# New Developments in High-Temperature Measurement Techniques

Review

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***Abstract*** *– Temperature can be measured via emitted thermal radiation of the measured object using Max Planck's law of thermal radiation, which describes the emission of thermal radiation as a function of temperature of an ideal black body. However, thermal radiation measurement requires accurately calibrated detectors. The calibration of such detectors has been significantly improved in the last years, yielding calibration uncertainties of the spectral responsivity of detectors down to 10-4 in National Metrology Institutes. The paper briefly reviews the experimental and physical principles of optical temperature measurement via emitted thermal radiation and then covers recent developments in calibration technologies. Finally, practical methods for transferring these low uncertainties already achieved in the National Metrological Institutes to industry are outlined.*

***Keywords*** *– cryogenic radiometer, photometry, radiometry, thermometry.*

## 1. INTRODUCTION

Every matter with a temperature above 0 K emits electromagnetic radiation, better known as thermal radiation or heat radiation. For a special type of body, the so-called black body, this emitted radiation can be calculated exactly by using Planck's law of radiation, which describes the emitted spectral radiance $L_{b,\lambda}$ as a sole function of the temperature of the black body.

$$L_{b,\lambda} = \frac{2hc^2}{\lambda^5} \frac{1}{\exp\left(\frac{hc}{\lambda kT}\right) - 1} \quad (1)$$

For non-ideal black bodies, their spectral radiance is also proportional to the spectral radiance according to Planck's law; however, a constant of proportionality, the emissivity $\varepsilon$, has to be taken into account. Vice versa, if the spectral radiance of a black body is measured, its temperature can also be calculated by using Planck's law of radiation described in equation (1).

The same experimental setup shown in Fig. 1 is used for both experiments, i.e., using a black body with a well-known temperature to generate calculable spectral radiance and, on the other hand, measuring the temperature of a black body by absolutely measuring its emitted thermal spectral radiance [1]. Such setup is called radiometric temperature measurement. The details of black bodies can be found in literature, e.g., in [1]. This paper describes calibration of optical detectors used for measuring thermal radiation.

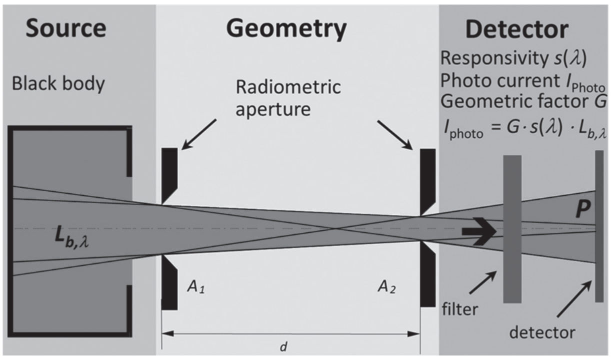



**Fig. 1**: Schematic setup for radiometric temperature measurement [1]

Nowadays, usually semiconducting devices, in particular photodiodes made of *Si* or *InGaAs,* are used for sensing emitted optical radiation.

The signal of a photodiode generated by absorbed optical radiation is an electrical current and the proportionality between the absorbed optical radiation power *P* and the generated electrical current $I_{Photot}$ is the so-called spectral responsivity $s(\lambda)$ according to

$$I_{photo} = s(\lambda) \cdot P = s(\lambda) \cdot G \cdot L_{b,\lambda} \quad (2)$$

The optical power *P* emitted by a black body radiator can be calculated by the emitted spectral radiance $L_{b,\lambda}$ as long as the geometrical conditions described by the geometric factor *G* are known. This is also shown in equation 2. Therefore, the spectral responsivity $s(\lambda)$ has the unit A/W.

For calculating the temperature of the black body via sensed thermal radiation, the spectral responsivity of the used detector has to be known. Photoelectric detectors have a spectral responsivity *s*(λ) according to the following equation 3 [1]

$$s(\lambda)=\frac{\left(1-r(\lambda)\right)\ \eta_{\mathrm{i}}(\lambda)\ n_{\mathrm{air}}\lambda e}{hc} \quad (3)$$

with $r(\lambda)$ the reflectance of the detector, $\eta_i(\lambda)$ the internal quantum efficiency, $n_{air}$ the index of refraction of air, *λ* the wavelength of the radiation in air, *e* the electron charge, *h* Planck's constant, and *c* the velocity of light. According to equation 3, the spectral responsivity of photoelectric detectors varies with the wavelength and depends on its reflectivity and its internal quantum efficiency. As both quantities cannot be predicted with sufficient accuracy, the spectral responsivity of such photoelectric detectors has to be calibrated with a detector standard. Electrical substitution detector standards have been used for a long time.

