



International Commission on Illumination  
Commission Internationale de l'Eclairage  
Internationale Beleuchtungskommission

# **CIE Software Check of luox.app**

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The task group also thanks S. Oh (South Korea) for his assistance in data compilation and analysis.

## CONTENTS

Summary .....	iv
1 Introduction .....	1
2 Test details .....	1
2.1 Software under test .....	1
2.2 Reference spectra .....	2
2.3 Reference software .....	3
2.4 Evaluation criteria .....	3
3 Results .....	4
3.1 Illuminance .....	4
3.2 Chromaticity coordinates CIE 1931 .....	5
3.3 Chromaticity coordinates CIE 1964 .....	5
3.4 $\alpha$ -opic irradiance .....	6
3.5 $\alpha$ -opic Equivalent Daylight Illuminance (EDI) .....	8
3.6 $\alpha$ -opic Efficacy of Luminous Radiation (ELR) .....	8
3.7 Other checks .....	9
4 Limitations of the CIE validation .....	9
5 Conclusions .....	9
References .....	9

## Summary

The University of Oxford has developed an open-access software platform known as *luox*, which incorporates elements of CIE publications for the calculation of certain quantities integrated from spectral data. Under the terms of a licence agreement between the University of Oxford and the CIE, the CIE has agreed to endorse the software following a black-box validation of the software. This is the report of that validation exercise, based on the work of an ad hoc task group of the CIE Board of Administration. The task group selected 43 spectra from various sources, 19 being spectra with 5 nm intervals and 24 being spectra with 1 nm intervals, and calculated luminance (illuminance),  $\alpha$ -opic radiances ( $\alpha$ -opic irradiances),  $\alpha$ -opic equivalent daylight luminances ( $\alpha$ -opic equivalent daylight illuminances),  $\alpha$ -opic efficacies of luminous radiation, and chromaticity coordinates using both *luox* and a variety of other available reference calculation tools, both public and private. Tolerance intervals were established for each quantity, and the deviation between the test values from *luox* and the reference values were calculated for each spectrum. The results for all of these evaluations showed consistency between the test values and the reference values. Based on these results, the CIE approves the following statement concerning the *luox* software, as per the aforementioned licence agreement:

“This software incorporates methods, formulae, spectral function calculations and spectra from the International Commission on Illumination (CIE). The CIE endorses this software having made a black-box evaluation of the software as of Feb. 11, 2021, finding that the software performs satisfactorily. This software is not a replacement for the CIE publications and works from which it is derived. The user is advised to consult the original publications and works for proper understanding of and calculation of the result of this software.”

## 1 Introduction

The University of Oxford has developed an open-access software platform known as *luox* (Spitschan 2021), which incorporates elements of CIE publications for the calculation of certain quantities integrated from spectral data. Under the terms of a licence agreement between the University of Oxford and the CIE, the CIE has agreed to endorse the software following a black-box validation of the software. This is the report of that validation exercise.

The purpose of *luox* is to support the research community by providing a simple, free tool for calculating quantities based on spectral measurements of a light source. The primary audience is expected to be researchers interested in the effects of light on physiology and behaviour. To that end, the quantities that are reported (depending on whether the input values are spectral radiance or spectral irradiance values) are luminance (illuminance),  $\alpha$ -opic radiances ( $\alpha$ -opic irradiances),  $\alpha$ -opic equivalent daylight luminances ( $\alpha$ -opic equivalent daylight illuminances),  $\alpha$ -opic efficacies of luminous radiation (see CIE 2018a for the definitions of these  $\alpha$ -opic quantities), and chromaticity coordinates (CIE 2018b).

## 2 Test details

### 2.1 Software under test

The test calculations were run on 2021-02-11, 12:45 CET to 13:06 CET. Version information:

- Latest tag: cie-validation
- Latest commit SHA: 948a3daa397ae64f7ac840b6d0a040e4200745e7

The source code is available at <https://github.com/luox-app/luox/> under MIT licence.

Figure 1 shows a subset of the settings used for the tests reported here, showing one batch of five of the test spectra.

**Upload spectrum and generate report**

**Step 1. Upload your spectral power distribution data.**

**Step 2. Tell us more about your data.**

My data contains  spectra with wavelength in nm. My measurements are labelled

,   and ☐ LED-B1. Each measurement column contains  in  per .

**Step 3. Check we have understood your input correctly.**

Check that we have loaded the correct number of observations. Also check the units of measurement. It may help to compare your spectra to a standard reference spectra. For example, if your measurements were made in daylight, check that they have a similar shape to **CIE Standard Illuminant D65**. Your data might be easier to read if you change the y-axis scale.

**Figure 1 — The test settings for a subset of the *luox* calculations reported here**

## 2.2 Reference spectra

The task group selected a variety of reference spectra to test, some with 5 nm intervals and some with 1 nm intervals. Some of the spectra were drawn from existing CIE documents; others were created for these tests, to provide extreme cases. Table 1 lists the spectra and their sources.

