# MSL Technical Guide 15

# Correcting Radiation Thermometers for Reflection Errors

## Introduction

Reflection errors occur in most practical applications of radiation thermometry. This technical guide describes the development of a simple graphical method (called a nomogram) for calculating reflection corrections, and gives instruction on its use.

The nomogram is applicable to both high-temperature and low-temperature thermometers, and enables operators to make corrections rapidly without the need for calculators or spreadsheets. It is also a useful tool for describing the impact of measurement uncertainty on temperatures corrected for reflection errors.

## At High Temperatures

In most high-temperature industrial processes, the object of interest is heated and, therefore, surrounded by hot walls and heaters. During measurement, the additional thermal radiation from the heaters and walls, reflected by the surface of interest, increases the temperature indicated by the radiation thermometer, leading to a reflection error.

Depending on conditions, reflection errors may range from a few degrees Celsius to several hundred degrees Celsius [1]. In some industries, such as the petrochemical [2] and steel industries, reflection errors are a well-recognised and long-standing problem [3–6], and it is now increasingly common for thermometer users to employ measurement strategies that minimise the reflection errors or to apply corrections for the reflections [1, 2].

Although reflection correction methods are now well-established, they are implemented in only a few high-temperature radiation thermometers. Furthermore, such thermometers tend to be expensive. Thus, many operators using hand-held thermometers to make high-temperature measurements do not have immediate access to an estimate of the true temperature of their plant.

## At Low Temperatures

Reflection errors also affect all measurements made near room temperature. Again, the object of interest is surrounded by walls and other objects at a similar or higher temperature, which are all emitting thermal radiation. Unlike high-temperature thermometers, low-temperature thermometers must also compensate for the radiation emitted by the thermometer's sensor. Most manufacturers of low-temperature thermometers employ a simple correction algorithm that eliminates both effects, but the algorithm implicitly assumes that the thermometer is at the same temperature as the walls (the source of the reflected radiation) [7]. When the thermometer and the walls are at different temperatures (in a coolstore, for example), large reflection errors occur.

Unfortunately, the limitations of these thermometers are rarely described in the thermometer manual or manufacturer's literature. The lack of information has two negative effects. Firstly, many users are unaware of the problems of reflection errors at low temperatures. Secondly, when the thermometer is not at the same temperature as its surroundings, the algorithm fails and reflection corrections must be calculated manually.

## The Nomogram

Figure 1 shows an example nomogram for a radiation thermometer operating at a wavelength of 1 μm. The procedure for correcting temperature readings consists of five simple steps [2]:

1. Set the emissivity on the thermometer to 1.0 in order to measure radiance temperatures.

2. Estimate the emissivity of the target ($\varepsilon = 0.7$ for the example of Figure 1).

3. Measure the average radiance temperature of the walls and plot the result on the left-hand edge of the nomogram, corresponding to $\varepsilon = 0$ ($T_w = 980$ ºC for the example of Figure 1).

4. Measure the radiance temperature of the target and plot the result on the nomogram on the vertical line corresponding to the target emissivity ($T_m = 940$ ºC for the example of Figure 1).

5. Draw a straight line through the two points, and extrapolate to $\varepsilon = 1.0$ to determine the true temperature of the target ($T_s$ is a little less than 920 ºC for the example of Figure 1; the actual value, calculated manually using equations (1) and (2) below, is 918 ºC).

This procedure applies to both high-temperature thermometers and low-temperature thermometers, but does require the emissivity setting on the radiation thermometer to be 1.0. This precludes the use of some fixed-emissivity instruments.

