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LED Measurement to Obtain Polychromatic Raydata and their Value for Simulations

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Abstract

LEDs, among their many features, offer the possibility to control and vary the spectral characteristics of the emitted radiation. Hence, the developers of luminaires need to simulate the color distribution of the desired optical system in addition to the illuminance. In order to do so, detailed data of the light source are needed and simulation techniques need to be able to deal with polychromatic light sources.

Many LEDs exhibit spectral distributions that vary depending on the viewing angle and depending on the location on the chip. These properties can be measured by a goniometric setup combining a radiance measuring system with a filter wheel and with a spectro-radiometer. The resulting polychromatic rayset can be used to model the characteristics of sophisticated LED based luminaires, e.g. for medical, architectural, or aircraft applications.Actual Situation.

Introduction

With the advent of LED based luminaires, the requirements for optical simulation and modeling have increased considerably. Among their many features, LEDs offer the possibility to control and vary the spectral characteristics of the emitted radiation. This can be done, e.g., by combining a number of LEDs with different characteristics on a single chip or by shifting the wavelengths of the actual substrate into a different range of the spectrum, e.g. by phosphorus coatings. In both cases, the developers of luminaires are faced with small light sources that emit spectra that can vary depending on the viewing angle and the emitting area.

The task of the optical simulation is to model optical elements that produce desired distributions of illuminance and color. Often, homogeneous distributions of both parameters are desired. These need to be based on detailed data of the light source and employ modeling techniques that are tailored to work with polychromatic light sources. In this paper, we will outline the source imaging measurement techniques and present modeling examples.

Originally, standard raysets have been produced by radiance or luminance (equipped with a V(λ) filter) cameras mounted on a goniometric setup. This technology is enhanced by outfitting the camera with a set of bandpass filters, thereby producing raysets for narrow wavelength ranges. The raysets can be further refined by measuring the LED by an additional spectro-radiometer. Spectrum data can be used to generate raysets for spectrum intervals that are tailored to the specific application.

Measurements and Simulation

The data needed to model a light source contain information about how much light is emitted from which part of the light source and into which direction. For incandescent light sources, it is usually safe to assume a spectral distribution that varies only slightly, if at all, depending on the viewing angle. For LEDs, however, this assumption no longer holds true, and the measurement techniques need to be extended.

For our experiments, we employ a standard radiance measuring system, consisting of a camera that is calibrated to yield spatially (referring to the geometry of the sample) resolved radiance information about the light source. This camera is mounted on a goniometric setup and can be moved across the surface of an imaginary sphere surrounding the sample, thus

Figure 1: **Radiance camera measurement system luca'color (a). System equipped with a filter wheel to generate spectrally resolved radiance images. spectrophoto/ radiometer SPR'3 (b)**

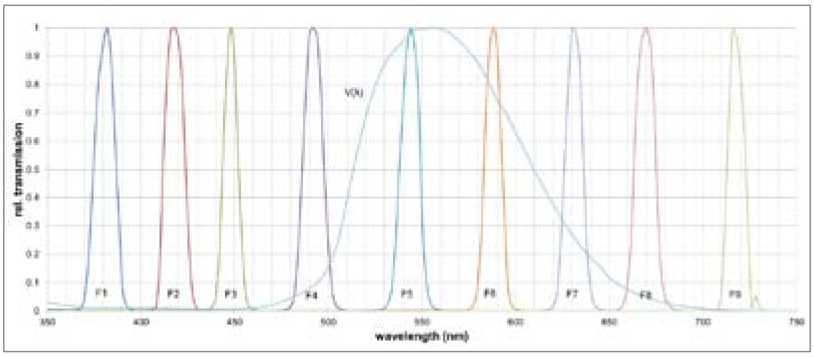

Figure 2: **Normalized transmission curves of set of filters used with the radiance camera**

