

Results of a NIST/VNIIOFI comparison of spectral-radiance measurements

*R. D. Saunders, C. E. Gibson, K. D. Mielenz,
V. I. Sapritsky, K. A. Sudarev, B. B. Khlevnoy,
S. N. Mekhontsev and G. D. Harchenko*

Abstract. A comparison of the spectral-radiance scales of the National Institute of Standards and Technology (NIST) and the All-Russian Research Institute for Optophysical Measurements (VNIIOFI) was carried out in 1989 and 1990. The spectral range of the comparison was between 240 nm and 2400 nm. The transfer standards were argon-filled tungsten ribbon filament lamps. The NIST/VNIIOFI agreement was 0,5 % to 1 % in the 240 nm to 800 nm range, and better than 0,5 % between 900 nm and 2400 nm. On average, the spectral radiances measured at the VNIIOFI were slightly higher than the NIST values.

1. Introduction

The accuracy and world-wide consistency of spectral-radiance measurements in the air-ultraviolet to near-infrared spectral region are essential for many practical radiometric measurements, ranging from atmospheric monitoring of the ozone layer to industrial applications. In the United States and Russia, where the national scales of spectral irradiance and luminous intensity are derived from a primary scale of spectral radiance, the accuracy of spectral-radiance calibrations is of great practical importance. In an attempt to establish the degree of comparability of these two fundamental optical radiation measurement scales, a comparison of the spectral-radiance scales of the NIST and the VNIIOFI from 240 nm to 2400 nm was undertaken. The results are reported here.

The NIST (then the NBS) participated in 1982 in a bilateral comparison [1] of spectral-radiance scales with the National Physical Laboratory (NPL) of the United Kingdom. This comparison suggested a 2 % to 5 % difference of these scales in the ultraviolet. This finding was, however, judged to be inconclusive because of the four comparison lamps (type 25/G gas-filled tungsten ribbon filament lamps developed at the NPL, and manufactured by the General Electric Company (UK))

were destroyed during shipment, and the remaining two lamps had also suffered severe impacts.

In a later comparison of spectral-irradiance measurements [2], conducted in 1989 and 1990 under the auspices of the Comité Consultatif de Photométrie et Radiométrie (CCPR), the measurements carried out at 350 nm by the NIST as pilot laboratory showed general agreement among the participants with a maximum difference of 3,65 % between the NIST and the VNIIOFI. Unlike the 1982 spectral-radiance results, in this comparison the agreement between the NIST and the NPL was within 0,17 % at 350 nm. Because the NIST scale of spectral irradiance is based on the NIST scale of spectral radiance [3], it is hoped that further bilateral comparisons of the spectral-radiance scales will help to resolve some of the discrepancies in the results of the various comparisons and establish better agreement among the national laboratories in reporting values of spectral-radiometric quantities.

2. Lamps

Each laboratory provided three spectral-radiance lamps for the comparison.

The NIST lamps, designated Q106, Q108 and Q109 and shown in Figure 1, were type 30A/6V/T24 argon-filled tungsten ribbon filament lamps with fused-silica windows, manufactured by the General Electric Company (US). The filament of these lamps is 3 mm wide by 15 mm long. The spectral-radiance calibrations of the lamps were performed for a rectangular target area 0,6 mm wide by 0,8 mm long, marked by an alignment notch in one edge of the filament. The lamps were operated on direct current. The lamp current was measured with a stable 0,01 Ω resistor and a 5^{1/2} digit

R. D. Saunders, C. E. Gibson and K. D. Mielenz: National Institute of Standards and Technology (NIST), Gaithersburg, MD 20899, USA.

V. I. Sapritsky*, K. A. Sudarev, B. B. Khlevnoy, S. N. Mekhontsev and G. D. Harchenko: All-Russian Research Institute for Optophysical Measurements (VNIIOFI), Ozernaya 46, 119361 Moscow, Russian Federation.

* Guest researcher at the NIST from 1991 to 1994.

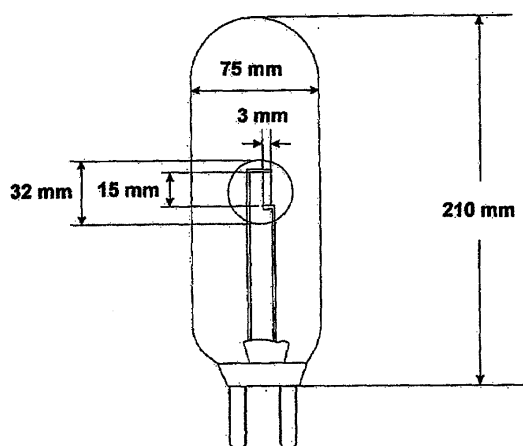


Figure 1. Dimensions of argon-filled tungsten ribbon filament lamps supplied by the NIST. The 32 mm diameter snout extends about 75 mm from the lamp envelope.

voltmeter to within ± 0.1 mA, and regulated to within ± 0.4 mA. Prior to calibration, each lamp was annealed for two hours at a radiance temperature of 2350°C .