**Table 1 — The full list of 43 spectra used for the test**

Name	5 nm	1 nm	Source
FL1	x		CIE 015:2018
FL2	x		CIE 015:2018
FL3	x		CIE 015:2018
CIE_A	x		CIE 015:2018
CIE_D65	x		CIE 015:2018
LED-B1		x	CIE 015:2018
LED-B2		x	CIE 015:2018
LED-B3	x	x	CIE 015:2018
LED-B4		x	CIE 015:2018
LED-B5		x	CIE 015:2018
LED-BH1		x	CIE 015:2018
LED-RGB1	x	x	CIE 015:2018
LED_B5_15000	x		A modified version of LED-B5 from CIE 015:2018 for a CCT of 15 000 K
4_laser	x		A 4-peak laser white light
LED-V1		x	CIE 015:2018
LED-V2		x	CIE 015:2018
HP1	x		CIE 015:2018
CIE_E	x		CIE 015:2018
Random	x <sup>*1</sup>	x	Fully random spectrum – Random spectra are non-continuous spectra developed with a random number generator used to identify if the system was biased towards more typical spectrum types.
GreenRandom	x <sup>*1</sup>	x	Random, biased towards green
RedRandom	x <sup>*1</sup>	x	Random, biased towards red
BlueRandom	x <sup>*1</sup>	x	Random, biased towards blue
Square verA		x	An arbitrary spectrum with square peaks, version A
Square verB		x	An arbitrary spectrum with square peaks, version B
Test CCT Limit+ (OUT)		x	A test spectrum with chromaticity just outside the upper limit of $\Delta_{uv} = 0,05$ above the Planckian locus
Test CCT Limit+ (IN)		x	A test spectrum with chromaticity just inside the upper limit of $\Delta_{uv} = 0,05$ above the Planckian locus
Test CCT Limit- (IN)		x	A test spectrum with chromaticity just outside the lower limit of $\Delta_{uv} = 0,05$ below the Planckian locus
Test CCT Limit- (OUT)		x	A test spectrum with chromaticity just inside the lower limit of $\Delta_{uv} = 0,05$ below the Planckian locus
LED blue		x	A blue LED, peak at 460 nm
LED green		x	A green LED, peak at 521 nm
LED orange		x	An orange LED, peak at 528 nm
LED red cut		x	A red LED, peak at 632 nm
Laser 650 nm		x	A single peak at 650 nm
<sup>*1</sup> There were two versions of the 5 nm random spectra, created from the 1 nm versions. One was truncated by taking the values at each 5 nm. The other was weighted by taking the average of the values 2 nm above and below each 5 nm value.			

## 2.3 Reference software

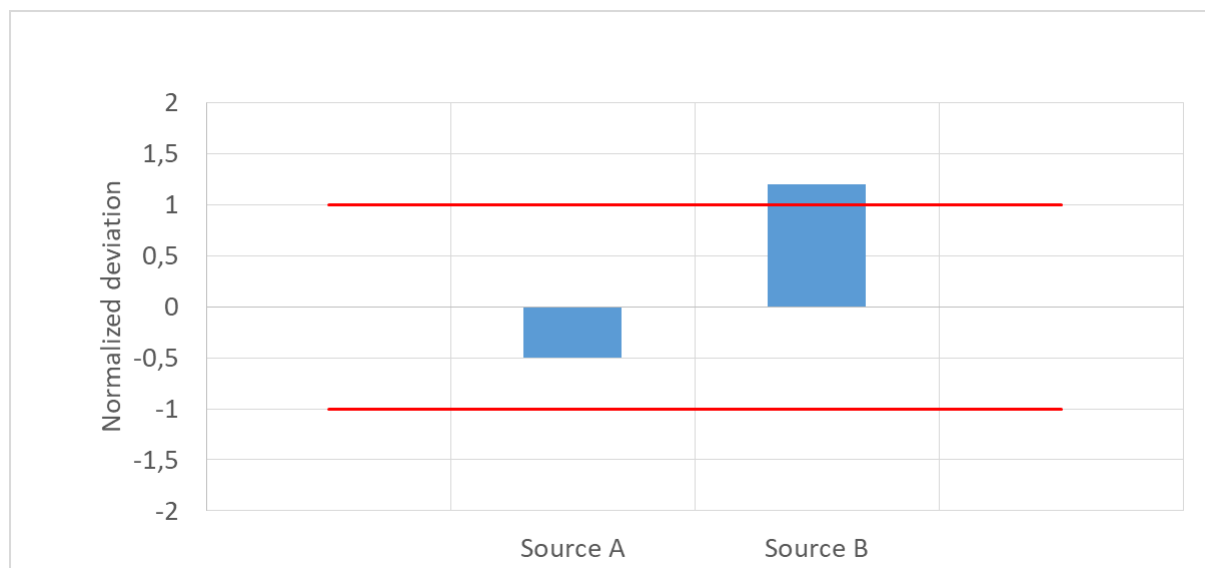
Results calculated by *luox* were compared to the CIE S 026 toolbox (version v1.049), CIE 224:2017, and two unpublished calculators: the NIST CQS calculator (Version 9.0.6 for 5 nm data and 9.0.7 for 1 nm data) (Ohno 2020) and the METAS calculator ActionSpectra (version 1.3.0.30) (METAS 2020). Table 2 lists the quantities that were checked. Reference values for each of the 43 spectra were averages of the results for each quantity, but as not all the reference calculators report all of the quantities, there were varying sample sizes for the calculations of each quantity.

