Spectral Light Meters for accurate measurements of LED lighting

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Talk Aims

What are the weaknesses and problems associated with using traditional light meters to measure LED based lighting products?

What’s different about contemporary spectral light meters and what are the advantages and benefits of using them?

How do spectral light meters help us exploit the many opportunities offered by LED lighting?
So what’s wrong with using a traditional lux meter to measure LED lighting?

Just because something has been ‘calibrated’, it doesn’t necessarily make it suitable for a particular measurement task.
Visible Light

Light is visible to humans in the 380nm to 780nm wavelength range....

...but not all wavelengths with the same sensitivity

The CIE $V(\lambda)$ curve describes the average spectral sensitivity of human visual perception of brightness. In use since 1924.

### Photometric Units

<table>
<thead>
<tr>
<th>Radiometric Quantity</th>
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</thead>
<tbody>
<tr>
<td>Irradiance</td>
<td>W/m²</td>
<td>Illuminance</td>
<td>lux</td>
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<tr>
<td>Radiance</td>
<td>W/(sr.m²)</td>
<td>Luminance</td>
<td>cd/m²</td>
</tr>
<tr>
<td>Radiant intensity</td>
<td>W/sr</td>
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<td>cd</td>
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<tr>
<td>Radiant flux</td>
<td>W</td>
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<td>lumens</td>
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www.gigahertz-optik.de/en-us/basics-light-measurement
Quality Indices Notation

- $V(\lambda)$ Mismatch: $f_1$
- UV Response: $f_{UV}$
- IR Response: $f_{IR}$
- Cosine Response (i): $f_2$
- Linearity: $f_3$
- Display Unit: $f_4$
- Fatigue: $f_5$
- Temperature Dependence: $f_{6,T}$
- Humidity Resistance: $f_{6,H}$
- Modulated Light: $f_7$
- Polarization: $f_8$
- Spatial Non-uniformity: $f_9$
- Range Change: $f_{11}$
- Focusing Distance (ii): $f_{12}$

Characterization of the performance of illuminance meters and luminance meters

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(i) Illuminance meters only   (ii) Luminance meters only
Spectral Mismatch Error

**V(λ) Mismatch** $f_1'$

Spectral mismatch is usually the most significant error source when photometers are used to measure LEDs.

Standard calibration of photometers is made with the CIE Illuminant A (2856K incandescent source).

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Spectral Mismatch Error

f1’ not a direct measure of LED measurement error, but can indicate likely error range for white LEDs.

~10% significant for energy bills and global warming.

Tony Bergen & Peter Blattner CIE Div 2, Photometry Standardization Developments for OLEDs and LEDs, LED Professional Review, Issue 41, Jan 2014.
Spectral Mismatch Error

Photometer errors when measuring coloured LEDs can be very much worse than white LEDs.
Cosine Error

Lux meter errors resulting from poor cosine response can be most significant when measuring extended light sources.

As a beam of light deviates from normal incidence, its area increases on the surface. The resulting reduction in irradiance is determined by the cosine of the angle of incidence.

Independent of lighting technology – not specific to LEDs.
Spectral Light Meters

Entrance optic (e.g. cosine diffuser)

Array detector (typically CMOS)

Meter with graphical display for spectra

Spectral light meter

Wavelength dispersion (i.e. diffraction grating)

CIE $V(\lambda)$ Photometric response - calculated

USB / Wi-Fi / etc

200 lux

Spectrum enables measurement of quality and effectiveness of light – not just efficiency

i.e. typically colour

Filter responses other than photometric $V(\lambda)$
Human eye has two types of photoreceptors for vision – Rods (~120 million) and Cones (~6 million). We have 3 types of cones – blue, green and red sensitive. Colour perception is via cones only.

1931 CIE released first standard observer for a 2° FOV – still in widespread use. The CIE 1931 colour matching functions $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$ can be implemented much more accurately in a spectral light meter rather than coloured filters in a tri-stimulus meter.
Correlated colour temperature (CCT) is a measure of light source’s colour appearance defined by the proximity of its chromaticity coordinates to the blackbody locus.

