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Transfer of Photometric Quantities at Arbitrary Distribution Temperatures

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Abstract

Characteristics of a photometric setup used for the measurement of photometric quantities at the National Institute of Metrology (UME) in Turkey are reported. A high accuracy method is developed to adjust the filaments of incandescent lamps with respect to the optical axis. The method also provides the basis for low uncertainty distance measurements between lamp filaments and photometers. Transfer of photometric quantities at arbitrary distribution temperatures is examined both theoretically and experimentally, and the results are compared to the calibration values of the Bureau International Des Poids Et Measures (BIPM), Paris, France.

1. Introduction

Photometric band of the electromagnetic spectrum corresponds to 380-780nm region according to the Commission Internationale de L'Eclairage (CIE) [1-2]. The photometric analog of power in optical radiometry is defined as luminous flux, and its unit is lumen (lm). Luminous flux is related to the radiometric power, given in watts (W), with the expression,

$$\Phi_v = K_m \int_\lambda \Phi_e(\lambda) V(\lambda) d\lambda \tag{1}$$

where Φ_v is the luminous flux (lm) and $\Phi_e(\lambda)$ is the spectral radiant flux concentration of light (W/nm). Here, K_m is equal to 683 lm/W and it comes from the definition of the SI unit of the luminous intensity "candela".[1] It is defined as the maximum spectral

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[1] The SI base unit, the candela (cd) was defined by the Conference Generale des Poids et Measures (CGPM) in 1979, as follows:

luminous efficacy corresponding to the peak wavelength $\lambda_m = 555$ nm for photopic vision. In Equation (1) the function $V(\lambda)$, which is determined by the CIE, is defined as the spectral luminous efficiency for photopic vision. It provides an averaged human response to visual sensitivities at different wavelengths.

The luminous flux, $d\Phi_v$, radiating from a point light source in a solid angle $d\Omega$ is defined as the luminous intensity

$$I_v = \frac{d\Phi_v}{d\Omega}, \tag{2}$$

where $d\Omega = S/r^2$ and S is the area subtended by the solid angle and r is the distance to the point source.

Photometers are devices which are used to measure various quantities of light according to their calibrated responsivity. As a rule, a photometer consists of a measuring head and a calibrated current amplifier. The measuring head basically consists of a precision aperture, an optical correction filter and a photodetector. The optical correction filter which is placed in front of the photodetector is designed so that an overall spectral response of as close to the $V(\lambda)$ function as possible is obtained. Photodetectors with high response uniformity and with close to unity internal quantum efficiencies should be selected in order to achieve high accuracy photometers.

A photometer produces an electrical current I which is related to the incident light by a luminous responsivity [3]. Further, the photocurrent, I is also related to the area of the precision aperture provided that the incident light overfills the aperture area. In this case, the photometer produces a current which is proportional to illuminance E_v. The unit of illuminance is defined as lumen per square meter (lm/m^2), or more commonly known as lux (lx). Illuminance is related to the area of the precision aperture A by

$$E_v = \frac{\Phi_v}{A}. \tag{3}$$

Calibration chains used for photometrical measurements at UME is shown in Figure 1. There are three chains based on standard lamps: luminous intensity, luminous flux and color temperature, which are illustrated in Figure 1a, 1b and 1c, respectively.

The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 $\times 10^{12}$ *hertz and that has a radiant intensity in that direction of (1/683) watt per steradian.*

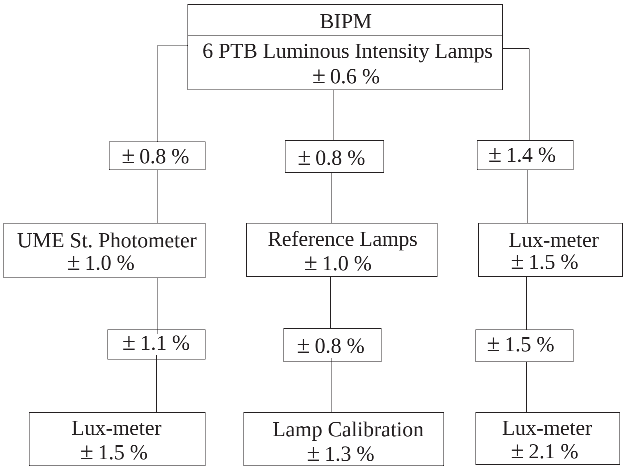

Figure 1a. Traceability chain for Luminous Intensity measurements.