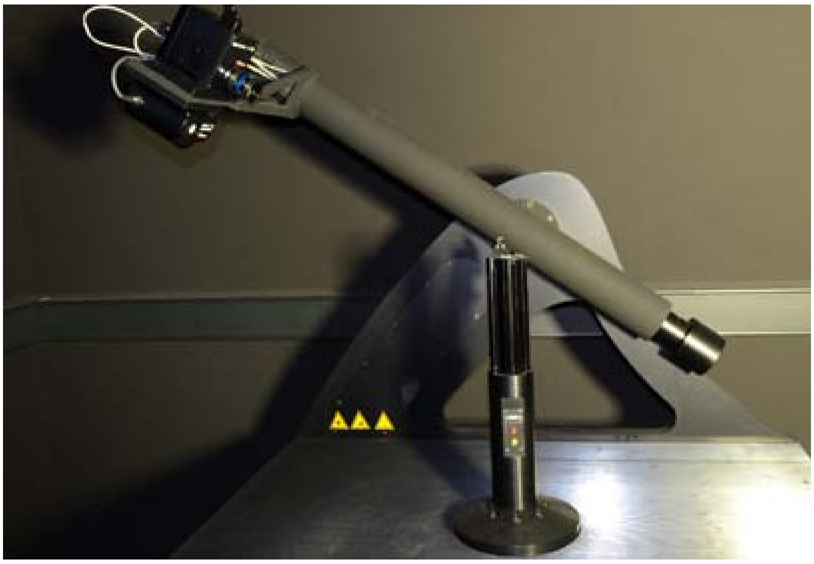

Figure 3: **Goniometric setup for polychromatic raydata generation. Center: sample LED. Top left: radiance camera luca'color, spectro-radiometer SPR'3**

Table 1: **Filter set used for the measurement of the sample LED package. Radiant power refers to the measurement conditions and cites the power in the wavelength band corresponding to the individual filters**

Filter No.	F0	F1	F2	F3	F4	F5	F6	F7	F8	F9
λ (peak) / nm	V(λ)	no filter	417	448	492	545	588	630	670	716
Abs. radiant power of sample LED (W)		546	12	95	57	134	113	112	18	5

measuring angularly (referring to the observation direction) resolved radiance data. The spectral information of the light source is measured by a spectro-radiometer that moves along with the camera and gathers spectral data at each point of observation measured by the camera. Combining the rayset measured by the radiance system with the spectra results in a detailed polychromatic rayset well suited for colorimetric simulation of the light source. Additionally, the spectro-radiometer data can be integrated to yield a spectrally resolved total flux measurement of the light source.

The radiance camera system used in the measurements is shown in Figure 1a. It consists of the radiance measurement camera luca'color that is combined with a filter wheel, which contains up to 10 filters. The filter wheel used for the measurements in this paper is outfitted with 9 bandpass filters and one V(λ) filter. Figure 2 shows a plot of the transmission curves of the bandpass filters. The filter characteristics are summarized in Table 1.

For a polychromatic raydata set, the LED is measured with a combination of filters of interest. For each of the filters, a raydata set is generated. For an absolute characterization of the radiant flux of each raydata set, a spectro-radiometer SPR'3 (shown in Figure 2b) is used in addition to the camera. The radiant flux that corresponds to each of the raydata sets is obtained by integrating the spectrum between the edges of the respective bandpass filter and then integrating these partial fluxes over the solid angle of the measurement (usually a hemisphere). For light sources that exhibit a spectrum that varies considerably with respect to the observation direction, it might be necessary to use the spectro-radiometer data to apply a scaling factor to the individual radiance images before generating the raydata set.

Figure 3 shows a picture of the measurement setup. The LED is mounted at the center of a goniometric setup. The camera system and the spectro-radiometer are mounted on a movable arm that rotates about an axis perpendicular to the back panel of the goniometer. The LED can be rotated about its vertical axis. Hence, a solid angle of over one hemisphere can be measured by the given setup.

