Spectral Light Meters for accurate measurements of LED lighting

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Qualität „Made in Germany".

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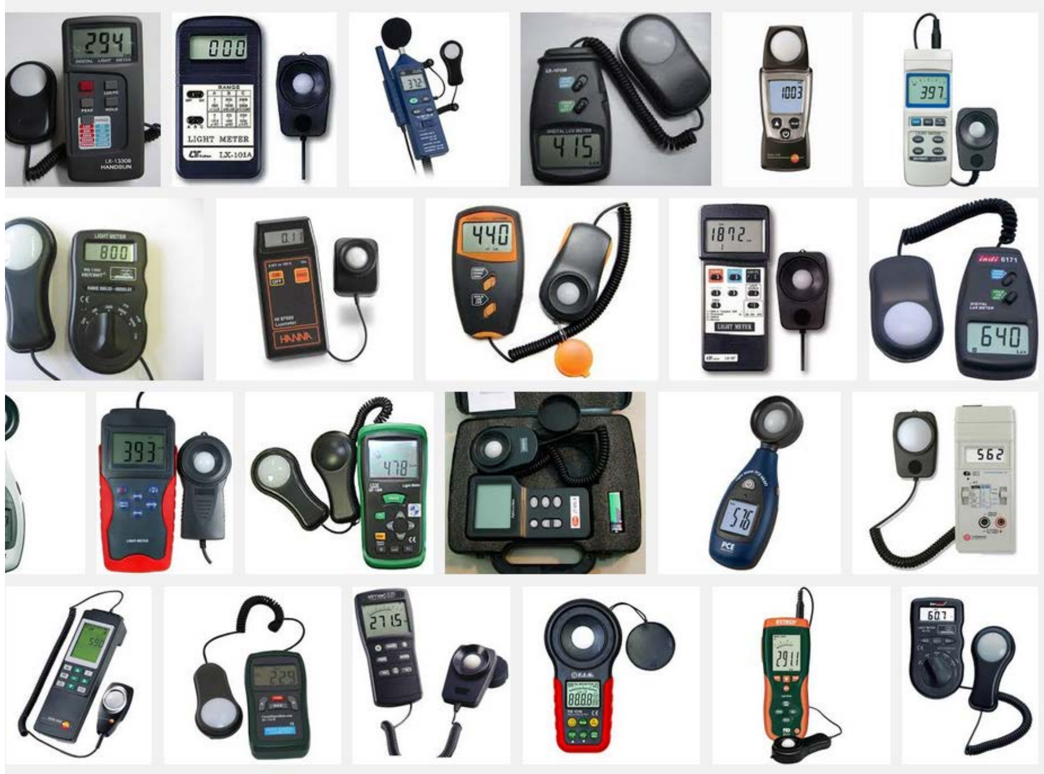
Presentation Aims

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 users exploit the many opportunities and benefits offered by LED lighting?

So what’s wrong with using a traditional lux meter to measure LED lighting?



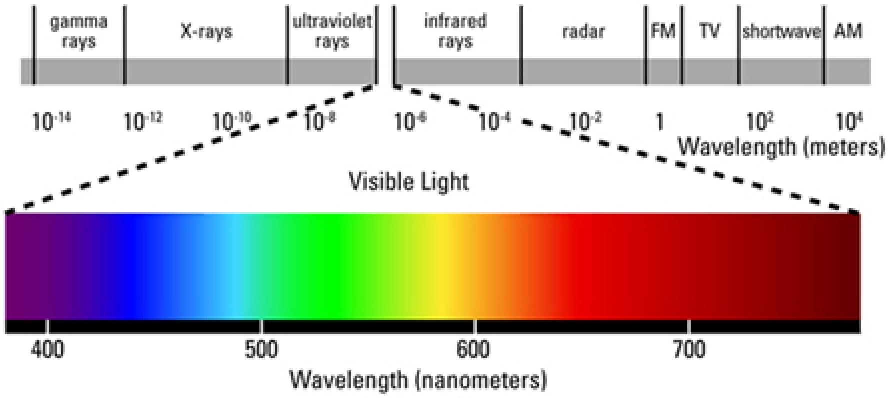
There are many, many types of light meters or ‘photometers’ available. The most commonly supplied photometers are lux meters costing from as little as 50 Euros to more than 1000 Euros. To what extent is it really true to say that none is suitable for measuring LEDs? Surely, if the meter has been calibrated it must be OK?

