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Long-Term Stability of 0.65-μm Radiation Thermometers at NMIJ

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Abstract Narrow-band radiation thermometers with center wavelengths near 0.65 μm are frequently used as standard thermometers at high temperatures. The long-term stability of ten Topcon 0.65-μm radiation thermometers was assessed at NMIJ by using fixed-point blackbodies and spectral responsivity measurements. Most of the changes are due to shifts in the center wavelength of the interference filters to longer wavelengths. Even when the center wavelengths shifted, the filter widths and transmittances remained quite stable for some radiation thermometers, but one was found for which the bandwidth increased from 15.7 to 17.2 nm and the transmittance decreased by 6%. Three Barr filters were found to be very stable in wavelength. The output signals of 0.65-μm Topcon radiation thermometers were within 2% · year^{-1} without correcting for the wavelength change and within 0.2% · year^{-1} after the correction. Keeping the objective lens clean is very important for radiation thermometers. Large output decreases were observed in early 2000 for many radiation thermometers at NMIJ. The output changes were as large as 1% and were recovered by cleaning the objective lens.

Keywords Calibration · Contamination · Fixed-point blackbody · Long-term stability · Radiation thermometer · Silicon detector · Wavelength shift

1 Introduction

Topcon 0.65-μm radiation thermometers [1] are used as standard radiation thermometers at high temperature. Their long-term stability is an important component of

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the uncertainty budget. The long-term stability of absolute radiometers was reported at a previous meeting [2]; however, little information is available about the long-term stability of radiation thermometers. Instability comprises both spectral and gain components. We studied the long-term stability of ten Topcon radiation thermometers by assessing the spectral component with a monochromator system and the gain component using fixed-point blackbodies of silver and copper.

2 Measurements

2.1 Topcon Radiation Thermometers

Topcon 0.65-μm radiation thermometers are designed to measure sources within the temperature range from 900 to 3,000°C. The measuring distance is from 200 mm to infinity. The minimum target size at 250 mm distance is 1 mm in diameter for thermometers RT1, RT2, and RT4 and is 0.5 mm for the other thermometers. The interference filter used to define the measuring wavelength was a W-type metal film for thermometers RT1, RT2, and RT3; a multi-layer dielectric film type for thermometers RT4, RT5, RT6, and RT7; and a hard-coating film type for thermometers RT8, RT9, and RT10 as shown in Table 1. An additional interference filter was used to suppress the out-of-band response of the latter seven thermometers.

2.2 Procedures

2.2.1 Monochromator System

A 150-W halogen lamp, a double-grating monochromator with a focal length of 250 mm, and a thermopile detector were used in this system. The wavelength of the monochromator was calibrated by using eleven spectral lines of a mercury lamp from 400 to 1,100 nm, and the average of the differences at 625 and 730 nm was used to correct the wavelength.

Table 1 Spectral characteristics of Topcon radiation thermometers

Thermometer	RT1, RT2, RT3	RT4	RT5, RT6, RT7	RT8, RT9, RT10
Filter 1	W-type	TO-399	DIF-BPF-2	Hard coating
Manufacturer	OCJ	Topcon	OCJ	Barr
Center (nm)	651	651	650	649.3
Bandwidth (nm)	14.7	13.3	16.8	14.7
Filter 2	none	DIF-BPF-2	DIF-BPF-2	DIF-BPF-2
Manufacturer	none	OCJ	OCJ	OCJ
Center (nm)	none	650	650	650
Bandwidth (nm)	none	100	100	100
Detector	S874-5K	S1336-5K	S1336-5K	S1336-5K

The center wavelength was defined as the average of the two half-maximum wavelengths in the spectral response curve. The mean effective wavelength was determined in the following way. First, the thermometer output V measuring a blackbody at temperature T was calculated from the spectral responsivity $R(\lambda)$ as

$$V(T) = a \int L(\lambda, T) R(\lambda) \mathrm{d}\lambda. \quad (1)$$

Here the coefficient a is determined by the copper-point calibration. Next, this scale was approximated by the following function with three coefficients, A, B, and C.

$$V(T) = \frac{C}{\exp\left(\frac{c_2}{AT+B}\right) - 1}. \quad (2)$$

Here, c_2 is the second radiation constant equal to 0.014388 mK. Then, the mean effective wavelength λ_M between the copper point T_{Cu} and the silver point T_{Ag} was approximated by the equation,

$$\lambda_M(T_{Cu}, T_{Ag}) = A(1 + B/AT_{Cu})(1 + B/AT_{Ag}). \quad (3)$$

2.2.2 Fixed-Point Blackbodies

Practical fixed-point blackbodies of copper and silver [3] were used for the gain stability check. The cylindro-conical graphite cavity 10 mm in diameter and 46 mm in length contains about 27 cm^3 of metal of purity better than 99.999% and has a stainless-steel aperture 6 mm in diameter. The emissivity was estimated to be greater than 0.999. The reproducibility of the copper-point plateau temperature was better than 0.01°C, and the long-term stability was better than 0.1°C or 0.1% of the output signal, even with different furnaces.

