640 \times 480 (NTSC); 640 \times 512 (PAL) |
| Frame rate | 30 Hz (NTSC); 25 Hz (PAL) |

A low F-number corresponds to a larger aperture, allowing more infrared radiation to enter the system, thereby enhancing both sensitivity and image quality, particularly in low-contrast thermal environments [8], [9]. However, due to the high cost and limited transmittance of infrared materials in the LWIR spectral range, the size of the optical elements must be kept minimal [9]. Therefore, to balance the need for a large aperture that maximizes radiation collection and the requirement to limit material usage and component size, an F-number (the ratio of the focal length to the entrance pupil diameter) was selected to be 1.0 in this study.

The three-lens triplet system is the simplest configuration that provides a sufficient number of structural parameters to correct the primary optical aberrations, making it suitable as a design configuration for systems that require a minimal number of optical elements [9]. The optical elements were made from commonly used LWIR

materials, Germanium (Ge) and Zinc Selenide (ZnSe), which are favorable for their good transmission and ability to reduce chromatic aberration when combined [10]. The initial lens configuration was determined analytically by solving the third-order aberration equations for thin lenses [11].

Once the initial parameters were defined, the design was optimized using Optical engineering software, the final system configuration is presented in Tab. 2, and the optical layout is illustrated in Fig. 1. The system consists of three spherical lenses made from Ge and ZnSe.

Tab. 2. Parameters of designed optical system on Zemax

| Lens | Surface | Radius (mm) | Thickness (mm) | Material | Semi-diameter (mm) |
|------|---------|-------------|----------------|-----------|--------------------|
| | OBJ | Infinity | Infinity | | Infinity |
| | 1 | Infinity | 20.000 | | 52.218 |
| 1 | 2 | 114.380 | 12.000 | Germanium | 52.000 |
| | 3 | 148.670 | 45.000 | | 48.000 |
| 2 | 4 | -267.900 | 10.000 | ZnSe | 36.000 |
| | 5 | -373.300 | 52.000 | | 39.000 |
| 3 | 6 | 41.980 | 8.000 | Germanium | 20.000 |
| | 7 | 42.640 | 16.430 | | 15.000 |
| | IMA | Infinity | - | | 7.059 |

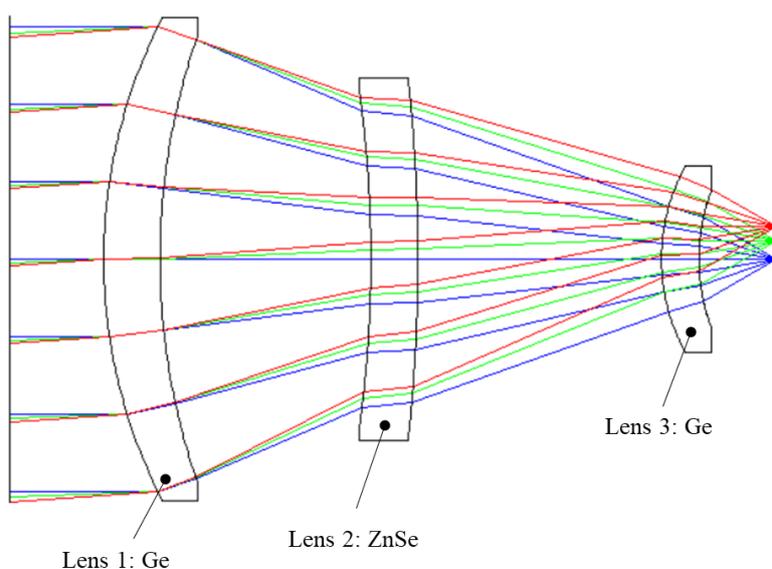


Fig. 1. Diagram of the designed optical system.

The designed system has the primary function of forming an image of the target and background onto the focal plane array sensor. Therefore, like other imaging optical systems, its imaging quality can be evaluated based on the fundamental criterion of the MTF. The MTF of an optical system is a measure of the system's ability to transfer contrast at different spatial frequencies from the object to the image. It quantifies how well the system preserves the details of an image by describing the variation in contrast as a function of spatial frequency [12].