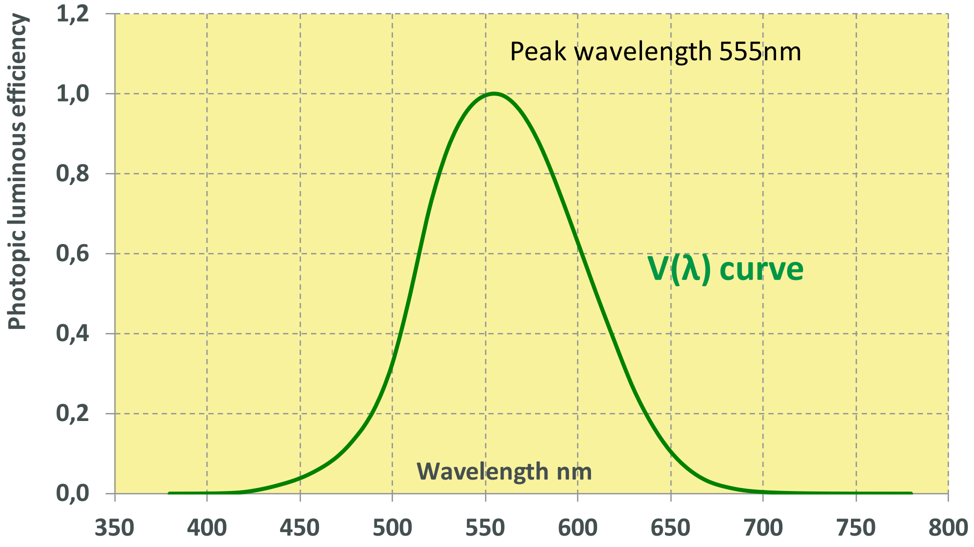
Just because something has been ‘calibrated’, it doesn’t necessarily make it suitable for a particular measurement task.

To explore the issues and imitations of photometers we need to remind ourselves of some physics from our school days

Visible Light

Visible white light is made up from the various colours of the rainbow – a spectrum of light. This equates to the part of the electromagnetic spectrum with wavelengths in the region of 380 to 780nm. But we don't have the same sensitivity to all of these wavelengths. Our eyes are much more sensitive to green light than to violet or deep red colours for example. Scientists were attempting to quantify this around 100 years ago and in 1924 the CIE issued the now universal photometric response or V-lambda curve. We now know that it is not perfect, but it is still the fundamental basis for our measurement of all photometric quantities.





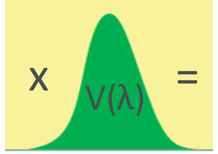
International Commission on Illumination
Commission Internationale de l'Eclairage
Internationale Beleuchtungskommission

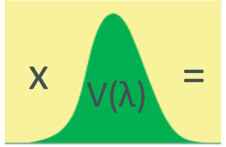
The CIE V(λ) curve describes the average spectral sensitivity of human visual perception of brightness. In use since 1924.

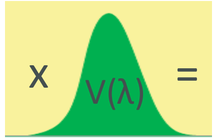
ISO 23539:2005 (CIE S010/E:2004)

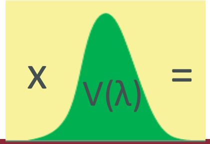
Photometric Units

Radiometric Quantity	Radiometric Unit	Photometric Quantity	Photometric Unit
Irradiance	W/m^2	Illuminance	lux
Radiance	$W/(sr.m^2)$	Luminance	cd/m^2
Radiant intensity	W/sr	Luminous intensity	cd
Radiant flux	W	Luminous flux	lumens



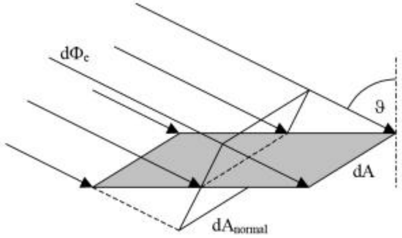


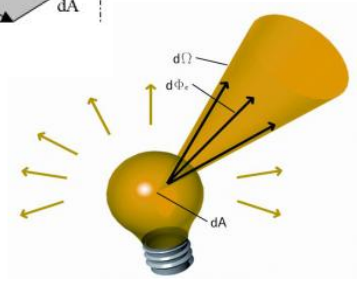




Visible light metrics or ‘photometric’ measurements are referred to as illuminance, luminance, luminous intensity, and luminous flux.