Figure 4 shows a photograph of a sample LED that was used for the measurements in this article. It consists of a 4-chip LED covered with a phosphorous globe top. One of the four LEDs emits red light at about 630 nm, the other three LEDs emit blue light at about 450 nm. The phosphorous coating then converts part of the blue radiation into larger wavelengths. As a result, the full LED

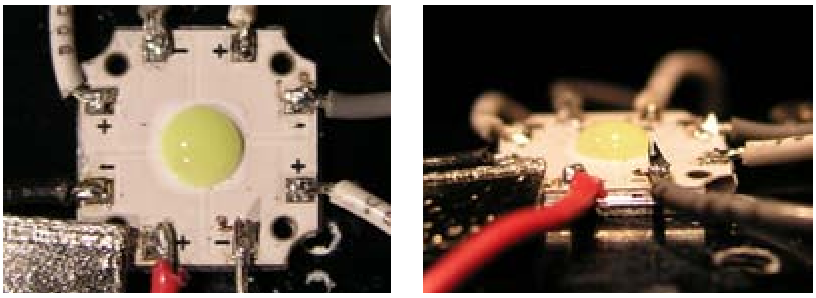

Figure 4: **Sample LED package consisting of three blue and one red LED chip covered by a phosphorous globe top**

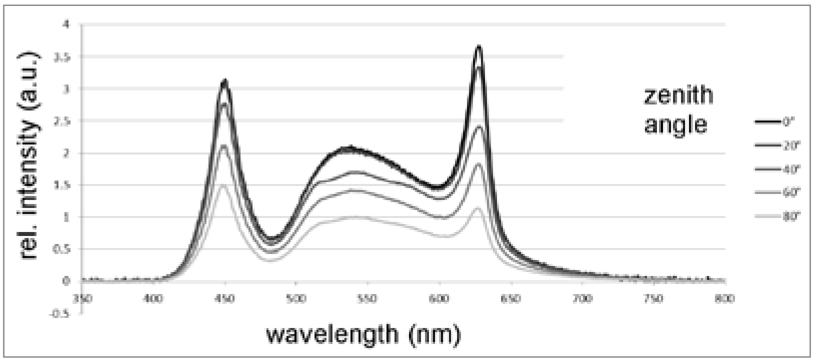

Figure 5: **Spectrum emitted by the LED package, parameterized by the observation angle (zenith angle)**

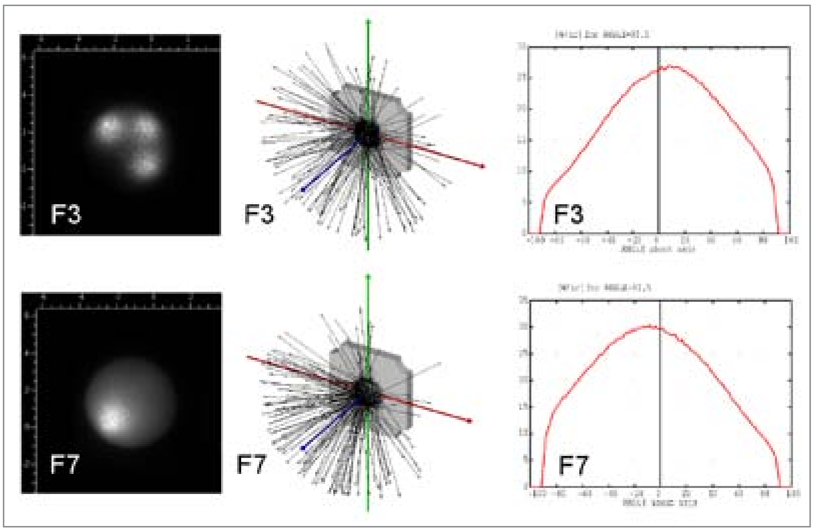

Figure 6: **Data and LED models for filters no. 3 (F3) and 7 (F7).** **Left: Radiance images (diameter of globe-top about 4 mm). Middle: Plot of a subset of rays and CAD sketch of LED package. Right: Vertical cut through the simulated far-field distribution**

package emits a white light spectrum, which can be tuned by varying the ratio between the light emitted by the red and blue LEDs.

The spectrum of the LED for various observation angles is shown in Figure 5. Observation angles (zenith angles) range from 0° (view from the top) up to 80° (approx.. side view). The radiant intensity decreases with increasing zenith angle. Clearly visible is also a change in the ratio between the blue and the red peak: At an observation angle of 0° the red peak exceeds the blue peak whereas at larger observation angles (40° and up in the Figure), the blue peak exceeds the red peak.

