A method of calculating spectral characteristics applied to optimize the thermal imaging system design

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ABSTRACT

In the design of thermal imaging systems, the selection of wavelengths and their relative weights plays a critical role in design optimization, directly influencing the system's final performance. The spectral characteristics of a thermal imaging system, which encompass the distribution of wavelengths within the primary optical beam, must be thoroughly analyzed prior to initiating the optical design process. These characteristics are shaped by key factors, including the target's emission spectrum, the medium's and optical component's transmission properties, and the detector sensitivity. This paper presents a detailed investigation and quantitative analysis of the spectral characteristics of a thermal imaging system under real-world environmental conditions, emphasizing their implications for system design. The findings provide valuable insights into how these spectral parameters influence design outcomes, contributing to enhanced research, optimized system development, and improved performance in practical applications.

Keywords: Thermal imaging system; Optical design; Spectral characteristics.

1. INTRODUCTION

More than visible-spectrum optical systems are required to meet practical observation demands, particularly for nighttime surveillance or detecting camouflaged and concealed targets during the day. The development of thermal imaging sensors has facilitated the research, design, and fabrication of thermal imaging systems to address these challenges. Thermal imaging technology has been established for decades in developed countries, achieving significant advancements and applications [1, 2]. In Vietnam, recognizing the importance of thermal imaging technology across various domains, especially in security and defence, has spurred increased research efforts in recent years. Numerous projects and initiatives have produced thermal imaging devices for weapon targeting, vehicle operation, surveillance, target tracking, and missile guidance [3-7].

The spectral characteristics are crucial parameters in the design and optimization of thermal imaging systems, requiring comprehensive analysis and calculation. These characteristics are typically expressed as spectral intensity coefficient curves, representing the relative intensities of radiation at different wavelengths within the primary optical beam. Analyzing these spectral characteristics makes it possible to determine the component wavelengths and their proportions, which serve as critical input parameters for system design optimization. Studying and calculating these characteristics significantly contributes to optimizing optical designs and enhancing system performance. Despite the practical importance of this topic, existing literature needs to include comprehensive studies that systematically address the factors influencing the spectral characteristics of thermal imaging systems or provide standardized methodologies for their quantitative determination. This paper presents an in-depth analysis, simulation, and calculation of the factors affecting the spectral characteristics of thermal imaging systems and evaluates their impact on design optimization. The proposed methodologies apply to a wide range of thermal imaging systems under real-world conditions, serving as a foundation for advancing research, optimizing system designs, and improving the effectiveness of thermal imaging equipment.

2. CALCULATION OF THE SPECTRAL CHARACTERISTICS

Figure 1 illustrates the image formation process of a thermal imaging optical system, incorporating all relevant factors. These factors affect the optical system's spectral characteristics, including the target's emission spectral characteristics, the transmittance of the air medium between the target and the observation device, the transmittance of the optical components, and the detector's spectral sensitivity.

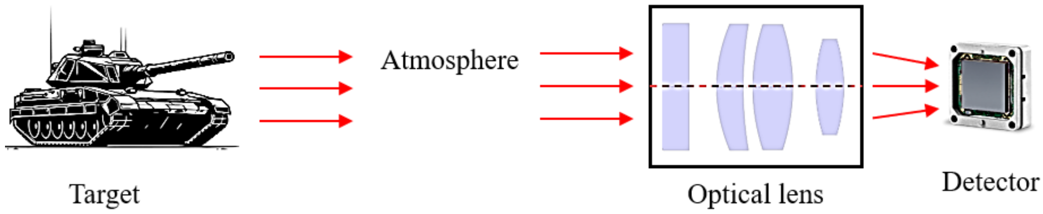

Figure 1. *The image formation process of a thermal imaging optical system.*

The spectral characteristics of the thermal imaging system are the product of the observed target's spectral characteristic coefficient, the medium's and optical component's transmittance, and the detector sensitivity, as shown in the following equation:

$$F_s(\lambda) = F_o(\lambda).F_i(\lambda).F_c(\lambda).F_d(\lambda) \tag{1}$$

Where: $F_s(\lambda)$ - Spectral characteristics of the thermal imaging system; λ - Wavelength; $F_o(\lambda)$ - Target's spectral characteristics; $F_i(\lambda)$ - Medium's transmittance; $F_c(\lambda)$ - Optical component's transmittance; $F_d(\lambda)$ - Detector sensitivity. The methods for calculating these spectral characteristic and transmittances are detailed below.