## 2. ELECTRICAL SUBSTITUTION RADIOMETERS

In an electrical substitution radiometer, the following technique is used for sensing electromagnetic radiation. A cavity with an absorptivity of approximately 1 – i.e., a nearly perfect absorber – is used as a thermal detector and kept at a constant temperature via electrical heating as shown in Fig. 2. As soon as electromagnetic radiation is absorbed by the thermal detector, its temperature is increased. To keep its temperature constant, electrical heating has to be lowered. In an ideal case, a decrease in electrical heating power is exactly compensated by the amount of absorbed optical radiation power. Therefore, a decrease in electrical heating power is equal to the received optical power measured by the thermal detector [1].


**Fig. 2**: Schematic of an electrical substitution radiometer [1]

To make this equality as good as possible, modern electrical substitution radiometers operate at cryogenic temperatures of about 5 K, yielding a perfect electrical heating of the detector by using superconducting connection wires and measuring the optically induced temperature rise with high accuracy semiconducting thermometers [2]. Such electrical substitution radiometer operating at cryogenic temperatures is called a *cryogenic radiometer*. Thermal detectors for typical cryogenic radiometers are cavity detectors, i.e., a tube with a large length to diameter ratio having a relatively large thermal mass. To heat this cavity detector to a detectable temperature increase requires relatively high optical power. Therefore, such cryogenic radiometers are usually used to calibrate optical power of lasers with optical power ranging between some mW and some hundred mW [1]. Laser radiation calibrated in such a way is then used to measure the spectral responsivity of photoelectrical detectors by irradiating these detectors with this absolutely calibrated laser power and measuring the generated electrical current of the detector as shown in Fig. 3.

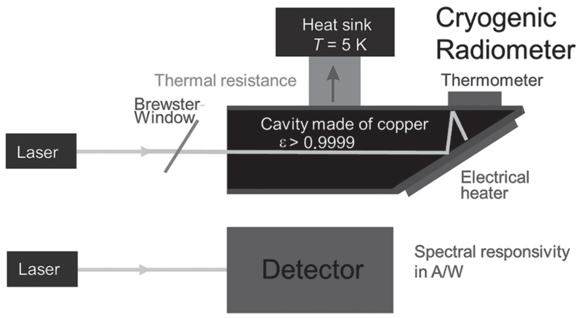



**Fig. 3**: Calibration of a detector with respect to the cryogenic substitution radiometer [1 ]

A typical calibration of a photoelectrical detector using calibrated laser radiation is then performed at about 14 different laser wavelengths. A typical calibration result obtained at the Physikalisch-Technische Bundesanstalt (PTB) is shown in Fig. 4 [1]. The actual calibration at the cryogenic radiometer of PTB is shown in Fig. 4 by dots.

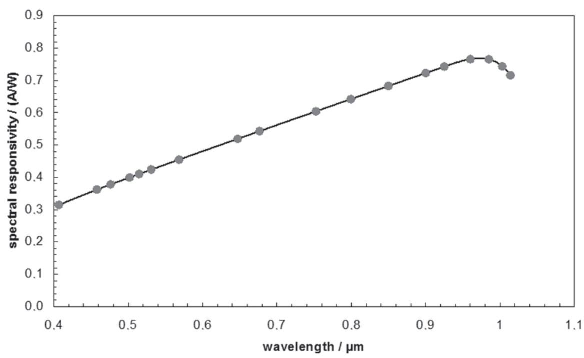



**Fig. 4**: A typical calibration curve of a silicon photodiode at the Physikalisch-Technische Bundesanstalt. Red dots: Calibration at the cryogenic radiometer, line: interpolation by a physical model [1 ]

To obtain a continuous spectral responsivity of the detector under test, the calibration values at single wavelengths are interpolated by using a physical model described in [1]. The relative uncertainty of the spectral responsivity of a detector calibrated in this way directly with respect to a cryogenic radiometer is in the order of $10^{-4}$ at PTB [1].