3 Results

3.1 Spectral Stability

Figure 1 shows the center wavelength shift of three thermometers, RT1, RT2, and RT3. W-type metal film interference filters were used for these thermometers. The center wavelength of RT1 changed 0.13 nm in 5 years while that of RT2 changed by 2.2 nm in 4 years. The bandwidth of RT2 broadened from 15.7 to 17.2 nm. The center wavelength shift of RT3 was small.

Figure 2 shows the center wavelength shift of four thermometers, RT4, RT5, RT6, and RT7. Multi-layer dielectric film interference filters were used for these thermometers. The center wavelength of RT4 shifted by 0.7 nm in 10 years. The center wavelength of RT5 changed little at first, but changed by 0.4 nm between 2001 and 2003 and by 2.2 nm between 2003 and 2005. The center wavelength of RT6 changed by 0.3 nm in

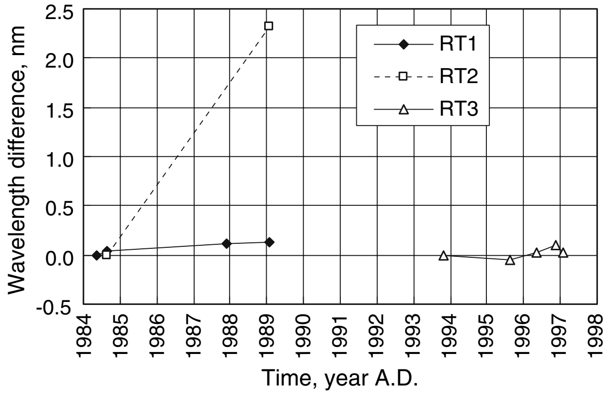

Fig. 1 Spectral stability of radiation thermometers RT1 (closed diamond), RT2 (open square), and RT3 (open triangle)

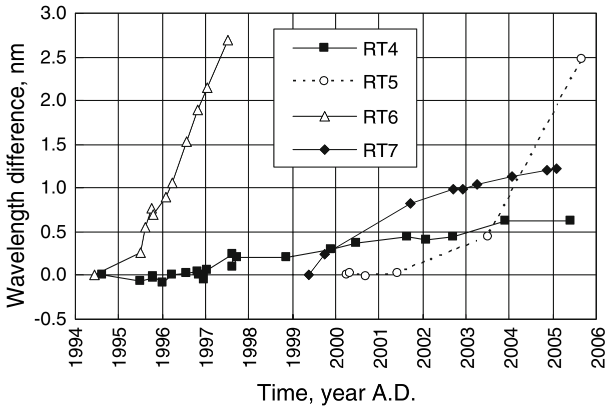

Fig. 2 Spectral stability of radiation thermometers RT4 (closed square), RT5 (open circle), RT6 (open triangle), and RT7 (closed diamond)

one year, then shifted by 2.5 nm over 2 years from 1995. The center wavelength of RT7 changed by 0.5 nm over 2 years from 1999, and then the rate of change decreased.

Figure 3 shows the wavelength shift of three thermometers, RT8, RT9, and RT10. Barr hard-coating interference filters were used for these thermometers. The center wavelengths of these three thermometers were very stable and shifted less than 0.1 nm.

3.2 Output Stability

In Fig. 4, the closed diamond shows the measured output ratio of thermometer RT4 at the copper point referenced to the initial measurement. The open square shows the output change caused by the wavelength shift calculated by the equation,

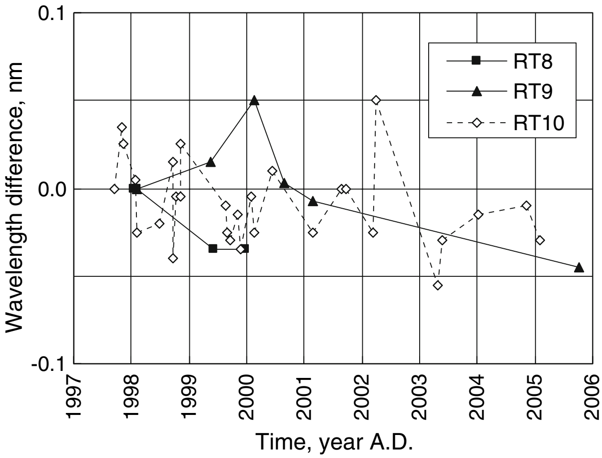

Fig. 3 Spectral stability of radiation thermometers RT8 (closed square), RT9 (closed triangle), and RT10 (open diamond)