One of the criteria for selecting a suitable objective lens for a given image detector is its Nyquist frequency f_N . In signal processing, the Nyquist frequency, named after Harry Nyquist, is a characteristic of a sampler, which converts a continuous function or signal into a discrete sequence. The Nyquist frequency represents the sampling limit of detector and is calculated using the formula: $f_N = 1000/2p_x$ [cycles/mm] where p_x is the pixel pitch in millimeters [12].

The Tau 2 detector has a pixel size of 17 μm , which corresponds to the maximum Nyquist frequency of 30 cycles/mm. Our target is to design a thermal system with an MTF value of not less than 0.25 at that frequency [13]. Figure 2 presents the MTF curves of the designed optical system at three values of FOV (field-of-view) on Zemax software.

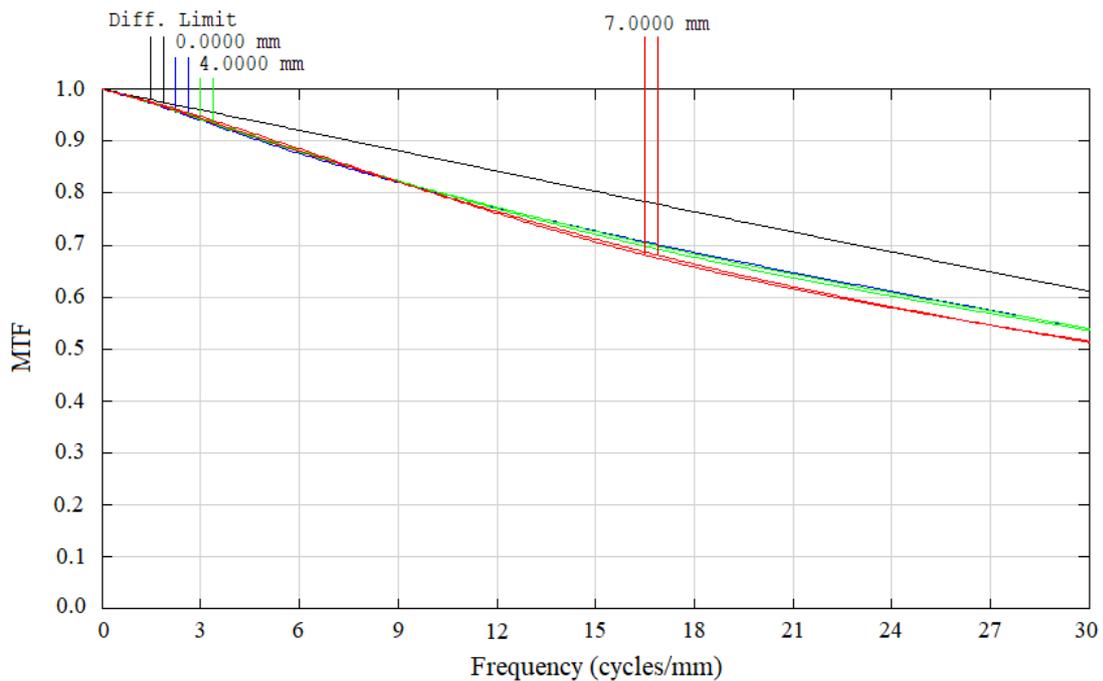


Fig. 2. The MTF curves of the designed optical system on Zemax.

The quality of the lens is evaluated using the MTF, particularly at the Nyquist frequency of the detector. For the selected Tau 2 sensor, the Nyquist frequency is 30 cycles/mm. In typical thermal imaging systems, the lens is expected to achieve an MTF value of no less than 0.25 at the Nyquist frequency. As shown in Fig. 2, the MTF simulation results obtained from Zemax indicate that the designed lens performs close to the diffraction limit, at which the system is almost free from aberrations. At the Nyquist frequency, the MTF exceeds 0.5, indicating a performance beyond the standard specification.

3. Experimental results and discussion

The thermal imaging lenses were fabricated using the SCG 100 grinding machine and the APL 120 polishing machine (Schneider), followed by coating with an anti-reflective layer using the Univex 400 coating machine (Leybold). The entire machining and optical coating process was conducted at the Laboratory of the Department of Optical-Electronic Devices, Le Quy Don Technical University.



Lens 1: Ge

Lens 2: ZnSe

Lens 3: Ge

Fig. 3. The fabricated lens of the Triplet system in Le Quy Don Technical University.