However, calibration at the cryogenic radiometer is quite time-consuming and it takes several days for each wavelength. Therefore, such procedure is not practical for everyday calibration. Such time- consuming calibration at the cryogenic radiometer is only performed for special transfer standard detectors with outstanding characteristics, in particular very low reflectivity, the so-called trap detectors [1, 3].

As the reflectivity of such detector is very low, almost no optical radiation entering this detector leaves such detector again. Therefore, the light is trapped within the detector, which is the reason for its name: a trap detector is a light trap. The simplest of these trap detectors is built of three silicon photodiodes arranged in the way that the incoming radiation undergoes 5 reflections, as shown in Fig. 5.

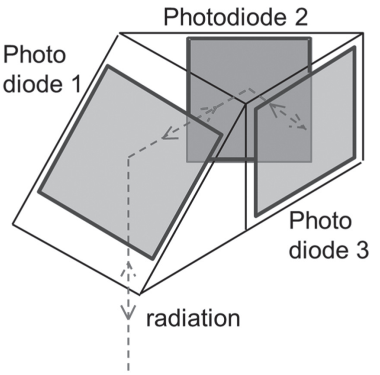



**Fig. 5**: A schematic view of a trap detector, showing both the path of the light (dotted line) and its reflections inside the trap [1]

These five reflections result in a reflection coefficient for this kind of trap detector of about 0.2 % instead of about 30 % for a single *Si* photodiode [1], i.e., if 1000 photons enter this trap detector, only 2 photons are re-emitted and 998 are absorbed. The spectral responsivity of such trap detectors can be calibrated with a relative uncertainty as low as $2x10^{-4}$ at PTB [1].

## 3. CALIBRATION OF OPTICAL DETECTORS USING TRAP DETECTORS AS TRANSFER STANDARDS

These trap detectors are then used to calibrate usual optical detectors like filter radiometers, photometers or radiation thermometers using the spectral comparator technique shown in Fig. 6. According Fig. 6, the spectral power behind an optical monochromator is measured for every wavelength by the absolutely calibrated trap detector. Then the detector under test (filter radiometer, photometer or radiation thermometer) senses the same optical power and the ratio of the two signals times the known absolute spectral responsivity of the trap detector results in the spectral responsivity of the detector under test. To allow for the lowest reachable uncertainties, the spectral comparator setup must be characterized and optimized with respect to stray-light, polarization and spatial homogeneity of optical radiation as well as wavelength stability [1]. Optical detectors themselves must also be characterized with respect to wavelength stability and temperature stability. At the PTB, such characterization has been performed at the highest metrological level and an example of an uncertainty budget for five different filter radiometers for their spectral irradiance responsivity is given in Table 1.

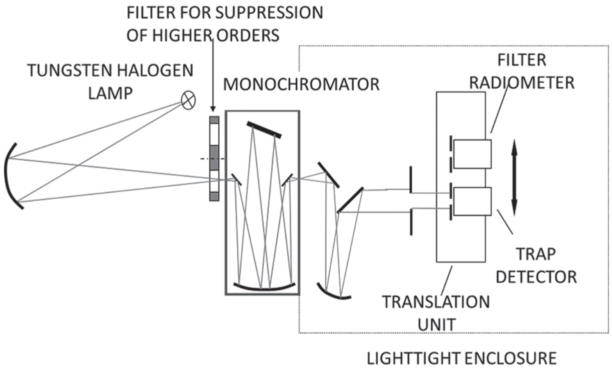



**Fig. 6**: Spectral comparator setup used for calibration of optical detectors [1]

**Table 1**: Uncertainty budget for five filter radiometers in the visible and near infrared spectral region [1]. The uncertainties are given at a coverage factor *k*=1, i.e., standard uncertainties

