FluxGage - A Photometric Test System

for LED Luminaires Based on Solar Panels

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Abstract

We present a novel photometric test system for LED luminaires. The new photometric system called „FluxGage" uses solar panels to detect and measure light. By placing a diffuser and a black pinhole array over a solar panels we achieve a detection surface which is also an absorber. This enables the system to be the same size as the DUT (Device Under Test), as opposed to an integrating sphere which is at least 3 times larger than the DUT. Simulations and experimental results show that this system can measure total flux with an uncertainty of 4.3%. The demonstrated system is used in 2π geometry. The system measures total flux, color parameters (CCT, CRI, chromaticity, etc.) and flicker.

1. Introduction

The integrating sphere is the standard instrument for measuring flux and color of light sources [1],[2]. The fundamental makings of the integrating sphere are its spherical geometry and the white diffusive coating on its interior. Integrating spheres must be at least 3 times larger than the DUT. Additionally, the effect of the DUT's absorption on the measurement (self-absorption) must be calibrated. With LED luminaire sizes ranging from several inches to several feet, the required integrating sphere diameter reaches 6-10 feet (2-3 meters).

The FluxGage system is based on an opposite approach – a detection surface which is also an absorber, ideally absorbing every photon emitted by the DUT. With this approach, spherical geometry is not required, the measurement device can be the size of the DUT, and the measurement does not depend on the DUT.

The detection surface should have the following properties:

- **It detects light, i.e. it transforms light into a measurable electrical signal.**
- **Light detection does not depend on angle.**
- **Very little reflection.**

The detection surface should have the following properties:

- **A diffuser is used to reduce the angle dependence of the solar panel responsivity.**
- **A dense array of pinholes is placed over the diffuser using black matte paint, thus making most of the surface black. The light incident on the panels is therefore spatially sampled by this dense array.**
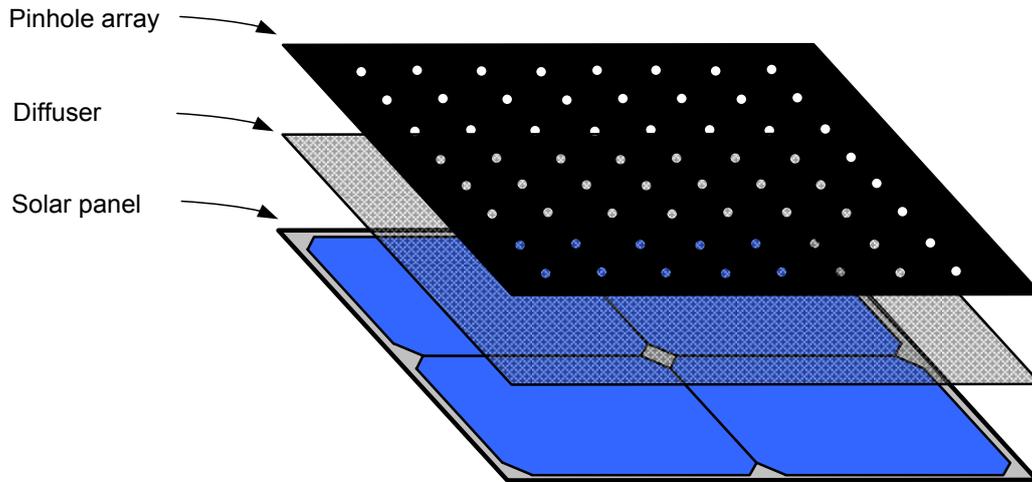
Pinhole array

Diffuser

Solar panel

Figure 1. Absorber Structure

The FluxGage system, based on this concept, provides a small and cost effective solution to LED luminaire testing.