To evaluate the optical quality of the lens and the operational performance of the thermal imaging camera, two key parameters were measured: the MTF and the MRTD. The MTF was assessed using the ORI system from Inframet, while the MRTD was evaluated with the IRCOL device from HGH. Based on the measured data, the detection, recognition, and identification ranges of the thermal imager can be determined in accordance with NATO standards.

3.1. Measuring the MTF of objective

The MTF was measured using the ORI test system, as illustrated in Fig. 4. The lens under test was positioned to project the image of a target located at its object plane into a collimator. The target was generated by a blackbody source combined with a

standard TG-I target generator for infrared. A high-resolution thermal imaging camera captured and magnified the resulting image for further analysis.

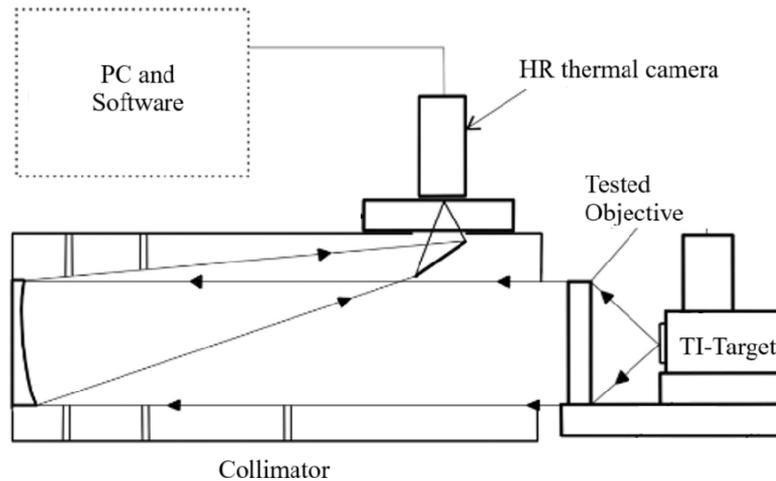


Fig. 4. Principle diagram of the ORI system.

The system allows to measure both vertical and horizontal MTF, and the MTF result is processed by the software, presented in Fig. 5. The on-axis MTF curve of the actual objective is quite near the diffraction limit curve. At Nyquist frequency of 30 cycles/mm, the MTF reaches 0.46, which is higher than the desired value and near that of the designed system. This shows that the fabricated objective is at good quality.

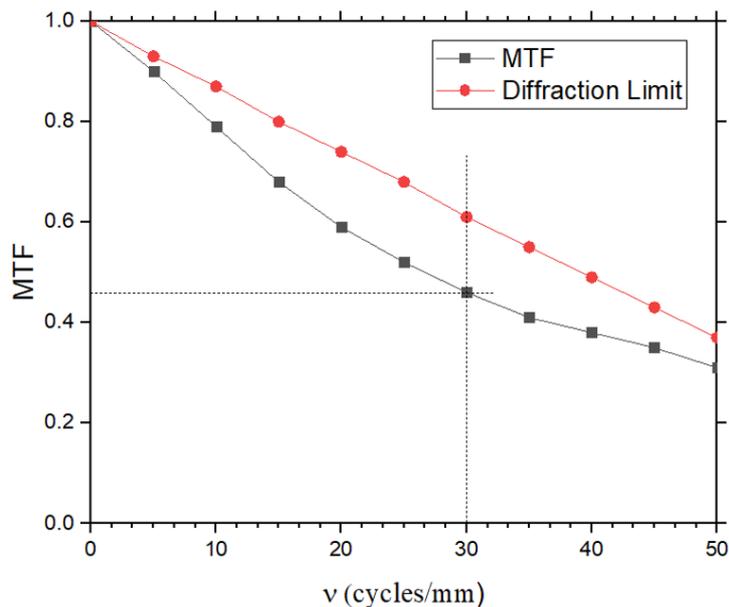


Fig. 5. MTF of the objective measured with ORI system.

3.2. Measuring the MRTD

The MRTD is widely regarded as the most critical performance metric for thermal imaging systems. It is a subjective parameter that characterizes the detection capability of the combined imager-observer system in resolving low-contrast details of an observed scene. MRTD is defined as a function of the minimum temperature difference between the bars of a standard 4-bar target and the background, which allows an observer to distinguish the bars as a thermal image, depending on the target's spatial frequency [9], [14].