## How the Nomogram Works

Reflection errors depend, amongst other things, on how the walls and other hot objects are distributed around the object of interest. However, most cases are similar to that shown in Figure 2: a small target object, whose temperature, $T_s$, we wish measure, inside a large uniformly hot enclosure with a wall temperature $T_w$. A thermometer viewing the target object measures infrared radiation comprised of an emitted component and a reflected component, so that the total signal is:

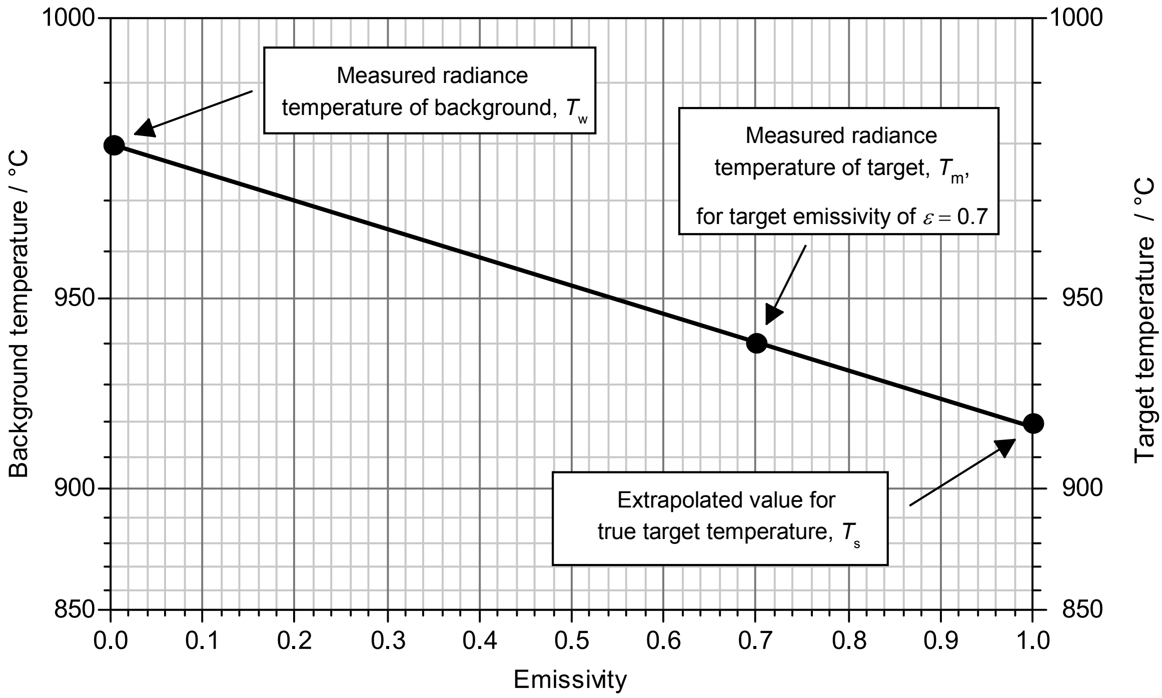


**Figure 1:** An example of the nomogram for a radiation thermometer operating at 1 μm.

$$S(T_m) = \varepsilon S(T_s) + (1-\varepsilon) S(T_w) \,. \qquad (1)$$

The first term on the right-hand side of equation (1) is the radiation emitted by the target, and the second term is the radiation originating from the walls and reflected by the target. The thermometer displays the measured temperature $T_m$. Equation (1) is referred to as the measurement equation. $\varepsilon$ is the emissivity of the target and $S(T)$ is the calibration equation for the thermometer.

For the purpose of correcting for reflections, $S(T)$ is approximately given by

$$S(T) = \exp\left(-c_2/\lambda T\right) , \qquad (2)$$

where $c_2 = 0.014388$ m.K is a constant, $\lambda$ is the operating wavelength of the thermometer, and the temperature $T$ is given in kelvins.

The reflection error is the difference between the measured target temperature, $T_m$, and the true target temperature, $T_s$.

Equations (1) and (2) form the basis of the nomogram. In practice, for any arbitrary geometry, the value that we use for $T_w$ is the average radiance temperature of the walls, rather than the true temperature. The radiance temperature of any object is simply defined as the temperature measured by the thermometer aimed at that object when the emissivity on the instrument is set to 1.0.

