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# Calculating model for equivalent thermal defocus amount in infrared imaging system

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## HIGHLIGHTS

- Analyze the equivalent effect of temperature variation and room-temperature defocus.
- A parameter called equivalent thermal defocus amount (ETDA) is defined.
- Room-temperature defocus has the same imaging effect as temperature changes by ETDA.
- Experiments on focal shift, aberration with temperature and ETDA prove our model.

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## ABSTRACT

The main effect of temperature change on infrared imaging system is the focus shift of infrared lenses. This paper analyzes the equivalent influence on imaging between the temperature change and the defocus at room temperature. In order to quantify the equivalence, we define an equivalent thermal defocus amount (ETDA). The ETDA describes the distance of the photosensitive surface shifting at room temperature, which has the same effect on imaging as the temperature changes. To model the ETDA, the expression of the focal shift as a function of temperature is obtained by solving partial differential equations for the thermal effect on light path firstly with some approximations. Then point spread functions of the thermal effect and defocus at room temperature are modeled based on wave aberration. The calculating model of ETDA is finally established by making their PSFs equal under the condition that the cutoff frequency of infrared imaging systems is much smaller than that of infrared lens. The experimental results indicate that defocus of ETDA at room temperature has the same influence on imaging as the thermal effect. Prospectively, experiments at high/low temperature can be replaced by experiments at room temperature with ETDA.

## 1. Introduction

The infrared imaging systems for military, industrial, space exploration and security applications are expected to perform satisfactorily at a large temperature scale. However, common infrared optical materials are characterized by larger variations in refraction index with temperature than visible materials. For instance, the change of refraction index respect to temperature for Germanium is over 100 times that of common optical glasses BK7 of the visible spectrum. Other temperature dependent parameters such as expansion coefficients of lens and metallic mounting also have influence on imaging quality when temperature changes. Therefore, it is of great challenge to keep the same performance at a large temperature scale.

In order to solve this problem, athermalization is necessary for optical systems, which includes passively mechanical compensation [1], actively mechanical compensation [2], optical compensation [3,4] and wavefront coding techniques [5,6]. All of these athermalization methods have a common hypothesis, which holds that the main effect of temperature change on infrared imaging systems is the focus of infrared lens shifting. Hence, athermalization can keep the same performance of imaging by maintaining focus of the infrared system over an extended temperature range. The hypothesis has yet been discussed in some literature. Thomas H. Jamieson considered that the variation in temperature caused the focus of single lens shifting and proposed an opto-thermal expansion coefficient

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[7]. Olivieri described a general method for the analysis of the thermal effect in optical systems and considered that the thermal effect on infrared imaging systems is mainly focus shift [8]. Kucherenko analyzed the variation of optical aberrations with temperature and showed that aberrations hardly change with temperature [9]. These researches show that focal shift with temperature is the major factor in degeneration of imaging quality and the variation of aberrations with temperature is negligible. Therefore, the thermal effect on infrared imaging systems has been called thermal defocus yet. The thermal defocus introduces focus shift, but the location of the photosensitive surface is almost constant. Meanwhile, the room-temperature defocus can be considered as misfocus by the photosensitive surface shift. Both of them are due to the reason that the focal plane and the photosensitive surface are not coincided with each other. To the best of our knowledge, there are few reports on the relationship between the thermal defocus (focus shift) and the room temperature defocus (displacement of photosensitive surface). Therefore, in this paper, we propose a calculating model for the equivalent thermal defocus amount (ETDA) which describes the equivalent distance of the photosensitive surface shifting at room temperature in teams of imaging quality as temperature change.

This paper is organized as follows: in Section 2, in order to link the focus shift with temperature, we use raytrace method to solve partial differential equations of the light paths with temperature. In Section 3, we give the definition of ETDA and describe the calculating model. Physical experiments on focal shift with temperature, aberration variation with temperature and ETDA are introduced in Section 4. Section 5 concludes this paper.

## 2. Thermal effect on focal shift

In order to link the focal shift to temperature, equations of light paths are obtained by applying the raytrace method to each surface of an infrared lens as

$$\begin{cases} \frac{1}{V_i} = c_i - \frac{n_{i-1}}{n_i}\left(c_i - \frac{1}{U_i}\right) \\ U_{i+1} = V_i - d_i \end{cases} \quad i = 1, \ldots, N, \tag{1}$$

where $U_i$ is the object point distance of the *i-th* surface $S_i$, $V_i$ is the conjugate point distance, $n_i$ is the refractive index of the *i-th* optical medium ($n_0$ is the refractive index of air), $c_i$ is the curvature of $S_i$, $d_i$ is the distance from the vertex of the surface $S_i$ to the vertex of the surface $S_{i+1}$. When $U_1 = +\infty$, the focus position $V_f$ of the lens can be achieved by making $V_f = V_N$. Derivative of Eq. (1) with respect to temperature $T$ yields:

$$\begin{cases} \frac{dV_i}{dT} = V_i^2 \frac{(n_i - n_{i-1})}{n_i}\alpha_i c_i + \frac{V_i^2}{U_i^2}\frac{n_{i-1}}{n_i}\frac{dU_i}{dT} + V_i^2\left(\frac{\beta_{i-1}}{n_{i-1}} - \frac{\beta_i}{n_i}\right)\frac{n_{i-1}(U_i c_i - 1)}{n_i U_i} \\ \frac{dU_{i+1}}{dT} = \frac{dV_i}{dT} - d_i\alpha_i \end{cases} \quad i = 1, \ldots, N, \tag{2}$$

where $\alpha_i$ is the material thermal expansion coefficient of the lens to which surface $S_i$ belongs and $\beta_i = dn_i/dT$. According to the temperature ranging from −20 °C to +60 °C, $\Delta U_i << U_i$ and $\Delta V_i << V_i$, implying that $U_i$ and $V_i$ can be considered as constants. With the initial condition $dU_1/dT = 0$, $U_1 = +\infty$, Eq. (2) is simplified to

$$\frac{dV_f}{dT} = \frac{dV_N}{dT} = T_c. \tag{3}$$

Eq. (3) shows that the focal shift is directly proportional to the temperature change. In addition, the scaling factor $T_c$ can be defined as the temperature coefficient of the infrared imaging system. By solving Eqs. (1) and (2), we have:

$$T_c = P_N + \sum_{i=1}^{N-1}\left(\frac{n_i}{n_N}(P_i - d_i\alpha_i)\prod_{j=i+1}^{N}\frac{V_j^2}{U_j^2}\right), \tag{4}$$

where $P_i = V_i^2\alpha_i c_i(n_i - n_{i-1})/n_i + V_i^2(\beta_{i-1} - \beta_i n_{i-1}/n_i)(U_i c_i - 1)/(n_i U_i)$.

$T_c$ can describe the sensitivity of an infrared system to temperature. The smaller $T_c$ means that the infrared system has a wider temperature range in which it can image clearly. Accordingly, the temperature coefficient $T_c$ can be used to guide infrared imaging system design.

## 3. ETDA and its calculating model for infrared imaging system

The thermal defocus leads the focus to shift, but the location of the photosensitive surface is almost constant. Meanwhile, the room-temperature defocus can be regarded as misfocus induced by the photosensitive surface shifting, but the location of focus is constant. Both of them are the case that the focal plane and the photosensitive surface are not coincided with each other. Because the point spread function (PSF) is used to predict imaging performance as a common image quality metrics, PSFs are firstly modeled under the two conditions in order to compare the thermal defocus and room-temperature defocus.

According to Fourier optics [10,11], the PSF of optical system can be modeled by wave aberration. If the optical system is ideal or Gaussian optical, the wave front at exit pupil will be spherical surface whose center is on the focal plane. However, the real wave front always deviates from spherical surface because of the aberration. The wave aberration can be denoted by $W(x,y;h)$ which represents the difference between the ideal spherical and real wave front surface with the aberration. $x$ and $y$ are coordinates in the pupil plane. $h$ denotes image height. Assuming that the monochromatic wave aberration of a focused infrared imaging system is represented by $W_0(x,y;h;\lambda)$ at room temperature $T_0$, the aberrated pupil function of the system is

$$P(x,y;h;\lambda) = \begin{cases} \exp\left(j\frac{2\pi}{\lambda}W_0(x,y;h;\lambda)\right), & (x,y) \text{ in pupil} \\ 0, & (x,y) \text{ outside pupil} \end{cases}. \tag{5}$$

Based on Fourier optics, the optical transfer function (OTF) is normalized as follows

$$\mathrm{OTF}(f_x,f_y;h;\lambda) = \frac{P(\lambda d f_x, \lambda d f_y;h;\lambda) \star P(\lambda d f_x, \lambda d f_y;h;\lambda)}{\iint |P(x,y;h;\lambda)|^2 dxdy}, \tag{6}$$

where $d$ is the distance from the exit pupil to the focus and ☆ denotes the correlation operation. The normalization amounts scale the OTF to have a value of 1 at the point (0, 0). To get the PSF of the system, the Fourier transform of OTF and simplification is taken as follow

$$\begin{aligned} \mathrm{PSF}(x,y;u;\lambda) &= \mathrm{IFFT}[\mathrm{OTF}(f_x,f_y;h;\lambda)] \\ &= \tfrac{1}{C}|\mathrm{FFT}[P(\lambda d f_x, \lambda d f_y;h;\lambda)]|^2, \end{aligned} \tag{7}$$

where $C$ is a normalized constant which makes the PSF have a sum value of 1. Regardless of the spectral distribution of light source, the PSF of the infrared image system is

$$\mathrm{PSF}(x,y;h) = \frac{1}{C}\int_{\lambda_1}^{\lambda_2}\mathrm{PSF}(x,y;h;\lambda)R(\lambda)d\lambda, \tag{8}$$

where $R(\lambda)$ is the normalized spectral responsivity of infrared detector and $[\lambda_1, \lambda_2]$ is the range of the spectral.

When temperature changes, as shown in Fig. 1, the focus of the infrared system moves from the photosensitive surface position A (real line) to B (dotted line). Thus, the wave aberration at temperature $T$ can be written as

$$W_T(x,y;h;\lambda) = W_0(x,y;h;\lambda) + W_{\Delta T}(x,y;h;\lambda), \tag{9}$$