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Color Coordinates and Uncertainty for Luminous Flux Secondary and Working Standard Lamps

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ABSTRACT: *Nowadays, the world is concern in estimating the uncertainty in measurements than before. Any color measurement is not complete without estimating the accompanying uncertainty. In this work, the color coordinates values of CIE 1931 (x,y) chromaticity coordinates, CIE 1960 (u, v) uniform color space (UCS) and CIE 1979 ($\bar{u}$,$\bar{v}$) uniform color space (UCS) are determined from their spectral power distributions for all NIS OSRAM total luminous flux secondary and working standard lamps. Theses lamps are classified in different groups depending on their correlated color temperatures (CCT). These lamps are very important for the routine work in photometry laboratory at National Institute of standards (NIS). A set up based on NIS Spectroradiometer ocean optics HR 2000 with uncertainty 4.7% and the photometric bench has been used for measuring the spectral power distribution of the lamps. The method of Guide to Expression of Uncertainty in Measurements (ISO) and the method of J. L Gardner in color measurements are applied to estimate the uncertainties in color of CIE 1931 (x,y) chromaticity coordinates, CIE 1960 (u, v) uniform color space (UCS) and CIE 1979 ($\bar{u}$,$\bar{v}$) uniform color space (UCS) for all NIS OSRAM total luminous flux secondary and working standard lamps. These uncertainty values are useful and very important for determining the uncertainty in color quantities such as correlated color temperature (CCT).*

KEYWORDS: *Spectral Power Distribution (SPD), Tristimulus Response Functions, Chromaticity Coordinates, Correlated Color Temperature (CCT), Secondary and Working Standard lamps, Uncertainty.*

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I. INTRODUCTION

Any Metrological field required accurate assessment of uncertainties by following principles descried in the ISO Guide to the Expression of Uncertainty in Measurement [1]. This Guide has been used in the national metrology institutes to provide traceable measurements to the calibration laboratories. The estimation of uncertainty in color measurements are difficult and very important because any measurement of color is not complete without an estimation of accompanied uncertainty. The methods of ISO Guide to the Expression of Uncertainty in Measurement [1] and the method of J. L. Gardner in color measurements [2-4] are applied to evaluate the uncertainties in chromaticity coordinates and uniform colour space for some of NIS luminous flux secondary and working standard lamps. The $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, $\bar{z}(\lambda)$ colour matching functions are tabulated [5] over the spectral range from 400-780 nm and used for all calculations presented in this paper as shown in Figure 1.

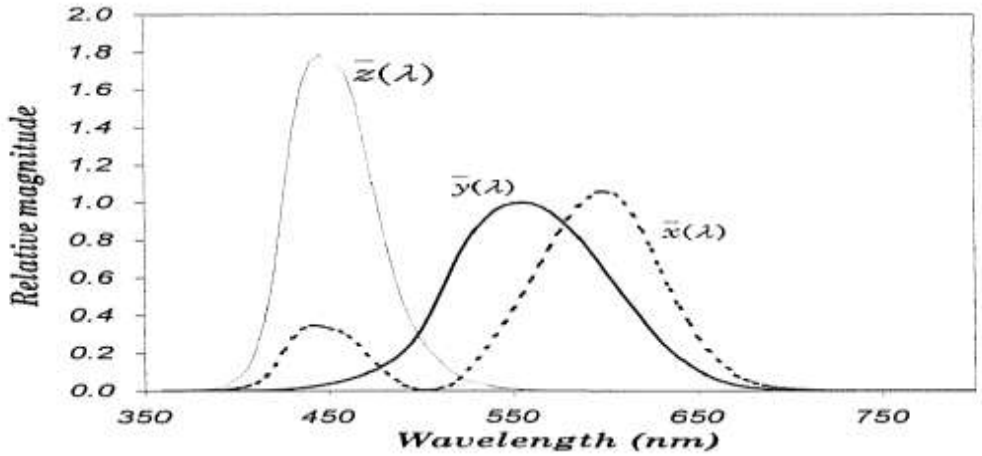

Figure 1. CIE 1931 color matching functions.

