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Realization of Radiance Temperature Scale from 500 K to 1,250 K by a Radiation Thermometer with a Thermal Detector

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Abstract The radiance temperature scale from 500 K to 1,250 K was realized by using a thermal detector transfer reference thermometer (TRT) with its spectral response centered at 3.9 μm. The TRT is calibrated at the four fixed points of tin, zinc, aluminum, and silver, and the scale is obtained by interpolation with Wien's equation, Planck's equation, the Sakuma–Hattori (SH) formula, and a Planckian SH (PSH) formula. The interpolation uncertainty dramatically decreases as the physical model for the interpolation equations becomes more realistic. The uncertainty of the scale is evaluated, including the repeatability of the calibration and the long-term stability of the TRT over a period of more than 20 months. The realized scale over part of the interpolation region was validated by comparing it with the ITS-90, resulting in excellent agreement within 0.09 K. The resulting uncertainty of the realized scale varies from 0.06 K to 0.38 K ($k = 1$), depending on the temperature.

Keywords Calibration · Fixed point · Interpolation equation · Temperature scale

1 Introduction

There are two schemes to realize the radiance temperature scale that differ from one another in the type of thermometer used to determine the reference temperature of the blackbodies; one uses a radiation thermometer and the other relies on a contact thermometer. The radiation thermometer method is advantageous when the blackbodies depart from ideal behavior. As long as the spectral band of the reference radiation thermometer is the same as that of the thermometer under test, the blackbody quality

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does not result in any systematic effect. On the other hand, the approach that uses a contact thermometer to establish the reference temperature is sensitive to systematic errors caused by the non-ideality of the blackbodies, so it is most useful in the low-temperature range where blackbodies and contact thermometers of high quality are available [1–3].

In the former scheme, the radiation thermometer can be calibrated either by the fundamental method or by the interpolation method. In the fundamental method, the spectral responsivity of the thermometer is calibrated. In practice, however, the accurate calibration of the spectral responsivity is a challenging task, especially in the wavelength range beyond 2 μm. Thus far, the fundamental method has been limited to the high-temperature range by using thermometers with peak spectral sensitivity below 1.6 μm. Sakuma et al. used an InGaAs thermometer to realize the radiance temperature scale above 427 K [4]. Chu et al. also used an InGaAs thermometer to verify the accuracy of the NPL blackbody reference source from 156°C to 600°C [5].

The interpolation method, in contrast, allows the choice of the spectral band to be independent of the realization of the spectral responsivity scale. Therefore, the low-temperature range below 500 K is usually realized in the interpolation method by using thermometers with peak spectral response at wavelengths longer than 2 μm. The obstacle to the interpolation method, however, is that several fixed points are required to evaluate the coefficients of the interpolation equation. Furthermore, the uncertainty in the interpolated and extrapolated regions is determined not only by the measurement uncertainty at the fixed points, but also depends on the interpolation equation used. Therefore, the uncertainty should decrease as the interpolation equation becomes more physically realistic.

In this article, we describe a realization of the temperature scale from 500 K to 1,250 K by the interpolation method using a pyroelectric detector transfer reference thermometer (TRT) developed by Heitronics under the TRIRAT project [6]. This TRT uses two spectral bands to cover the temperature range from 223 K to 1,273 K, although we have used only the spectral band near 3.9 μm for the medium temperature range for the work reported here. We calibrated the TRT at the fixed points of tin, zinc, aluminum, and silver, and interpolated the temperature scale using four different interpolation equations based on different physical models to verify the correlation between the interpolation uncertainty and the physical models. We validated the new scale over part of the interpolation region by comparison with a temperature scale based on a spectrally characterized Si-based reference thermometer. The long-term stability of the TRT was also evaluated over a period of more than 20 months.

2 Interpolation Equations

When we realize a temperature scale using a radiation thermometer and multiple fixed-point blackbodies, the choice of interpolation equation is important, especially in validating the scale in both the interpolated and extrapolated regions.

