MSL Technical Guide 29

Focus Effect in Thermal Imagers

Introduction

In recent years, technological advances have led to the availability of relatively low-cost thermal imaging systems based on uncooled micro-bolometer detector arrays. These systems, which typically measure temperatures in the range –20 ℃ to 350 ℃, are used in a wide range of applications, such as electrical and mechanical monitoring and maintenance, building inspection and maintenance, and medical diagnosis. While many of these applications are qualitative in nature (e.g., identifying hot or cold spots), thermal imagers are increasingly being used quantitatively to measure absolute temperatures. This, in turn, has increased the demand for absolute accuracy and, therefore, calibration of thermal imagers.

Calibration procedures for thermal imagers are largely the same as for single-spot infrared (IR) thermometers (see MSL Technical Guide 22 [1]), but with the additional requirement that the spatial uniformity of the pixel array must also be determined. As for IR thermometers, thermal imagers are typically very sensitive to the size-of-source effect (SSE), so that the errors measured during calibration depend very much on the ratio of the target size to measurement distance. A detailed discussion of the SSE can be found in MSL Technical Guide 26 [2].

A further complication in the calibration of thermal imagers arises from the fact that many of these instruments include a focus adjustment in order to generate a good quality image. The implementation of this focus adjustment differs according to the design criteria of the instrument – some thermal imagers are designed to optimise resolution and image quality, while others are designed to retain radiometric accuracy (temperature measurement ability) at all focus settings. In the case of the former, the temperature readings on the imager will depend on the focus setting, so a calibration certificate will only be valid for the particular focus setting used during the calibration. This focus effect behaves in a similar manner to the SSE and produces temperature errors in addition to those caused by the SSE.

This technical guide discusses the origin of the focus effect in those instruments that exhibit it, and describes a simple test to determine whether or not a thermal imager has been designed for radiometric accuracy and is thus immunity to the focus effect. While there are methods available for determining focus effect corrections and reporting these on a calibration certificate (see [3]), these methods are not discussed in this technical guide because of the complexity required to obtain full accuracy. Rather, the purpose of this technical guide is to bring the focus effect to the attention of calibration laboratories (and users) and to provide advice on the appropriate use of focusable thermal imagers.

The Origin of the Focus Effect

An IR thermometer or thermal imager determines temperature by measuring the amount of infrared radiation emitted by a target and using a physical relationship known as Planck’s law to convert the measured signal into a temperature value. This requires an optical system containing two fixed defining apertures, sometimes known as the field stop and the aperture stop.

For an optical system that includes a lens, the field stop, in conjunction with the magnification of the optical system, defines the area on the target from which radiation is detected (i.e., the field of view). For a thermal imager, each pixel effectively becomes the field stop for the corresponding part of the target.

The aperture stop, on the other hand, defines the solid angle of the cone of rays detected. The aperture stop is similar to the *f*-stop in a traditional camera – adjusting its size changes the amount of radiant flux reaching the detector (for a camera, light reaching the film – or these days, the CCD). For thermometry, the aperture stop must remain fixed at the size used during calibration so that the same flux is always measured for a given target temperature.

Figure 1 shows a schematic of a basic thermal imager, with the field of view shown for an individual pixel.

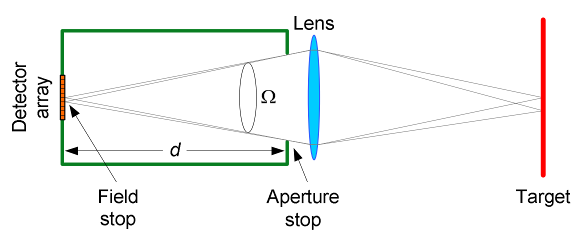

Figure 1. Schematic of a basic thermal imager with the field of view for a single pixel shown on the target. The flux incident on the pixel is proportional to the solid angle Ω.