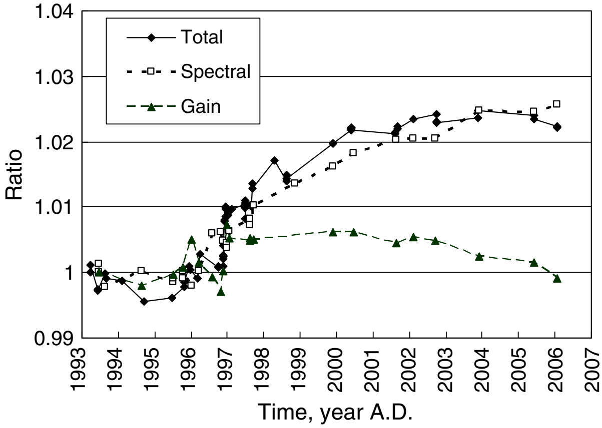

Fig. 4 Output ratio of radiation thermometer RT4 at the copper point referenced to the initial measurement (closed diamond). Open square denotes the wavelength contribution. Closed triangle denotes the gain contribution

$$\frac{dV}{V} = \left(-\frac{5}{\lambda} + \frac{c_2}{\lambda^2 T}\right) d\lambda. \tag{4}$$

The closed triangle shows the gain shift calculated as the total output change minus the wavelength contribution. The total output change was about 2%, and the wavelength contribution changes closely with the total output change. The gain change was within 0.5%.

Similar data are shown in Fig. 5 for thermometer RT5. The total output change was 6% from 1999 to 2005. The change was caused by the wavelength contribution, denoted as an open square. The gain contribution was less than 0.8%. The rapid

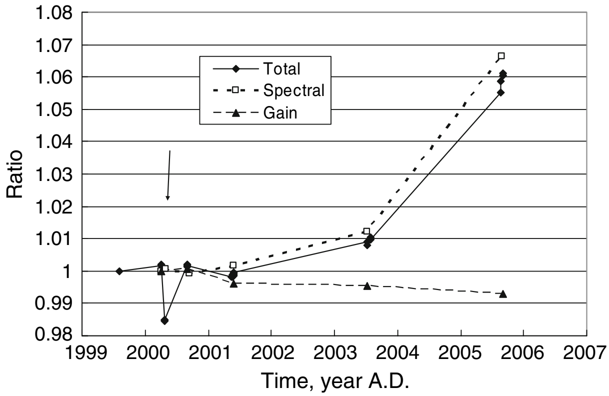

Fig. 5 Output ratio of radiation thermometer RT5 at the copper point referenced to the initial measurement (closed diamond). Open square denotes the wavelength contribution. Closed triangle denotes the gain contribution. Arrow indicates contamination of the objective lens

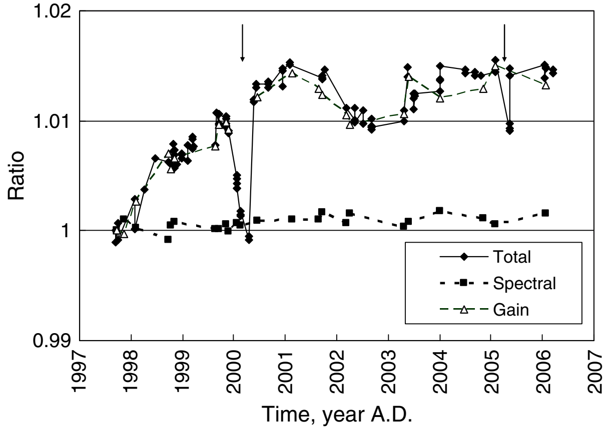

Fig. 6 Output ratio of radiation thermometer RT10 at the copper point referenced to the initial measurement (closed diamond). Closed square denotes the wavelength contribution. Open triangle denotes the gain contribution. Arrow indicates contamination of the objective lens

decrease of 1.5% in 2000 indicated by the arrow is caused by the contamination of the objective lens. The output recovered to its original level after cleaning the lens.

Figure 6 shows the case for thermometer RT10. The total output increased by 1.5% in 9 years. Because the effective wavelength was very stable, the wavelength contribution changed less than 0.2%. The change was ascribed to the gain contribution. Contamination of the objective lens resulted in a decrease in the output of 1% in 2000 and 0.5% in 2005; the output signal recovered after cleaning the lens in both cases.