The simplest equation comes from Wien's approximation of Planck's equation:

$$S = a_1/\exp\left(\frac{c_2}{a_2 T}\right), \tag{1}$$

where c_2 is the second radiation constant, 0.014388 m · K, and a_1, a_2 are the fit coefficients. Equation 1 is effective only when Wien's approximation is valid and the spectral bandwidth is narrow enough to neglect the temperature dependence of the effective wavelength. Planck's interpolation equation can be obtained by adding (−1) to the denominator of Eq. 1:

$$S = \frac{a_1}{\exp\left(\frac{c_2}{a_2 T}\right) - 1} \tag{2}$$

By considering the temperature dependence of the effective wavelength for a finite spectral bandwidth, we obtain the Sakuma–Hattori (SH) formula [7] with the additional coefficient a_3:

$$S = \frac{a_1}{\exp\left(\frac{c_2}{a_2 T + a_3}\right)}. \tag{3}$$

Finally, the Planckian SH (PSH) formula is obtained by adding (−1) to the denominator of Eq. 3:

$$S = \frac{a_1}{\exp\left(\frac{c_2}{a_2 T + a_3}\right) - 1}. \tag{4}$$

We expect Eqs. 2 and 4 to represent more realistic physical models, but they require, compared to Eqs. 1 and 3, a more complex nonlinear fitting procedure to determine the coefficients. In all cases, the coefficient a_2 is related to the spectral band of the radiation thermometer.

3 Instruments

3.1 Transfer Reference Thermometer

The TRT (Heitronics, Germany, Model TRT-2) operates in two temperature ranges: the low-temperature (LT) range from 223 K to 573 K and the medium temperature (MT) range from 423 K to 1,273 K. The spectral response is from 8 μm to 14 μm for the LT range and is centered at 3.9 μm with a bandwidth of 0.4 μm for the MT range. The TRT adopts a pyroelectric detector and zinc selenide optics to cover the spectral range from 3 μm to 15 μm. The field of view is 5.8 mm in diameter at a measuring distance of 390 mm. The TRT can display the output in terms of temperature or radiation intensity. When measuring the fixed-point blackbodies, the intensity output is

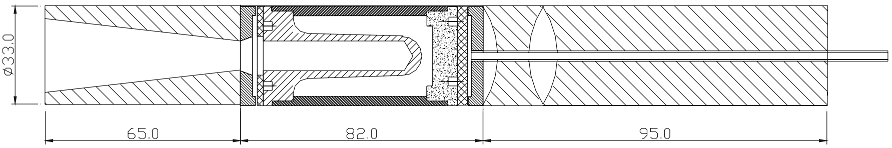

Fig. 1 Drawing of a fixed-point cell installed in a furnace

acquired using a computer via a RS-232C interface with a response time of 3 s, which is controlled by KRISS-designed software.

3.2 Fixed-point Blackbodies

Four fixed-point cells filled with tin, aluminum, zinc, and silver are used in the experiment. The cells consist of a crucible and a cavity made of high-purity graphite. The tin and aluminum cells were supplied by Isotech (UK) and filled by KRISS with high-purity metal of 6N purity to about 90% of the cell volume of 18 cm^3. The zinc- and silver-point cells were constructed and filled by KRISS. The cells are kept in an argon environment, as they are encapsulated in an Inconel-housing to which the gas tube is connected. The cell can be replaced by another cell filled with different metal by disassembling it from the housing.

To realize the melting and freezing points, the cell housing is installed in the center of a furnace supplied by Isotech (Model: 979 Pegasus R). Figure 1 shows how the fixed-point cell is installed in the furnace. The front side of the cell housing is insulated by a cylindrical block with a conical view port, while the rear side has two blocks of insulation with holes for gas tubes. The cavity is designed in the shape of a cylindrical cone with an apex angle of 120°, with the emissivity calculated to be 0.9995 ± 0.0002.