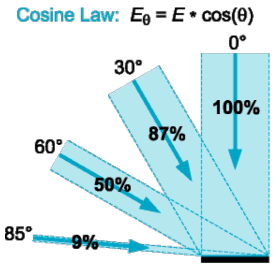
An appropriate entrance optic is required for the different metric, e.g. diffuser for lux, sphere for lumens, lens for cd…. But all require the application of the photometric response to the absolute ‘radiometric’ measurement.

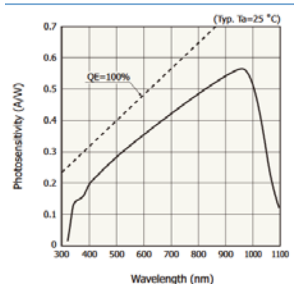


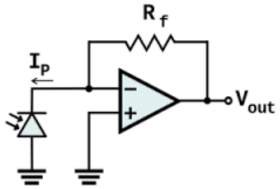


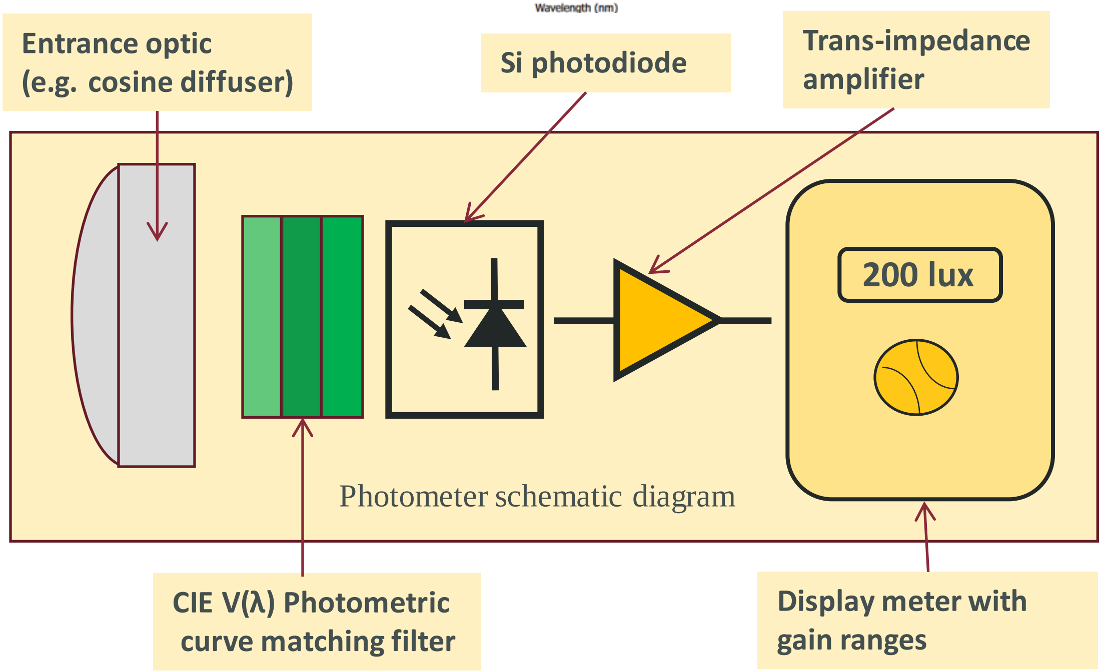
www.gigahertz-optik.de/en-us/basics-light-measurement

Photometers

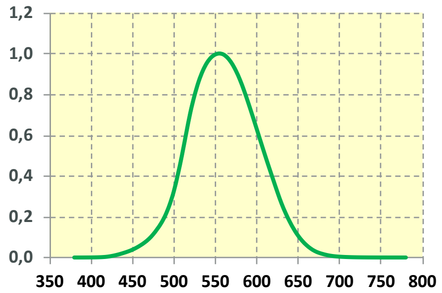








Photometer schematic diagram



Photometers comprise a suitable entrance optic for the required metric, an optical filter to achieve the required photometric response, photodetector, amplifier and display. Most commonly the entrance optic will be a cosine diffuser enabling the measurement of lux. The photometric filter is most important. It needs to be designed so that the overall spectral response of the system including the entrance optic and photodetector matches the V-lambda curve.