Different colour light sources can have the same CCT.

Limited accuracy and range of CCT with tri-stimulus meters.
The colour rendering of a light source is a measure of its ability to realistically reproduce the colour of an object.

CIE 13.3-1995 “Method of measuring and specifying colour rendering properties of light sources”

Colour fidelity metric only. First released 1965, updated in 1974. $R_a$ is average of $R_1 - R_8$.

The CIE General Colour Rendering Index, $R_a$, does not agree well with perception of some light sources, notably LED light sources that contain narrow spectral bands.

Test colour samples according to CIE 13.3

CRI can only be determined with spectral data of light source
Colour Rendering – TM30


TM-30-15 uses 99 colour samples to characterize the difference between the test source and reference illuminant. Uses CIECAM02 (uniform colour space).

More comprehensive set of numerical and graphical outputs than CIE CRI system

http://www.ies.org

Fidelity Index, $R_f$
Gamut Index, $R_g$
Color Vector/Saturation Graphics
16 hue-based fidelity indices
16 hue-based chroma indices
1 skin-specific fidelity index
99 individual fidelity value

TM-30-15 metrics can only be determined with spectral data of light source
Cones are not uniformly distributed within the fovea – few blue cones in the central region.

Only with spectral data can these different weighting functions be implemented.

Scotopic Vision

Under low light (scotopic) conditions only rods produce a visual signal.
In normal (photopic) conditions only cones produce visual signal (rods are saturated).

Photopic lighting condition $\sim 3 \text{cd/m}^2$  Scotopic lighting condition $\sim < 0.03 \text{cd/m}^2$

The standard scotopic luminosity function or $V'(\lambda)$ was adopted by the CIE in 1951
Mesopic Vision

The eye operates in the mesopic region in many important situations:
- Night time driving;
- Emergency escape lighting;
- Marine signalling.

LED lighting has potential to offer good colour rendering with high mesopic efficiency. Using the mesopic system to calculate the effective luminance of cool white light sources results in significant changes in their apparent efficacy.

CIE 191: System for mesopic photometry
Research over the past 15+ years has shown that as well as the rod and cones responsible for our vision, our retinas also have intrinsically photosensitive retinal ganglion cells (ipRGCs) that play a major role in entraining our circadian rhythms. Much activity in this field due to the ease with which the spectral output and intensity of LEDs can be controlled as well as the flexibility in constructing luminaires (and the commercial opportunities this gives rise to!).


http://lucasgroup.lab.ls.manchester.ac.uk/research/measuringmelanopicilluminance/
Clouding of the lens in the eye with age results in lower light transmission, particularly in the blue region.

Another effect requiring spectral data!
Human Centric Lighting -standards

Research is still in relatively early stages but guidelines and standards for the measurement and incorporation of circadian lighting are emerging.

- **CIE Technical Note CIE TN 003:2015 Report on the First International Workshop on Circadian and Neurophysiological Photometry.**
- **prEN 16791 Quantifying irradiance for eye-mediated non-image forming effects of light in humans**
- **DIN SPEC 5031-100 Melanopic effects of ocular light on human beings - Quantities, symbols and action spectra**
- **EN 12464-1:2011 Lighting of indoor work places** (gives some guidance only)
- **The WELL Building Standard** [https://www.wellcertified.com/](https://www.wellcertified.com/)
  (specifies lighting conditions in terms of Equivalent Melanopic Lux)
- **DIN SPEC 67600:2013-04 (E) Biologically effective illumination - Design guidelines**
  (bases its recommendations solely on melanopic illumination)

**Vertical illumination levels (at eye level) more important in HCL due to distribution of ipRGC’s – we are optimised for blue light from the sky!**

Horticultural Lighting

Photosynthetically Active Radiation, PAR, 400-700nm

Much research and IP regarding optimum spectral content of grow lights.

Blue and red LEDs may offer greatest PAR efficacy, but is this best for crop yields?