Table 2 summarizes the linear regression of the long-term output changes of ten thermometers. Change rates of the total output, the wavelength contribution, and the gain contribution are shown as well as the standard deviation of the regression line. Large standard deviations were caused by either the data scatter or the nonlinear

Table 2 Radiation thermometer number, total output change rate, its wavelength and gain contributions, and their standard deviations from the regression lines

Thermometer	Change rate (% · year^{-1})			Standard deviation (%)		
	Total output	Wavelength contribution	Gain contribution	Total output	Wavelength contribution	Gain contribution
RT1	0.23	0.08	0.12	0.33	0.10	0.36
RT2	−0.56	0.76	−1.32			
RT3	−0.16	0.17	−0.16	0.92	0.14	0.51
RT4	0.27	0.21	0.01	0.43	0.37	0.30
RT5	0.97	1.17	−0.14	1.15	1.13	0.13
RT6	1.92	2.84	−0.33	0.61	0.63	0.47
RT7	0.44	0.29	0.16	0.09	0.04	0.10
RT8	−0.08	−0.08	−0.01			
RT9	−0.06	−0.01	−0.06	0.22	0.03	0.24
RT10	0.14	0.02	0.15	0.25	0.05	0.26

change, as in Fig. 5. The total output change was largest for thermometer RT6 and amounted to 2% · year^{-1}. The output decrease was largest for RT2 and was −0.6% · year^{-1}. The gain contribution change was large and negative for RT2 and RT6, but was small for the other eight thermometers.

4 Discussion

4.1 Spectral Stability

Typically, the center wavelengths of interference filters increase 0.06 nm · year^{-1}, but changes up to 0.2 nm · year^{-1} have been observed [4]. This applies to thermometers RT4 (0.08 nm · year^{-1}) and RT7 (0.11 nm · year^{-1}). Thermometers RT2, RT5, and RT6 showed larger wavelength shifts of 0.5, 1.0, and 1.3 nm · year^{-1}, respectively. Thermometers RT1 (0.03 nm · year^{-1}) and RT3 with W-type metal interference filters showed smaller wavelength shifts.

Three thermometers, RT8, RT9, and RT10, with a Barr hard-coating filter, showed almost no shift in wavelength. This kind of filter is used in a radiometer on a satellite and therefore is stable at ambient conditions.

When the center wavelength changes by dλ, the temperature change dT at the blackbody temperature T is calculated from Eq. 4,

$$\mathrm{d}T = \left(1 - \frac{5}{\frac{c_2}{\lambda T}}\right) T \frac{\mathrm{d}\lambda}{\lambda}. \tag{5}$$

When the center wavelength changes by 0.2 nm, the temperature changes at the copper point, 1,500, and 2,000°C are 0.30, 0.33, and 0.34 °C, respectively.

4.2 Output Stability

Many of the radiation thermometer outputs increased with long-term use. Table 2 indicates that the cause of the output increase was mainly the shift of the center wavelength to longer wavelengths. This applies to thermometers RT4, RT5, RT6, and RT7. After correcting for the wavelength contribution, the gain contribution shows a stability of better than $0.2\% \cdot \text{year}^{-1}$, except for RT2 and RT6. The interference filter of RT2 shifted to longer wavelengths, its bandwidth widened, and the transmittance decrease was estimated as 6.5%. The gain contribution decrease rate of RT6 was estimated as $0.33\% \cdot \text{year}^{-1}$.

The output change of $\mathrm{d}V/V$ (change of gain) influences the temperature scale as follows:

$$\mathrm{d}T = \frac{\lambda T^2}{c_2} \frac{\mathrm{d}V}{V} \tag{6}$$

The output change of 0.2% influences the temperature at the copper point, 1,500, and 2,000 °C by 0.17, 0.28, and 0.47 °C, respectively.

4.3 Contamination

In the year 2000, we experienced contamination of the objective lenses of four radiation thermometers, RT5, RT8, RT9, and RT10, as shown in Figs. 5 and 6. The output decrease was about 1%. At that time, a building next to the laboratory was under construction and polluted air may have come in through the air conditioning. After cleaning the objective, the output signals came back to the original levels.

Another possible source of contamination was a high-temperature blackbody used up to 2,500 °C. We added an air curtain in front of the blackbody to prevent direct contamination of the objective lens. In 2005, we found RT10 was again contaminated by 0.5%. As before, the output signal recovered after cleaning the lens. We need further study of the contamination source.

5 Conclusion

The long-term stability of ten Topcon 0.65-μm radiation thermometers was studied. The output signal of some radiation thermometers increased due to the center wavelength shifting to longer wavelengths. The Barr hard-coating interference filters were very stable. Excluding the wavelength shift, the output signal of the thermometers was stable within $0.2\% \cdot \text{year}^{-1}$. The contamination of the objective lens affected the signal by 1%. It is important to be careful to prevent contamination of the objective lens.

This paper is the integration of two papers dealing with the stability of 0.65-μm standard radiation thermometers that are only available in Japanese:

1. Spectral stability *Trans. Soc. Instrum. Control Eng*. **42**, 591 (2006) [in Japanese]
2. Output stability *Trans. Soc. Instrum. Control Eng*. **43**, 271 (2007) [in Japanese]

We hope that the results will be disseminated to a wider audience through their publication here.

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