**Table 2 — List of quantities checked**

Illuminance (lx)
CIE 1931 chromaticity coordinate, $x$
CIE 1931 chromaticity coordinate, $y$
CIE 1964 chromaticity coordinate, $x_{10}$
CIE 1964 chromaticity coordinate, $y_{10}$
S-cone-opic irradiance ( $\text{mW}\cdot\text{m}^{-2}$ )
M-cone-opic irradiance ( $\text{mW}\cdot\text{m}^{-2}$ )
L-cone-opic irradiance ( $\text{mW}\cdot\text{m}^{-2}$ )
Rhodopic irradiance ( $\text{mW}\cdot\text{m}^{-2}$ )
Melanopic irradiance ( $\text{mW}\cdot\text{m}^{-2}$ )
S-cone-opic EDI (lx)
M-cone-opic EDI (lx)
L-cone-opic EDI (lx)
Rhodopic EDI (lx)
Melanopic EDI (lx)
S-cone-opic ELR ( $\text{mW}\cdot\text{lm}^{-1}$ )
M-cone-opic ELR ( $\text{mW}\cdot\text{lm}^{-1}$ )
L-cone-opic ELR ( $\text{mW}\cdot\text{lm}^{-1}$ )
Rhodopic ELR ( $\text{mW}\cdot\text{lm}^{-1}$ )
Melanopic ELR ( $\text{mW}\cdot\text{lm}^{-1}$ )

## 2.4 Evaluation criteria

For each quantity a reference value and a symmetric tolerance interval around zero were defined based on various criteria. In the following figures normalized deviations and tolerance intervals are shown ranging from  $-1$  to  $+1$ . The normalization is obtained by dividing the deviation by the upper tolerance limit. The deviation of the test software from the reference value was normalized to the tolerance interval by dividing the deviation by the upper limit of the tolerance interval. If the absolute value of the normalized deviation was larger than 1, the result was judged to be inconsistent. Figure 2 shows a hypothetical example in which the software returns a slightly smaller value for Source A than the reference value, but still within the tolerance interval, whereas for Source B the software returns a larger value than reference value and outside of the tolerance interval.

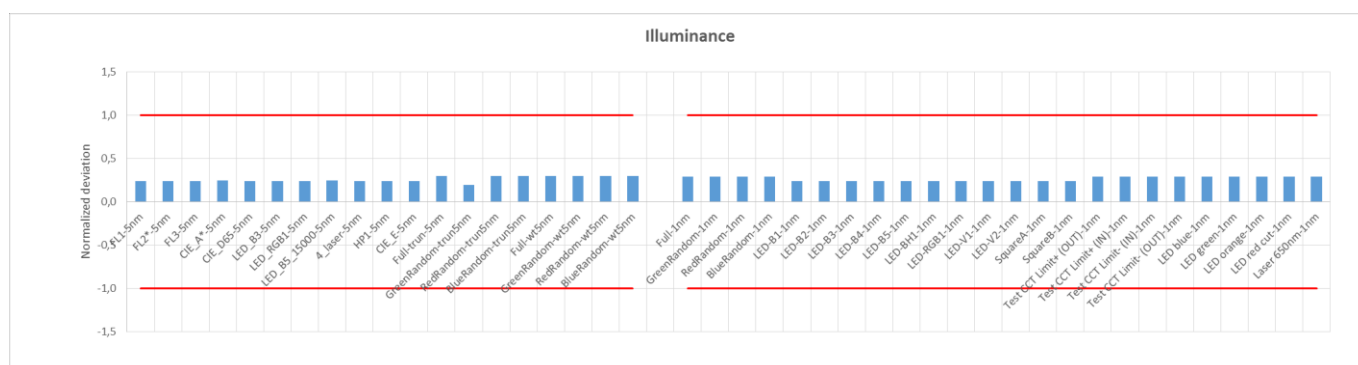


**Figure 2 — A schematic example of how the results were evaluated, with lines marking the normalized tolerance interval and bars representing the normalized deviation (from the reference value) for each spectrum**

### 3 Results

#### 3.1 Illuminance

Figure 3 shows the results for illuminance. In this and all figures showing the results, the 5 nm spectra are grouped on the left, and the 1 nm spectra are grouped on the right. The deviation in the illuminance results mainly originates in the different tools using slightly different values for the maximum luminous efficacy,  $K_m$ , arising from different assumptions concerning the refractive index of air and from rounding. The upper limit of the tolerance interval is  $5 \times 10^{-6}$  of the reference value.