Photometers

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ISO/CIE 19476:2014 (CIE S 023/E:2013)
Characterization of the performance of illuminance meters and luminance meters

Quality Indices	Notation
V(λ) 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}

(i) Illuminance meters only *(ii) Luminance meters only*

How do we assess how good a photometer is?

There is a comprehensive set of quality indices defined, but most manufacturers don’t specify many of them. They include rejection of UV and IR, linearity, temperature dependence, etc. But in practice, one quality index is most important for LED measurements.

V(λ) Mismatch	f_1'

Spectral Mismatch Error

V(λ) Mismatch | f_1'

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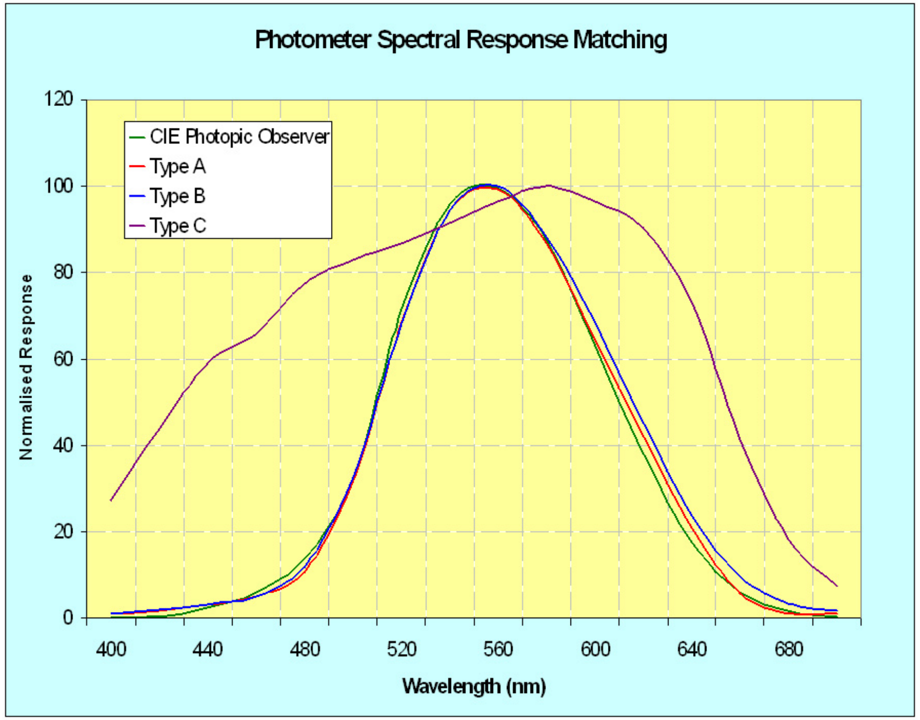
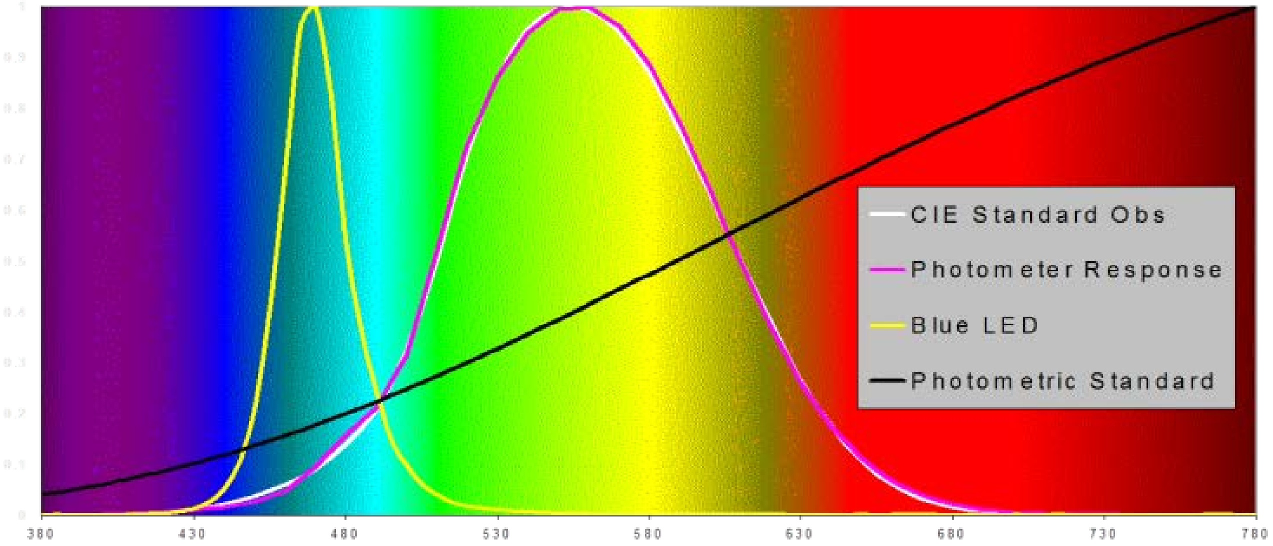