| | relative uncertainty in spectral responsivity times $10^{-4}$ | | | | |
|---|---|---|---|---|---|
| **Uncertainty contribution** | **676 nm** | **800 nm** | **900 nm** | **1000 nm** | **1595 nm** |
| 1. Spectral responsivity of transfer detector | 1 | 1 | 1 | 4.4 | 17 |
| 2. Non-linearity correction to transfer detector | | | 1 | 1 | |
| 3. Aperture area of transfer detector | 1.6 | 1.6 | 1.6 | 1.6 | 2.7 |
| 4. Diffraction of transfer detector aperture | 1 | 1 | 1 | 1 | 1 |
| 5. Distance from exit slit | 0.3 | 0.3 | 0.3 | 0.3 | 0.5 |
| 6. Temperature coefficient of transfer detector | 0.1 | 0.1 | 0.1 | 2 | |
| 7. Temperature coefficient of FR | 0.5 | 0.4 | 0.3 | 0.5 | 0.3 |
| 8. Homogeneity of spectral comparator beam | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| 9. Stability of Tungsten–halogen lamp | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| 10. Reproducibility | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| 11. Uncertainty of centre wavelength | 1.7 (800 °C) | 1.4 (660 °C) | 1.5 (457 °C) | 1.3 (419 °C) | 1.8 (419 °C) |
| **Sum in quadrature** | **2.9** | **2.7** | **2.9** | **5.5** | **17.4** |
| In terms of temperature uncertainty (mk) | 16 (800 °C) | 13 (660 °C) | 10 (457 °C) | 18 (419 °C) | 93 (419 °C) |

## 4. APPLICATION OF ABSOLUTELY CALIBRATED OPTICAL DETECTORS TO MEASURE TEMPERATURES

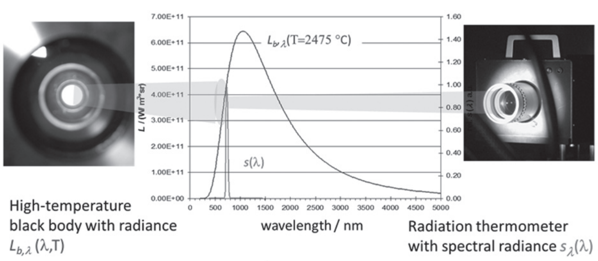
As such filter radiometers can be used to measure the temperature of black body radiators according to equation 1, the resulting uncertainty in the temperature at the lowest measurable temperature for each filter radiometer is also given in Table 1. Such temperature measurement using emitted thermal radiation and equation 1 is usually performed according to Fig. 1. If the aperture of the black body and its distance to the absolutely calibrated filter radiometer is known, the measured signal of the filter radiometer together with equation 1 can be used to determine the temperature of the black body with the lowest uncertainties, as given in Table 1 [1]. Such measurements have been performed to identify novel high-temperature fixed-points for improving the high-temperature part of the International Temperature Scale of 1990 (ITS-90) [1]. The ITS-90 is based on temperature fixed-points embodied by the freezing point of metals at temperatures above 100 °C. Up to now, the fixed-point with the highest temperature is the copper freezing point at a temperature of about 1084 °C. To improve the accuracy of the ITS-90 at temperatures above 1084 °C, new temperature fixed-points are necessary. A solution to the material problems present at such high-temperatures are fixed-points based on a mixture of carbon and metal within a carbon-based crucible, forming a eutectic. Such material combination is named a metal-carbon eutectic. At even higher temperatures, a mixture of metal carbon and metal carbide can be used. Such kind of fixed-point is then called a metal-carbon carbide eutectic. These novel temperature fixed-points have been investigated in the temperature range from 1150 °C to 2750 °C. The results of some of such measurements are given in Table 2 [1].

**Table 2**: Temperature measurements of metal- carbon and metal carbon-carbide eutectics [1]. Uncertainties are given at a coverage factor *k*=2, i.e., expanded standard uncertainties

| Material | melting temperature / °C | uncertainty ($k$=2) |
|---|---|---|
| TiC-C | 2757.98 | 0.45 |
| Re-C | 2473.00 | 0.39 |
| Ru-C | 1954.06 | 0.39 |
| Pt-C | 1738.64 | 0.32 |
| Pd-C | 1491.94 | 0.26 |
| Co-C | 1324.08 | 0.22 |