The Guide to the Expression of Uncertainty in Measurement (GUM) gives the Law of Propagation of Uncertainty.

$$u_c^2(y) = \sum_{i=1}^{n}\left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i) + 2\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\frac{\partial f}{\partial x_i}\frac{\partial f}{x_j}u(x_i, x_j) \quad (1)$$

which applies for a measurement model of the form

$$Y = f(X_1, X_2, X_3....., X_i,.....) \quad (2)$$

where an estimate x_i of quantity X_i *has* an associated uncertainty $u(x_i)$, the squared combined standard uncertainty (the combined variance) is the sum of two terms in equation (3). The first term is the sum of the squares of the standard uncertainties $u(x_i)$ (the sum of the variances) associated with each individual effect multiplied by the relevant sensitivity coefficient (the partial derivative) [1, 6]. By applying the law of propagation of uncertainty [7, 8] as the following equation:

$$u^2 = \sum_{\text{var}iable}\left(\frac{\partial f}{\partial \text{var}iable}\right)^2 \times u^2(\text{var}iale) \quad (3)$$

1.1 Color Coordinates

If spectral of irradiance E (λ) are made at the corresponding wavelengths, the tristimulus response are:

$$X = \sum_i E_i \bar{x}_i, \quad Y = \sum_i E_i \bar{y}_i \text{ , and } \quad Z = \sum_i E_i \bar{z}_i$$

Where $\bar{x}_i$, $\bar{y}_i$ and $\bar{z}_i$ are tabulated values of the tristimulus response functions.

E_i is the (relative) spectral irradiance at wavelength i

Then CIE 1931 (x,y) chromaticity coordinates are defined as [2 - 4]

$$x = \sum E_i \bar{x}_i / \sum E_i \bar{t}_i \quad (4)$$

$$y = \sum E_i \bar{y}_i / \sum E_i \bar{t}_i \quad (5)$$

and

$$\bar{t}_i = \bar{x}_i + \bar{y}_i + \bar{z}_i \quad (6)$$

The transforms of (*x*, *y*) CIE 1960 (*u*, *v*) uniform color space (UCS) are defined as [2 - 4]

The (u, v) transforms of (x, y) can be rewritten as

$$u = 4X/(X + 15Y + 3Z) \tag{7}$$

and

$$v = 6Y/(X + 15Y + 3Z) \tag{8}$$

The transforms of (x, y) CIE 1979 ($\bar{u}$, $\bar{v}$) uniform color space (UCS) are a simple rescaling of the superseded (u, v) as $\bar{u} = u$ and $\bar{v} = 3v/2$ [2 - 4]:
Then

$$\bar{u} = 4X/(X + 15Y + 3Z) \tag{9}$$

and

$$\bar{v} = 18Y/2(X + 15Y + 3Z) \tag{10}$$

1.2 Uncertainties of color coordinates

From the propagation law of uncertainty [1], the square of the standard uncertainty in x and y is given by [2 - 4]

$$u_c(x) = \alpha\left(\sum E_i^2 \bar{x}_i^2 - 2x\sum E_i^2 \bar{x}_i \bar{t}_i + x^2 \sum E_i^2 \bar{t}_i^2\right)^{1/2} / \sum E_i \bar{t}_i \tag{11}$$

$$u_c(y) = \alpha\left(\sum E_i^2 \bar{y}_i^2 - 2y\sum E_i^2 \bar{y}_i \bar{t}_i + y^2 \sum E_i^2 \bar{t}_i^2\right)^{1/2} / \sum E_i \bar{t}_i \tag{12}$$

The correlation coefficients for the tristimulus responses is given by the following equation:

$$r_{xy} = \sum E_i^2 \bar{x}_i \bar{y}_i / \sqrt{\sum E_i^2 \bar{x}_i^2 \sum E_i^2 \bar{y}_i^2} \tag{13}$$

From the propagation law of uncertainty [1], the square of the standard uncertainty in u and v is given by [2 - 4]

$$\begin{aligned} u_c(u) = \{&(u-4)^2 \sum E_i^2 \bar{x}_i^2 + u^2(225\sum E_i^2 \bar{y}_i^2 \\ &+ 9\sum E_i^2 \bar{z}_i^2) + 30u(u-4)\sum E_i^2 \bar{x}_i \bar{y}_i + \\ &6u(u-4)\sum E_i^2 \bar{x}_i \bar{z}_i + 90u^2 \sum E_i^2 \bar{y}_i \bar{z}_i)\}^{1/2} / \\ &\sum E_i \bar{x}_i + \sum 15E_i \bar{y}_i + 3\sum E_i \bar{z}_i \end{aligned} \tag{14}$$

