

RESEARCH ARTICLE

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Characterizing a linear pyrometer at the National Metrology Institute of South Africa

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Abstract. A linear pyrometer is used to realize the International Temperature Scale of 1990 (ITS-90) for temperature ranges above 961.78 °C in most National Metrology Institute (NMI) radiation thermometry labs. The different components of the linear pyrometer system working together to measure temperature may exhibit some errors which should be accounted for. The errors can be characterized by several equipment parameters that should be measured before the radiation thermometer is used to realize ITS-90 temperatures. Relative spectral responsivity (s), size of source effect (SSE), gain ratio (GR), non-linearity (NL), distance effect (DE), temperature coefficient and zero drift are all major equipment parameters that characterize the efficiency of a linear pyrometer in realizing ITS-90. In this work, an attempt was made to describe and demonstrate these major parameters by using actual measured characterization results of a linear pyrometer. Uncertainty contributions from some of the parameters considered in scale realizations was also demonstrated using the measurement results.

Keywords: Radiation / Planck / pyrometer / spectral / responsivity and gain

1 Introduction

Detector-based linear radiation thermometers, whose operation is based on Planck's law of thermal radiation, have been used to realize ITS-90 temperatures above 961.78 °C. These kinds of radiation thermometers are designed to have several optical and electrical components that work together as a system in an efficient manner. Accurate measurement of temperature using this kind of radiation thermometer requires a thorough understanding of the different optical components' behaviors. For this reason, a system-level characterization of a linear pyrometer is critical before the instrument is used to realize ITS-90. A system-level characterization includes measurement of relative spectral responsivity (s), size of source effect (SSE), gain ratio (GR), non-linearity (NL), distance effect (DE), temperature coefficient and zero offset drift. The characterization of these parameters allows determining the optimum efficiency of a linear pyrometer in realizing ITS-90. The characterization results are used to either correct measurement results or be included in the measurement uncertainty [1–3].

Some of the characterized parameters are the major uncertainty contributors in ITS-90 scale realization [3]. In the lower temperature range where three to four ITS-90 fixed points are available the uncertainty contributions from NL and SSE are considered. However, the uncertainty contribution from these parameters is lower than the contribution from the fixed-point measurements. In the higher temperature range where only one ITS-90 fixed point measurement, and s measurement is available uncertainty contributions from NL, SSE, GR and s are considered. In the high temperature range the contribution from s is higher than the contributions from the other parameters.

This article discusses the different equipment parameters and their characterization by taking actual experimental results. In using the experimental results, an attempt will be made to describe the parameters' technical importance, uncertainty contribution and the effect they have when the linear pyrometer is used to realize ITS-90 temperature.

2 Linear pyrometer

A linear pyrometer is an opto-electrical equipment used to realize ITS-90 temperatures above the silver (Ag) point. Its operation is based on Planck's law of thermal radiation and

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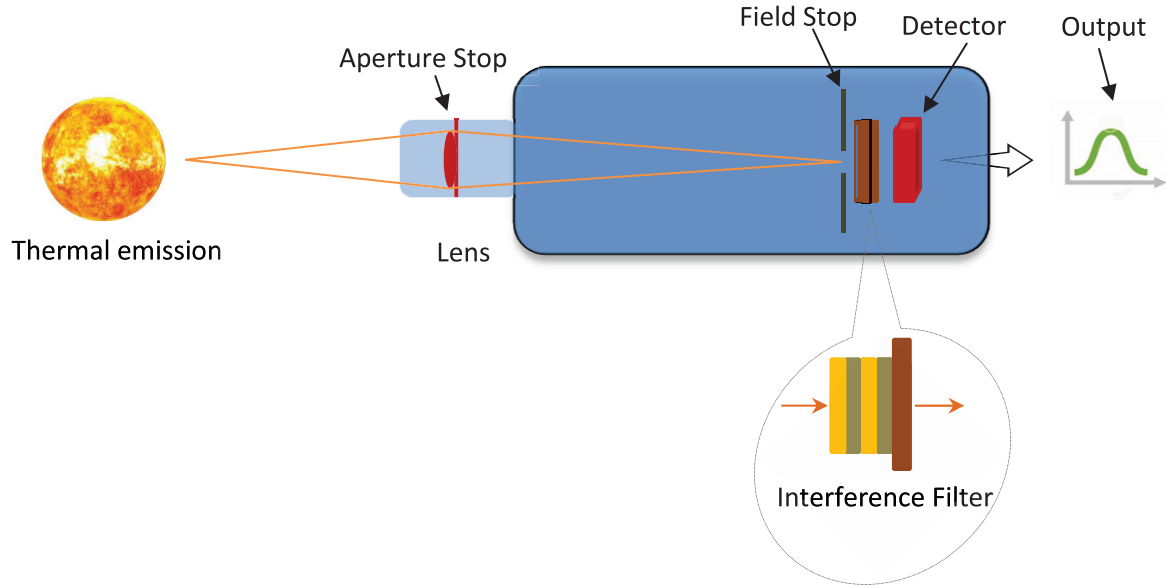


Fig. 1. A linear pyrometer and components.

the output signal is related to the target temperature as explained by its calibration equation in equation (1) [4–7]

$$V = \int_0^{\infty} S(\lambda) L_B(T, \lambda) d\lambda,$$

where V : pyrometer signal; $S(\lambda)$: spectral responsivity; $L_B(\lambda)$: spectral radiance; T : temperature; λ : wavelength.