No commercially available photometer offers a perfect match to the V-lambda curve. The f_1’ metric offers a single % value relating to the closeness of match to the v-lambda curve. A DIN classification is often used i.e. Class A, B, C to indicate overall quality.

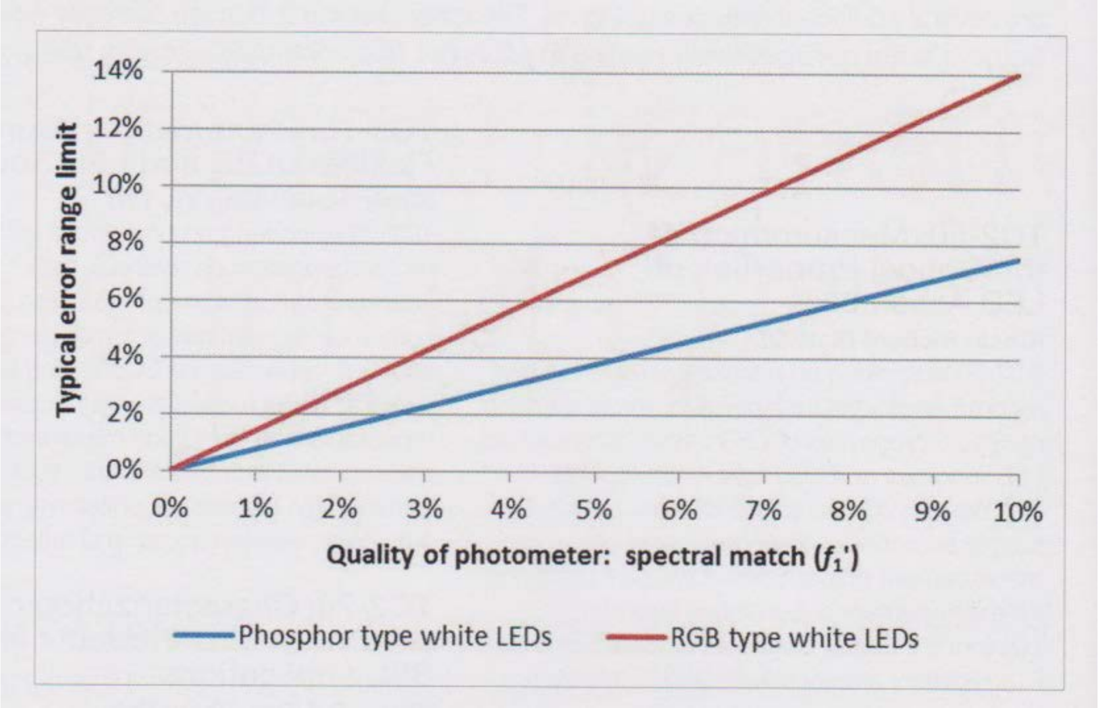
The important point here is that photometers are generally calibrated against an incandescent source (CIE illuminant A 2856K) which has nice smooth spectral response (black line). But LEDs have a very different spectral response, most commonly with strong blue peak. Plot below shows very high quality DIN Class A photometer response and blue LED illustrating a source of error.