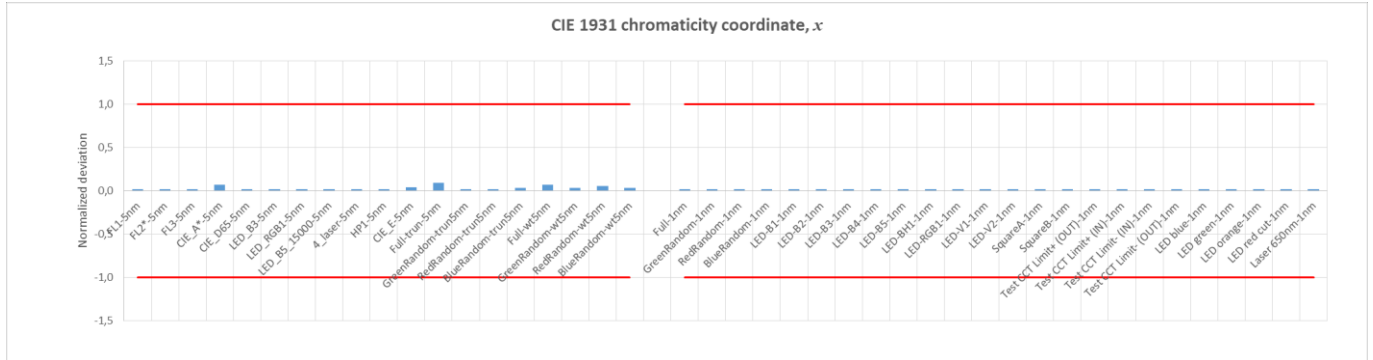
**Figure 3 — Evaluation results for the illuminance comparison of the 43 spectra presented in Table 1**

The results are all consistent with the reference values.

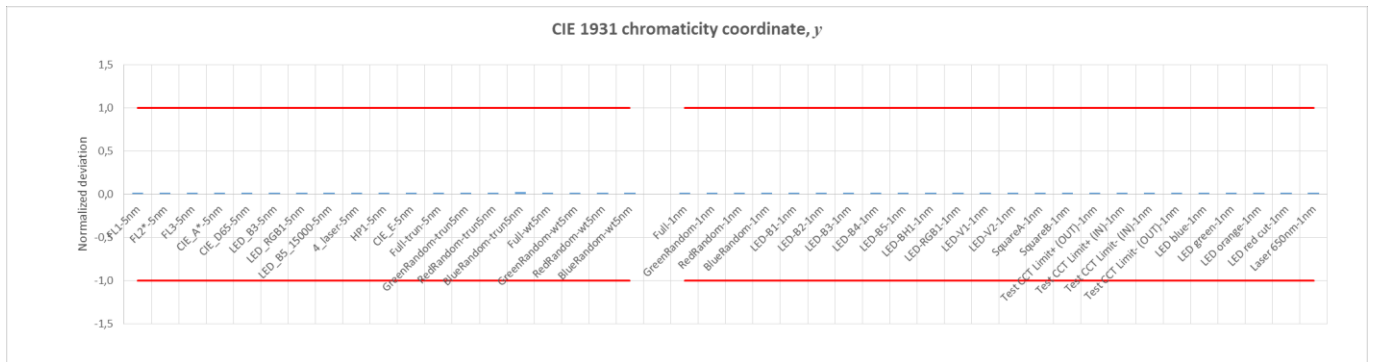


### 3.2 Chromaticity coordinates CIE 1931

Figure 4 and Figure 5 show the results for the calculations of the CIE 1931  $x$  and  $y$  chromaticity coordinates, respectively. The upper limit of the tolerance interval was  $1 \times 10^{-7}$  (absolute).



