Assessing the accuracy of emerging lighting simulation tools: Predicting spectral power distribution and illuminance

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Assessing the accuracy of emerging lighting simulation tools:
Predicting spectral power distribution and illuminance

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INTRODUCTION

This paper summarizes initial results from an ongoing study that seeks to validate emerging software tools for lighting. Existing software tools for simulating light (used here to refer to optical radiation from 380 nm to 780 nm) vary in the methods used to represent the spectrum of daylight and electric light sources throughout architectural scenes. Until relatively recently, lighting simulations were primarily used to predict photopic quantities, characterized by the human visual response V(λ), at the horizontal task-plane. To limit computational complexity while remaining within acceptable levels of accuracy for predicting photopic quantities, spectral power distributions (SPDs) of light sources and spectral reflectance distributions (SRDs) of room surfaces are often treated as spectrally neutral or reduced to three spectral bands in existing tools.

The need to estimate the spectral characteristics of light reaching the eye of occupants for prediction of non-visual physiological responses, with spectral sensitivities that differ from V(λ), has motivated the development of new lighting software tools such as ALFA (Solemma, 2022) and Lark (Lark, 2015). These tools predict spectral irradiance values at user-selected viewing positions throughout the space, which can be used to calculate several visual and non-visual lighting metrics (CIE 2018, Lucas and others 2014, Rea and Figueiro 2018). These software tools use Radiance, an open-source command-line lighting calculation toolkit, which uses three spectral bands (red, green, and blue or RGB) to characterize light source SPD and surface SRDs. Ashdown (2011) reported that SRDs represented by RGB color bands are adequate for calculating photopic quantities and Radiance has been validated to some extent for predicting these quantities in architectural scenes with electric light (Grynberg 1989) and daylight (Mardaljevic 1995, 2000, 2001, 2004).

Two studies by Pierson and others (2021a, 2021b) compared calculated results of daylight and electric lighting using Lark (3 and 9 spectral bands) and ALFA (81 spectral bands) to physical measurements collected in a small office. For daylit scenes, a tradeoff was observed between accuracy and simulation time for 3-band versus 9-band simulations. ALFA's 81-band approach provided more accurate predictions of spectral irradiance in electric lighting scenes compared to 3-band and 9-band but errors greater than 20% at some measurement locations for a fluorescent lighting condition and for a warm LED lighting condition. Other researchers have also studied the accuracy of ALFA spectral simulations of daylight (Balakrishnan and Jakubiec 2019).

Past validations did not consider LED spectra, which can have multiple narrow peaks across the visible spectrum. Abboushi and others (2020) analyzed 1,302 light source SPDs, 1,229 of which were LED spectra. Overall, they reported that the mean absolute percent error in using three spectral bands to predict a group of nine lighting metrics was 19% relative to an 81-band baseline; this error was reduced to 4% when increasing spectral resolution to 9-bands. Of the LED sources, 776 were phosphor-converted (PC) "blue pump" LEDs and 453 were color-mixed (CM) LEDs, which typically have several defined narrow-band peaks in their spectral distribution. When estimating melanopic irradiance for these SPDs, the error for a 3-band analysis was 21% for the CM LEDs and 9% for PC LEDs; errors were reduced to 2% for both LED types using a 9-band analysis.

The present study compared ALFA-predicted spectral irradiances and photopic illuminances to corresponding measurements captured in a laboratory environment with LED luminaires. The intended scope of this investigation was to validate the ALFA tool for calculations of LED electric lighting systems in interiors.

METHODS

Laboratory Environment

The laboratory environment was 5.59 m by 5.56 m (18.3 ft by 18.2 ft) with a ceiling height of 2.81 m (9.23 ft). Figure 1 shows a plan and photograph of the room. Although not pictured, there was a small entrance to the room on the South wall that was covered with the same materials as the room walls. The dimensions of the room were measured with a Lecia DISTO laser measuring device. The room surfaces were spectrally neutral with painted white walls, white acoustic ceiling tiles, and light grey floor tiles. A CM-600d spectrophotometer with a spectral resolution of 10 nm was used to measure the spectral reflectance distribution (SRD) and specularity of the room surfaces; results are shown in Figure 2.