2.1. Spectral characteristics of target

The temperature and surface characteristics of the target determine the intensity and distribution of the thermal radiation emitted by the target. Different targets have different emission characteristics due to variation in material and surface properties, represented by the emissivity coefficient. When the target has surface properties similar to an ideal black body, its emissivity coefficient equals 1. In this case, the target's spectral characteristics can be calculated using Planck's law as follows [8]:

$$F_o(\lambda) = \frac{2hc^2}{\lambda^5\left(\exp\left(\frac{hc}{\lambda k_B T}\right) - 1\right)} \tag{2}$$

Where: h - Planck's constant; c - Light speed in a vacuum; k_B - Boltzmann constant; T - Absolute temperature of the target's surface. For targets that are not ideal black bodies, the target's spectral characteristics can be calculated by the following formula based on the emissivity coefficient [9]:

$$F(\lambda) = F_o(\lambda).\varepsilon_\lambda \tag{3}$$

Where ε_λ is the target's emissivity coefficient at wavelength λ. Since the optical system optimization process only uses the relative value of the radiated intensity, if the target's emissivity coefficient ε_λ does not vary with wavelength, formula (2) can still be used.

2.2. Transmittance of medium

In typical observation conditions, air is the transmission medium for light from the target to the observation device. Air is a mixture of gases, including nitrogen (78%), oxygen (21%), carbon dioxide, water vapor, and other gases (1%). Depending on environmental conditions, weather, and geographic location, air may also contain dust, smoke, and aerosol particles suspended within it. The transmittance of the air medium is the product of the transmittance of all its components, including the effects of light absorption and scattering by aerosol particles in the air, as shown in the following equation:

$$F_i(\lambda) = \exp\left(-m\left(\tau_a + \tau_g + \tau_w + \tau_o + \tau_r + \cdots\right)\right) \quad (4)$$

Where: m - Relative air mass corresponding to the light path; τ_x - Optical depth of the corresponding components, with x representing a for absorption and scattering by aerosol particles, g for absorption by carbon dioxide and oxygen, w for absorption by water vapor, o for absorption by other gases such as nitrogen dioxide and ozone, and r for the effects of Raman and Rayleigh scattering in the atmosphere [10].

Measuring the parameters and directly calculating the air transmittance based on the above formula for specific environmental conditions is complex and difficult to implement. However, commercial software can be used to simulate the air transmittance based on the formula above with simpler input parameters. An example of such software is Modtran [11].

2.3. Transmittance of optical components

The optical components of the optical system in the observation device can include lenses, flat plates, or prisms. The transmittance of an individual component is the product of two coefficients: the transmittance of the component's surface and the material inside the component. The first one is primarily determined by the coating of the surface, which is coated with a transmission layer that achieves a high transmittance of 0.98. The second one is determined by the properties of the optical material and its thickness. The transmittance of an optical system is calculated as the product of the transmittances of all optical components within that system [12].

$$F_c(\lambda) = \prod f_c(\lambda) \quad (5)$$

where f_c is the transmittance of each optical component.

2.4. Detector sensitivity

The thermal imaging detector converts thermal radiation energy into the corresponding electrical signal and processes this signal for display. The intensity of the electrical signal at each pixel is proportional to the thermal radiation intensity it receives. However, the detector photoelectric conversion efficiency varies with wavelength, creating a characteristic curve representing its photoelectric conversion efficiency, known as spectral sensitivity or sensitivity. Each type of detector will have a different sensitivity curve, typically obtained through measurements using specialized equipment.

3. IMPACT OF SPECTRAL CHARACTERISTICS TO OPTICAL SYSTEM OPTIMIZATION

3.1. The role of spectral characteristics in optical system design

For optical systems with multiple wavelengths involved in image formation, each wavelength in the main beam will create a different image when passing through the system. One single point light can generate multiple point images at different positions. When designing an optical system, it is necessary to optimize image quality to achieve the best observation efficiency, one of which is optimizing the spot diagram. The main beam's component wavelength and ratio are important input parameters for the optimization problem.