It's complicated - temperature, humidity, air circulation, soil moisture and mineral content, etc are all factors too 😊

Photosynthesis depends on the amount of photons. Planck–Einstein relation, \( E = \frac{hc}{\lambda} \), allows us to determine this from the spectral data.

Lux and lumens are not meaningful for plants.
**Horticultural Lighting – PAR metrics**

**Photosynthetic Photon Flux (PPF):** measurement of the total number of photons emitted by a light source each second within PAR wavelength range. Measured in $\mu$mol/s. Analogous to ‘lumens’ for visible light.

**Photosynthetic Photon Flux Density (PPFD):** measurement of the total number of photons within PAR wavelength range that reach a surface each second measured over a one square meter area. Measured in $\mu$mol/m²/s. Analogous to ‘lux’ for visible light.

**Day Light Integral (DLI):** cumulative measurement of the total number of photons within PAR wavelength range that reach a surface during 24 hour period, measured over a one square meter area. Measured in mol/m²/d.

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**Dictionary**

**PAR** is a much misused term – not quantitative, just descriptive - Photosynthetically Active Radiation. Generally accepted as radiation within 400-700nm.

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The mole is the SI base unit (symbol mol) for the amount of a substance i.e. photons in this context. 
1 mol = $6.0221415\times10^{23}$ (“Avogadro’s number”)
Agricultural and aquacultural lighting

**Domestic Fowl Photopic Spectral Response**

Data source: “Spectral sensitivity of the domestic fowl (Gallus g. domesticus)” N. B. PRESCOTT AND C. M. (1999)
Light is used for therapeutic purposes such as the treatment of jaundice (hyperbilirubinemia) in new born infants.

The European market specifies:

$$E_b = \text{integrated irradiance } 400 \text{ to } 550\text{nm, in mW/cm}^2$$

Whereas the USA market requires:
Average spectral irradiance over the 460 to 490nm range in accordance with American Academy of Pediatrics latest recommendations, in µW/cm$^2$/nm

Spectral light meters enable the accurate measurement of phototherapy sources according to all international standards.
Blue Light Hazard

More specialist application - extended wavelength range 300-700nm
Standards require particular measurement geometries

IEC TR 62778:2014 Application of IEC 62471 for the assessment of blue light hazard to light sources and luminaires

IEC 62471:2006 Photobiological safety of lamps and lamp systems

Blue light weighted radiance 300-700nm at 200mm in an 11mrad FOV

Includes UV and IR hazards too, 200-3000nm

https://www.hdwarrior.co.uk/2009/05/09/led-light-damage/
Enhanced Spectral Light Meters

- additional measurement capabilities such as Flicker measurement;
- higher levels of accuracy resulting from improved stray light rejection and linearity correction.

LED Flicker – detrimental health effects such as triggering photosensitive epilepsy and stroboscopic effects. Results from drive and control circuitry

IEEE Std 1789 (2015) "Recommended Practice for Modulating Current in High-Brightness LEDs for Mitigating Health Risks to Viewers"

Traceable Calibration

Be cautious about:

• Manufacturer’s claims of ‘traceable’ calibration. *Check for relevant accreditation by DAkkS, UKAS, etc to ISO 17025*;

• Simple % ‘accuracy’ claims. *Look for details of calibration conditions and uncertainty*;

• Unrealistic accuracy claims – *how does it relate to uncertainty from National Measurement Institutes*
To conclude:

- Spectral mismatch errors with photometers are often significant when measuring LEDs/SSL;
- Spectral light meters remove spectral mismatch error and enable colour measurements;
- Any action spectra (filter function) may be applied within its spectral range;
- Enable development and testing of LED products for non-GLS / novel / high value applications;
- Traceable calibration is essential.

Spectral matching to:

- Photometric curve $V(\lambda)$
- Scotopic curve $V'(\lambda)$
- Colour matching
- Mesopic
- Melanopic
- PAR
- Bilirubin
- Blue light hazard
- Chicken vision
- Etc, etc …
Thank you for your attention.

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