**Figure 4 — Evaluation results for the CIE 1931  $x$  chromaticity coordinate comparison of the 43 spectra presented in Table 1**

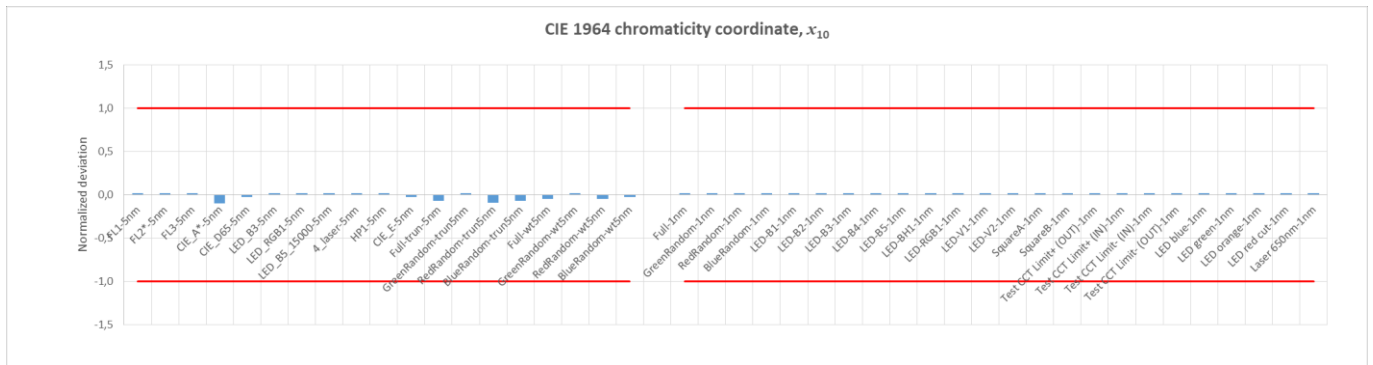


**Figure 5 — Evaluation results for the CIE 1931  $y$  chromaticity coordinate comparison of the 43 spectra presented in Table 1**

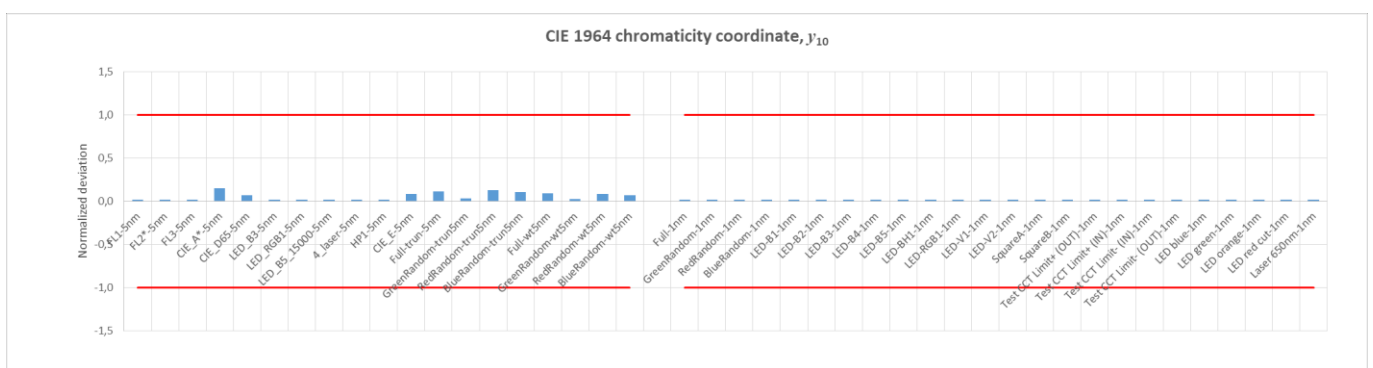
The results were consistent with the reference values for both chromaticity coordinates.

### 3.3 Chromaticity coordinates CIE 1964

Figure 6 and Figure 7 show the results for the calculations of the CIE 1964  $x_{10}$  and  $y_{10}$  chromaticity coordinates, respectively. The upper limit of the tolerance interval was  $1 \times 10^{-7}$  (absolute).



**Figure 6 — Evaluation results for the CIE 1964  $x_{10}$  chromaticity coordinate comparison of the 43 spectra presented in Table 1**

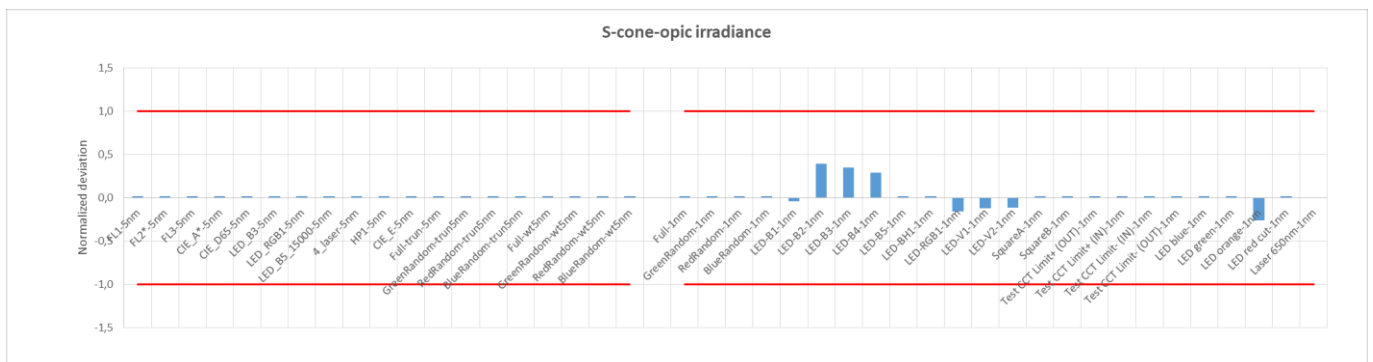


**Figure 7 — Evaluation results for the CIE 1964  $y_{10}$  chromaticity coordinate comparison of the 43 spectra presented in Table 1**