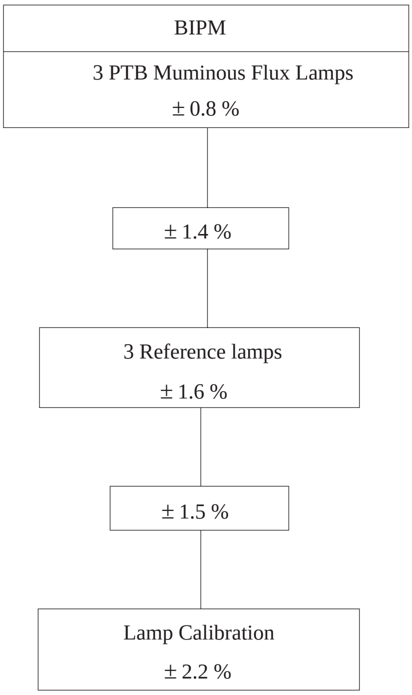

Figure 1b. Traceability chain for Luminous Flux measurements.

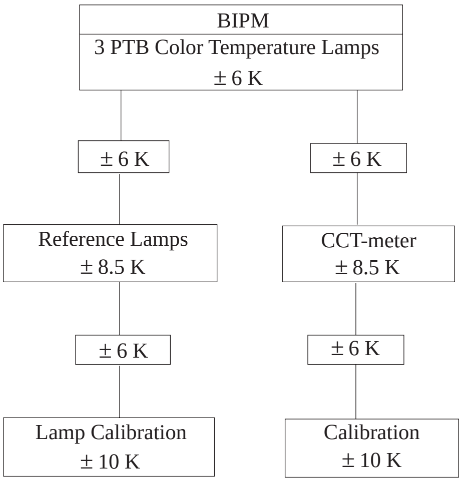

Figure 1c. Traceability chain for Color Temperature measurements.

For operation, lamps are powered by a constant current source which can be set with a resolution of $10^{-6}A$ under computer control. The current flowing through a lamp is independently monitored across a 0.1Ω calibrated precision shunt resistor. The voltage drop across lamps is also monitored by the system. The correlated-color temperature[2] operating point of incandescent lamps is measured by a calibrated diode-array type spectroradiometer.

As recommended by the CIE [4], for a fixed distribution temperature the relative spectral distribution of A-type illuminants are taken to be approximately equal to the spectral distribution of a blackbody radiator at the same distribution temperature, and is defined as 2856K for the standard A-type illuminant. This type of incandescent lamp can also be operated at different distribution temperatures. In such a case, the spectral distribution of emitted light corresponds to the spectral distribution behaviour of blackbody radiation at the set distribution temperature. In practice, bandpass filters in the range 400-750 nm with bandpass widths of 10 to 50 nm may be used in the photometrical measurements. In such cases, the deviation from the spectral distribution of a lamp $S(\lambda, T)$ and $M_{e,\lambda}(\lambda, T)$ must be less than 10%. This condition is satisfied by the photometric measurement system at UME.

The spectral radiance distribution of a blackbody radiator is defined by the Planck distribution and is given by

$$M_{e,\lambda}(\lambda, T) = C_1 \frac{1}{\lambda^5 (e^{C_2/\lambda T})} \; W/m^3, \tag{4}$$

where $C_1 = 3.74150 \times 10^{-16}\; Wm^2$ and $C_2 = 1.4388.10^{-2}$ Km.