## 5. TRANSFER OF LOW UNCERTAINTIES TO INDUSTRY

As described in Section 3, detectors for optical radiation in the visible and near infrared spectral range can be calibrated with relative uncertainties as low as some parts in $10^{-4}$ at some National Metrology Laboratories, e.g., the PTB. However, such calibrations are time-consuming and require elaborated equipment and well trained and experienced personnel. This is not practical for day-to-day calibration in industrial and scientific applications. However, as described in Section 4, such kind of absolutely calibrated optical radiation detectors can be used to absolutely calibrate the temperature of high-temperature metal-carbon eutectic fixed-points. As shown in Table 2, such high-temperature fixed-points deliver stable temperatures within an uncertainty better than 0.5 K (*k*=2) at temperatures as high as 2750 °C. Black body radiators based on such fixed-points can therefore be used to practically check and re-calibrate optical detectors used in industrial applications [1]. E.g., one high-temperature fixed-point is sufficient to check the stability of a radiation thermometer or a photometer according the procedure shown in Fig. 7.




$$I_{photo}(T) = G \cdot \int L_{s,\lambda}(\lambda, T)\; s(\lambda)\, d\lambda \text{ [A]}$$

**Fig. 7:** Scheme for stability check of a radiation thermometer or photometer using high-temperature fixed-points

As the emitted radiance of the high-temperature fixed-point is stable over time, the stability of a radiation thermometer or photometer is performed simply by measuring the signal $I_{Photo}$ of the device under test when pointing in the entrance opening of the black body. As long as the output signal of the device is within the desired range of the calibrated value, the device under test has not changed and can be used further on. Only if the signal deviates significantly, re-calibration of the device under test is necessary. The blue curve in Fig. 7 shows the spectral radiance emitted by the fixed-point black body. The red curve shows the part of the spectral radiance measured by the radiation thermometer and the equation shown in Fig. 7 shows a mathematical relation of these two quantities and the measured photocurrent.

If the radiation thermometer under test has only a small spectral bandwidth, its spectral responsivity can be calibrated by using three different eutectic high-temperature fixed-points, as depicted in Fig. 8.

Measuring three different high-temperature fixed-points results in three different signals obtained by the radiation thermometer. As the radiation thermometer has a small spectral bandwidth, its photocurrent output $I_{Photo}$ can be described by the following equation 3 [1].

$$I_{Photo} = \frac{C}{\exp\left(\frac{c_2}{AT+B}\right) - 1} \quad (4)$$

In equation 3, the constant $c_2$ = 14388 µm·K is the second Planck's constant and *A*, *B*, and *C* are parameters that can be determined by three different measurements of the photocurrent $I_{Photo}$ using black body radiators with three different accurately known temperatures.

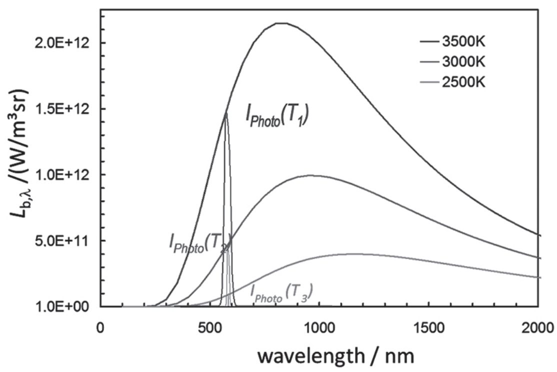



**Fig. 8:** Scheme for the calibration of small bandwidth radiation thermometers using three different high-temperature fixed-points .

## 6. CONCLUSION

In Sections 2 and 3, the absolute calibration of optical radiation detectors using high-end optical calibration facilities with a resulting relative uncertainty as low as some parts in $10^{-4}$ at National Metrology Institutes is described. Such absolutely calibrated detectors have been used to measure the temperature of high-temperature metal-carbon eutectic fixed-point black body radiators with outstanding low uncertainty ranging between some hundred mK ($k$=2) and temperatures of about 2750 °C, as depicted in Section 4. Section 5 presents practical calibration schemes enabling an easy calibration of optical radiation detectors used in industry, like radiation thermometers or photometers, by applying high-temperature metal-carbon eutectic fixed-point black bodies.

## 7. ACKNOWLEDGEMENT

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