Theoretically, the influence of all component wavelengths involved in image formation must be evaluated when optimizing. However, this is not feasible when the operating wavelength is a range with many component wavelengths. In practice, the common method is to use only the central, upper, and lower wavelengths of the spectrum range to optimize the optical system design. Additionally, the design optimization process needs to determine the relative ratio of these component wavelengths.

Let the wavelength and corresponding ratio values be λ_o, λ_{min}, λ_{max} and α_o, α_{min}, α_{max}, respectively. When optimizing the pixel diagram, an optimization problem is formulated with the point image radius function as a multivariate function $D(R_{1i}, R_{2i}, d_i, \rho_i(\lambda), \dots)$, where the goal is to minimize this function. In this, the variables $R_{1i}, R_{2i}, d_i, \rho_i(\lambda)$ represent the diameter of the two surfaces, the thickness, and the refractive index corresponding to the wavelength λ of lens i. If using an aspherical lens surface, the radius R_{1i} must be replaced by variables representing that surface's equation. This optimization problem is usually set up and solved using specialized optical design software, and in this paper, we use Zemax software. Changes in the values of λ_o, λ_{min}, λ_{max} and α_o, α_{min}, α_{max} will lead to changes in the input parameters of the optimization problem, thereby altering the output results. Below, we present a design optimization example for a specific optical system to evaluate the aspects quantitatively and intuitively.

3.2. Optimizing optical system design using spectral characteristics

The example is based on the thermal imaging module of the MOS-1 optical-electronic observatory product, which our research team designed and fabricated. Figure 2 shows an exterior image of the MOS-1 observatory and a schematic of its thermal imaging system. Table 1 presents the parameters of the thermal imaging system. The process to calculate the spectral characteristics and assess their impact on the optimization of optical system design is as follows: First, determine the parameters of the environment, climate, observation distance, parameters of optical components, and detector; Next, input these parameters into formulas (2), (3), (4) and the Motran software to calculate the target's emission spectrum, environment's and optical component's transmittance, and collect the detector sensitivity data; Use formula (1) to calculate the spectral characteristics of the optical system, thereby determining the wavelength values and ratios λ_o, λ_{min}, λ_{max} and α_o, α_{min}, α_{max} ; Finally, these parameters are inputted into Zemax software to calculate the results.

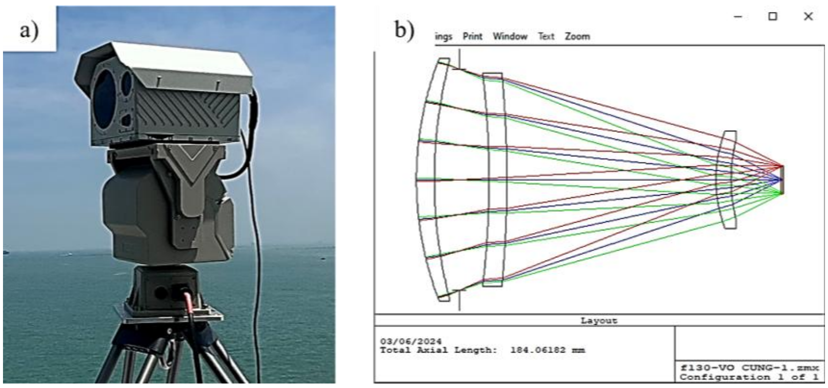

Figure 2. *Exterior image (a) and schematic of thermal imaging system of MOS-1 (b).*

Table 1. *Parameters of the thermal imaging system of MOS-1.*

No.	Parameters	Value
1	Target	Human, Vehicle
2	Observation distance	Up to 10 km
3	Climate	Tropical climate
4	Environment	Mountains, forests, rural
5	Number of optical components	4 (3 lenses and 2 windows)
6	Components material	Germanium
7	Detector	Tau 2, Flir

Figure 3 presents the results of calculating the factors affecting the spectral characteristics of the optical system. In figure 3a, the emission spectrum is calculated for a target such as a person or a vehicle with a surface temperature ranging from 30 °C to 50 °C, and the average value is for calculation. Figure 3b shows the transmittance of the air corresponding to 10 km observation distance. The results include the original value (solid line) and the value after averaging filtering to reduce noise (dashed line). Figure 3c shows the transmittance of the optical components calculated for one component and for an optical system with four components. Figure 3d shows the detector sensitivity from the manufacturer's product catalog [13].