4 Results

The TRT is calibrated in the MT range by using the tin (505.078 K), zinc (692.677 K), aluminum (933.473 K), and silver (1234.93 K) fixed-point blackbodies. Figures 2 and 3 show the measured melting and freezing curves of the zinc and silver points, respectively. The silver point shows the characteristic curve of pure metals, including supercooling of 4.2 K before the freezing plateau, while the zinc point does not show any significant supercooling. We realized two melts and freezes per day for each fixed-point cell before cooling the furnace to replace the cell.

Table 1 summarizes the results of the fixed-point calibration of the TRT. The plateau signals are obtained by averaging the data over most of the flat part of the melting and freezing plateaux, which corresponds to 60% of each plateau. Their standard deviations are listed in the last column of Table 1. The results show that the differences between the melting and freezing signals of tin and zinc are significant, considering the plateau signal reproducibility of about 10 mK. The systematic difference is expected to be caused by the size-of-source effect (SSE) of the thermometer [6]. During melting, the temperature outside of the blackbody aperture is higher than that of the cavity, while

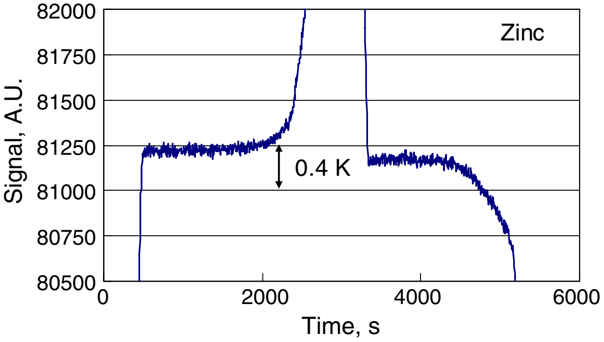

Fig. 2 Measured melting and freezing curve of the zinc point

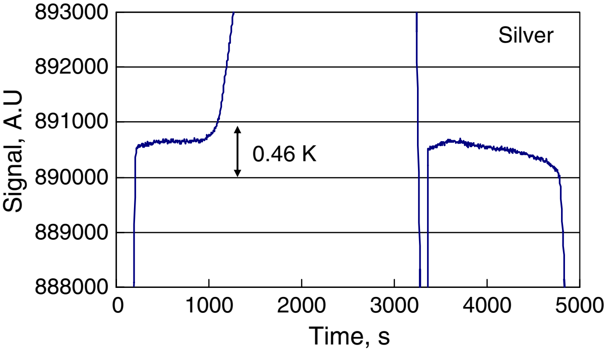

Fig. 3 Measured melting and freezing curve of the silver point

during freezing the outside temperature is lower than that of the aperture. Although the minimum target size (5.8 mm diameter) claimed from geometric optics is smaller than that of the blackbody aperture (10 mm), the radiation emitted from the furnace assembly outside of the aperture can affect the melting and freezing plateau signals. This means that the influence of the SSE can be cancelled by averaging the melting and freezing plateau signals of a fixed-point blackbody.

The TRT can be used to establish a temperature scale by fitting the four different interpolation equations (Eqs. 1–4) to the measured fixed-point signals (variable S) of Table 1 and the defined temperatures (variable T) of the fixed points. The emissivity-corrected signals have been used to determine the coefficients of the equations. Since, the number of fixed points is greater than the number of coefficients for all four equations, a least squares method can be applied. Figure 4 shows the temperature differences of the interpolation equations expressed with respect to Planck's equation, Eq. 2. It is surprising that Planck's equation with only two parameters agrees within 0.02 K with the PSH formula with three parameters.