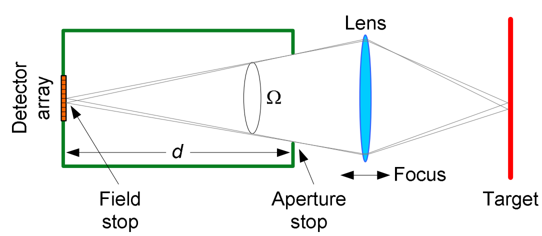

Figure 2. Focusing the thermal imager is achieved by moving the position of the lens on the target side of the aperture stop, leaving Ω unchanged from Figure 1.

The flux, Φ, incident on each pixel is given by

$$\Phi = A_{\text{pixel}} \Omega \tau L , \quad (1)$$

where A_{pixel} is the area of the pixel, Ω is the solid angle subtended by the aperture stop at the detector, τ is the transmittance of the lens, and L is the radiance of the target, which is determined by its temperature. If the distance, d, between the aperture stop and the detector is sufficiently large, the solid angle can be approximated by $\Omega = A_{\text{aperture}} / d^2$, and equation (1) becomes

$$\Phi = A_{\text{pixel}} \frac{A_{\text{aperture}}}{d^2} \tau L , \quad (2)$$

where A_{aperture} is the area of the aperture stop.

Changing the focus of the thermal imager in Figure 1 is achieved by moving the position of the lens, such as shown in Figure 2. Provided the lens has a sufficiently large diameter compared to the diameter of the aperture stop, the solid angle Ω is the same in Figure 2 as in Figure 1. Thus, the flux arriving at the pixel is still given by equation (2). This type of construction, where the lens moves on the target side of the aperture stop, allows correct radiometric measurements to be made. The combined factor in front of the L in equation (2) (i.e., $A_{\text{pixel}} A_{\text{aperture}} \tau / d^2$) is a fixed 'calibration factor' that is determined by the manufacturer during the initial calibration.

Consider now the situation where the aperture stop is defined by the lens itself (or its holder). Figures 3 and 4 demonstrate two different focus settings. In this case, the flux given by equation (2) is different for the two settings because the value of d, and hence Ω, has changed, thus the calibration factor is different from the manufacturer's value. The ratio of the fluxes in the two figures is given by

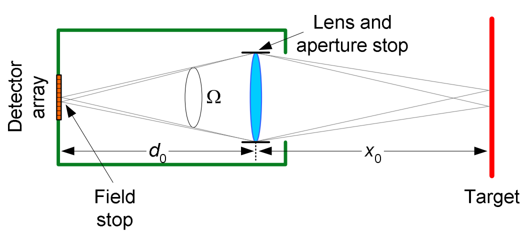

Figure 3. A thermal imager not designed for radiometric accuracy, where the holder of the focusing lens is the aperture stop.

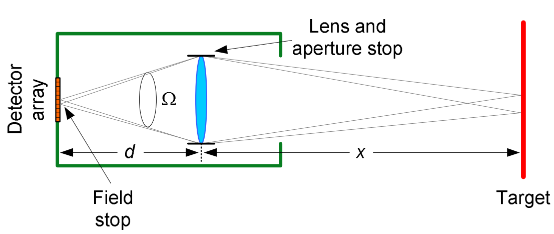

Figure 4. Changing the focus setting of the thermal imager in Figure 3 changes the value of Ω and, thus, the flux falling on the pixel also changes.

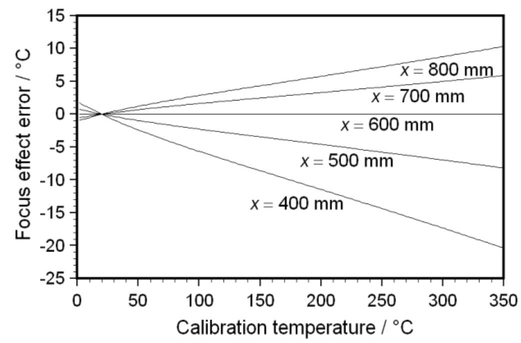

Figure 5. Expected error, as a function of focus distance x, in the reading of an 8–14 µm thermal imager with a focal length of 50 mm, constructed as in Figure 3, originally calibrated by the manufacturer at a distance of 600 mm.

$$\frac{\Phi}{\Phi_0} = \frac{d_0^2}{d^2} , \quad (3)$$

where d_0 and Φ_0 correspond to values for one focus setting (e.g., during the manufacturer's initial calibration), and d and Φ for a different focus setting (e.g., during a subsequent recalibration). Thus, for a fixed-temperature target, the reading on the thermal imager will change with the focus setting.