Equations (1) and (2) are too awkward to allow a quick estimate of the true temperature *in situ* at the time the measurements are made. The nomogram is a graphical tool designed to simplify the implementation of these equations and to provide insight into the effects on the equations as the parameters are varied.

The nomogram is based on the formula for a straight line between two points $(0, y_1)$ and $(1, y_2)$:

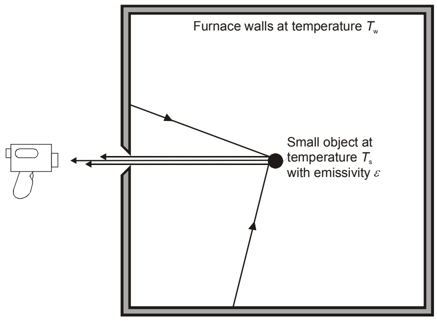


**Figure 2:** A simple pictorial representation of how reflection errors occur.

$$y(x) = y_1(1-x) + y_2 x \,. \qquad (3)$$

This equation has the same functional form as the measurement equation (1), and if we make the replacements $y(x) = S(T_m)$, $y_1 = S(T_w)$, $y_2 = S(T_s)$, and $x = \varepsilon$, the equations are the same. This means that a straight line drawn on a graph will relate all three temperatures, $T_m$, $T_s$, and $T_w$, so long as the scale on the vertical temperature axis of the graph is marked in direct proportion to the thermometer signal, $S(T)$. If you look closely at Figure 1 you will see that the temperatures marked on the vertical axis are not equally spaced. On nomograms for low-temperature thermometers, this non-linearity is less noticeable.

## Application to Uncertainty Propagation

We can also use the nomogram to analyse the effects of uncertainties or errors in the measurements. The propagation of uncertainties and errors is usually understood in terms of so-called sensitivity coefficients [8], which are derived by differentiating the measurement equation with respect to all the measured variables. For equation (1), the propagation-of-error equation is

$$dS(T_\mathrm{s}) = \frac{1}{\varepsilon} dS(T_\mathrm{m}) - \frac{1-\varepsilon}{\varepsilon} dS(T_\mathrm{w}) + \frac{S(T_\mathrm{w}) - S(T_\mathrm{m})}{\varepsilon^2} d\varepsilon \,. \quad (4)$$

This equation tells us the scaling factors used to covert errors in the measurements into errors in the corrected temperature. These scaling factors are the coefficients of the differentials or errors, $dS(T_\mathrm{m})$, $dS(T_\mathrm{w})$, and $d\varepsilon$, and are called sensitivity coefficients.

For the mathematically challenged, this equation does not help much. Fortunately, the nomogram can be used to estimate the effects of errors or uncertainties in the different measurements.

Figure 3 shows the influence of errors in background radiance temperature on the estimate of the target temperature. One can visualise a line on the graph as a lever with the fulcrum at the target radiance temperature. Hence, an increased wall radiance temperature lowers the estimate of target temperature; this shows that the sensitivity coefficient for wall radiance is negative. We can also see that the uncertainty in target temperature is amplified by the ratio of the lengths of the two lever arms. In summary, errors in the background radiance propagate with the sensitivity coefficient

$$\frac{\partial S(T_\mathrm{s})}{\partial S(T_\mathrm{w})} = -\frac{1-\varepsilon}{\varepsilon} \,, \quad (5)$$

and this is one of the terms in equation (4) .