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)



Spectral Mismatch Error



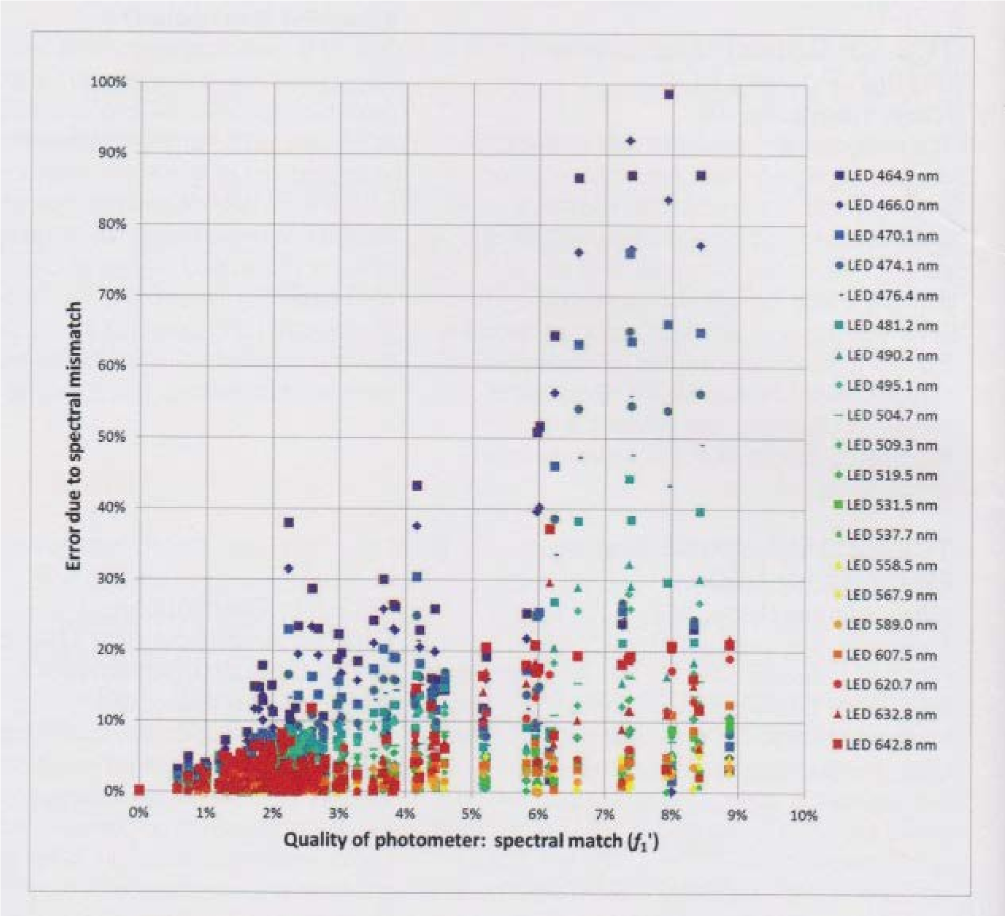
Tony Bergen & Peter Blattner CIE Div 2, *Photometry Standardization Developments for OLEDs and LEDs*, LED Professional Review, Issue 41, Jan 2014.

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

The f_1' error is not a direct measure of how accurate photometers are when measuring LEDs but as shown by the work of Bergen and Blattner, it's a good indicator. They tested more than 100 commercially available photometers. The important point is that they were all correctly calibrated photometers.