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[2] For typical incandescent lamps the differences between correlated-color temperature and distribution temperature are small (a few degrees of Kelvin). Therefore the term distribution temperature is used in the following sections.

2. Photometric Set-up

Measurement of photometric quantities are carried out at dark room conditions by using a photometric setup as shown in simplified form in Figure 2. The setup is quite simple compared to similar setups used in [3,5]. The bench is 570 cm long and 30 cm wide. It has a long steel rail mounted on top of a 15cm thick, regulated surface marble tabletop. Two similarly constructed but shorter benches are also placed in parallel to and at the back of the main bench. They are used for mounting the two visible laser diodes (LD1 and LD2), as shown in Fig. 2. These lasers are needed for optimum adjustment of lamp filaments with respect to the optical axis. The longitudinal optical axis which runs parallel to the rail is marked by the first laser beam. It can be adjusted in three coordinates until the laser beam passes through the center holes of the baffles. For fine adjustments a precision vernier height gauge is used to make sure that the laser beam runs parallel to the rail.

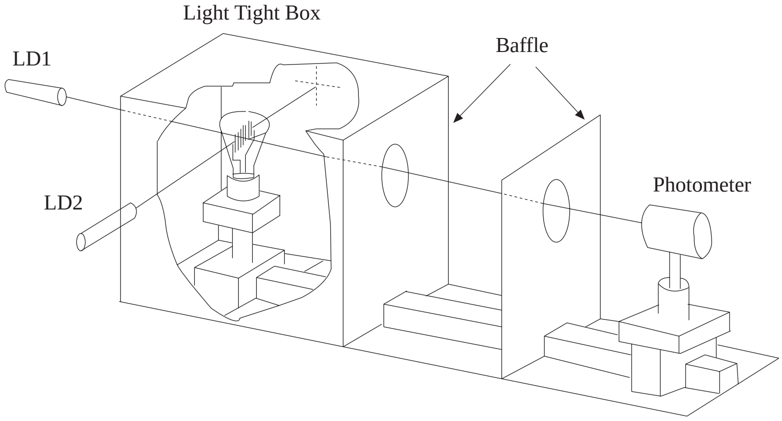

Figure 2. Setup used for the measurement of photometric quantities.

In order to align the two laser beams at right angles to each other, a cube-beamsplitter is initially put in the place of lamps. By adjusting the lasers and the cube-beamsplitter the two beams are made perpendicular to each other. After the removal of the cube-beamsplitter, the intersection point of the two laser beams determines the reference point of the photometric set-up.

The following procedure is used for aligning lamp filaments. First, a lamp is positioned so that laser beam I, which runs along the main optical bench, passes through the midpoint of the lamps' filament (position I in Figure 3). Then, the lamp is adjusted in vertical direction so that the beam from the LD2 goes through the tip of the filament wires (position II). In this position, the lamp is adjusted around its axis until bright laser light spots can be observed at each tip of the filament wire. Then, the first step is repeated to ensure that the beam from LD1 goes through the mid-point of the filament. In the final step (position III), the lamp is moved upwards until the beam from LD2 passes through the center point of the lamp where the filament wire meets the contact ends. At this position, a final check of the straightness of the filament wire is performed by observing the shadow of the filament wire on a screen which is placed at the other side of the lamp as shown in Figure 3. A shadow in the form of a single line on the screen indicates that the lamp position is correctly aligned, and that it is positioned at right angle with respect to the optical axis.

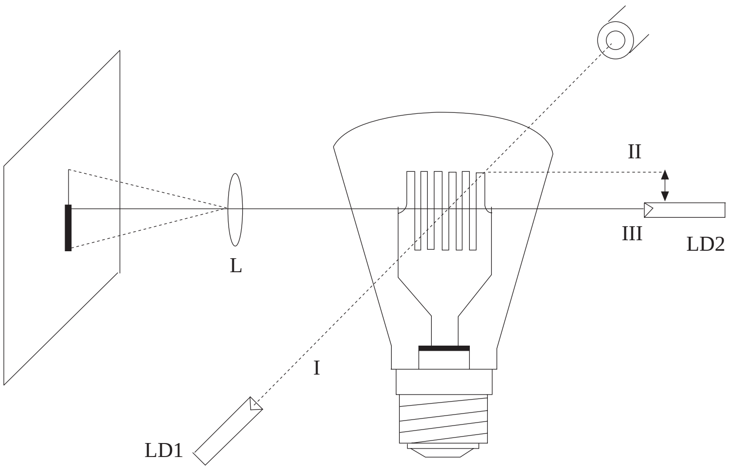

Figure 3. The lamp filament alignment procedure.