By using the thin lens formula:

$$\frac{1}{x} + \frac{1}{d} = \frac{1}{f} , \quad (4)$$

equation (3) can be rewritten in terms of the focal length of the lens, f, and the distance, x, from the lens to the target:

$$\frac{\Phi}{\Phi_0} = \frac{x_0^2 (x - f)^2}{x^2 (x_0 - f)^2} . \quad (5)$$

Thus, for a system with a focal length of $f = 50$ mm, originally calibrated at a working distance of $x_0 = 600$ mm, and subsequently recalibrated at a distance of $x = 300$ mm, the measured flux would be too low by about 20 %. Conversely, when focusing at infinity, the measured flux would be too high by about 20 %. Figure 5 plots the equivalent temperature error for an 8–14 µm thermal imager with a 50 mm focal length lens for several different working distances.

Diagnosing the Focus Effect

In practice, the optical configuration of a thermal imaging system will be more complicated than the simple arrangement shown in Figures 1 to 4, and it is unlikely that the optical details will be given in the thermal imager's specifications. Thus, calculating the possible focus effect errors, as done for Figure 5, is not practicable, and the errors must be determined experimentally.

A simple test to determine whether the optical system is configured as in Figure 1 and is immune to the focus effect, or as in Figure 3 and will suffer from the focus effect, is as follows. Set up a blackbody at the highest temperature at which the thermal imager will be calibrated and let it stabilise. Place the thermal imager a few centimetres away from the blackbody and take a temperature reading in the centre of the image with the focus set to one extreme, then a second temperature reading with the focus set to the other extreme. If the readings are the same, or very close to each other, then the thermal imager is designed for radiometric accuracy and there will be no focus effect errors, otherwise if there is a significant change in the readings then the focus effect is an issue.

Note that the images during this test will not be in focus, but so long as the centre of the image is well overfilled by the blackbody the temperature readings should not be affected by being out of focus. This is the reason for carrying out the measurements close to the blackbody. Additionally, if the blackbody presents the same angular size to the thermal imager, any errors due to the size-of-source effect will be the same for both measurements, and thus any change in the reading is due purely to the focus effect (i.e., due to the change in the size of the solid angle of the aperture stop as the focus is changed).

Dealing with the Focus Effect

If the focus effect test described above indicates that the thermal imager is designed for radiometric accuracy, then nothing further needs to be done, other than carrying out the calibration in the usual manner, including accounting for the size-of-source effect. (SSE) The calibration should then be valid for any focus setting.

However, if the focus effect is present, then there are two ways to deal with the issue. If the effect is small (compared to the instrument's accuracy specifications), then it can be included as an uncertainty component in the total calibration uncertainty. This uncertainty can be determined by assuming that difference between the readings at the two extreme focus settings represent the limits of a rectangular distribution, and the standard uncertainty is the estimated as the difference in these two readings divided by $\sqrt{12}$. The calibration would then be carried out at the focus setting that gives a reading midway between the two extreme readings.

If the focus effect is large, then the methods described in [3] can be used to determine corrections as a function of focus setting and temperature. However, when coupled with the need to apply SSE corrections, use of such an instrument to determine absolute temperatures becomes very complicated. One way to simplify matters is to calibrate the thermal imager at a single focus setting and to specify on the calibration certificate that the quoted accuracy only applies for this one focus setting. Such instruments could reasonably be used at other focus settings for qualitative measurements, but information about its absolute accuracy would be lost.

References

[1] MSL Technical Guide 22: "Calibration of Low-Temperature Infrared Thermometers", http://msl.irl.cri.nz.

[2] MSL Technical Guide 26: "Size-of-Source Effect in Infrared Thermometers", http://msl.irl.cri.nz.

[3] P Saunders, "A Focus Effect in some Thermal Imaging Systems", submitted to *Temperature: Its Measurement and Control in Science and Industry*, Vol. 8.

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