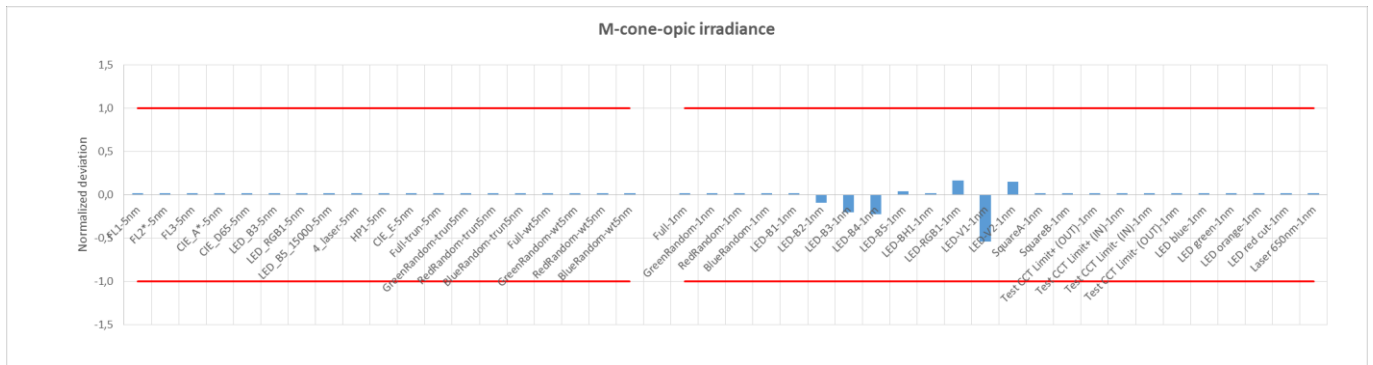
The results were consistent with the reference values for both chromaticity coordinates.

### 3.4 $\alpha$ -opic irradiance

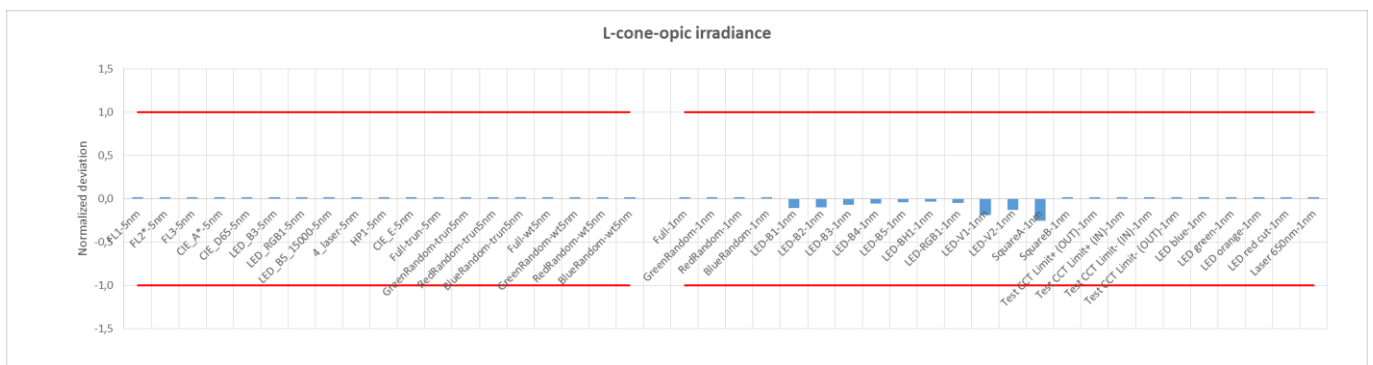
All five  $\alpha$ -opic irradiance values were compared; Figure 8 to Figure 12 show the comparison results for all five  $\alpha$ -opic irradiances. The upper limit of the tolerance interval was either  $1 \times 10^{-8}$  (L-cone-opic irradiance) or  $1 \times 10^{-10}$  (all other  $\alpha$ -opic irradiances) of the reference value.