In this study, MRTD measurements were conducted using the IRCOL test system developed by HGH, incorporating the Infratest software for fully automated testing. The test configuration is illustrated in Fig. 6. In this setup, the 4-bar target is positioned at the focal plane of the infrared collimator input, while the thermal imaging camera under evaluation is placed at the collimator output. The radiation source used to illuminate the target is a blackbody with a thermal resolution of 0.1 mK. The collimator consists of an off-axis parabolic mirror and a secondary flat steering mirror, with a focal length of 1000 mm and an F-number of 6.67, making it suitable for testing long-range optical systems.

A series of 4-bar targets with different spatial frequencies is mounted on a rotary wheel, allowing for quick and accurate switching between targets during testing. The ambient temperature during all measurements was maintained at 24°C to ensure stable testing conditions.

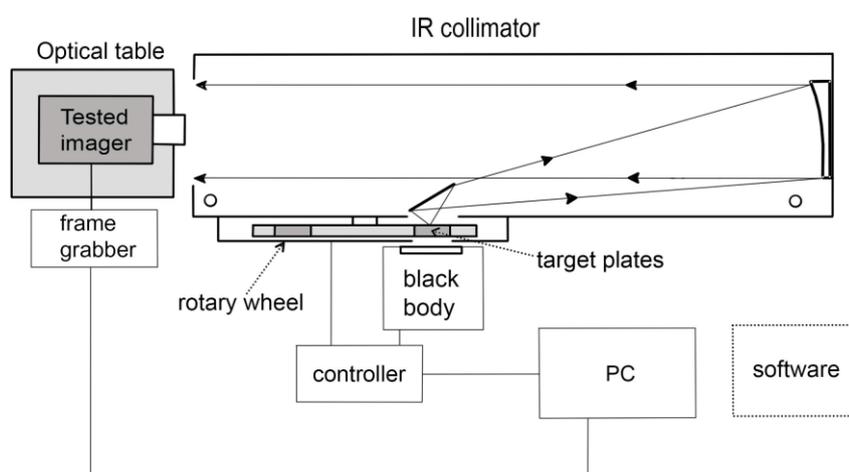


Fig. 6. Principle diagram of the variable target testing system.

The MRTD is evaluated using four-bar targets, which are typically placed at the focal plane of a collimator. The viewing angle in the image space is determined by the ratio of the image height to the focal length of the objective lens. Based on this, the Nyquist frequency used in MRTD evaluation (expressed in cycles per milliradian) is defined as the ratio of the objective lens focal length (in millimeters) to the pitch of two adjacent pixels on the image sensor (in micrometers). The test is performed at three spatial frequency levels (low, medium, and high), each closely approximating the Nyquist frequency, which is 2.94 cy/mrad. The test procedure is in accordance with STANAG 4349 about measuring the MRTD of thermal cameras [15]. The results is shown in Fig. 7.

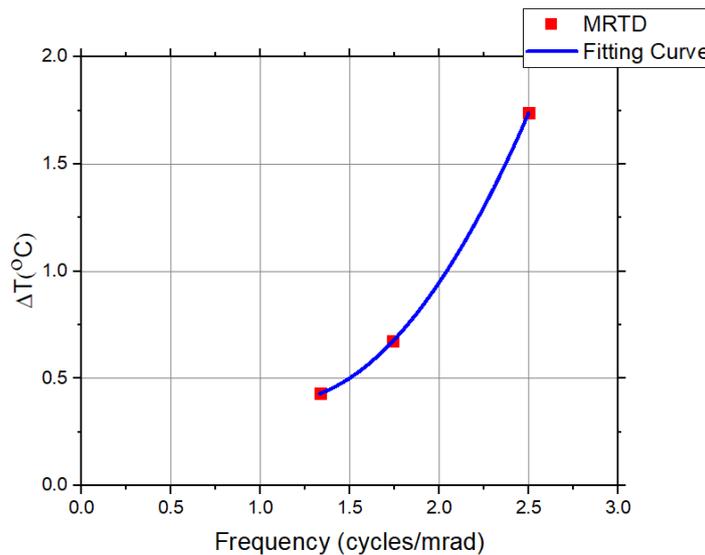


Fig. 7. MRTD diagram.