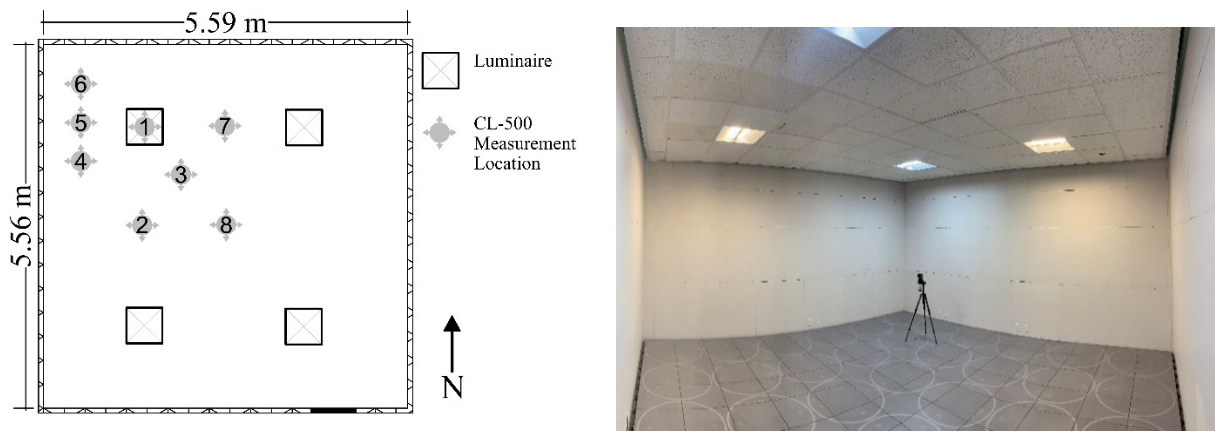


Figure 1. Floorplan (left) and photograph (right) of laboratory environment. In the floorplan image, the icon at each point has arrows to indicate the four primary view directions used for the vertical illuminance measurements. The photo shows the mixed CCT lighting condition as viewed from near the door on the south wall, with the meter located at measurement point 1.

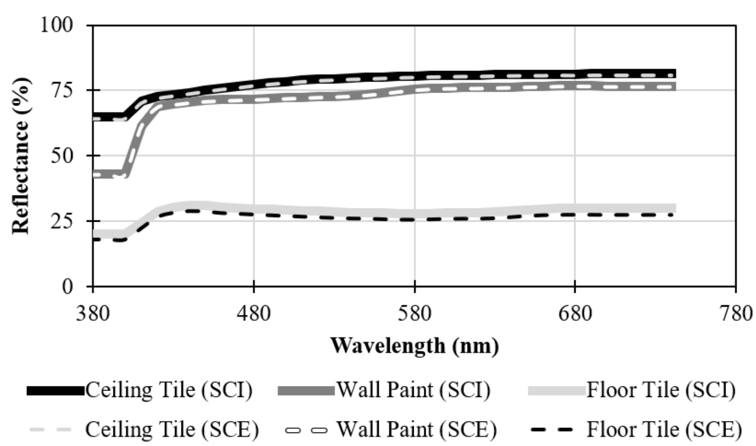
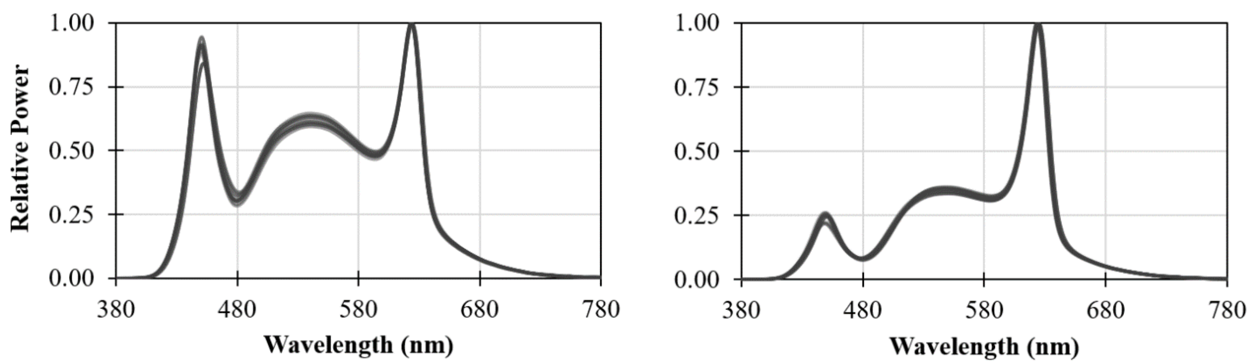


Figure 2. Spectral reflectance distribution of room surfaces. For each surface, measurements at three locations were captured with a calibrated Konica Minolta CM-600d spectrophotometer; the mean values of the three

measurements are shown here. The measurements included spectral reflectance values with the specular component included (SCI) and specular component excluded (SCE). Measurements were captured in 10 nm increments from 380 to 740 nm.