And

$$\begin{aligned} u_c(v) = \{&9(5v-2)^2 \sum E_i^2 \bar{y}_i^2 + v^2(\sum E_i^2 \bar{x}_i^2 + \\ &9\sum E_i^2 \bar{z}_i^2) + 6v(5v-2)\sum E_i^2 \bar{x}_i \bar{y}_i + \\ &6v^2 \sum E_i^2 \bar{x}_i \bar{z}_i + 18v(5v-2)\sum E_i^2 \bar{y}_i \bar{z}_i)\}^{1/2} / \\ &\sum E_i \bar{x}_i + \sum 15E_i \bar{y}_i + 3\sum E_i \bar{z}_i \end{aligned} \tag{15}$$

II. MEASUREMENTS AND EXPERIMENTS

The spectral power distribution of NIS luminous flux secondary and working standard lamps measured using the photometric bench and spectroradiometer ocean optics HR 2000 at NIS with uncertainty 4.7% (9). Light to be measured is guided into entrance port of spectroradiometer through an optical fiber and the spectrum is output through the USB port to a PC for a data acquisition as shown in Figure 2 [10]. The spectroradiometric measurements of light sources are performed based on CIE 63-1984 method recommended by International Electrotechnical Commission (IEC) [11]. The employed spectroradiometer is periodically calibrated using a standard source of irradiance based on standard method [12]. Measurements were performed in a conditioned dark room and maintaining the temperature at $(25 \pm 2)^0 C$.

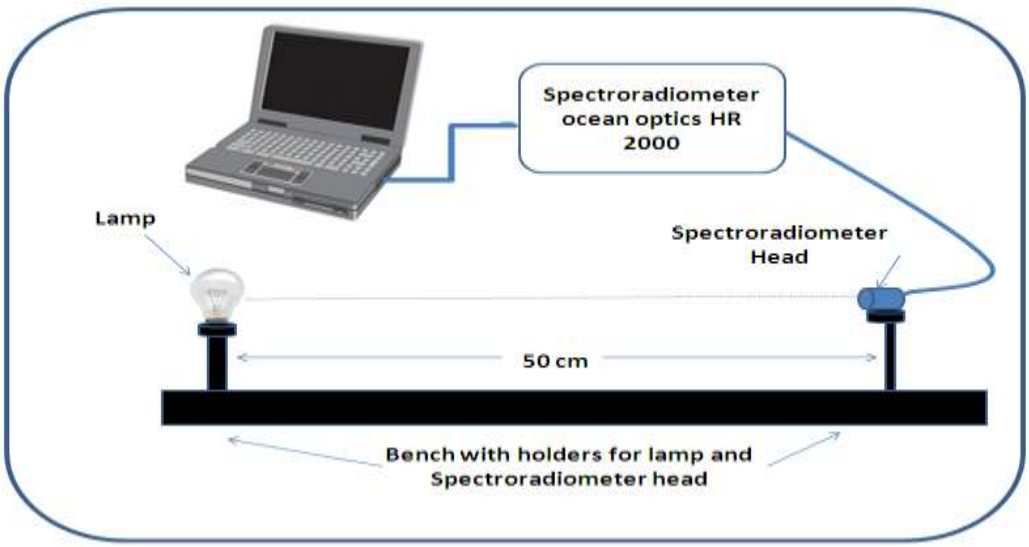

Figure. 2. Set up of measuring the spectral power distribution of NIS total luminous flux secondary and working standard lamps.

The electrical control parameters of the NIS OSRAM total luminous flux secondary and working standard lamps are tabulated in the tables from table 1 to table 8. The lamps calibrated at different correlated color temperature ranged from 2790 kelvin to 2351 to use in routine calibration work in our photometric laboratory [13, 14].

Table 1. The Electrical Control Results for Secondary Standard Lamps with CCT=2750

NIS Secondary Standard Lamps	SET Current (amperes)	Voltage (Volts)	Color temperature (Kelvin)
NIS-E21	1.7869	102.1	2750
NIS-E22	1.7991	101.6	2750

Table 2. The Electrical Control Results for Secondary Standard Lamps with CCT=2400

NIS Secondary Standard Lamps	SET Current (amperes)	Voltage (Volts)	Color temperature (Kelvin)
NIS-E31	0.20482	91.9	2400
NIS-E32	0.20315	92.0	2400
NIS-E33	0.20382	92.4	2400