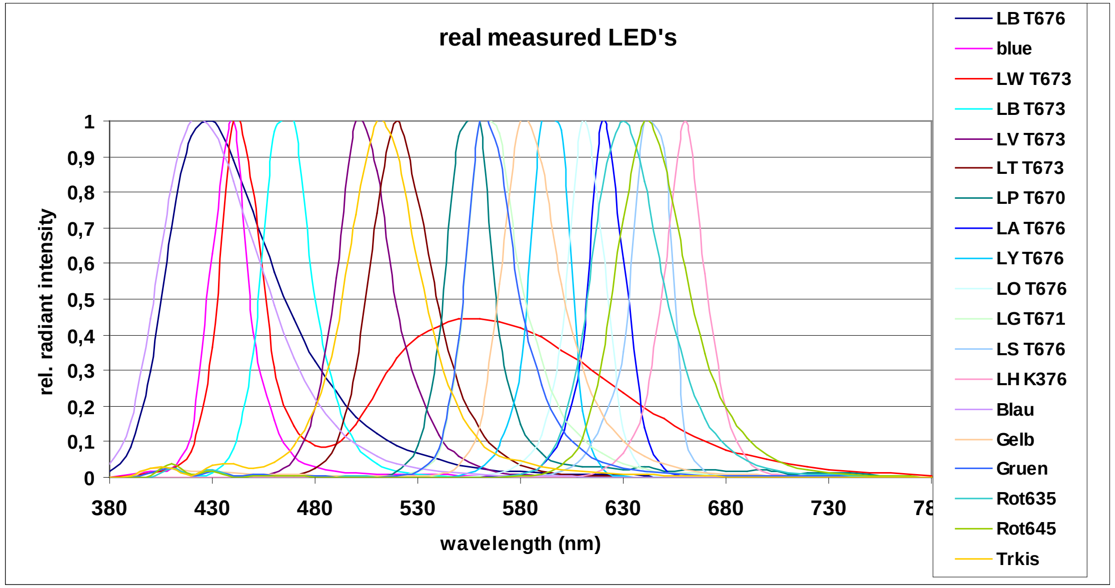
How significant is this? Energy efficiency is a main driver for LED technology. Most of us would consider 10% error in our energy bills significant.

Spectral Mismatch Error



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

The situation is much worse if measuring coloured LEDs. This work by Bergen and Blattner shows that calibrated photometers are giving errors of many 10s of % due to their spectral mismatch error.

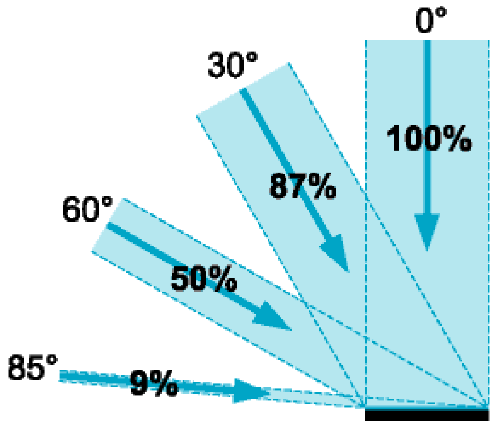


Photometer errors when measuring coloured LEDs can be very much worse than white LEDs

Cosine Error

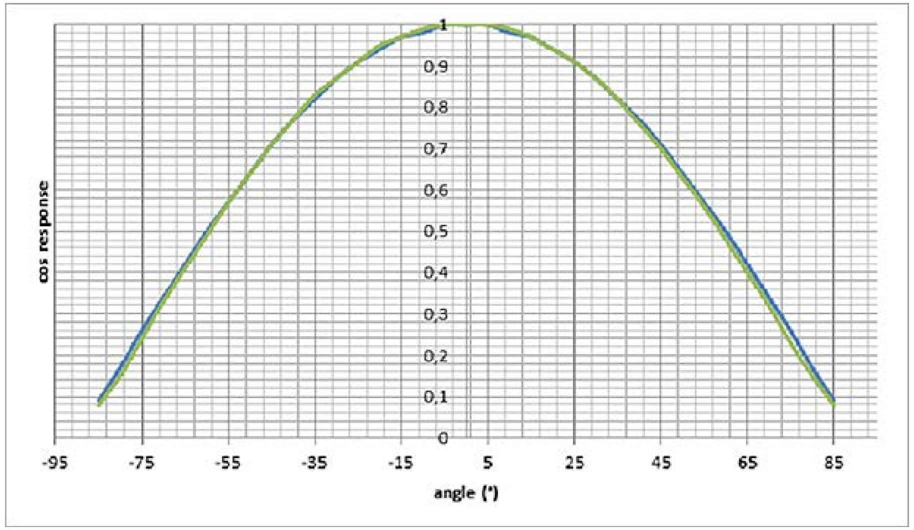
Cosine Response	f_2

Cosine Law: $E_\theta = E \cdot \cos(\theta)$



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



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

The other important quality metric for lux meters is their cosine match. This is not specific to LED lighting but is also very important for the measurement of any extended light source.