The 'goodness-of-fit' corresponding to the quadrature sum of the residuals is summarized together with the coefficients of the four interpolation equations in Table 2. The residuals dramatically decrease as the equation becomes more realistic by adding

Table 1 Fixed-point calibration data of the transfer standard thermometer

Fixed points	Melting/freezing	Plateau signal (TRT display)	Average (emissivity corrected)	Std. dev. (K)
Tin (505.078 K)	M	11094	11086 (11092)	0.060
	F	11082		
	M	11094		
	F	11075		
Zinc (692.677 K)	M	81239	81206 (81246)	0.051
	F	81188		
	M	81225		
	F	81171		
Aluminum (933.473 K)	M	327398	327392 (327556)	0.030
	F	327413		
	M	327332		
Silver (1234.93 K)	F	327425	890655 (891100)	0.023
	M	890643		
	F	890727		
	M	890625		
	F	890625		

Table 2 Goodness-of-fit for the four interpolation equations

Interpolation equations	Coefficients	Goodness-of-fit (K)
Wien	$a_1 = 1.8267 \times 10^7$ $a_2 = 3.8423 \times 10^{-6}$	5.50
Planck	$a_1 = 1.7015 \times 10^7$ $a_2 = 3.8831 \times 10^{-6}$	0.033
Sakuma–Hattori	$a_1 = 2.1020 \times 10^7$ $a_2 = 3.6226 \times 10^{-6}$ $a_3 = 7.7836 \times 10^{-5}$	0.99
Planckian Sakuma–Hattori	$a_1 = 1.6993 \times 10^7$ $a_2 = 3.8854 \times 10^{-6}$ $a_3 = -8.5266 \times 10^{-7}$	0.002

(-1) to the denominator, as shown in Eqs. 2 and 4. The goodness-of-fit decreases from 5.50 K to 0.033 K as Wien's equation (Eq. 1) is replaced with Planck's equation (Eq. 2) and decreases from 0.99 K to 0.002 K as the SH formula (Eq. 3) is replaced with the PSH formula (Eq. 4). Introducing (-1) in the denominator of the equations results in much more improvement in the fit than introducing an additional parameter to account for the temperature dependence of the effective wavelength. Furthermore, note that a_2 of Eqs. 2 and 4 is closer to the TRT spectral band of 3.9 μm specified by the manufacturer.

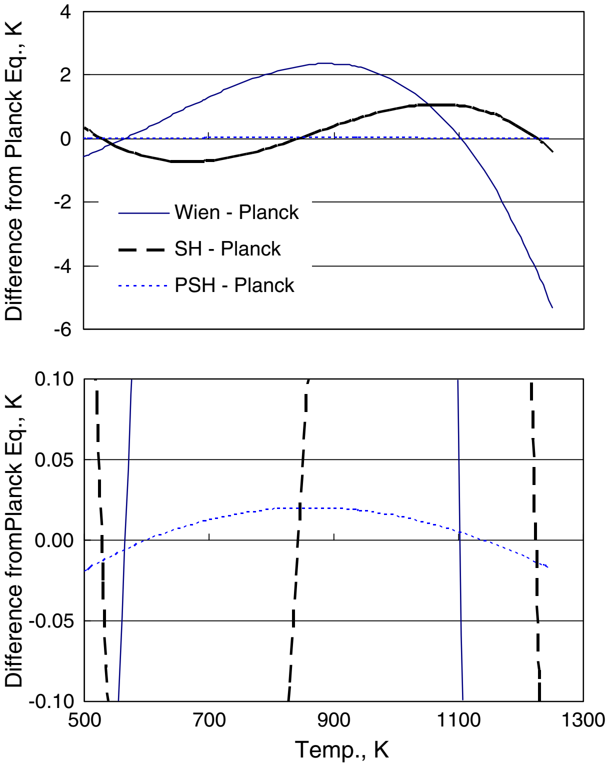

Fig. 4 Temperature scale differences of the three interpolation equations relative to Planck's equation

The results of Fig. 4 and Table 2 show a clear correlation between the interpolation uncertainty and the physical models: the interpolation uncertainty decreases as the physical model for the interpolation equation becomes closer to the physical reality. Such a correlation can be observed only when the uncertainty of the TRT and its calibration at the fixed points is sufficiently low to resolve the approximations in the physical models of the interpolation equations. The accuracy of the calibration increases with the number of fixed points and, accordingly, the easier it becomes to resolve the differences between the interpolation equations. We conclude from our observations that four fixed points are sufficient to resolve the difference between the interpolation equations and to evaluate the accuracy of the TRT calibration.