Table 3. The Electrical Control Results for working standard Lamps with CCT=2351

NIS Working Standard Lamps	SET Current (amperes)	Voltage (Volts)	Color temperature (Kelvin)
NIS-F1	0.20345	90.7	2351
NIS-F2	0.20362	90.3	2351
NIS-F3	0.20484	91.0	2351
NIS-F4	0.20435	91.0	2351
NIS-F5	0.20319	90.4	2351

Table 4. The Electrical Control Results for working standard Lamps with CCT=2693

NIS Working Standard Lamps	SET Current (amperes)	Voltage (Volts)	Color temperature (Kelvin)
NIS-F7	0.37883	108.7	2693
NIS-F9	0.38033	109.5	2693

Table 5. The Electrical Control Results for working standard Lamps with CCT=2761

NIS Working Standard Lamps	SET Current (amperes)	Voltage (Volts)	Color temperature (Kelvin)
NIS-F11	0.57724	108.5	2761
NIS-F13	0.57850	108.2	2761
NIS-F14	0.58203	109.4	2761

Table 6. The Electrical Control Results for working standard Lamps with CCT=2737

NIS Working Standard Lamps	SET Current (amperes)	Voltage (Volts)	Color temperature (Kelvin)
NIS-F16	0.70383	109.2	2737
NIS-F17	0.70389	106.9	2737
NIS-F18	0.71908	109.0	2737
NIS-F20	0.71005	109.0	2737

Table 7. The Electrical Control Results for working standard Lamps with CCT=2788

NIS Working Standard Lamps	SET Current (amperes)	Voltage (Volts)	Color temperature (Kelvin)
NIS-F23	0.90384	105.5	2788
NIS-F24	0.90491	106.6	2788
NIS-F25	0.90735	106.7	2788

Table 8. The Electrical Control Results for working standard Lamps with CCT=2790

NIS Working Standard Lamps	SET Current (amperes)	Voltage (Volts)	Color temperature (Kelvin)
NIS-F26	1.7911	101.8	2790
NIS-F27	1.7853	101.4	2790
NIS-F29	1.7820	101.1	2790
NIS-F30	1.7923	100.3	2790

III. RESULTS AND DISCUSSIONS

The results of measuring the spectral power distribution of some of NIS luminous flux secondary and working standard lamps in photometry and radiometry division at National Institute of standards (NIS) shown in Figure 3. It shows the spectral power distribution (SPDs) diagrams for the lamps and their radiant power emitted by the source at each wavelength over the visible region (400 to 780 nm). It is found that the lamps have its own characteristics and they emit their spectrum in the visible region with different spectral distributions.

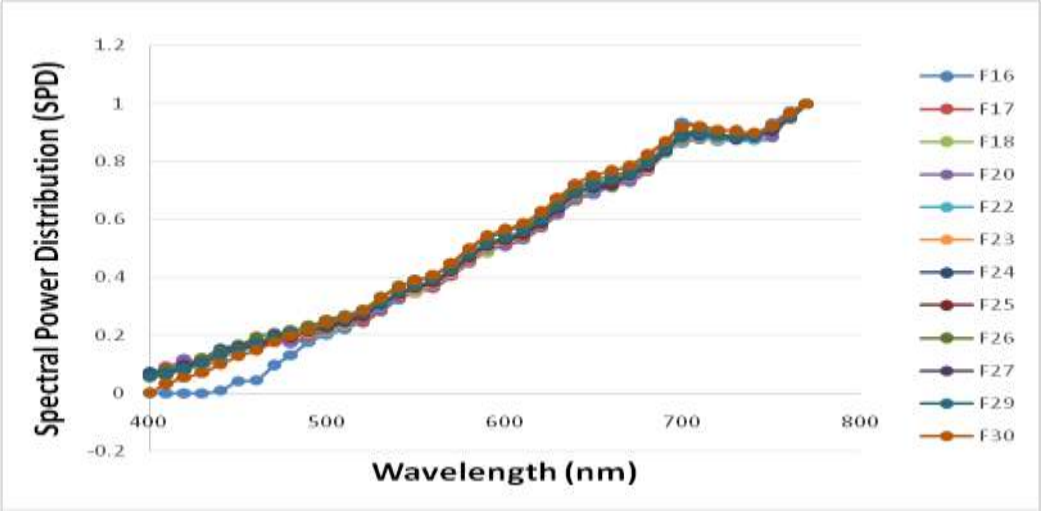

Figure 3. the spectral power distribution of some working standard lamps.