In the next sections we will discuss:

- **System description**
- **How total flux and color properties (CCT, CRI, Duv) are measured.**
- **Error budget analysis based on simulations.**
- **Experimental results of a full system based on this technology.**
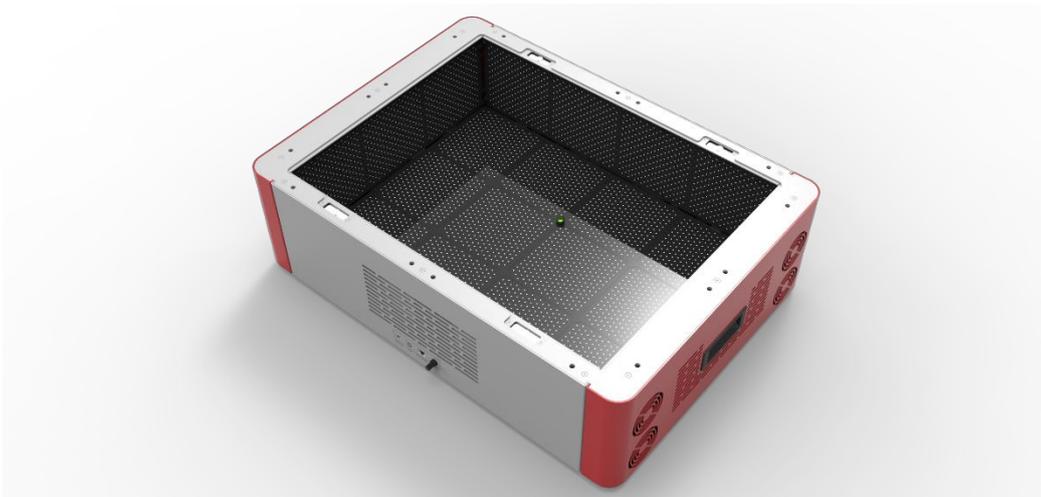
2. System Description

Figure 2. FluxGage System

An image of the FluxGage system is presented in Figure 2. The solar panel absorbers on the inside walls make the measurement cavity. The small green circle indicates the position of a fiber optic sensor which delivers light to a spectrometer inside the system. The small orange circle indicates the position of a photodiode which is used to measure flicker. An integrated temperature sensor monitors the temperature inside the system and controls the fans seen on the side.

3. Total flux measurement analytic model

In this section we present the mathematical derivation of the total flux measurement. We assume the solar panel responsivity is spatially uniform and is not sensitive to illumination angle. We further assume a spectrometer is used to sample the spectrum of the DUT and that the spectral content of the DUT is uniform in all directions. A more realistic analysis is brought in the next section.

The total current, I, produced by the solar panels is given by

$$(1) \quad I = \int R(\lambda)\Phi_e(\lambda)$$

Where $R(\lambda)$ is the responsivity of the solar panels (including the pinholes) in [A/W·nm], and $\Phi_e(\lambda)$ is the spectral flux of the DUT in [W/nm]. The spectrometer is measuring the normalized spectrum $S(\lambda)$ given by:

$$(2) \quad S(\lambda) = \frac{\Phi_e(\lambda)}{\Phi_e}$$

Where Φ_e is the total flux of the DUT in [W]. The normalization is achieved by scaling $S(\lambda)$ such that $\int S(\lambda)d\lambda = 1$. Having measured $S(\lambda)$ with the spectrometer, color quality parameters such as CCT, CRI, and chromaticity can be calculated directly.

Substituting (2) into (1) and rearranging yields

$$(3) \quad \Phi_e = \frac{I}{\int R(\lambda)S(\lambda)d\lambda}$$

Substituting again into (2) yields

$$(4) \quad \Phi_e(\lambda) = I\frac{S(\lambda)}{\int R(\lambda)S(\lambda)d\lambda}$$

Having obtained $\Phi_e(\lambda)$, the total luminous flux in lumens can be calculated using:

$$(5) \quad \Phi_v = \int \Phi_e(\lambda)V(\lambda)d\lambda = I\frac{\int S(\lambda)V(\lambda)d\lambda}{\int R(\lambda)S(\lambda)d\lambda}$$

Where $V(\lambda)$ is the photopic function.