Finally, the temperature scale disseminated by the TRT is obtained by interpolation using Planck's equation with the coefficients shown in Table 2 for the temperature range from 500 K to 1,250 K. The main contributions to the uncertainty of the scale arise from the fixed-point realizations, the interpolation, and the repeatability of the calibration. The component of the fixed-point realization includes contributions due to the impurity of the metal, deviations from ideal blackbody behavior (emissivity <1), and ambiguity of the plateau signals, which is estimated to be 0.05% in terms of radiance. The interpolation uncertainty is estimated from the goodness-of-fit for

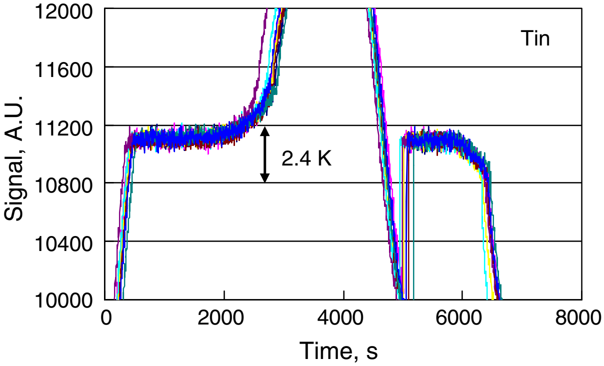

Fig. 5 Repeatability measurement of the tin-point realization

Table 3 Repeatability of the freezing signal for the tin point measured during a week

Experiment No	Freezing signal
1	11091
2	11098
3	11088
4	11088
5	11095
6	11087
7	11087
8	11094
Average	11091
Rel. std. uncertainty (%)	0.014
Std. uncertainty (K)	0.010

Planck's equation in Table 2 and the scale difference between Planck's equation and the PSH formula in Fig. 4. Repeatability of the fixed-point calibration was examined by successive measurements using the tin-point blackbody; we realized the melting and freezing curves eight times during one week, and the results are shown in Fig. 5 and in Table 3. The repeatability of the freezing signals is 0.014%, which is equivalent to 0.01 K at the tin point. We assume that the repeatability uncertainty propagates to other temperatures in terms of radiance. Table 4 summarizes the uncertainty of the realized temperature scale. Without considering the long-term stability, the combined standard uncertainty of the temperature scale ranges from 0.02 K to 0.13 K.

To evaluate the long-term stability of the scale, we repeated the calibration of the TRT at the tin and silver points over a long time scale: the tin point was measured over a period of 23 months and the silver point over 10 months. The results are shown in Fig. 6 as the relative change of the TRT signal at the tin and silver points. Note that the signal drift at the silver point shows the same trend as that at the tin point,

Table 4 Uncertainty of the realized temperature scale

Uncertainty components	Temperature (K)						
	505.08	600	692.68	800	933.47	1100	1234.93
	Standard uncertainty (K)						
Fixed point	0.02	0.03	0.04	0.05	0.07	0.09	0.12
Repeatability	0.01	0.01	0.02	0.03	0.03	0.05	0.06
Interpolation	–	0.04	–	0.04	–	0.04	–
Combined ($k = 1$)	0.02	0.05	0.04	0.07	0.08	0.11	0.13
Long-term stability	0.06	0.08	0.11	0.15	0.20	0.28	0.36
Combined ($k = 1$)	0.06	0.10	0.12	0.17	0.22	0.31	0.38