The VNIIOFI lamps, designated N25, N57 and N186 and shown in Figure 2, were type TRU 1100-2350 argon-filled tungsten ribbon filament lamps with ultraviolet transmitting windows, manufactured at the Moscow Lamp Factory. The filament of these lamps is 2.8 mm wide by 20 mm long. The calibrated target area (1.0 mm wide by 1.0 mm long) was marked by a wire pointer near the centre of the ribbon. The lamps were operated on direct current which was measured to within ± 0.2 mA, and regulated to within ± 0.2 mA.

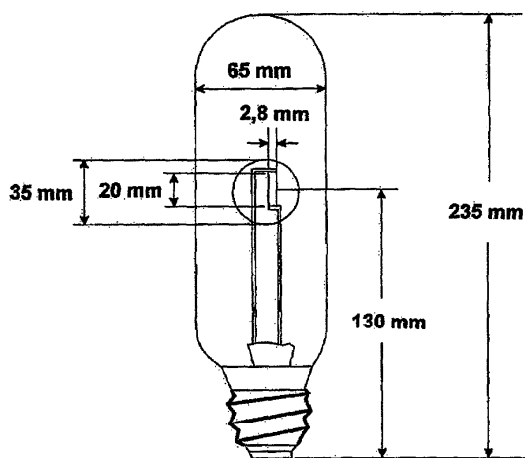


Figure 2. Dimensions of argon-filled tungsten ribbon filament lamps supplied by the VNIIOFI. The 35 mm diameter snout extends about 6 mm from the lamp envelope.

From the spectral-radiance measurements performed in the comparison, the average radiance temperature of the lamps at 654.6 nm was approximately 2456 K (NIST lamps) and 2319 K (VNIIOFI lamps).

3. Measurement procedures and uncertainties

3.1 The NIST

The NIST measurements of spectral radiance [4, 5] were based on a measurement chain starting from a standard black body at the freezing temperature of gold, $T_{\text{Au}} = 1337.33$ K. The gold-point black body was used to set the temperature of a Quinn-Lee type vacuum tungsten ribbon filament lamp to 1337.33 K by spectral-radiance comparison at 654.6 nm.

The 1337 K lamp was used to determine the temperature of a General Electric Company (UK) high-stability vacuum lamp at 1530 K by spectral-radiance comparison at 654.6 nm. The 1530 K lamp was used to determine the temperature of a variable-temperature black body up to approximately 2600 K by spectral-radiance comparison at 654.6 nm. The calibration of the comparison lamps was carried out by spectral-radiance comparison with the variable-temperature black body at wavelengths from 240 nm to 2400 nm. The black body was set at temperatures to yield spectral radiances similar to those of the comparison lamps in order to avoid reliance on large linearity corrections. All of these calibrations were performed in the NIST Facility for Automated Spectroradiometric Calibrations (FASCAL).

Following the 1989 NIST measurement of T_{Au} [6] and the adoption by the NIST in 1992 of the Bureau International des Poids et Mesures (BIPM) guidelines for expressing uncertainties [7], the relative expanded uncertainties of the NIST scale of spectral radiance were revised. The relative expanded uncertainty is equal to k times the combined standard uncertainty, where k = the coverage factor = 2. The level of confidence corresponding to these relative expanded uncertainties is 95% (2σ).

3.2 The VNIIOFI

The measurement method that was employed at the VNIIOFI is described in [8]. A variable-temperature black body and an electrically calibrated cavity radiometer inside a vacuum chamber were used to measure the ratio of the total radiant fluxes of the black body at temperatures near 1800 K and 2700 K. With the radiometer moved off the axis of the black body and the black-body radiation transmitting through a vacuum window, a spectroradiometer was used to measure the ratio of the spectral radiance of the black body at these temperatures over a range of wavelengths, as well as the ratio of the spectral radiance of the tungsten ribbon filament lamp to the black body. The three ratios were used to compute the spectral radiance of the lamps in absolute units.