Lighting System

Four 61 cm by 61 cm (2 ft by 2 ft) LED recessed luminaires (CREE CR22™) with adjustable CCT capabilities from 3000 to 5000 K were installed in the ceiling. Luminaires were spaced 2.44 m (8 ft) on center with at least 1 m (3.25 ft) between the edge of the luminaire and the nearest wall. This study examined three lighting conditions: all four luminaires set to 3000 K, all four luminaires set to 5000 K, and a mixed CCT condition where two luminaires were set to 3000 K and two were set to 5000 K (pictured in Figure 1). For each lighting condition, a calibrated Konica Minolta CL-500a illuminance spectrophotometer was used to capture three



spectral power distribution (SPD) measurements across the face of each luminaire, within 7.6 cm (3 in). Examples of the resulting SPDs are shown in Figure 3.

Figure 3. Spectral power distributions for 5000 K (left) and 3000 K (right) conditions of luminaires. Twelve total measurements were captured for each lighting condition (3 measurements per luminaire, per lighting condition). Measurements were captured in 1 nm increments from 380 to 780 nm.

Measurement Procedure

As shown in Figure 1, eight measurement points were selected to capture a range of conditions relative to the luminaires and room surfaces: directly underneath a luminaire (point 1), locations between luminaires (points 2, 3, 7 and 8), and points between the luminaire grid and wall surfaces (points 4-6). The Konica Minolta CL-500a illuminance spectrophotometer with a spectral resolution of 1 nm was used to capture horizontal measurements 76.2 cm (2.5 ft) above finished floor (AFF) and vertical measurements 101 cm (3.33 ft) AFF; the vertical measurements were taken in four viewing directions at each point that were aligned with the primary room axes.

The spectrophotometer was mounted to a tripod for the measurements. To ensure that the meter was properly aligned for the vertical measurements, a three-way bullseye bubble level was used. The Lecia DISTO laser measuring tool was used to ensure that the aiming of the meter for vertical measures was perpendicular to the facing wall, and to document the precise location of each measurement point for use in defining the calculation points in the simulation software.

In addition to the five illuminance measurements (one horizontal and four vertical) at each of the eight locations for each of the three lighting conditions, a set of three independent repeated measurements was collected at points 1 and 2 for each of the five measurements, for each of the three lighting conditions. These repeated measures were used to compare the measurement uncertainty resulting from the positioning of the meter with the variability in the measured data based on the variables of interest (location, aiming, lighting condition).

Simulation Procedure

The geometry of the laboratory environment and luminaire locations were modeled using Rhino3D (McNeel and others, 2022). Lighting simulation parameters including measured material SRDs, luminaire SPDs, and calculation point locations were defined within the ALFA plug-in (version 0.6.0.0). Material SRDs were defined using the average of the three measurement points for each surface shown in Figure 2.The light source SPDs were defined for each luminaire using a CL-500a measurement directly beneath the center of the luminaire, for each lighting condition, as shown in Figure 3. Manufacturer-provided IES digital photometric files were used to define the luminous intensity distribution of the luminaires.

Individual calculation points were positioned in the Rhino model at the measurement locations and view directions shown in Figure 1 using the dimensions recorded for the meter location. The vertical calculation points were offset from the center of the tripod by 13.4 cm, accounting for the difference in distance between the meter's photocell and the center of the tripod.

One simulation was conducted for each of the lighting conditions using the Radiance settings chosen as default by ALFA (-ab =6, -lw = 0.01, 20 passes). Output included the x,y,z locations and corresponding view vectors for each calculation point as well as predicted values for illuminance (lux) and 81-band spectral irradiance (mW/m^2nm) from 380 to 780 nm.