The linear pyrometer is opto-electrical, owing to the optical and electrical components constituting it. Figure 1 shows the components of a linear pyrometer where the emitted radiation is focused on the field stop with an objective lens, thereby limiting the target size, and the optical interference filter selects the required wavelength range before the radiation is visible to the detector. In measuring the temperature of the thermal source, the thermal emission will pass through the different components of the pyrometer. Hence, the detection of the emission will be affected at each component point, considering the source and the surrounding environment, resulting in the overall performance change of the pyrometer. Characterizing a pyrometer will allow us to quantify these effects.

3 Metrological characterization

Linear pyrometers that are used in the ITS-90 realization have refined designs aimed at decreasing the negative performance effects of small imperfections. Characterization of a pyrometer is the process by which the distinctive properties of pyrometers can be probed and measured. Characterizing a pyrometer allows for quantifying the different properties of the pyrometer. A pyrometer can be characterized by measuring the number of equipment parameters that represent different properties, such as DE, SSE and s , among others. Each of the characterized

parameters is discussed using experimental data of the characterization of the NMISA LP4 and CHINO IR-RST90H linear pyrometers measured at the National Metrology Institute of Japan (NMIJ) and NMISA [2].

3.1 Distance effect (DE)

DE is due to the output change of the radiation thermometer, when the distance between the source and the thermometer changes. This effect is due to the influence of focal lengths on the output of the pyrometer [2]. Hence, it is important to consider the DE when the thermometer is used at a different distance than at which it was calibrated.

Experimentally, the DE is measured by changing the position of the target source in front of the pyrometer or vice versa. For this research, the measurement was done from the shortest distance determined for the pyrometer under test to the longest distance in both directions. The shortest distance was determined for the NMISA LP4 and found to be 595 mm. This is done by focusing the NMISA LP4 on a target without using the focusing knob (which can be opened to the fullest) and moving the NMISA LP4 back and forth. Zero current measurement is done before and after the DE measurement. The DE measurement should be corrected for the zero-current measurement.

The signal at a reference distance must be corrected for DE if the thermometer is used at a different distance as follows:

$$V_c = \frac{V_m}{1 + DE}, \quad (2)$$

where V_c : corrected signal; V_m : measured signal.

Figure 2 shows the result obtained for such a measurement, repeated for three different aperture sizes (namely 6 mm, 12 mm and 24 mm). In the figure, it is shown that above the working distance of the thermometer

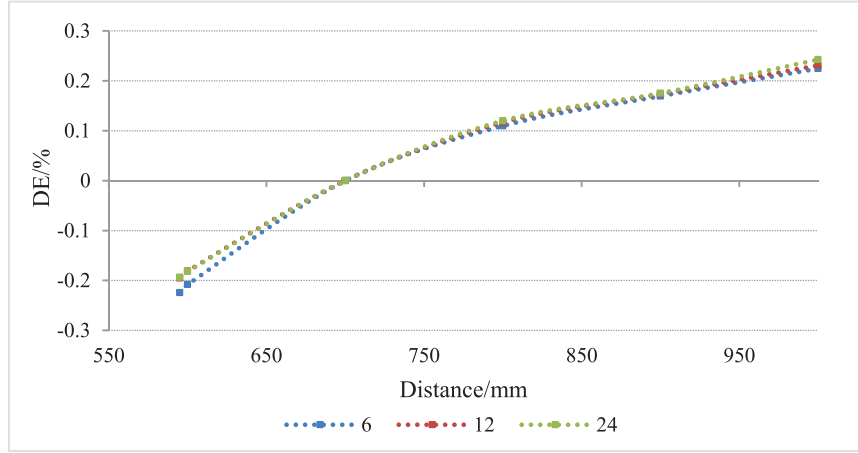


Fig. 2. DE measurement result of NMISA LP4 (at 900 nm) measured at 6 mm, 12 mm and 24 mm aperture sizes.

(700 mm) for any of the apertures used, the longer the distance is the higher the DE will be, thereby forcing the resulting output to decrease. The uncertainty contribution from DE measurement can be estimated from the focus adjustment and distance measurement error. It usually is a very small value.

3.2 Gain ratio (GR)

A radiation thermometer instrument will usually have a few gain settings, for instance, NMISA LP4 has three range settings (R1, R2, R3) and NMISA CHINO IR-RST90H has H, M, and L gain settings. The measurement at a reference fixed point might have been made at a gain setting different from the one used at other measurements, and this prompts us to consider the GR. GR measurement is done to check the reproducibility of the measurement done at each gain setting. The reproducibility of the different gain settings is considered an uncertainty component. It will influence the calibration uncertainty of the linear pyrometer [8].

Figure 3 depicts the range-ratio measurement result of the NMISA LP4 and CHINO IR-RST90H. The uncertainty of the range ratio is determined by the reproducibility of the different gain settings.