4. Comparison schedule

The comparison was initially intended to cover the range 255 nm to 2400 nm. The NIST carried out measurements throughout this range. The VNIOFI measured the NIST lamps down to 240 nm and the VNIOFI lamps down to 250 nm.

The following measurements were performed:

- 1989: initial calibration of NIST lamps at the NIST, and VNIOFI lamps at the VNIOFI.
- 1989: exchange of lamps, calibration of VNIOFI lamps by the NIST, and vice versa.
- 1990: exchange of lamps, repeat calibration of lamps by the NIST and the VNIOFI.
- 1990: repeat measurement of lamp Q108 by the VNIOFI.

Accordingly, lamp Q108 was measured twice by each laboratory. Lamps Q106 and Q109 were measured twice by the NIST and once by the VNIOFI. Lamps N25, N57 and N186 were measured twice by the VNIOFI and once by the NIST.

The comparison was "blind"; that is, results were not revealed until repeat calibrations had been completed.

5. Measurement results and data analysis

The difference between NIST and VNIOFI measurements is expressed in the form

percentage difference

$$= 100 \times (L_{\lambda, \text{VNIOFI}} - L_{\lambda, \text{NIST}}) / L_{\lambda, \text{NIST}} \quad (1)$$

The VNIOFI spectral-radiance values were consistently higher than the NIST values. The percentage differences for the individual lamps were between 0,1 % and 2,7 % in the 240 nm to 800 nm range, and between 0,1 % and 1,7 % in the 900 nm to 2400 nm range.

6. Conclusion

The results of the comparison are plotted in Figure 3. The solid lines represent the combined uncertainties of the ratio measurement of a particular lamp due to the combined uncertainties reported by the NIST and the VNIOFI. As may be seen from the figure, most of the reported measurements fall within the expected range. The average difference is within 0,5 % to 1 % in the 240 nm to 800 nm range, and better than 0,5 % between 900 nm and 2400 nm. This agreement is within

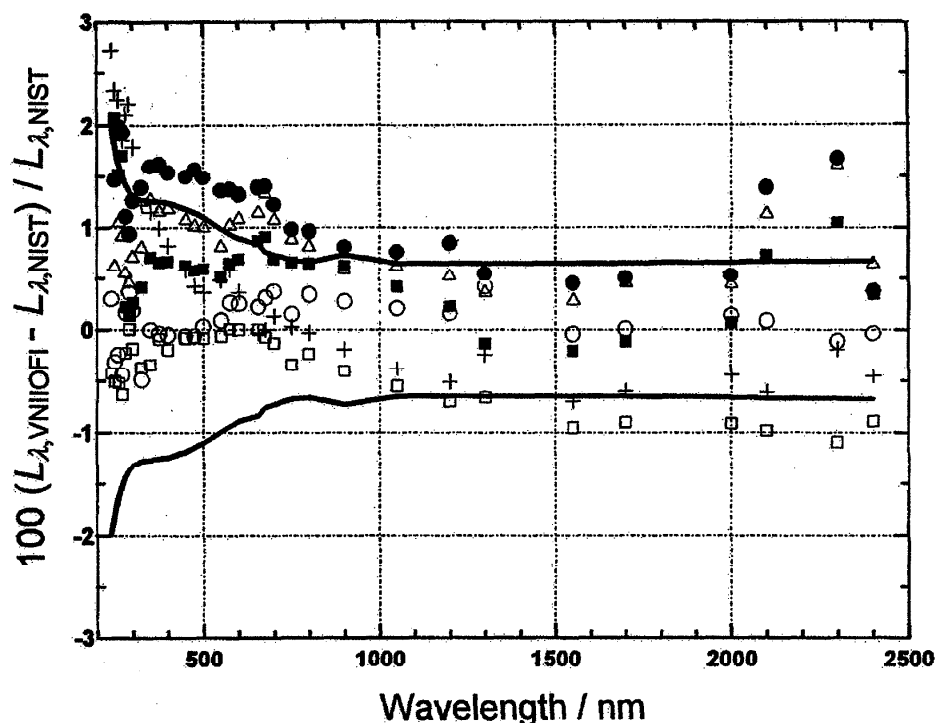


Figure 3. Comparison of NIST and VNIOFI spectral-radiance scales. Solid lines, total uncertainty; ○, Q106; □, Q108; +, Q109; △, N25; ●, N57; ■, N186.