For photometrical measurements (e.g., luminous intensity, or color temperature), similar to many other metrology institutes, Osram Wi41G type lamps with tungsten filaments are mainly used in UME. One advantage of these type of lamps is that because of their flat and symmetrical filament structure they are well suited to the alignment procedure described above. As a result of the finite size of the laser spots, the uncertainty of determining the center point of the lamp filament is estimated to be ± 0.3 mm.

For minimizing stray light, optical bench, walls and the ceiling of the laboratory, and the baffles used on the bench are all painted black. Lamps are kept in a light-tight box in order to keep the stray light levels to less than 0.05 % on the photometer side. Laboratory conditions are stabilized to the ambient temperature of 23.0 ± 1.0°C with 0.2°C/hour and 0.4°C/day maximum change rate, and with the humidity of $45 \pm 5\%$.

3. Transfer of Photometric Quantities

Using primary standard lamps, transfer of luminous intensities can be obtained in two ways as illustrated in the calibration chain given in Figure 1a.

The first method requires a calibrated reference standard photometer. Calibration of the reference standard photometer (i.e., the determination of the photometer's responsivity in terms of A/lx) is first obtained from the luminous intensity of the primary standard lamps and from the distance measurements between lamp filaments and the reference entrance plane of the reference photometer. Then, working standard lamps can be calibrated directly by the use of the calibrated reference standard photometer.

Another alternative, which is preferred at UME and used in this work, can be described as follows. First, primary standard lamps are operated at the precise operating conditions specified in their calibration certificates. Then, at a fixed distance away from lamp filaments, the photocurrent value of each lamp is measured by means of any photometer, and the ratio of the specified candela value of each lamp to the corresponding photocurrent value is recorded. In the next step, each of the group of uncalibrated lamps are electrically adjusted until they operate at the same distribution temperature as the primary standard lamps. In the final step, the candela value of each uncalibrated lamp is calculated from the multiplication of the photocurrent value measured for this lamp with the averaged candela to photocurrent ratio of the primary standard lamps.

High accuracy photometric measurements are carried out as follows. Photometer heads or test devices are mounted on linear translation stages using special mounts which are free to move along the rail. Photometer heads are positioned using a precision vernier height gauge as a reference plane in such a way that the reference entrance plane of photometric heads coincide with the front surface plane of the translational stages. As a result the front surface of the translational stage determines the position of the entrance reference plane of the photometric heads on the distance scale of the rail. The rail is marked of at every 0.1m of the first 0.5m from the lamp and at every 0.5m of the rest of the 5.7m long optical rail.

The distance measurement contributes to the uncertainty in some photometric measurements. Calibrations or transfer of quantities from one lamp to another, or from one photometric head to another are generally done by the method of substitution, which does not require absolute distance measurement. The uncertainty of the distance measurements in the set-up is estimated to be less than ± 0.5 mm.

Three lamps with numbers 770, 831 and 806 were being used as the luminous intensity working standard lamps at UME until recently. The candela values of these lamps are obtained by direct transfer at 2856K from the national luminous intensity standard lamps with numbers 758, 765, 731, 753, 769 and 736, which are traceable to the German national candela standard unit.