RESULTS

To characterize the differences between laboratory measurements and software simulations, the error was calculated for each data pair as (predicted value - measured value), and the percent error was expressed as ((predicted value – measured value) / measured value) X 100. The mean absolute percent error (MAPE) was calculated for comparing specific sets of data points of interest.

Spectral power distribution

SPD (characterized by power values at individual wavelengths in 5 nm increments beginning at 380 nm) was determined at eight eye positions for four viewing directions at each point, for each of the three lighting system settings, resulting in 96 data points. The absolute percent errors between the measured spectral power and the simulated spectral power for all vertical and horizontal measurements for each of the three lighting conditions between 400 and 700 nm are shown in Figure 5, and the distribution of MAPE values for each lighting condition is summarized in Table 1.

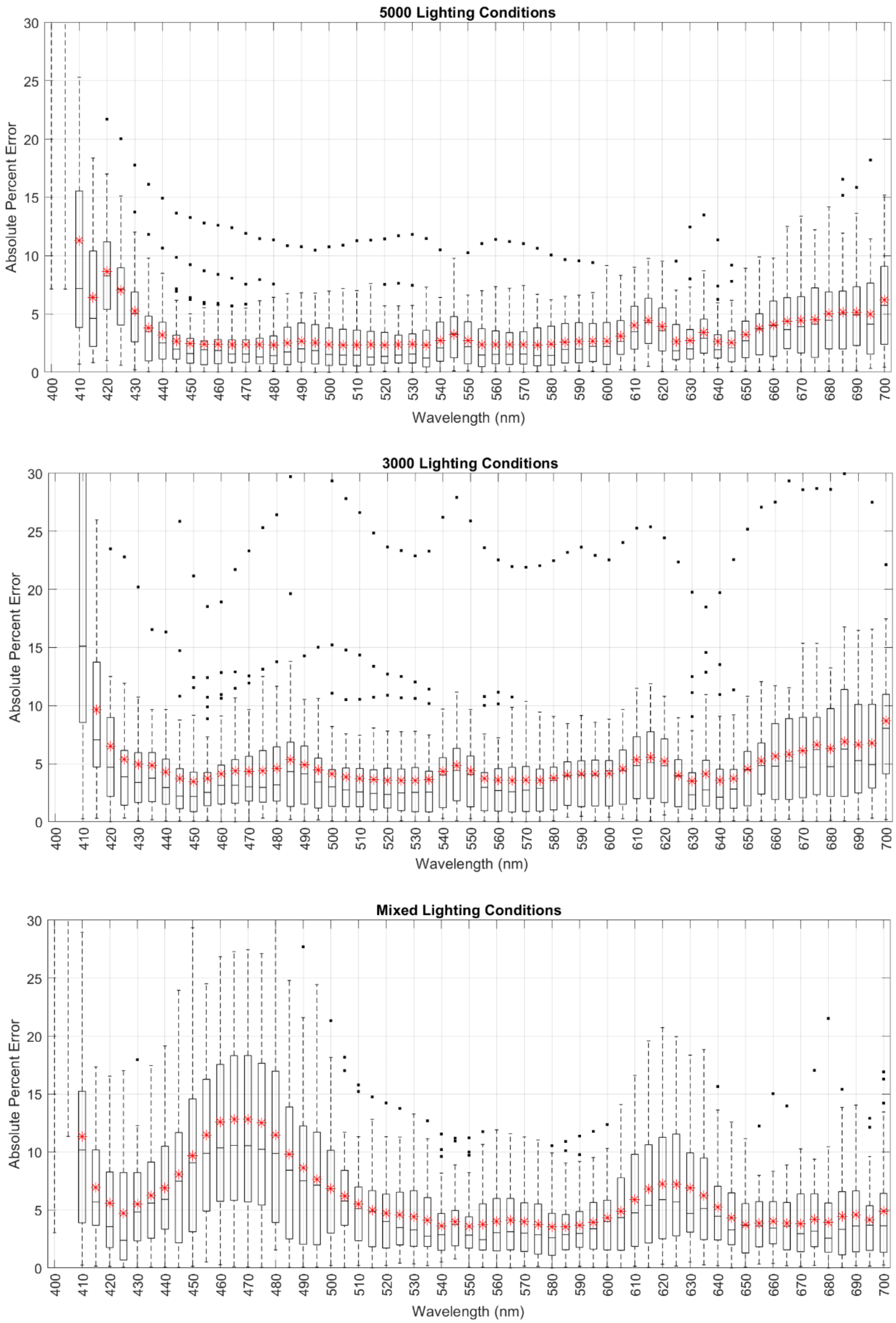


Figure 4: Absolute percent error for SPDs measured with spectrophotometer versus simulated with ALFA for 5 nm spectral bins. Figures are shown for the individual 5000 K, 3000 K, and Mixed conditions. The central line on each box indicates the median value, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually with black dots. Outliers are defined as data that is 1.5 times greater than the interquartile range. Red asterisks indicate the mean absolute percent error for each spectral bin.