This varying shape of the spectrum as depicted in Figure 5 nicely shows why a polychromatic rayset is important for an accurate simulation of a multicolor LED like the one shown here. With varying observation angle, the spectrum clearly changes its shape. While a change of total power contained in the spectrum is directly reflected in any single rayset, a change of shape of a spectrum can only be accounted for by a polychromatic rayset. Here, not only the geometric information about the origin of the rays is accurately reflected. The individual radiant intensities for the different wavelength bands are contained in the rayset as well.

Parts of the polychromatic rayset are shown in Figure 6. The upper three images belong to the rayset measured with filter no. 3. The lower three images belong to the rayset measured with filter no. 7. The two images on the left are radiance images of the LED as seen from the top. Clearly visible are the three blue LED chips (top left) and the single red LED chip (bottom left). The globe top can also be seen in the bottom left image scattering parts of the red light.

The two middle images show plots of the raysets derived from the radiance images for filters 3 and 7. A subset of rays is depicted and traced back to a CAD sketch of the LED package. In accordance with the radiance images, the majority of the rays originate from the three blue LED chips (upper plot) for filter 3, and from the single red LED chip for filter 7 (lower left corner in the lower plot).

The two images on the right side show vertical cuts through the far-field light intensity distributions. The intensity distribution for filter no. 3 is shifted towards positive angles, i.e. towards the "upper" side of the LED package that houses two blue LED chips. The intensity distribution for filter no. 7 is shifted towards negative angles, i.e. towards the "lower" side of the LED package that houses the red and one blue chip. Thus, the far-field light intensity distributions are not symmetric with respect to the geometry of the LED package. To account for this fact, a polychromatic rayset is essential to be able to accurately model the given LED. This asymmetry is also depicted in Figures 7 and 8.

Figure 7 shows radiance plots that are derived from the rayset. The plots are based on rays whose direction is within +/- 2° from the vertical axis of the LED. Shown are plots for filters V(λ), no filter, and F3 (top from left to right) and filters F5, F7, and F9 (bottom from left to right). All plots are scaled relative to the maximum radiance present in the plot. Please refer to Table 1 for information about the absolute radiant power present in the rayset. The plot belonging to the

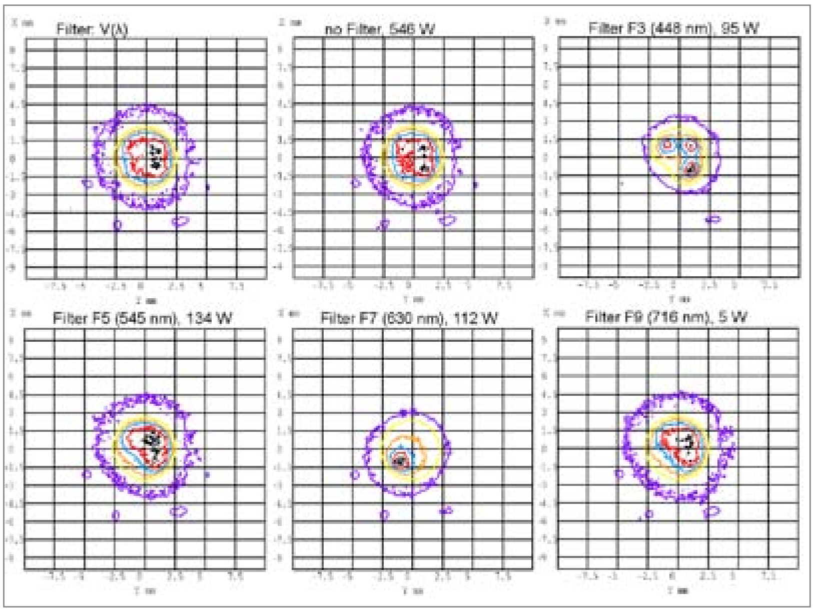

Figure 7: **Radiance distributions for different filters. Distributions based on rays that are within +/- 2° of the vertical axis. Plots normalized to respective maximum radiance**