4. Error budget analysis

In this section we examine several systematic uncertainty contributors in a real FluxGage system, and ways to mitigate them. These factors are:

- Uniformity of solar panel responsivity
- The dependence of the solar panels responsivity on illumination angle
- Localized spectrum measurement
- Secondary reflections from the DUT

4.1. Uniformity of solar panel responsivity

We tested 5 solar panels, each with 6 monocrystalline silicon solar cells (156x156mm) which were custom produced for this project. The panels were illuminated with white, red, green and blue LEDs. We measured the photocurrent produced by every cell. The uniformity of the photocurrent was better than ±0.3%. This indicates that solar cells technology is very mature and reliable and a high degree of uniformity in the solar panels can be achieved.

4.2. Angular dependence of the solar panels responsivity on illumination angle

Figure 3 shows the responsivity as function of illumination angle, K(θ), of the solar panels to white LED light with and without the diffuser. Ideally K(θ) should equal 1, indicating the panels responsivity does not change with illumination angle.
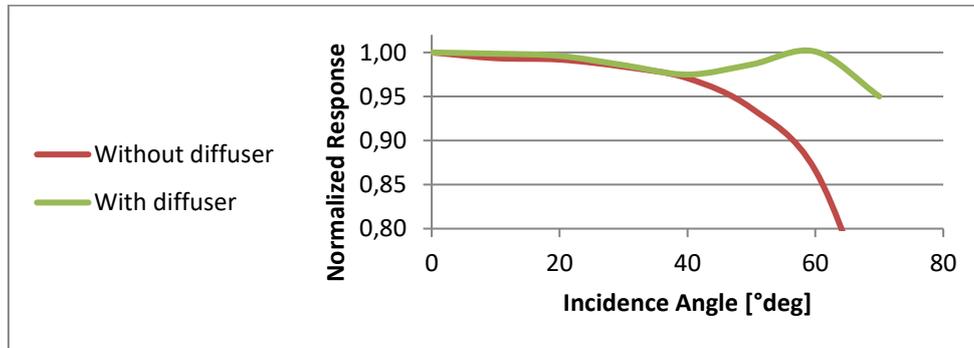

Figure 3. Illumination angle dependency of solar panels with and without diffuser

We developed a MATLAB simulation in order to analyze the effect of K(θ) on measurement accuracy. The concept of the simulation is shown in Figure 4.
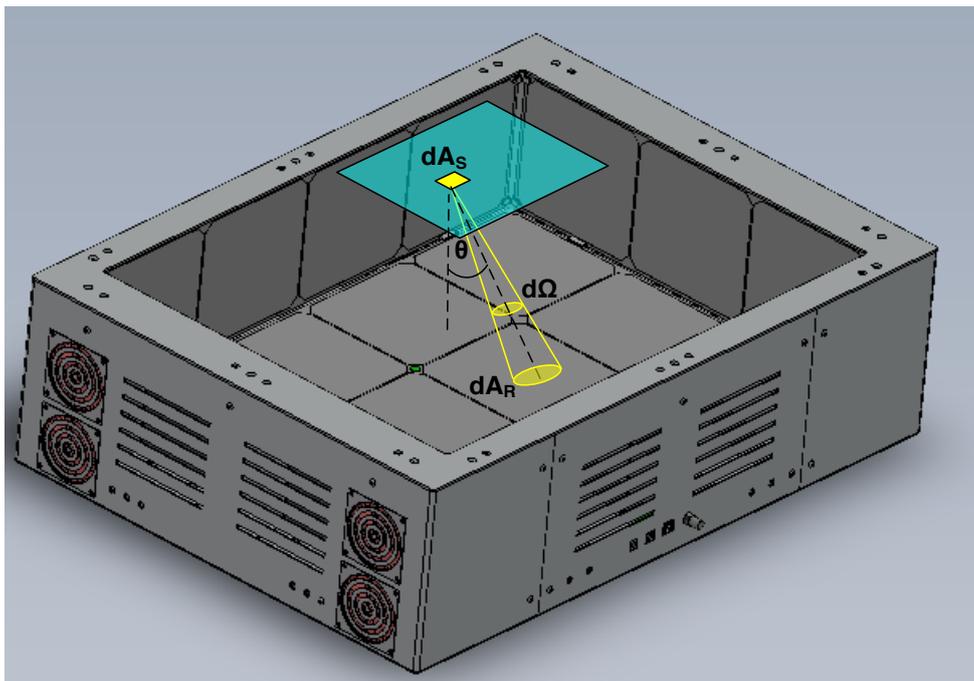