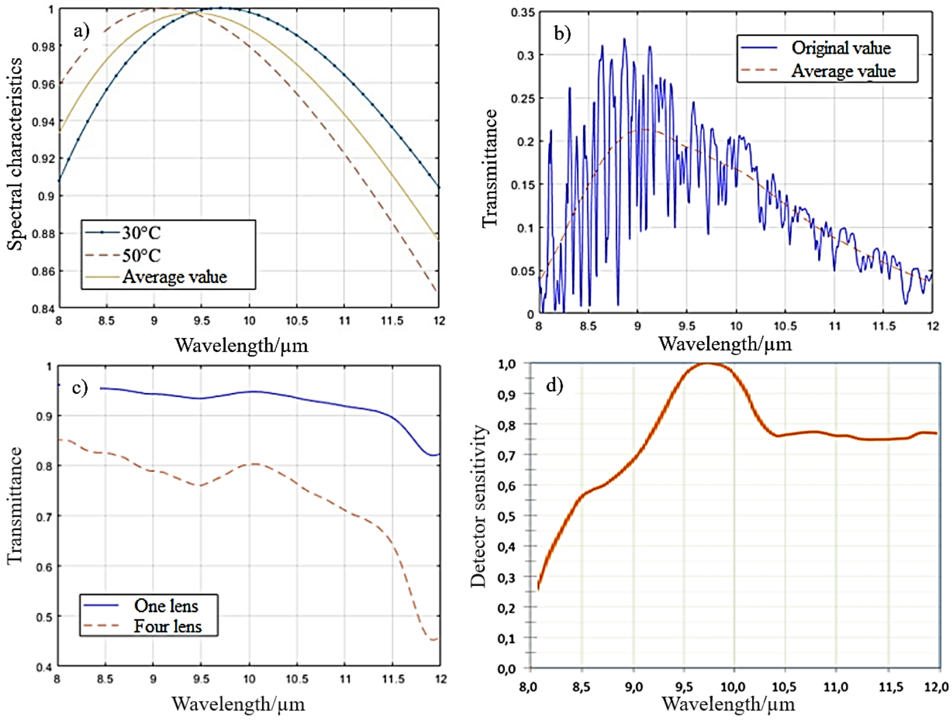

Figure 3. *The factors affecting the spectral characteristics of the optical system: a) Target's emission spectrum; b) Air transmittance; c) Optical component's transmittance; d) Detector sensitivity.*

Figure 4 presents the spectral characteristics of this optical system by substituting the factors affecting it into formula (1), including actual values (solid line) and normalized values (dashed line). The maximum value corresponds to a wavelength of 9.6 µm, and the minimum is at the two boundary wavelengths. From this, the wavelength and the wavelength ratio in the main beam are calculated: λ_o=9.6 µm, λ_{min} =8 µm, λ_{max} =12 µm và α_o=1, α_{min}=0.05, α_{max}=0.08. The calculation results indicate that the wavelength and the ratio of component wavelengths in the main beam differ significantly from the default values (which are typically selected as: λ_o=10 µm, λ_{min} =8 µm, λ_{max} =12 µm và α_o=1, α_{min}=1, α_{max}=1).