Figure 4 shows the influence of uncertainty in the measured target radiance temperature. Again we can visualise the lines as levers, this time with the fulcrum at the wall radiance temperature. In this case, an increased target radiance temperature results in an increased true target temperature, so the sensitivity coefficient must be positive. Also, the uncertainty is amplified by the ratio of the positions on the lever arm and is equal to $1/\varepsilon$. Hence, the sensitivity coefficient is

$$\frac{\partial S(T_\mathrm{s})}{\partial S(T_\mathrm{m})} = \frac{1}{\varepsilon} \,. \quad (6)$$

Figure 5 shows the propagated uncertainty for the estimate of the emissivity. This case is slightly more complicated than the two above, but the lever model can be applied here too. First we must translate the horizontal movement (due to the uncertainty in the emissivity) to a vertical movement using the slope on the lever, $\left(S(T_\mathrm{w}) - S(T_\mathrm{m})\right)/\varepsilon$ . Now the situation is identical to that in Figure 4, so the effect is further scaled by the factor $1/\varepsilon$. Hence, the sensitivity coefficient for the uncertainty in the emissivity is

$$\frac{\partial S(T_\mathrm{s})}{\partial \varepsilon} = \frac{S(T_\mathrm{w}) - S(T_\mathrm{m})}{\varepsilon^2} \,. \quad (7)$$

The most interesting instance of Figure 5 is when the measured background and target radiance temperatures are the same, and the nomogram line is horizontal. In this case, the uncertainty in the emissivity has no effect on the estimated target temperature. This corresponds to viewing a blackbody cavity. This observation can also be drawn from equation (1) by substituting $T_\mathrm{w} = T_\mathrm{s}$.

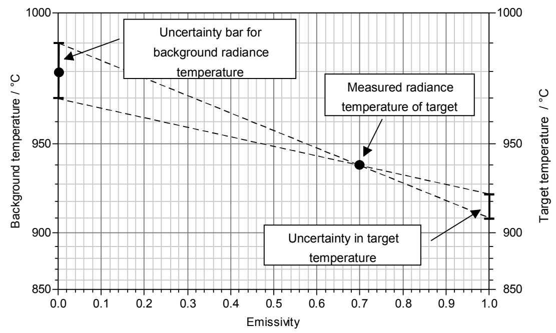


**Figure 3.** Propagation of uncertainty for background radiance temperature.

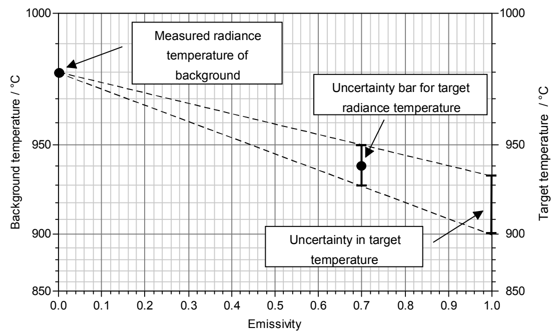


**Figure 4.** Propagation of uncertainty for target radiance temperature.

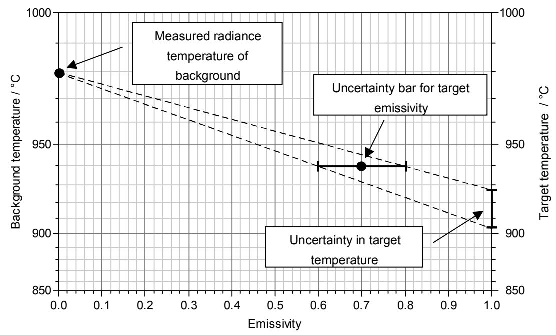


**Figure 5.** Propagation of uncertainty for target emissivity.

## Conclusion

The nomogram is a convenient tool for rapid determination of reflection errors and for visualisation of the effects of the various parameters on radiation thermometry measurements.

Different nomograms are required for thermometers operating at different wavelengths. The example presented in Figures 2 to 5 is for a 1 μm thermometer typically used in high-temperature industries for targets at 600 °C and above. For applications near room temperature, 10 μm thermometers are commonly used. A nomogram for these thermometers has a much more linear vertical axis.

MSL can provide nomogram-creation software suitable for any wavelength and temperature range.

## References


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