3.3 Non-linearity (NL)

The spectral-radiance ratio of black body (BB) radiance at a reference and secondary ITS-90 temperature may be determined through an experimentally determined detector signal ratio, as long as the detector and associated electronics are linear. The NL of a radiation thermometer originates from the non-ideal performance of the detector, electronics or both. Radiation thermometers are often used to assign the radiance temperature of sources using a signal ratio that may differ by five decades or more. Hence, a low uncertainty measurement using such thermometers requires characterization for its linearity. This kind of characterization of the thermometer is critically important when realizing ITS-90 above the Ag point. This kind of characterization is not critical in a temperature range where interpolation is possible [2,9].

NL characterization may be done through three recognized methods, namely superposition, attenuation and the differential or AC method. The experimental procedure to conduct a superposition (signal doubling) NL characterization method involves a radiating source; for example, a furnace and aperture selector device. The radiation thermometer is aligned and focused in front of a radiating BB source at the working distance of the thermometer. The aperture selector is placed in front of the thermometer and the aperture selectively closes the thermometer opening while it measures, in order, fully closed (Φ_0), left side closed (Φ_L), fully open (Φ), right side closed (Φ_R) and fully closed (Φ_0) again. The left closed flux and the right closed flux are approximately equivalent. The zero current value must be taken into consideration when calculating the NL.

$$\Phi_R \approx \Phi_L, \quad (3)$$

$$\left(\frac{\Phi_R - \Phi_L}{\Phi} \right) < 0.2\%, \quad (4)$$

$$NL = \frac{\Phi + \Phi_0 - \Phi_L - \Phi_R}{\Phi - \Phi_0}. \quad (5)$$

The NL is a function of wavelength and photocurrent. The NL for all temperature points in the range of operation may be determined through the signal doubling method from the fixed-point measurement signal and the measured NL values at selected temperature points. The uncertainty of the NL determination can be estimated from the uncertainty of an NL measurement of two consecutive temperature points estimated from the standard deviation data [10]. Figure 4A shows a sample NL measurement at 743 °C and Figures 4B and 4C depict the temperature deviation due to NL and the NL uncertainty determined for the scale realized in the higher and lower temperature ranges respectively. Figure 4B show that the NL has a bigger effect in temperature ranges above the Copper (Cu) point where the scale realization is through extrapolation; however,

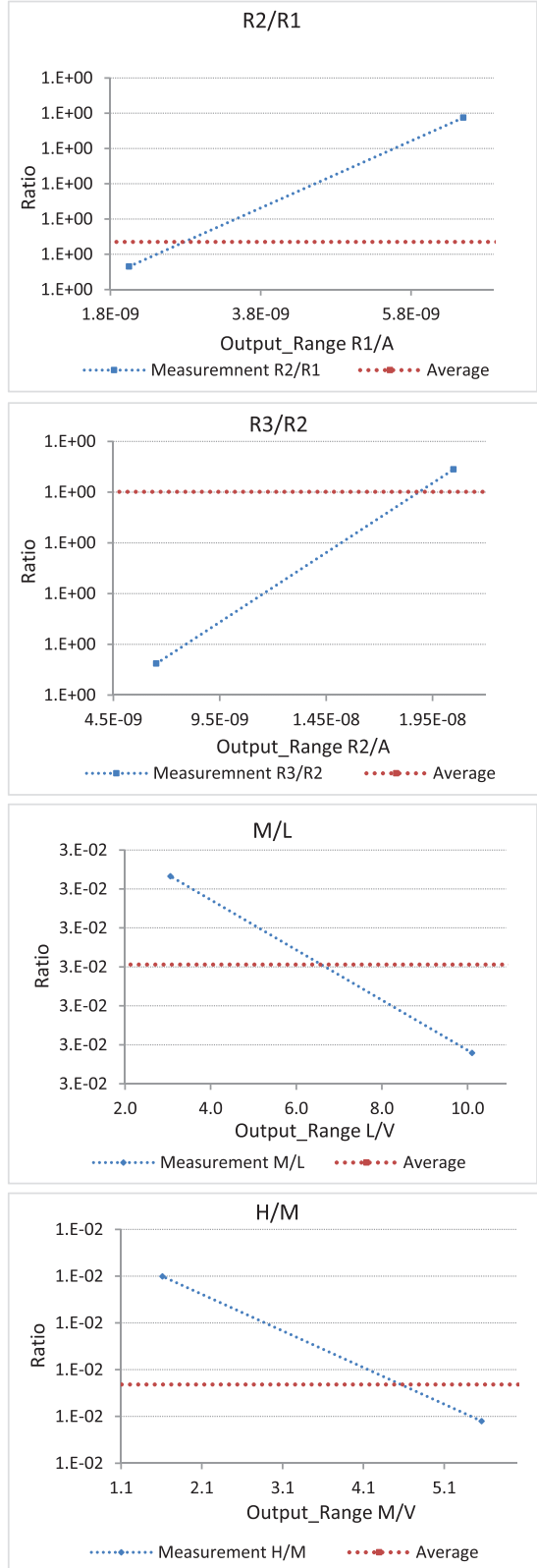


Fig. 3. GR measurement of NMISA LP4 and CHINOIR-RST90H.

as shown in Figure 4C in regions where interpolation is employed, the effect is very small with small temperature deviation and uncertainty.