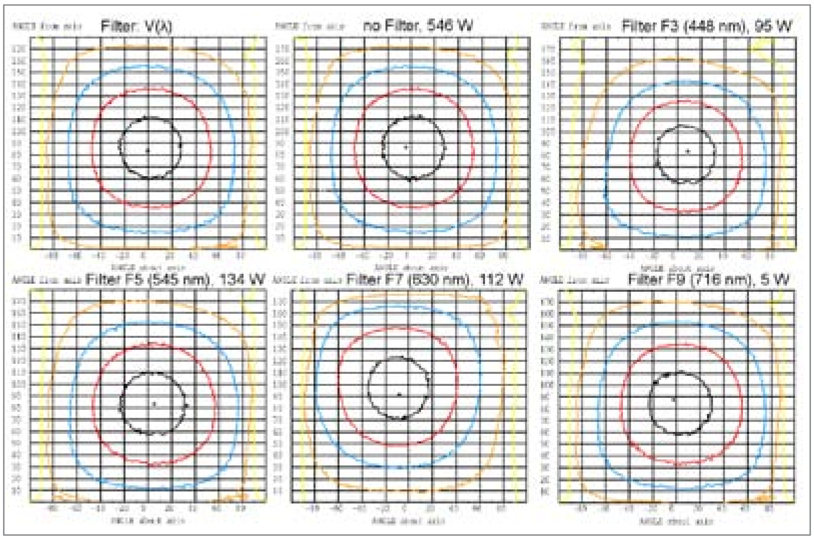

Figure 8: **Far-field radiant intensity distributions. Filters identical to the ones used in Figure 7. Plots show lines of constant radiant intensity. Plots normalized to respective maximum intensity**

rayset measured without a filter (top middle) displays a fairly uniform radiance distribution with just a slightly higher radiance at the locations of the three blue chips. During the measurement, all chips were operated at the same constant current of 350 mA; a slight bias of the current towards the red LED could produce a truly uniform radiance distribution. Comparing the plot measured without a filter to the one measured with a V(λ) filter (top left), we see that the luminance distribution measured with the V(λ) filter is just as uniform as the radiance distribution measured without a filter. The distinct characteristics of the blue and red LED chips are not captured by either measurement but are reflected in the other four plots in Figure 7: The radiance distribution measured with filter F3 (top left) distinctly shows the locations of the three blue LED chips, whereas the radiance distribution measured with filter F7 (bottom middle) clearly displays the location of the red LED chip.

A different view of the model derived from the rayset is shown in Figure 8. The figure shows simulated far-field distributions for the same filter configurations that are used in Figure 7. Displayed are lines of constant radiant intensity. Just like seen in Figure 7, the plots look fairly symmetrical for raysets derived from measurements with no filter (top middle) and V(λ) filter (top left). Plots that correspond to filters F3 (top right) and F7 (bottom middle) show a clear deviation from this symmetry.

The measurements of the sample LED presented here rely on the radiance images for the different filters and used the spectro-radiometer data to measure the radiant flux for the individual wavelength bands. For light sources that require an even more precise rayset, the spectro-radiometer data can also be used to apply a weighting to the individual images before the rayset is generated. Like this, the wavelength band corresponding to one filter can be subdivided into smaller bands. The radiance image is used to supply the geometric information about the origin of the rays. Radiant intensity information is taken from the spectrum. Like this, raysets can be produced with wavelength resolutions that are in principle limited by only the resolution of the spectro-radiometer. This might be of interest for spectra that consist of one or more narrow emission regions.

Conclusion

Present day technologies increasingly employ LED packages that consist of multiple LED chips of different color. Additional phosphorous coatings might be used that shift the emitted radiation into further wavelength bands. These LED packages allow tuning the combined radiation according to the desired color characteristics of the application. Simulating such LED packages in order to design the application needs to rely on accurate raydata of the source. Standard monochromatic raysets are insufficient for this task; however a polychromatic rayset can be used to accurately model the multicolored source. Such a polychromatic rayset can be generated by a radiance camera system that is combined with a set of filters spanning the full range of the emission of the source. Depending on the characteristics of the spectrum of the source, the resolution of the spectral bands of the filters can be enhanced by using the spectro-radiometer data. These data are also used to determine the absolute radiant power associated with the individual raysets. ■