Figure 4. FluxGage MATLAB simulation concept

In the MATLAB model, the LED luminaire is positioned over the FluxGage opening. The luminaire surface is divided into area elements dA_S, and the FluxGage detection surfaces are divided into area elements dA_R. For every dA_S and dA_R we calculate the flux element $d\Phi_v$ incident on dA_R based on the subtended solid angle $d\Omega$ and the luminance, L.

The total incident flux is given by $\Phi_v = \iint_{A_S A_R} d\Phi_v$, and the total detected flux is given by

$$\Phi'_v = \iint_{A_S A_R} K(\theta) d\Phi_v.$$

The change in the ratio between Φv and Φ'v for different luminaire sizes and illumination beam angles is the uncertainty contribution of K(θ). As the luminaire size and beam angle increase, more rays hit the panels at slant angles and the effect of K(θ) is more noticeable.

Figure 5 shows a false color representation of the detected irradiance on the bottom and side walls of the FluxGage for a luminaire which is 40cm long, 30cm wide and has a beam angle of 120° FWHM (Full Width Half Maximum).
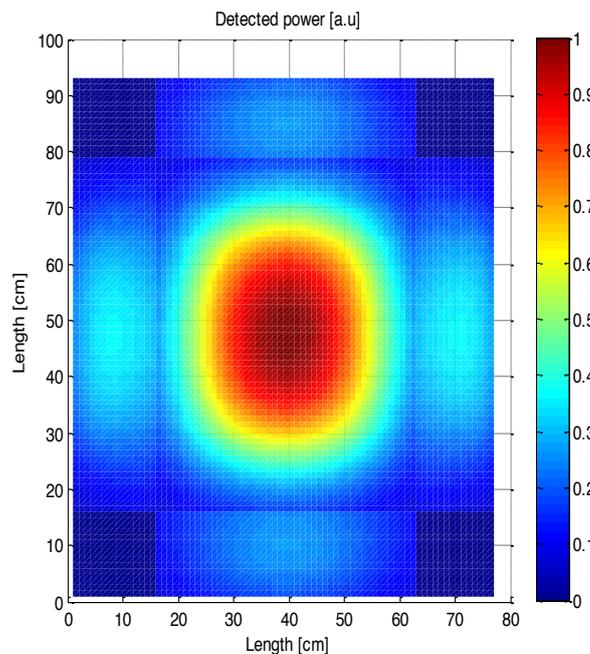

Figure 5. Simulation of the detected power as function of position on the bottom and side walls.

The simulation results show that the error due to the sensitivity to illumination angle, K(θ), is between -1.2% (for a small and narrow beam DUT) and -6.3% (for a large and wide beam DUT). If the system is calibrated using a calibration standard with a beam angle of 80° FWHM, the error will be shifted to ±2.6%. Furthermore, since this is a systematic and predictable error, a correction factor can be applied based on the size and beam angle of the luminaire being measured.

4.3. Localized spectrum measurement

In an integrating sphere system, the measured spectrum represents an average of the light emitted by the light source. In the FluxGage system, the spectrum is sampled at a single position as seen in Figure 2. If the spectral flux of the source is the same in all directions, the measured spectrum and the average spectrum are the same, however, this is not a realistic case. The uniformity of the spectrum affects both the color measurement accuracy and the total flux measurement accuracy.

This uncertainty is evaluated using equations (1)-(5). We modeled several LEDs with spectral flux $\Phi e(\lambda)$ and used different spectra for $S(\lambda)$, representing the fact that the spectrometer is measuring a different spectrum than the average spectrum of the light source.