3.4 Relative responsivity (s)

Radiation thermometers determine the temperature of a radiance source using the detector after the signal is selected through an interference filter. The detector responsivity is dependent on the radiance wavelength, bandwidth (BW), target and surrounding temperature, as well as the amount of radiation. The radiation thermometer spectral responsivity is normally a detector signal response to a radiance detected for the wavelength range it perceives.

The spectral responsivity of a radiation thermometer should be characterized in order to determine the responsivity of the detector to a radiance signal. The spectral responsivity of a radiation thermometer may be measured using a monochromator by comparing it with a reference detector's responsivity. The responsivity of the reference detector is also compared with that of thermopile detectors, whose responsivity is flat in the wavelength region of interest. The spectral responsivity is expressed relative to a reference Si-detector's responsivity [2,9,11]. The relative responsivity is determined as equation (6) and is expressed as a normalized value:

$$s(\lambda) = \frac{I_{LP4}}{I_{Si}}, \quad (6)$$

where s : relative responsivity; I_{LP4} and I_{Si} : measured signals of the NMISA LP4 and the Silicon (Si) reference detector, respectively.

The following are some of the uncertainty components in determining the relative responsivity of a radiation thermometer and the complete discussion can be found in [3].

- Stability of monochromator;
- Reproducibility of scan;
- Thermopile detector;
- Scatter and polarization;
- Wavelength drift of the filter; and
- Out of band response.

The relative spectral responsivity (logarithmic scale) determined for NMISA LP4 from an actual measurement is displayed in Figure 5.

The out-of-band radiation signal of the interference filters used in radiation thermometers should be blocked adequately in order to avoid residual radiation in the wings. The out-of-band blocking should prevent significant errors in the temperature measurement. For instance, the out-of-band blocking at 10^{-5} is usually required for a 10 nm BW signal. Specialized interference filters may be used to make the blocking more effective. In Figure 5 the out of band signal is well blocked confirming that the 900 nm filter will result in very little error originating from the out-of-band signal.

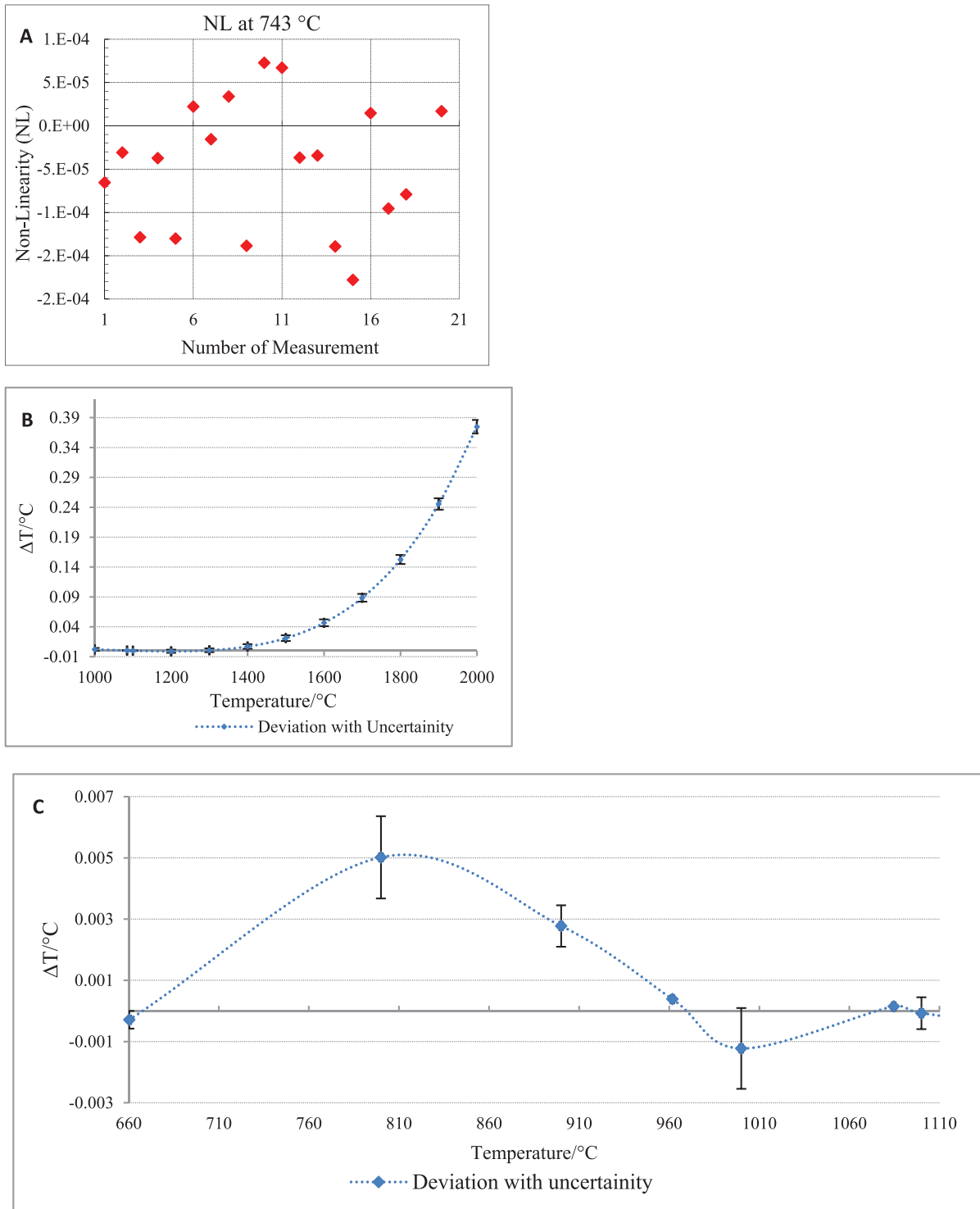


Fig. 4. NL measurement of the NMISA LP4 and associated scale uncertainty.