3.1 The values of color coordinates

The values of CIE 1931 (x,y) chromaticity coordinates, CIE 1960 (*u*, *v*) uniform color space (UCS) and CIE 1979 (u^*, v^*) uniform color space (UCS) for NIS OSRAM total luminous flux secondary and working standard lamps are tabulated in the tables from table 9 to table 16. The lamps are classified and calibrated depending on their correlated color temperature which are ranged from 2790 kelvin to 2351.

Table. 9 The color coordinates values for secondary standard lamps with CCT=2750

Secondary standard lamps	x	y	u	v	u'	v'
E21	0.465	0.416	0.264	0.353	0.264	0.530
E22	0.448	0.397	0.261	0.347	0.261	0.520
E24	0.464	0.414	0.264	0.353	0.264	0.529

Table. 10 The color coordinates values for secondary standard lamps with CCT=2400

Secondary standard lamps	x	y	u	v	u'	v'
E31	0.614	0.385	0.384	0.361	0.384	0.542
E32	0.605	0.394	0.372	0.363	0.372	0.544
E33	0.467	0.389	0.278	0.347	0.278	0.520

Table. 11 The color coordinates values for working standard lamps with CCT=2351

Working standard lamps	x	y	u	v	u'	v'
F1	0.426	0.358	0.265	0.333	0.265	0.500
F2	0.454	0.379	0.273	0.342	0.273	0.514
F3	0.421	0.346	0.267	0.329	0.267	0.493
F4	0.604	0.395	0.370	0.363	0.370	0.544
F5	0.428	0.342	0.274	0.328	0.274	0.492

Table. 12 The color coordinates values for working standard lamps with CCT=2693

Working standard lamps	x	y	u	v	u'	v'
F7	0.445	0.384	0.265	0.343	0.265	0.515
F9	0.452	0.395	0.265	0.347	0.265	0.520

Table. 13 The color coordinates values for working standard lamps with CCT=2761

Working standard lamps	x	y	u	v	u'	v'
F11	0.452	0.400	0.262	0.348	0.262	0.522
F13	0.443	0.389	0.261	0.344	0.261	0.516
F14	0.494	0.443	0.270	0.363	0.270	0.544

Table. 14 The color coordinates values for working standard lamps with CCT=2737

Working standard lamps	x	y	u	v	u'	v'
F16	0.495	0.441	0.271	0.362	0.271	0.544
F17	0.449	0.392	0.263	0.346	0.263	0.518
F18	0.450	0.396	0.263	0.347	0.263	0.520
F20	0.451	0.398	0.263	0.348	0.263	0.521
F22	0.452	0.400	0.262	0.348	0.262	0.522

Table. 15 The color coordinates values for working standard Lamps with CCT=2788

Working standard lamps	x	y	u	v	u'	v'
F23	0.449	0.397	0.261	0.347	0.261	0.521
F24	0.447	0.395	0.261	0.346	0.261	0.519
F25	0.447	0.395	0.261	0.346	0.261	0.519

Table. 16 The color coordinates values for working standard Lamps with CCT= 2790

Working standard lamps	x	y	u	v	u'	v'
F26	0.445	0.397	0.259	0.346	0.259	0.520
F27	0.447	0.397	0.261	0.347	0.261	0.520
F29	0.449	0.398	0.261	0.347	0.261	0.521
F30	0.460	0.412	0.262	0.352	0.262	0.521

IV. THE UNCERTAINTY VALUES OF COLOR COORDINATES

The uncertainty values of CIE 1931 (x,y) chromaticity coordinates, CIE 1960 (u, v) uniform color space (UCS) and CIE 1979 (u^*, v^*) uniform color space (UCS) for NIS OSRAM total luminous flux secondary and working standard lamps are tabulated in the tables from table 17 to table 24 depending on their correlated color temperature .

Table. 17 The uncertainty of color coordinates values for secondary standard lamps with CCT=2750

Secondary standard lamps	uc(x)	uc(y)	uc(u)	uc(v)	uc(u')	uc(v')
E21	0.05039	0.01681	0.00458	0.00602	0.00458	0.00687
E22	0.04707	0.01571	0.00519	0.00691	0.00519	0.00778
E24	0.05024	0.01674	0.00435	0.00570	0.00435	0.00653

Table. 18 The uncertainty of color coordinates values for secondary standard lamps with CCT=2400