According to CIE publication [4], the spectral radiant flux of A-type illuminants is related to the spectral radiance distribution of a blackbody by the expression

$$\Phi_e(\lambda) = SM_{e,\lambda}(\lambda, T), \tag{5}$$

where S is cross-sectional area with the dimension of square-meters. From relations (1) and (4), the total flux can be expressed as

$$\Phi_v(\lambda) = K_m S \int_\lambda M_{e,\lambda}(\lambda, T) \cdot V(\lambda, T) d\lambda. \tag{6}$$

Assuming that the distribution temperature of a standard lamp changes from T_1 to T_2, then from Equations (2), (3) and (6) it follows that

$$\frac{I_1}{I_2} = \frac{\Phi_{V_{v1}}}{\Phi_{V_{v2}}} = \frac{E_{v1}}{E_{v2}} = \frac{I_{v1}}{I_{v2}} = \frac{\int_\lambda M_{e,\lambda}(\lambda, T_1)V(\lambda)d\lambda}{\int_\lambda M_{e,\lambda}(\lambda, T_2)V(\lambda)d\lambda} = \boldsymbol{m} \tag{7}$$

where I_1 and I_2 are photocurrents measured with the photometric head. They are proportional to the incident light fluxes corresponding to the distribution temperatures T_1 and T_2 of the light source, respectively. The resultant Equation (7), shows that the ratios of photometric quantities corresponding to different distribution temperatures are given by a constant. The integrals given in Equation (7) can be calculated using the CIE tabulated values of the $V(\lambda)$ function. From Equation (7), the constant **m** value is calculated for the distribution temperatures of 2856K and 2800K as

$$\boldsymbol{m} = \frac{I_{v1}}{I_{v2}} = 1.1935. \tag{8}$$

From relation (8) and from the candela values of the working standard lamps at 2856K, candela values at 2800K can be calculated easily. The values are shown in the Table.

Table. Results of luminous intensity transfers.

Lamp No.	I_V(2856)	I_V(2800)calc	I_V(2800)UME	I_V(2800)BIPM	ΔI_V(%)
770	279.7	234.3	230.2	231.4	-0.5
831	270.8	226.9	222.6	223.4	-0.3
806	274.6	230.1	227.8	228.6	-0.3

The candela values at 2800 K can also be measured directly. In order to facilitate these measurements, at first lamps are operated at 2856K and the photocurrent produced by each lamp I_1 is recorded. In the next step, electric current of each lamp was adjusted until its distribution temperature, which is monitored with an array spectro-radiometer, reaches to 2800K. At this temperature the photocurrent I_2 is then recorded for each lamp. Using these measured values at 2800K, luminous intensity of each lamp is finally calculated using

$$I_{V2} = \frac{I_{V1}.I_2}{I_1}. \tag{9}$$

The resultant candela values for each lamp is also shown in the Table.

In order to verify the accuracy of the above results the same set of lamps have been sent to the Bureau of International Poids et Measures (BIPM) for calibration. The results of the BIPM calibration at 2800K for the set of lamps are compared in the Table.

As shown in the Table, the difference between the results of BIPM and UME, ΔI_V, is equal to or less than 0.5%. These results clearly show that using the photometric bench at UME, a high accuracy transfer of photometric quantities is achievable. At present the traceability of luminous intensity related measurements at UME are provided through these lamps.

In order to illustrate the method used for the transfer of photometric quantities a further example is considered below.

For any two wavelengths arbitrarily chosen in the photometric spectrum, for example one from blue and one from the red region, from Equation (7) it follows that

$$\begin{aligned} B &= \Delta\Phi_{Blue} = K_M S\, M(\lambda_{Blue}, T)V(\lambda_{Blue})\Delta\lambda \\ R &= \Delta\Phi_{Red} = K_M S\, M(\lambda_{Red}, T)V(\lambda_{Red})\Delta\lambda. \end{aligned} \tag{10}$$

By taking the ratio, one obtains,

$$\frac{B}{R} = a\frac{M(\lambda_{Blue}, T)}{M(\lambda_{Red}, T)}, \tag{11}$$

where a is given by $a = \frac{V(\lambda_{Blue})}{V(\lambda_{Red})}$. By inserting relation (4) into relation (11) and then taking the logarithm of both sides the following relationship is obtained:

$$\ln(B/R)_T = (d/T) + a, \tag{12}$$

where d is given by $d = c_2(1/\lambda_R - 1/\lambda_B)$. From Eqn. (12) it is clearly seen that at a definite wavelength and temperature, the blue to red ratio is constant. Therefore, in photometry, this ratio is sometimes used to express the color temperature of A-type lamps. The blue to red ratio dependence on temperature can be calculated from (12) and is shown in Figure 4.