3.5 Size of source effect (SSE)

SSE is caused by lens aberrations and stray radiation dispersed between the source and field stop of the thermometer. These aberrations depend on how refined the optical design of the thermometer is, especially

concerning the size of the lenses and their relative positions to each other. SSE of a radiation thermometer originates when the radiating sources used during the calibration and the temperature measurement differ in size and uniformity. The photocurrent or voltage measurement at a fixed point should be corrected for

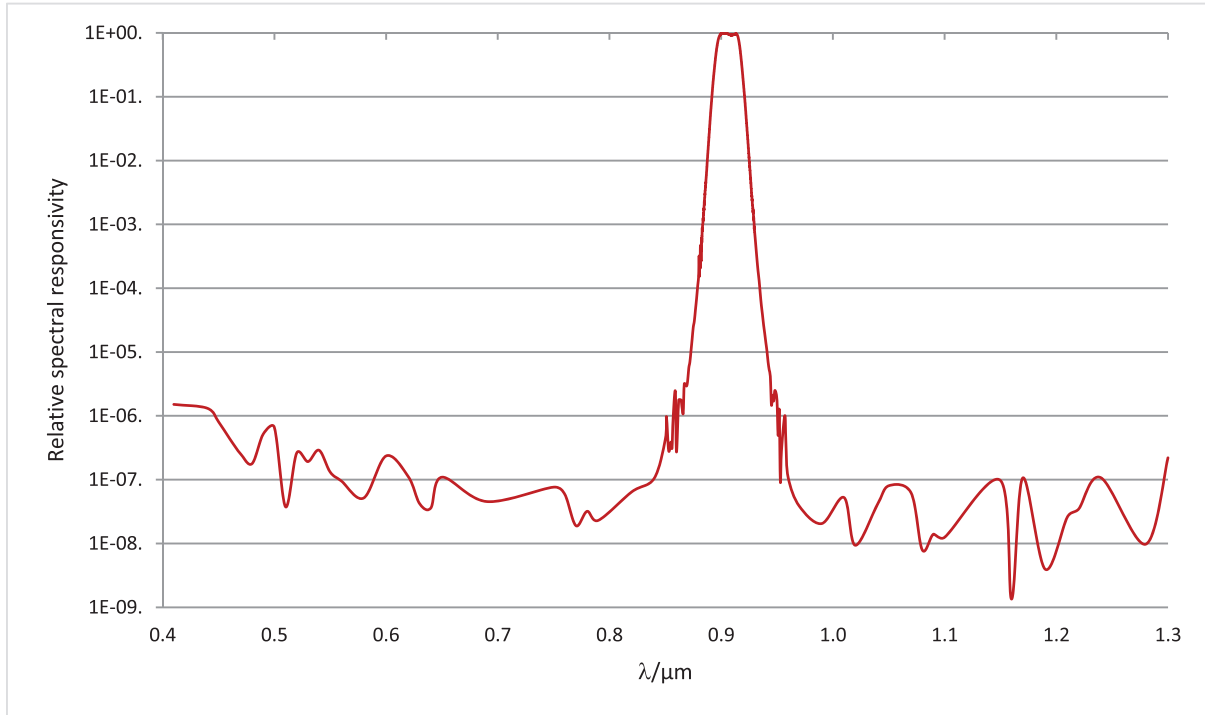


Fig. 5. Relative spectral responsivity of NMISA LP4 measured at NMIJ.



Fig. 6. Different size apertures for SSE measurement (not to scale).

the SSE if the effect is larger. The increase in the signal with the size of the source, even when uniform in temperature, requires SSE corrections to be applied when calibrating radiation thermometers. In other cases, the SSE will be included in the uncertainty [12–16].

SSE is critical in precision measurement and should be determined and considered when the aperture size of the radiation source to be measured is different from the reference aperture used to calibrate it. Different methods are used to evaluate the SSE, namely the indirect and direct methods. These are discussed below.

Direct Method

In the direct method, a radiation thermometer under test views a uniform circular source of varying diameters. The thermometer is focused on a uniform radiance source whose aperture may easily be changed using differently sized apertures (shown in Fig. 6) and the signal is recorded at each changing aperture. The SSE in the direct method may easily be determined by taking the ratio of the measured signal at a given diameter aperture to that at the largest diameter aperture as shown in equation (7). Figure 6

depicts the different size apertures that may be used to measure SSE through the direct method.

$$\text{SSE} = \frac{V_m}{V_{\max}}. \quad (7)$$

Indirect Method

In the indirect method, the radiation thermometer views a uniform circular source with a central obscuration slightly larger than the target size of the thermometer. The obscuration may be from a differently sized black silk printed on a circular quartz disk framed in front of the uniform source. For each obscuration size, two signal measurements are taken. The first measurement is taken by focusing through the obscuration and the second by focusing through the clear side, as shown in Figure 7. The SSE in the indirect method is given by the ratio of the signal measured through the obscuration to the one made on the clear side. This method results in a lower-uncertainty SSE and thus makes it preferable.

