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RADIATION THERMOMETRY BASED ON RADIOMETRIC STANDARD

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Abstract – A new temperature measurement process based on radiometric standard has been realised at BNM INM. A radiance-meter is used to calibrate a tunable monochromatic source which is compared to a black body with a spectral spectroradiometer. The radiance meter is calibrated against a cryogenic radiometer. The spectral radiance measurement wavelength is selected by the spectroradiometer. The temperature is then deduced from the spectral radiance with the Planck's law [1],[2]. The monochromatic source can be scanned over 10 nm around 830 nm in order to measure the slit function of the spectroradiometer. The stability of the monochromatic source, is about 10^{-4} over one hour. This set up can be used to measure high temperatures above 2000°C without comparison to ITS90 fixed point [3].

Keywords: high temperature, radiance meter, Planck radiation, radiometry.

1. INTRODUCTION

The international Temperature Scale of 1990 above 960°C is realised with fixed points black bodies having a reproducibility about 50 mK. The temperature of these fixed points is imposed by the freezing temperature of a pure metal (silver, gold, copper). The temperature of a black body is usually obtained by direct comparison with a fixed point of the ITS90. The unicity of the ITS90 can be checked either with an international comparison or by measuring the thermodynamic temperature of ITS90 fixed points. The calibration of a fixed point with a spectroradiometric method leads to the determination of its thermodynamic temperature. In addition, an international comparison of the ITS90 has shown some discrepancies larger than the reproducibility and the measurement uncertainty (10 mK).

To have a relative uncertainty smaller than 10 mK around 1000 °C, the relative uncertainty on the spectral radiance L_λ emitted by a black body must stay under 10^{-4} and a relative uncertainty on the wavelength λ under 10^{-5}.

2.MEASUREMENT PRINCIPLE

The Planck's law expresses the black body's spectral radiance $L_{bb}(\lambda, T, \varepsilon)$ [$Wsr^{-1}m^{-3}$] as a function of its temperature T and its emissity ε, where λ is the detection wavelength.

$$L_{bb}(\lambda,T,\varepsilon) = \frac{\varepsilon C_1}{\lambda^5\left(e^{\frac{C_2}{\lambda T}}-1\right)} \quad (1)$$

C_1 = 1.191 042 722(93) x 10^{-16} [W m^2]
C_2 = 1.438 7752(25) x 10^{-2} [m K]

Radiance is a physical unit of flux per solid angle unit and per surface unit. Its measurement requires the determination of the instrument viewing solid angle and the source emitting area which are computed in a so called "geometrical factor G". Then, spectroradiometric measurement of spectral radiance requires a narrow spectral bandwidth.

The simplest radiance meter can be constituted by two centred diaphragms, a spectral filter and a photodetector. However, the spectral filter introduces big calibration uncertainties (10^{-3}) caused by inter reflections between the filter and the detector. For this reason, our radiance meter has no spectral filter. Thus it cannot be used directly in front of a black body. For this reason, we use a transfer monochromatic source which is an intergating sphere irradiated with a monomode laser beam whose linewidth is very narrow.

Our experimental procedure has two steps. First, the radiance meter measures the radiance $L_1(\lambda_0)$ of a monochromatic tunable source used as a radiance transfer and whose emission wavelength is λ_0. Then, a spectroradiometer compares the monochromatic source against the black body (see figure 1).

The radiance $L_1(\lambda_0)$ of the monochromatic source is measured with the radiance meter :

$$L_1(\lambda_0) = I_1 / [G_1 S_1(\lambda_0)] \quad (2)$$

with G_1 a geometrical factor, $S_1(\lambda_0)$ the photodetector spectral sensitivity and I_1 the photocurrent.

The monochromatic source is then viewed by the spectroradiometer. The delivered current I_2 is then :

$$I_2 = G_2 T(\lambda_0) L_1(\lambda_0) \quad (3)$$

with $T(\lambda_0)$ the spectroradiometer slit scattering function at the laser wavelength λ_0 and G_2 its geometrical factor.

The detection of the black body radiation with the spectroradiometer gives a photocurrent I_{bb} :

$$I_{bb} = \int G_2 T(\lambda) L_{bb}(\lambda, T, \varepsilon)\, d\lambda \quad (4)$$

Thus, the comparison between the monochromatic source and the black body is expressed by the ratio I_{bb}/I_2 :

$$I_{bb} / I_2 = \int T(\lambda)/T(\lambda_0)\, L_{bb}(\lambda, T, \varepsilon)/L_1(\lambda_0)\, d\lambda \qquad (5)$$

Where the scattering slit function $T(\lambda)$ of the spectroradiometer is calibrated with the monochromatic tunable source. The black body spectral radiance $L_{bb}(\lambda, T, \varepsilon)$ is numerically computed from equation 5. The black body temperature is then deduced with Planck's law (equation 1).