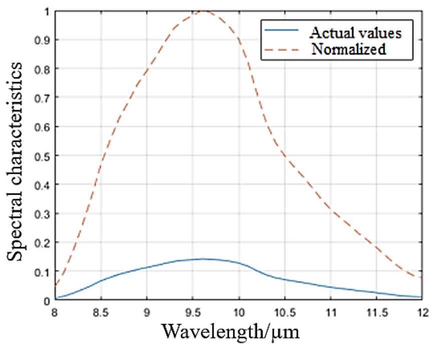

Figure 4. *Spectral characteristics of the thermal imaging system of MOS-1.*

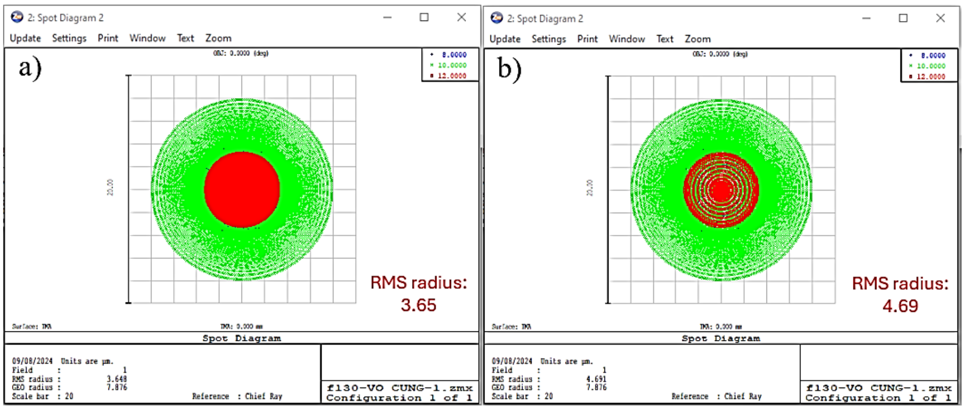

Figure 5. *Spot diagram of the optical system using default and calculated wavelength and ratio values: a) Default values; b) Calculated values.*

The spot diagram is a criterion used to evaluate the image quality of the optical system based on the radius of the point image of a point light passing through the system. The smaller the radius of the point image, the higher the image quality of the optical system. The spot diagram of the thermal imaging system is used to evaluate the influence of spectral characteristics on the optimization of optical design. When designing the thermal imaging system of the MOS-1 observatory, initially, when the spectral characteristics were not yet calculated, the wavelength ratios in the surveyed wavelength range were chosen based on default values, specifically 1, 1, 1, corresponding to wavelengths of 8 µm, 10 µm, and 12 µm. The optimized result of the spot diagram achieved the smallest radius of 3.65 µm (figure 5a). When the calculated wavelength and ratios obtained above were substituted into the design, the spot diagram was recalculated. The actual radius value obtained was 4.69 µm (figure 5b), which is a 28% increase compared to the optimal value. It can be seen that using the default wavelength and ratios to optimize the thermal imaging system design led to a suboptimal design result that did not match the actual situation. Replacing these default values with the calculated one could optimize the optical system design, thereby improving the quality of the system's design.

4. CONCLUSIONS

The results presented in this paper indicate that environmental factors and optical components significantly affect the spectral characteristics of thermal imaging systems, particularly for systems with far observation distances and a large number of optical components. Designing optical systems without fully accounting for the factors influencing spectral characteristics leads to inaccurate input parameters and suboptimal design outcomes. This paper outlines a comprehensive and generalized procedure for calculating the spectral characteristics of thermal imaging systems under practical conditions. This approach can be applied to any thermal imaging system designed with specific operational conditions. The study serves as a foundation for improving the design quality, manufacturing processes, and operational efficiency of modern high-performance thermal imaging systems.

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TÓM TẮT

Phương pháp tính toán hệ số đặc trưng phổ ứng dụng cho tối ưu thiết kế hệ quang ảnh nhiệt

Trong thiết kế hệ quang ảnh nhiệt, bước sóng thành phần và tỉ lệ của chúng là tham số đầu vào cho bài toán tối ưu hóa thiết kế và ảnh hưởng trực tiếp đến kết quả tối ưu. Đặc trưng phổ của hệ quang ảnh nhiệt bao hàm toàn bộ thành phần, tỉ lệ của các bước sóng trong chùm tia chính, vì vậy, cần tính toán làm cơ sở tối ưu thiết kế hệ quang. Đặc trưng phổ phát xạ của mục tiêu, hệ số truyền qua của môi trường và của các chi tiết quang học, độ nhạy của đầu thu là các yếu tố ảnh hưởng đến đặc trưng phổ của hệ. Bài báo trình bày phương pháp nghiên cứu, tính toán đặc trưng phổ của hệ quang ảnh nhiệt trong điều kiện thực tế và đánh giá ảnh hưởng của nó đến tối ưu thiết kế hệ quang. Kết quả nghiên cứu cho phép đánh giá định lượng ảnh hưởng của đặc trưng phổ đến kết quả tối ưu thiết kế của hệ quang ảnh nhiệt. Nội dung bài báo có ý nghĩa quan trọng trong việc nghiên cứu, tính toán, cải thiện thiết kế và nâng cao hiệu quả sử dụng các hệ quang ảnh nhiệt trong điều kiện môi trường sử dụng thực tế.

Từ khoá: Hệ quang ảnh nhiệt; Thiết kế quang học; Đặc trưng phổ.