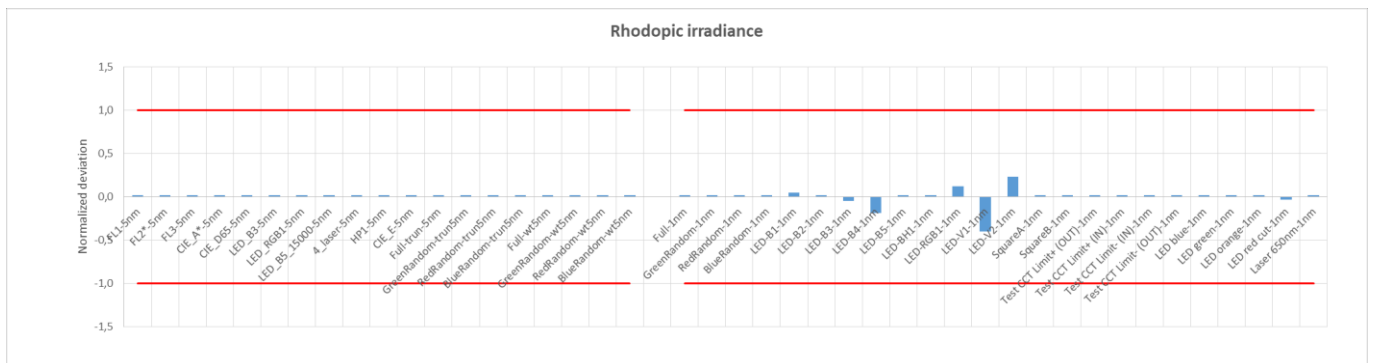
**Figure 8 — Evaluation results for the S-cone-opic irradiance comparison of the 43 spectra presented in Table 1**



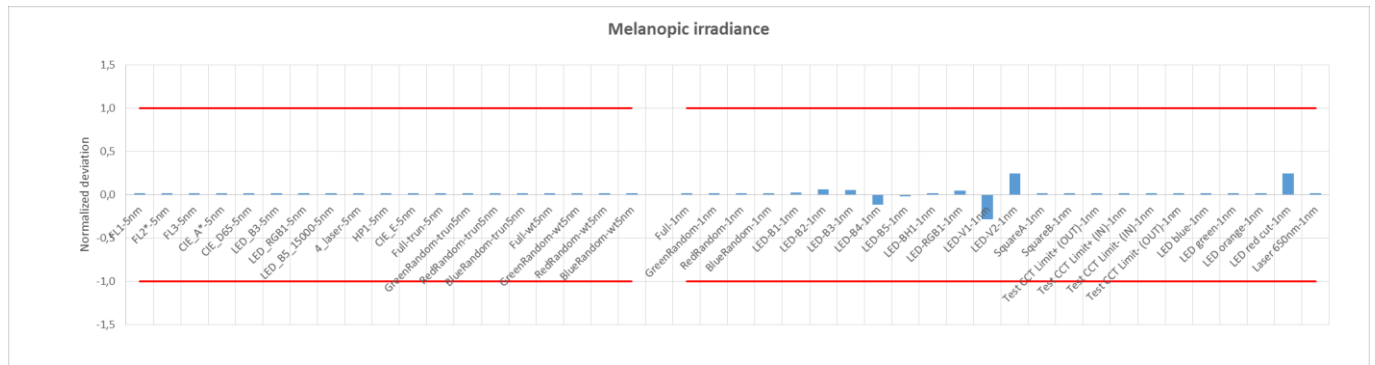
**Figure 9 — Evaluation results for the M-cone-opic irradiance comparison of the 43 spectra presented in Table 1**



**Figure 10 — Evaluation results for the L-cone-opic irradiance comparison of the 43 spectra presented in Table 1**



**Figure 11 — Evaluation results for the rhodopic irradiance comparison of the 43 spectra presented in Table 1**

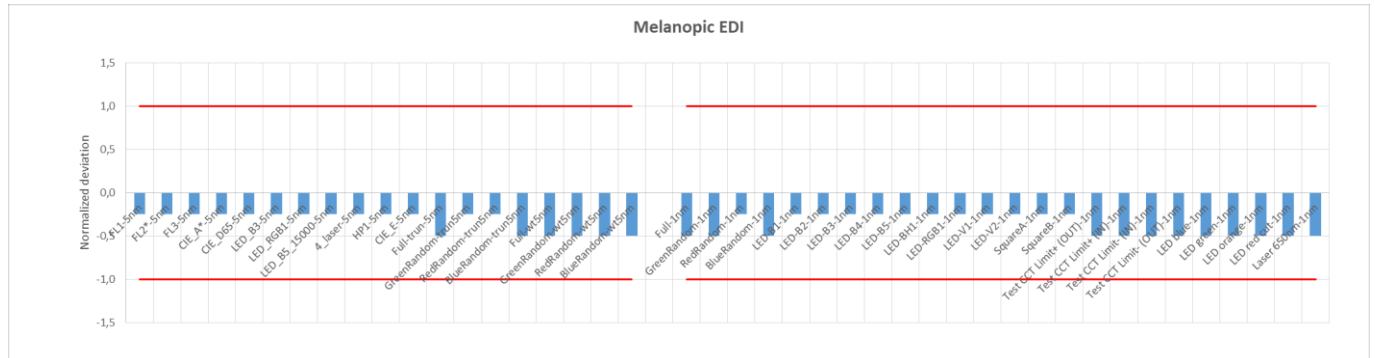


**Figure 12 — Evaluation results for the melanopic irradiance comparison of the 43 spectra presented in Table 1**

The results were consistent with the reference values in each case.