Secondary standard lamps	uc(x)	uc(y)	uc(u)	uc(v)	uc(u')	uc(v')
E31	0.03815	0.01430	0.04829	0.02043	0.04829	0.07243
E32	0.03858	0.01461	0.04233	0.01949	0.04233	0.06349
E33	0.03062	0.01337	0.01369	0.01363	0.01369	0.02054

Table. 19 The uncertainty of color coordinates values for working standard lamps with CCT=2351

Working standard lamps	uc(x)	uc(y)	uc(u)	uc(v)	uc(u')	uc(v')
F1	0.03091	0.01214	0.01001	0.01169	0.01001	0.01501
F2	0.03002	0.01291	0.01261	0.06328	0.01261	0.01891
F3	0.03188	0.01165	0.01022	0.01132	0.01022	0.01533
F4	0.03758	0.01453	0.04264	0.01982	0.04264	0.06396
F5	0.03189	0.01143	0.01214	0.01189	0.01214	0.01821

Table. 20 The uncertainty of color coordinates values for working standard lamps with CCT=2693

Working standard lamps	uc(x)	uc(y)	uc(u)	uc(v)	uc(u')	uc(v')
F7	0.04406	0.01484	0.00743	0.00896	0.00743	0.01115
F9	0.04277	0.01523	0.00764	0.00948	0.00764	0.01146

Table. 21 The uncertainty of color coordinates values for working standard lamps with CCT=2761

Working standard lamps	uc(x)	uc(y)	uc(u)	uc(v)	uc(u')	uc(v')
F11	0.04730	0.01587	0.00660	0.00867	0.00660	0.00989
F13	0.04577	0.01520	0.00663	0.00862	0.00663	0.00994
F14	0.05097	0.01798	0.00786	0.00988	0.00786	0.01179

Table.22 The uncertainty of color coordinates values for working standard Lamps with CCT=2737

Working standard lamps	uc(x)	uc(y)	uc(u)	uc(v)	uc(u')	uc(v')
F16	0.04997	0.01782	0.00820	0.01007	0.00820	0.01230
F17	0.04540	0.01534	0.00703	0.00885	0.00703	0.01054
F18	0.04566	0.01553	0.00691	0.00887	0.00691	0.01037
F20	0.04569	0.01565	0.00691	0.00887	0.00691	0.01037
F22	0.04700	0.01584	0.00666	0.00871	0.00666	0.00999

Table. 23 The uncertainty of color coordinates values for working standard Lamps with CCT=2788

Working standard lamps	uc(x)	uc(y)	uc(u)	uc(v)	uc(u')	uc(v')
F23	0.04666	0.01566	0.00657	0.00866	0.00657	0.00985
F24	0.04741	0.01561	0.26127	0.34618	0.26127	0.39191
F25	0.04717	0.01577	0.00651	0.00860	0.00651	0.00976

Table .24 The uncertainty of color coordinates values for working standard Lamps with CCT=2790

Working standard lamps	uc(x)	uc(y)	uc(u)	uc(v)	uc(u')	uc(v')
F26	0.04978	0.01588	0.00578	0.00804	0.00578	0.00866
F27	0.04791	0.01574	0.00628	0.00841	0.00628	0.00943
F29	0.04802	0.01581	0.00631	0.00843	0.00631	0.00947
F30	0.05094	0.01667	0.00625	0.00840	0.00625	0.00938

V. CONCLUSIONS

In this work, the color coordinates values of CIE 1931 (x,y) chromaticity coordinates, CIE 1960 (*u*, *v*) uniform color space (UCS) and CIE 1979 (u^*, v^*) uniform color space (UCS) are determined from their spectral power distributions for all NIS OSRAM total luminous flux secondary and working standard lamps. Theses lamps are classified in different groups depending on their correlated color temperatures (CCT). These lamps are very important for the routine work in photometry laboratory at National Institute of standards (NIS). A set up based on NIS Spectroradiometer ocean optics HR 2000 with uncertainty 4.7% and the photometric bench has been used for measuring the spectral power distribution of the lamps. The method of Guide to Expression of Uncertainty in Measurements (ISO) and the method of J. L Gardner in color measurements are applied to estimate the uncertainties in color of CIE 1931 (x,y) chromaticity coordinates, CIE 1960 (*u*, *v*) uniform color space (UCS) and CIE 1979 (u^*, v^*) uniform color space (UCS) for all NIS OSRAM total luminous flux secondary and working standard lamps. These uncertainty values are useful and very important for determining the uncertainty in color quantities such as correlated color temperature (CCT).

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