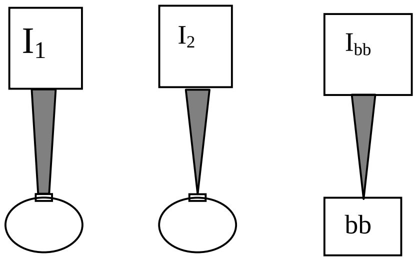


Figure 1 : sphere and black body radiance comparison

3. MONOCHROMATIC TRANSFER SOURCE

This source is a 50 mm radius integrating sphere irradiated with an extended cavity diode laser beam. The output emitting surface of the integrating sphere is delimited by a calibrated diaphragm attached to it.

Before illumination of the diffusing sphere, the laser propagates in a multimode optical fibre shaken in an ultrasonic bath. The speckle noise resulting from laser interferences inside the diffusing sphere is then cancelled. A detector on the sphere is included in a feedback loop for sphere radiance stabilisation. The sphere output radiance noise and stability obtained is about 10^{-4} over one hour.

The polarisation rate of the sphere output is $2.7\ 10^{-3}$ (see figure 2) with a relative uncertainty about 10%. As the spectroradiometer polarizability is about 15%, the polarizability correction is about $2\ 10^{-4}$. However this correction can be eliminated with the use of a polarizer placed on the output optical beam of the spectroradiometer.

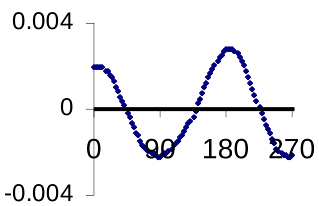


Figure 2 : output sphere polarization

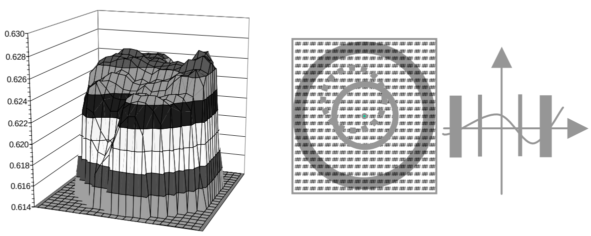


Figure 3 : Sphere output spatial radiance homogeneity

The mapping of the output sphere shows some inhomogeneity at a level 0.1 % (see fig.2). An error on the sphere positionning about 0.1mm gives raise to a correction uncertainty about 0.04 % after averaging on the viewed emitting surface.

The emitting area analysed by the spectroradiometer and by the radiance meter are different. Due to the spatial inhomogeneity of the sphere output radiance, the averaged radiance analysed by the instrument is no more equal and has to be corrected. This correction is about 0.02%.

The laser spectral width is 2.10^{-7} nm. Its wavelength is measured with a lambda meter and it is computer controlled. The laser wavelength can be tuned over 10 nm around the laser emission line (830 nm).

4. RADIANCE METER

The radiance meter is constituted with a pair of centred diaphragms and a trap photodetector which includes three silicon photodiodes. These photodiodes are assembled so as the optical reflectivity of the trap detector is negligible (five reflections are necessary), as well as its spatial response homogeneity (averaged with the three photodiodes). As the trap detector reflecti is negligible (less than 10^{-5}), its spectral sensitivity $S(\lambda)$ is given by the formula :

$$S(\lambda)\,[A/W] = \frac{I\ \lambda[nm]\ Q(\lambda)}{1239{,}48} \qquad (6)$$

Where $Q(\lambda)$ is its quantum efficiency. The relative uncertainty of calibration of trap detector sensitivity against the BNM INM cryogenic radiometer is about 5.10^{-4} in the visible range. A physical model based on the work of Kubarsep has been used to extrapolate the trap detector quantum efficiency. Its spectral sensitivity is then deduced from equation (6). The geometrical factor G_1 of the radiance meter (see relation 2) is a function of the diaphragms radius R_1, R_2 (5 mm) and the distance d (300 mm) separating them:

$$G_1 = \frac{\pi^2}{2}\left(d^2 + R_1^2 + R_2^2 - \sqrt{\left(d^2 + R_1^2 + R_2^2\right)^2 - 4R_1^2R_2^2}\right) \qquad (7)$$

One diaphragm is attached to the sphere output port. The other one is attached to the trap detector. Their distance remains constant with a set of three metal concentric rods which assume also the diaphragms centring. An uncertainty about 0.5 µm on the radius of the diaphragms and 10 µm for their distance gives a 10^{-4} calibration relative uncertainty on the geometrical extent G_1.

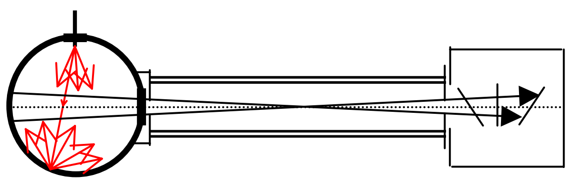


Figure 4 : radiance meter principle

5. SPECTRORADIOMETER

The spectroradiometer selects the geometric extent G_2 (see relation 4) of the source optical beam. It includes a simple pass Czeny Turner monochromator associated with an interference filter.