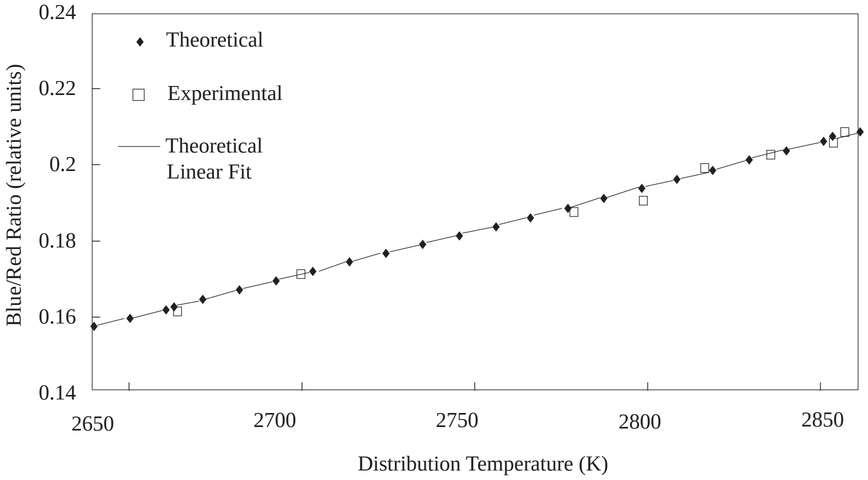

Figure 4. Blue to red ratio dependence.

For two different temperatures T_1 and T_2, blue to red ratios are found to be related as

$$\ln(B/R)_{T_2} = \ln(B/R)_{T_1} - d(1/T_1 - 1/T_2). \tag{13}$$

Therefore, if the value of $(B/R)_{T1}$ is known, then the value of $(B/R)_{T2}$ at an arbitrary temperature T2 can be calculated from relation (13). For example, for the blue to red ratio measured of $(B/R)_{2856} = 0.2078$ at 2856K, at 2800K the $(B/R)_{2800}$ value for the same lamp can be calculated as 0.1938. In Figure 4, measured blue to red ratio dependence on temperature is plotted for the lamp number 770. From this figure, it is clearly seen that the difference between the calculated and measured values is not greater than 1.5%. This slight deviation is much less than the ten percent requirement explained earlier and it is mainly attributed to color temperature measurements.

4. Conclusions

A photometric set-up is developed which provides the basis for high accuracy transfer of photometric quantities at UME. It is shown that accurate transfer of photometric quantities can be achieved theoretically or experimentally using the procedures described in previous sections. The ratios of photometric quantities at arbitrary distribution temperatures is shown to be invariant, providing the basis for theoretical transfers. In the example case of luminous intensity transfers the comparison with BIPM results shows that a difference of less than 0.5% in candela values is achievable.

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References

[1] The basis of physical photometry, CIE Publication: N18.2 (TC-1.2), Paris (1983).

[2] International lighting vocabulary, 4th ed., CIE Publication: N:17.4 (Joint public. IEC/CIE:IEC Pub. 50(845)), (1987) 34.

[3] C.L. Cromer, et.al., Applied Optics, **32** (1993) 2936.

[4] Colorimetry, CIE Publications: N15(E-1.3.1), Paris (1971).

[5] G. Czibula, E. Krochmann, Proc.SPIE: 171, 14th Symp. on Photonic Measurements, ISBN 0-8194-0877-8, (1993) 92.