Table 1: Frequency of mean absolute percent errors for SPDs. The frequency (count) of MAPE values for each of the three lighting conditions is shown in 5% bins. There are 61 values for each condition; 5 nm increments from 400 – 700 nm.

MAPE	5000 K	3000 K	Mixed
0 to 5%	50	41	30
>5 to 10%	8	17	20
>10 to 15%	1	0	7
>15 to 20%	0	0	0
>20% +	2	3	4

Illuminances

The predicted versus measured horizontal illuminances were compared at the eight analysis points for each of the three lighting conditions, for a total of 24 data pairs. The average horizontal illuminance was 419.5 lx; the corresponding predicted average illuminance was 424.4 lx. Compared to the measured values, the predicted values had a range of differences from (-3.0) lx to 24.1 lx. The MAPE for the 24 pairs was 1.4%. The repeated measures produced a MAPE of 0.94% for horizontal illuminance.

The predicted versus measured vertical illuminances were compared for four viewing directions at each of the eight analysis points, for each of the three lighting conditions, for a total of 96 data pairs. The average vertical illuminance for the 96 measurements was 227.1 lx; the corresponding predicted average illuminance was 227.0 lx. Compared to the measured values, the predicted values had a range of differences from (-42.9) lx to 26.3 lx. The MAPE for the 96 pairs was 3.8%. The repeated measures produced a MAPE of 1.69% for vertical illuminance.

DISCUSSION AND CONCLUSION

Although the errors in illuminance predicted by the software were greater than the uncertainty in the measurement procedures (as documented by repeated measurements), the errors were relatively small at 1.4% for horizontal and 3.8% for vertical illuminances. Given the many sources of uncertainty in the underlying assumptions of the software and in the instrumentation and procedures for the field measurements, MAPE values of less than 5% seem reasonable for most lighting simulations of architectural environments. These relatively low errors for illuminance are reassuring, given that the Radiance toolkit was optimized for predicting photopic quantities.

Beyond illuminance, further consideration of the errors in predicting spectral quantities is revealing. Table 1 shows that each lighting condition had a small number of spectral bins where the MAPE value exceeded 20%; however, each of these values occurred in bins of 420 nm or less. The power values were very low in these bins and the wavelengths are mostly outside of the photopic or melanopic response functions, so these large percentage errors are of little practical significance for the current analyses.

The spectral bins that are the most relevant for photopic quantities are between 505 and 605 nm, since the V(λ) response peaks at about 555 nm. Figure 5 shows that all three lighting conditions have very low MAPE values in this range. However, the melanopic response peaks at about 490 nm, so the spectral bins from 465 to 515 nm are relevant, and the graph for the Mixed lighting condition shows some higher MAPE values in these bins. In fact, six of the seven MAPE values shown in Table 1 that are greater than 10% for this condition are between 450 and 480 nm.

These increased errors are concerning, since any errors in predicted spectral irradiance in this range are likely to have a larger influence on the calculation of non-visual metrics like equivalent melanopic lux (EML) or melanopic equivalent daylight illuminance (m-EDI). Software tools to predict these non-visual metrics are becoming more important as guidelines such as the WELL Building Standard (IWBI 2020) become more widely used. The fact that these increased errors were observed for the mixed SPD condition is also concerning, since that situation is common for spaces with both daylight and electric light.

Ongoing work is exploring how these errors in SPD prediction might translate to errors in predicted non-visual metrics, and future work will expand the range of conditions for which the potential errors in predictive software are investigated. The sources of these errors also need further exploration, to assess the relative uncertainties arising from software, instruments, and measurement practices. Results of these studies can inform design professionals in their use of these predictive tools and can inform the tool developers for ongoing improvements in the accuracy of the software.

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