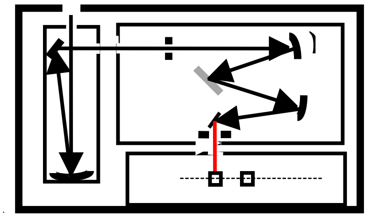


Figure 5 : spectroradiometer principle

The detection spectral bandwidth is about 7 nm. Two well circular diaphragms are used to define the selected wavelength by rotation of the optical grating included in the monochromator. With this set up, the spectroradiometer collects photons coming from an emitting area which is the image of the entering diaphragm of the monochromator. For this instrument, the magnification is 1.

The uncertainty associated to the comparison of the black body signal against the integrating sphere is mainly caused by the monochromator slit scattering function measurement, the detection noise, and the "size of source effect".

This latest measurement correction factor is due to the detection of photons emitted from the surrounding part of the black body. The measurement method used to estimate this correction is the so called "indirect method". A black spot stops the photons coming from the theoretical instrument field of view. An external black diaphragm define the size of the brightness effective source whose geometry is annular. The photons detected are then coming from the field that should be out of view of the spectroradiometer. This measurement has been done with a theoretical field of view diameter equal to 0,5mm, a black spot diameter equal to 3mm and an external diaphragm which is varied from 3 to 40 mm. This experiment has been done at two different detection wavelength : 650 and 950 nm (see figure 6). Finally, the correction factor interpolated at 830 nm and corresponding to a 40mm source diameter is about 6.7 10^{-3}.

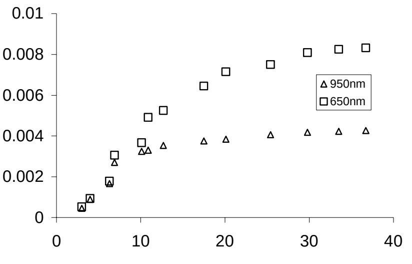


Figure 6 : size of source effect

The calibration of the monochromator slit scattering function has been done with two complementary methods. In the two cases, the optical source is our laser injected integrating sphere. In the first method, the laser wavelength is fixed and the optical grating is rotated. This method is usual, but it does not correspond to the spectroradiometer configuration used in the thermodynamic temperature measurement. In the second method, the grating is fixed, and the laser wavelength is tuned. This later method corresponds to the operating configuration of the spectroradiometer. One has to be careful in order to compare properly the results given by the two methods. Due to the fact that the monochromator is a simple pass Czeny Turner, high order diffraction modes are detected when viewing a broadband spectral source like a black body. These high order diffraction modes has to be attenuated with an interference filter. Otherwise the black body radiance detection is no more monochromatic. For this reason an interference filter is placed after the monochromator. Its effective wavelength is 830 nm. The spectroradiometer scattering slit function measurement is shown on figure 7. It has been done with the two methods, with and without interference filter. This calibration is used to estimate the integral in the equation (5). The numerical integration of the slit scattering function measured differs depending on the presence or not of the interference filter.

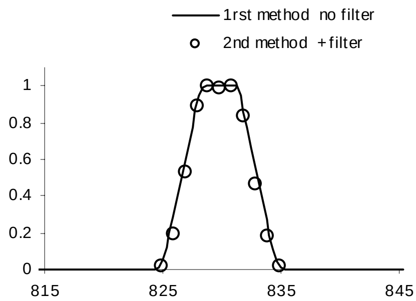
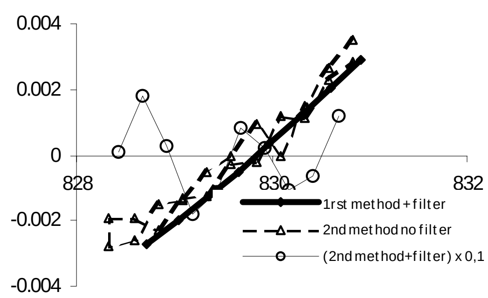


Figure 7 : spectroradiometer slit scattering function

The presence of laser beam interferences introduced by the spectral filter explains the curves difference. A zoom on the spectroradiometer slit scattering function plateau demonstrates vey well this effect. With no filter the "plateau" obtained is equivalent with the two methods. It shows oscillations when the laser wavelength is scanned in the presence of the filter. The interference amplitude is about 2%. With no filter, the slit scattering function is equivalent between the two methods. It has to be calibrated with a broadband spectral source like a black body due to the interferences.



6. CONCLUSIONS

The experimental radiometric method presented in this paper allows the radiometric determination of thermodynamic temperature of a black body. It is based on radiometric trap detector standard. The metrological study of this methods has been presented. The radiometric corrections have been studied and estimated, as well as the uncertainties attached to it. A thesis work on the size of source effect correction uncertainty determination started in our laboratory. A first step in the validation of the method is the measurement of the temperature of fixed point of the ITS90. A second step will be the determination of thermodynamic temperature of this fixed point with a smaller uncertainty.

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