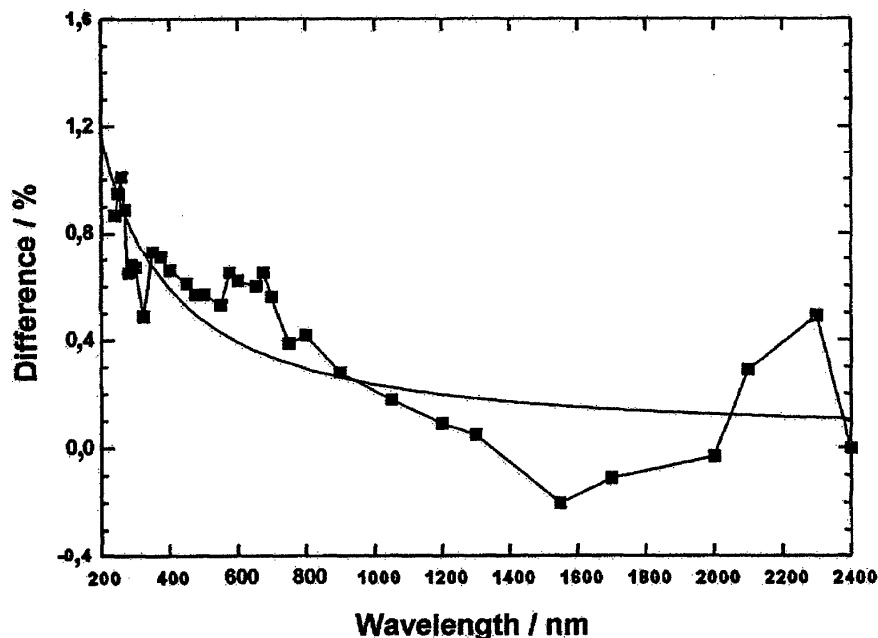


Figure 4. Average percentage difference in spectral radiance between the NIST and the VNIIOFI (—■—) and spectral-radiance difference of black bodies at 2461 K and 2460 K (—).

the 95 % confidence level of the comparison at all wavelengths. In fact, the overall agreement is within the 67 % confidence level at all except three wavelengths ($\lambda=655$ nm, 700 nm and 2300 nm).

It was noted that, overall, the average spectral radiances measured at the VNIIOFI were slightly higher than those measured at the NIST at all but three wavelengths ($\lambda=1550$ nm, 1700 nm and 2000 nm). This may indicate a small difference in the temperature scales maintained at the two laboratories. Figure 4 shows the average difference from the intercomparison and the results of a calculation based on Wien's approximation to Planck's law for black-body radiation. The solid line represents the spectral radiance ratio (Wien approximation, c_2 =second radiation constant),

$$\begin{aligned} L_{\lambda}(\lambda, 2461 \text{ K})/L_{\lambda}(\lambda, 2460 \text{ K}) \\ = \exp \{ (c_2/\lambda) [1/(2460 \text{ K}) - 1/(2461 \text{ K})] \}, \quad (2) \end{aligned}$$

of two black bodies at 2461 K and 2460 K. This curve resembles the observed overall NIST and VNIIOFI agreement, from which one might conclude that the VNIIOFI temperature scale is higher than the NIST scale by 1 K, assuming that the trend evidenced by the average difference is indicative of a systematic correction. The small difference is, however, within the uncertainty of this comparison, and also within the uncertainties of the NIST and VNIIOFI radiance temperature scales.

The NIST and VNIIOFI agreement for the individual lamps indicated differences outside the expected range shown by the solid lines in Figure 3 in a number of individual measurements at specific wavelengths. The percentage differences of the results obtained by the two laboratories exceeded the 95 % confidence level in 17 % of the individual measurements on the NIST lamps, and 41 % of the individual measurements on the VNIIOFI lamps. This suggests that the NIST lamps may have been more stable during the comparison than the VNIIOFI lamps, and that the uncertainty estimates of individual lamp measurements may not adequately represent lamp stability. The agreement in the individual measurements on the NIST lamps was better, as can be seen from the distribution of points in Figure 3. The mean difference of the measurements on the NIST lamps was 0.078 % and on the VNIIOFI lamps it was 0.81 %. This difference could in part be due to operational aspects of employing the two different lamps. The different bases and filament structures of the lamps may be the cause of alignment variance and hence result in measurement differences.

Note. Specific firms and trade names are identified in this paper for the sole purpose of adequately describing experimental or test procedures. In no event does such identification imply recommendation or endorsement by the National Institute of Standards and Technology of a particular product; nor does it imply that a named instrument is necessarily the best available for the purpose it serves.

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