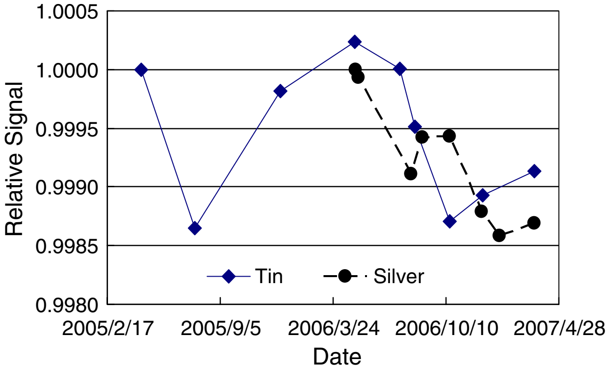

Fig. 6 Long-term stability measurement of the tin and silver points

which indicates that the long-term drift originates from the TRT. During 10 months, the drift did not exceed 0.15%, which corresponds to a standard uncertainty of 0.06 K and 0.36 K for the tin and silver points, respectively, assuming a rectangular probability distribution. The combined standard uncertainty of the realized temperature scale, including the long-term stability, is listed in the last row of Table 4 and varies from 0.06 K to 0.38 K over the temperature range.

The temperature scale is disseminated by calibrating radiation thermometers from customers using transfer standard blackbodies with large apertures. Therefore, the uncertainty of the dissemination includes the temperature instability of the transfer blackbody and the differences caused by the SSE.

5 Validation of the Temperature Scale

KRISS maintains the national temperature standards above 600 K by the fundamental method (spectrally characterized detector), using a model LP4 (IKE, Germany) reference radiation thermometer with a Si detector. The spectral responsivity of the LP4

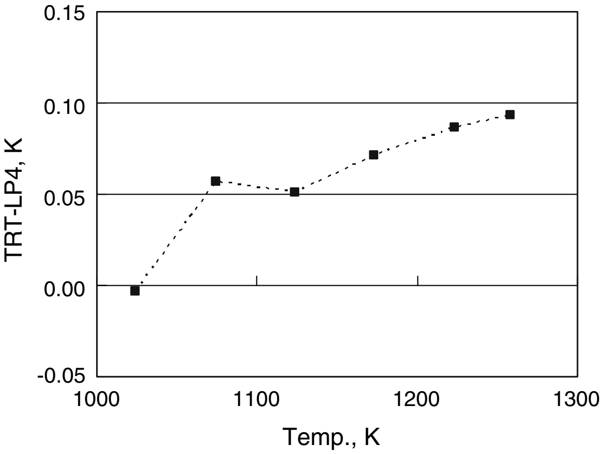

Fig. 7 Temperature differences between the scale using the TRT and the scale using the LP4

is measured using a spectral responsivity comparator consisting of a double-grating monochromator, tungsten-halogen lamp, and a single-element Si reference detector. The Si reference detector is calibrated against a Si trap detector that is calibrated using well-prepared laser beams traceable to the KRISS absolute cryogenic radiometer. Following the definition of the ITS-90, the LP4 is calibrated using the KRISS reference silver and copper-point blackbodies. The new temperature scale from 500 K to 1,250 K realized by the TRT partly overlaps the scale maintained by the LP4. To validate the new scale, we compared the two scales above 1,023 K using a blackbody formed by a dummy fixed-point cell, without any metal filling, installed in the same furnace as shown in Fig. 1. The temperature difference between the two scales is depicted in Fig. 7. The difference increases from −0.003 K at 1,024 K to +0.09 K near the silver point, but remains less than the overall uncertainty of the TRT and the LP4.

6 Conclusion

We realized the radiance temperature scale from 500 K to 1,250 K by calibrating a thermal detector TRT using the tin, zinc, aluminum, and silver-point blackbodies. Four different interpolation equations (Wien's equation, Planck's equation, SH formula, and PSH formula) were tested, and the goodness-of-fit values in terms of Chi-square were 5.5, 0.033, 0.98, and 0.002 K, respectively. The correlation of the interpolation uncertainty with the accuracy of the physical models was verified. The scale realized using Planck's equation has a standard uncertainty from 0.06 K to 0.38 K, including the repeatability of the fixed-point calibration and the long-term stability evaluated over a period of more than 20 months. Comparison of the interpolated scale of the TRT with the ITS-90 scale using the LP4 in the overlapping range from 1,023 K to 1,258 K resulted in agreement within the combined uncertainty of the TRT and the LP4.

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