3.3. Calculating the detection, recognition, and identification ranges (DRI)

The detection, recognition, and identification (DRI) range is defined as the maximum distance at which an electro-optical system with a known MRTD is capable of detecting, recognizing, or identifying a target. These ranges depend on several factors, including target size, temperature difference between the target and the background, the atmospheric transmission coefficient, and the desired probability of detection, recognition, or identification. The DRI ranges were calculated based on MRTD measurement results, assuming a temperature difference of 2°C between the target and the background, and an atmospheric transmission coefficient of 0.2 (km⁻¹), corresponding to good atmospheric conditions according to NATO standards.

Table 3 presents the calculated DRI distances corresponding to specific probabilities for detection, recognition, and identification of a tank target (3 m × 5 m, corresponding to the front and lateral sides). The results indicate that, at a 50% probability, the recognition distance reaches 1365 meters for the front view and 3572 meters for the lateral view of the tank. This means the average recognition range for observing a tank is over 2000 meters. These results are also consistent with the findings of a commercial product published by Flir [8].

Tab. 3. The DRI distances at specified probability

| Probability (%) | Detection (m) | | Recognition (m) | | Identification (m) | |
|-----------------|---------------|----------------|-----------------|----------------|--------------------|----------------|
| | <i>Front</i> | <i>Lateral</i> | <i>Front</i> | <i>Lateral</i> | <i>Front</i> | <i>Lateral</i> |
| 10 | 15006.00 | 25010.00 | 4413.53 | 7355.88 | 1365.40 | 3572.86 |
| 20 | 12505.00 | 20841.67 | 3410.45 | 5684.09 | 1171.53 | 1506.77 |
| 30 | 10718.57 | 17864.29 | 1613.02 | 4809.62 | 1047.68 | 1391.11 |
| 40 | 9378.75 | 15631.25 | 1489.67 | 4168.33 | 925.04 | 1271.96 |
| 50 | 7503.00 | 12505.00 | 1365.40 | 3572.86 | 829.91 | 1175.82 |
| 60 | 6252.50 | 10420.83 | 1264.40 | 3126.25 | 746.07 | 1087.94 |
| 70 | 5359.29 | 8932.14 | 1171.53 | 1506.77 | 672.38 | 985.15 |
| 80 | 4689.38 | 7815.63 | 1047.68 | 1391.11 | 598.13 | 881.53 |
| 90 | 4168.33 | 6947.22 | 913.31 | 1260.29 | 517.50 | 768.74 |

4. Conclusion

In this study, a compact optical system consisting of only three lenses was designed to achieve an MTF value of 0.5 at the Nyquist frequency, approaching the diffraction limit. Due to the exclusive use of spherical surfaces, the measured MTF after fabrication closely matched the theoretical prediction, with a value of 0.46 at the Nyquist frequency—significantly exceeding the typical requirements for thermal imaging devices.

Through MRTD measurements, the operational range of the system was evaluated and shown to be excellent. This marks the first time that a thermal imaging camera has been entirely designed, fabricated, and tested domestically, yielding highly promising results for the development of thermal sights based on uncooled detectors.

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THIẾT KẾ VÀ CHẾ TẠO KÍNH NGẮM ẢNH NHIỆT CHO XE TĂNG

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Tóm tắt: Nghiên cứu này trình bày lần đầu tiên tại Việt Nam việc thiết kế và chế tạo thành công kính ngắm ảnh nhiệt cho pháo tăng, sử dụng cảm biến không làm lạnh hoạt động trong dải hồng ngoại dài (LWIR). Vật kính tiêu cự 100 mm chỉ gồm ba thấu kính có bề mặt làm việc là mặt cầu, đã được đánh giá thông qua hàm truyền điều biến (MTF). Kết quả đo hàm MTF sau chế tạo đạt giá trị xấp xỉ 0,5 tại tần số không gian 30 lp/mm, gần đạt giới hạn nhiễu xạ. Bằng việc đo độ phân giải nhỏ nhất chênh lệch nhiệt độ (MRTD) cho thấy kính ngắm có khả năng nhận diện mục tiêu xe tăng ở khoảng cách trên 2 km.

Từ khóa: Camera ảnh nhiệt; hệ thống ảnh nhiệt; kính ngắm trên tăng; MRTD.

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