### 3.5 $\alpha$ -opic Equivalent Daylight Illuminance (EDI)

All five  $\alpha$ -opic EDI values were compared, and the results for melanopic EDI are shown in Figure 13. The upper limit of the tolerance interval was set to  $2 \times 10^{-5}$  of the reference value. The deviation and the large tolerance interval relate to differences in the precision of constants for daylight D65. CIE S 026:2018 specifies 4 digits for the  $\alpha$ -opic efficacies of luminous radiation for daylight (D65),  $K_{\alpha,v}^{D65}$ , for each  $\alpha$ -opic action spectrum, and this has been implemented in *luox*; the CIE toolbox (CIE 2020) uses an unrounded value with 15 digits for these constants.

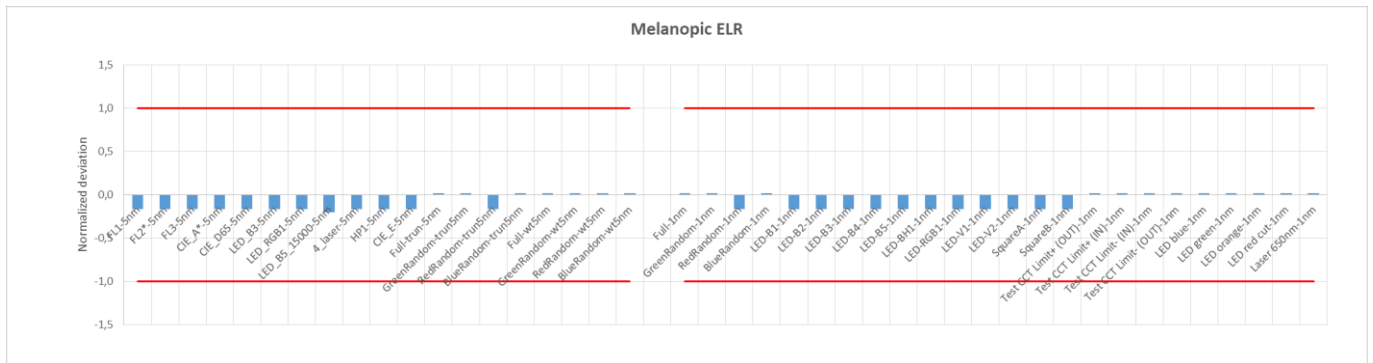


**Figure 13 — Evaluation results for the melanopic EDI comparison of the 43 spectra presented in Table 1**

The results were consistent with the reference values in each case, for melanopic EDI and for all of the other  $\alpha$ -opic EDIs analysed (not shown here).

### 3.6 $\alpha$ -opic Efficacy of Luminous Radiation (ELR)

All five  $\alpha$ -opic ELR values were compared, and the results for melanopic ELR are shown in Figure 14. Based on the spread of the reference values, the upper limit of the tolerance interval was set to  $2 \times 10^{-6}$  of the reference value.



**Figure 14 — Evaluation results for the melanopic ELR comparison of the 43 spectra presented in Table 1**

The results were consistent with the reference values in each case, for melanopic ELR and for all of the other  $\alpha$ -opic ELRs analysed (not shown here).

### 3.7 Other checks

An evaluation of tables of standard values used by *luox* was made and all of the tables are correct. There is a very minor deviation in the values of the CIE colour matching function in the CIE 1931 standard colorimetric system,  $\bar{y}$ , at a few wavelengths above 819 nm due to the truncation of the last digit (at a level of  $2 \times 10^{-13}$ ).

## 4 Limitations of the CIE validation

This is a black box validation. The *luox* source code was not examined in detail. For some combinations of spectra and quantities, only one reference calculator was available. All of the checks were performed with uniform 1 nm and 5 nm interval data.

## 5 Conclusions

Based on these results, the CIE approves the following statement concerning the *luox* software, as per the aforementioned licence agreement:

“This software incorporates methods, formulae, spectral function calculations and spectra from the International Commission on Illumination (CIE). The CIE endorses this software having made a black-box evaluation of the software as of Feb. 11, 2021, finding that the software performs satisfactorily. This software is not a replacement for the CIE publications and works from which it is derived. The user is advised to consult the original publications and works for proper understanding of and calculation of the result of this software.”

## References

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