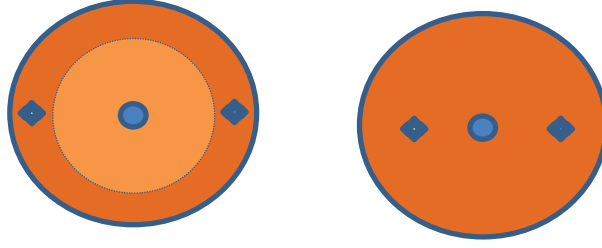


Fig. 7. Indirect method SSE measurement in the case of wide bright area and narrow bright area.

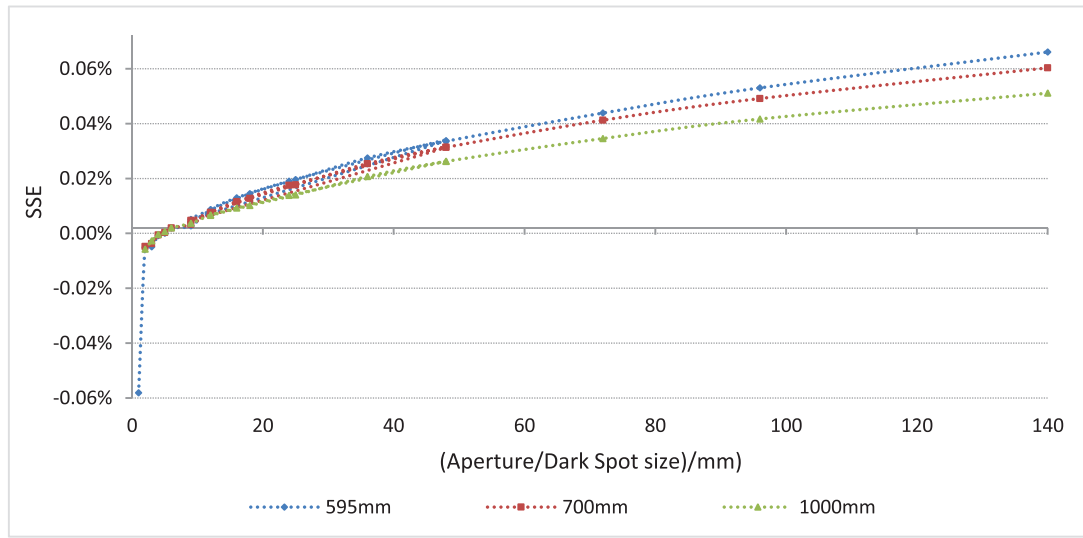


Fig. 8. SSE of NMISA LP4 determined using the indirect method.

The uncertainty in determining the SSE is contributed from the following parameters and the complete discussion can be found in [3].

- Reference black spot;
- Aperture or black spot size;
- Black spot measurement output;
- Bright area measurement output;
- Measuring distance; and
- Reproducibility of determining the SSE.

Typical SSE is less than 1 and the uncertainty is at a level of 0.005%. If the SSE is not corrected for the reason that it is insignificant, it will be considered an uncertainty. The signal correction for the SSE is as follows:

$$V_c = \frac{V_m}{1 + \text{SSE}}. \quad (8)$$

Zero-current measurement should be performed before and after SSE measurement and the signal should be corrected. Figure 8 indicates an indirect method of SSE measurement of NMISA 900 nm wavelength LP4 at various distances from the target (at 595, 700 and 1000 mm) using both aperture and dark spots. The 6 mm sized dark spot is used as a reference dark spot size corresponding to the fixed-point BB source aperture size, where the fixed-point

realization is made. The figure depicts an increase in SSE for an increase in aperture/dark spot size above the reference dark spot size.