In an extreme case where the measured spectra $S(\lambda)$ has a CCT of 2500°K and $\Phi e(\lambda)$ has an average CCT of 2600°K, the error in the CCT is obviously 100°K , and the error in the flux measurement is 8%. Experiments with some real luminaires give an uncertainty of about ±15°K in the CCT and ±2% in the total flux.

By using a split fiber sensor, the spectrum can be sampled at several positions on the FluxGage surface thus reducing the incurred uncertainty.

4.4. Secondary reflection from the DUT

In an integrating sphere, self-absorption of the DUT has a large effect on the measurement. This is because the DUT changes the average reflectivity of the sphere which, in turn, greatly affects the sphere's throughput [3]. Calculating this effect is not practical due to the infinite number of reflections that occur inside the sphere, and it must be calibrated for every DUT.

In the FluxGage system, the reflectivity of the black pinhole array seen in Figure 1 is about 4%. This means that up to 4% of the DUT's flux is reflected back towards the DUT. A large and reflective DUT may reflect this light back into the FluxGage, while a small or non-reflective DUT will reflect very little. Consequently, the effect of the DUT ranges between 0% and 4%. We should only consider a single reflection, as the next one will be attenuated to a negligible level (4% of 4% = 0.16%).

Several correction methods can be applied:

- Adding a fixed 2% to the initial calibration to shift the error from 0%-4% to ±2%.
- Apply a phenomenological correction based on the size and tone of the luminaire surface.
- Add a light source for automatic secondary reflection correction.

4.5. Summary of error budget analysis

The uncertainties discussed in the previous sub sections are summarized in the following table. Since there are systematic errors, that are summed arithmetically and not geometrically (rms). The resulting uncertainty is 7.8%. By applying various correction factors as described earlier we estimate an uncertainty of 4.3% can be reached which is comparable with good integrating sphere systems.

Uncertainty contributor	Uncertainty	Uncertainty with correction factors
Initial total flux calibration	1%	1%
Non uniformity of solar panel responsivity	0.3%	0.3%
Angular response of the solar panel	2.5%	1%
Localized spectrum measuring	2%	1%
Secondary reflection from the DUT	2%	1%
Total	**7.8%**	**4.3%**

Figure 6. Table showing the total uncertainty of the FluxGage.

5. Experimental results

A FluxGage system was built and tested. The unit size is 770mmX560X230mm. The size of the measurement opening is 640mmX480mm. The unit was calibrated using a tungsten halogen standard (Labsphere FFS-400). Several LED sources (BridgeLux VARO 29 CoB) were measured using a reference system which included a 1 meter integrating sphere from Labsphere and a spectrometer (OceanOptics Torus). The integrating sphere was calibrated with the same tungsten halogen source.

We compared the results of the integrating sphere and the FluxGage. For total flux values between 1,000 lumens and 30,000 lumens and for CCT values between 2700K and 5700K, the difference was up to 1% in the CCT and 1.5% in the total flux.

We then moved a LED source across the opening and 'mapped' the measured flux. Using this information, various luminaires were synthesized by superposition of the measured data. The results of the synthesized luminaires were in very good agreement with the simulation presented in section This shows that the system is very .4.2 predictable and that correction factors based on the size and illumination angle of the DUT can be applied.

6. Conclusions

We presented the FluxGage, a LED luminaire tester. This system provides a small and cost effective solution for testing LED luminaires in 2pi geometry. The black measurement surface and the lack of multiple reflections make the system much more predictable and allow using information about the DUT such as size, beam angle and surface reflectivity, to calculate correction factors.

7. References

[1]   Michael Bukshtab, "Applied Photometry, Radiometry, and Measurements of Optical Losses", ISBN-13: 978-9400721647.

[2]   IESNA LM79 Standard. ISBN: 978-0-87995-226-6

[3]   Jonn A. Jacquez and Hans F. Kuppenheim, "Theory of the Integrating Sphere",Journal of the Optical Society of America, Vol. 45, Issue 6,pp. 460-470,(1955)