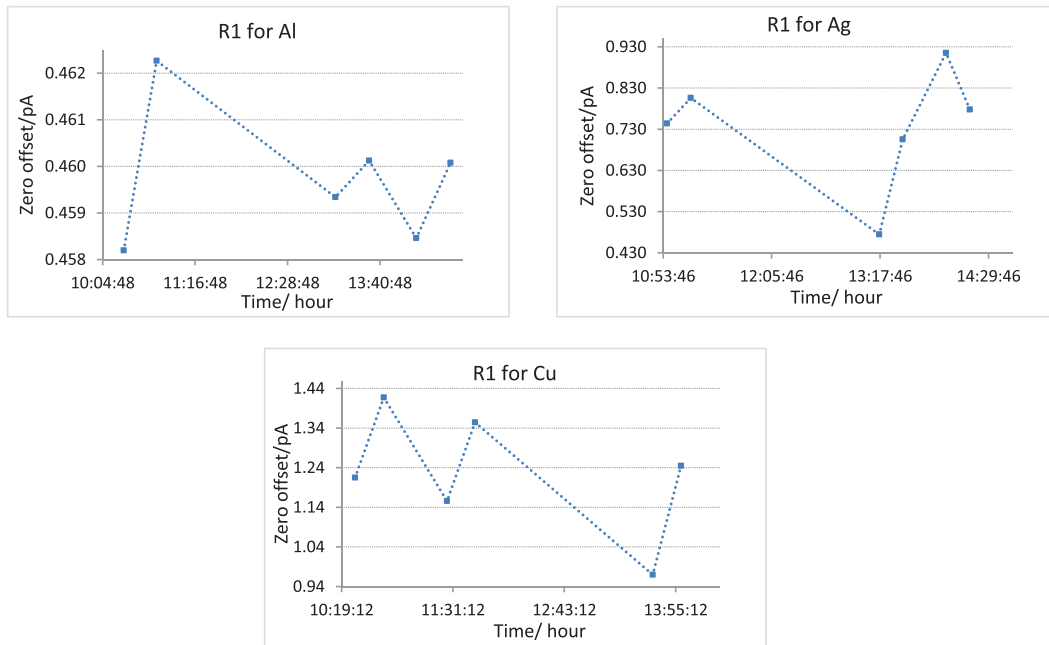
3.6 Temperature coefficient

Surrounding temperature is known to affect the performance of a radiation thermometer. The optical detectors, interference filter, blocking filter and feedback resistance of the operational amplifier performance change with the surrounding temperature change. The cumulative effect is termed the temperature coefficient of the radiation thermometer. It may be determined (roughly) through experimental values taken at two different room temperature points by using equation (10) and the radiation thermometer signal can be corrected for the surrounding temperature effect as in equation (9) [17]:

$$V_c = \frac{V_m - V_0}{GR * (1 + \alpha(T_{amb} - 22))}, \quad (9)$$

$$\alpha = \frac{V_{T2} - V_{T1}}{T_2 - T_1}, \quad (10)$$

A. NMISA LP4 linear pyrometer range R1 measured drift at fixed points of aluminum (Al), Ag, and Cu.



B. NMISA CHINO IR-RST90H range L and M measured drift at fixed points Zinc (Zn), Al, and Cu.

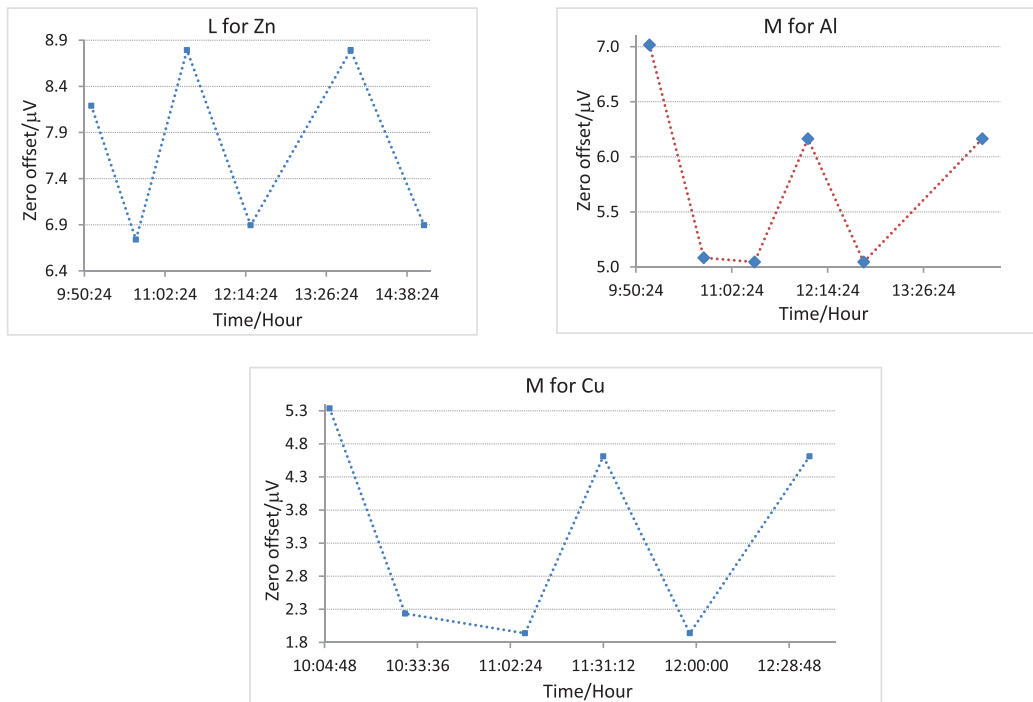


Fig. 9. Zero-offset measurement result of NMISA LP4 and CHINO IR-RST90H measured at NMISA.

Table 1. Low temperature scale uncertainty contributions.

Temperature/°C	$u(k=1)/^{\circ}\text{C}$	
	NL	SSE
660	0	0.004
800	0.0004	0.008
900	0.0004	0.007
962	0	0.007
1000	0.0004	0.006
1085	0	0.008
1100	0.0001	0.009

where α : temperature coefficient; T_{amb} : Ambient temperature; V_{T1} and V_{T2} : voltage measured at temperatures T_1 and T_2 respectively; GR : gain ratio; V_o : zero current voltage.

This effect is minimized by putting the surrounding temperature-sensitive components of the radiation thermometer in a thermostat where their surrounding temperature may better be controlled. Linear pyrometers such as NMISA LP4 are designed with such features, and this improves the temperature measurement accuracy of the thermometer.

3.7 Zero-offset drift

It is especially important to measure the zero-offset drift of the thermometer every time a fixed-point measurement or a characterization of a thermometer is conducted. The zero offset drift is determined by the measurement of the zero-current voltage before and after the fixed-point measurement or characterization. The zero offset is related to the electronic drift of the amplifier and the measurement signal should be corrected for this kind of drift [3]. The zero-offset drift behavior of a liner pyrometer is mainly dependent on the design of the amplifier for instance in Figure 9 option A it is shown that the zero-offset for LP4 increases with target temperature while in option B with an increase in target temperature the offset decreases for the CHINO.

4 Uncertainty contribution in scale realization

Realizing ITS-90 scale using radiation thermometer can be achieved with three to four ITS-90 fixed point measurement or with one ITS-90 fixed point measurement and Relative responsivity measurement. A 900nm LP4 was measured at Al, Ag, and Cu ITS-90 fixed points and relative responsivity was measured. ITS-90 scale was realized from 660 °C to 1100 °C and from 1000 °C to 2000 °C. The uncertainty contributions of some of the characteristic parameters discussed in Section 3 are discussed quantitatively in the following subsections.

4.1 Number of ITS-90 fixed points

The 900 nm LP4 was measured at Al, Ag, and Cu ITS-90 fixed points to realize ITS-90 scale in the lower temperature

range of 660 °C to 1100 °C. The characterized NL and SSE are the main contributors in the realized scale uncertainty.

The NL was characterized at selected temperature points in the temperature range of 660 °C to 1100 °C. The NL and its uncertainty contribution for all the temperature points in the scale was determined as discussed in Section 3.3. The SSE and its uncertainty contribution is determined as discussed in Section 3.5. The following table shows the uncertainty contribution determined in realizing ITS-90 in the lower temperature range.

Table 1 shows that the uncertainty contribution from NL is lower than the contribution from the SSE. The NL & SSE uncertainty values vary with a small margin within the temperature range the scale is realized.

4.2 ITS-90 fixed point & responsivity measurement

The 900 nm LP4 was measured at Cu ITS-90 fixed point to realize ITS-90 scale in the higher temperature range of 1000 °C to 2000 °C. The characterized NL, SSE, GR and s have all contributed in the realized scale uncertainty.

The NL was characterized at selected temperature points in the temperature range of 1000 °C to 2000 °C. The SSE and GR characterization and uncertainty determination method is discussed in Section 3.

The relative responsivity of the thermometer was measured, and the corresponding uncertainty was determined as discussed in Section 3.4. The following table shows the uncertainty contribution determined in realizing ITS-90 in the higher temperature range.

Table 2 lists the uncertainty contribution from the characterized parameters in the realized scale. The uncertainty contribution from the SSE, NL, s and GR seem to increase with temperature especially in the extrapolated region (above Cu point). The uncertainty contribution from s is higher than the contributions from the other parameters.

5 Conclusion

This paper described the different equipment parameters that characterize infrared thermometers. It also discussed the characterization method used based on experimentally determined measurement data. Furthermore, the paper describes the uncertainty contributions from the major characterized parameters in the ITS-90 scale realizations.

The experimental results showed the effect of the characterization results on the accuracy of the thermometer when measuring temperature. For instance, the relative responsivity measurement result was critical when the instrument was calibrated for high-temperature applications. A refined responsivity measurement data in conjunction with a fixed-point measurement at the Cu point are the only parameters that provided traceability for the calibration of the instrument above the Cu point and, hence, its characterization accuracy was critical. Additionally, the accuracy of the NL measurement was a serious point of uncertainty, especially at elevated temperature measurements. Since most values were extrapolated above the Cu point, unrefined characterization values were amplified in the higher-temperature range and hence the effect was high.

Table 2. High temperature scale uncertainty contributions.

Temperature/°C	$u(k=1)/^{\circ}\text{C}$			
	SSE	NL	s	GR
1000	0.007	0.0008	0.02	0.004
1084.62	0.007	0	0	0
1200	0.009	0.0010	0.03	0.006
1400	0.012	0.0036	0.09	0.010
1600	0.015	0.0077	0.16	0.012
1800	0.019	0.0126	0.24	0.015
2000	0.022	0.0222	0.34	0.018

The document described that some of the characterized parameter results were used to correct the measurement signal, and some were used as uncertainty components. The careful characterization and evaluation of these parameters were critical, as they might affect temperature measurement results and their uncertainty. The document also described some of the responsivity and SSE measurements contributing to uncertainties that should be determined as accurately and practicable as possible so as not to affect the high-accuracy measurement capability of the thermometer.

The quantitative demonstration on the uncertainty contributions from the major parameters in the realized scales were presented. The uncertainty contributions from NL, SSE, s , and GR parameters were dominant when realizing scale in the higher temperature range via extrapolation. In realizing a scale in the lower temperature scale via interpolation, the uncertainty contributions from NL and SSE were not as dominant in the higher temperature case.

Note to the reader: The equation 1 was corrected in the Erratum Int. J. Metrol. Qual. Eng. 14, 6 (2023) <https://doi.org/10.1051/ijmqe/2023007>, published on 1 may 2023.

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