Just because a meter has a piece of white, apparently diffusing plastic it doesn't necessarily have a good match to the required cosine function.

Spectral Light Meters

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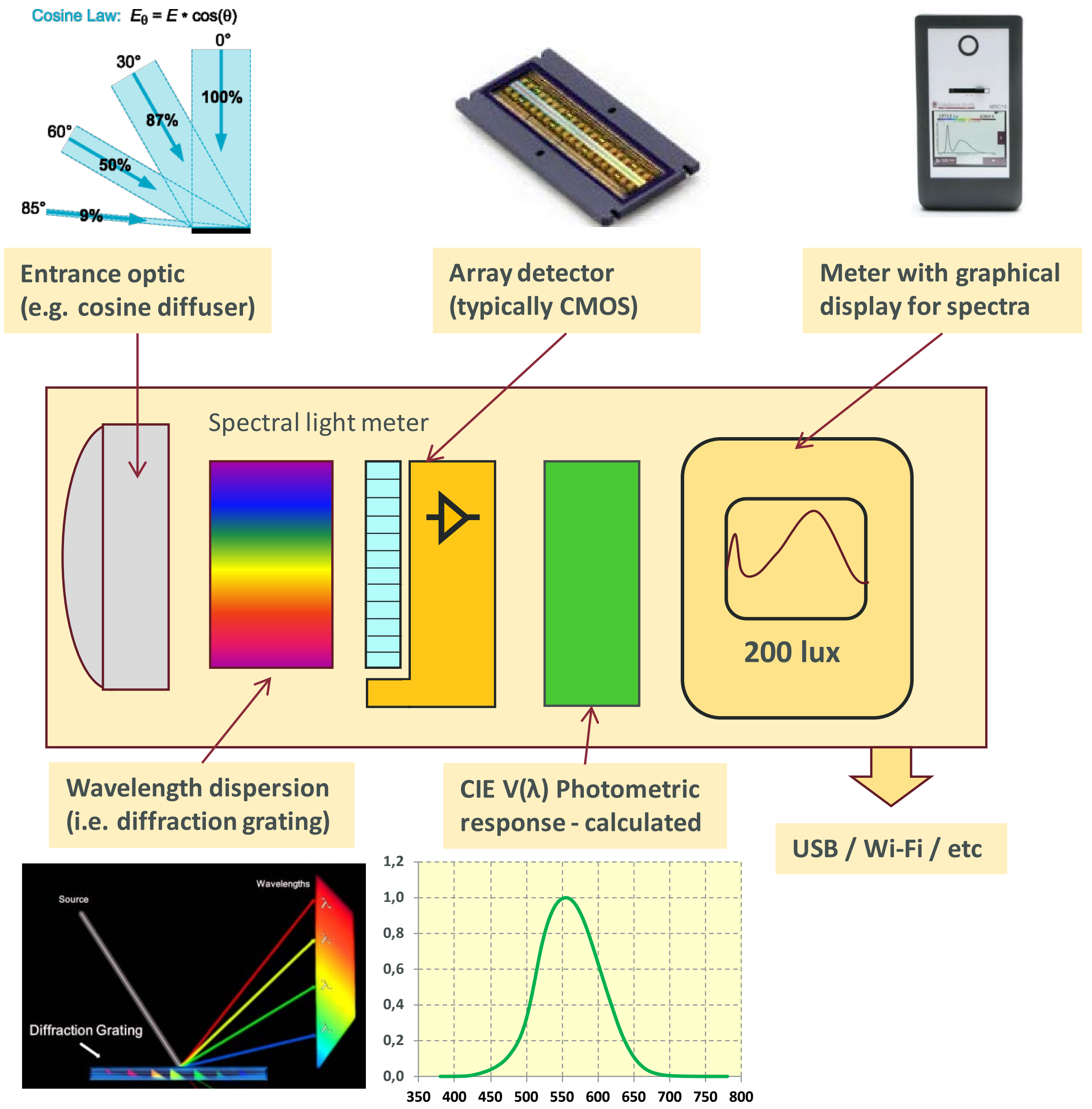
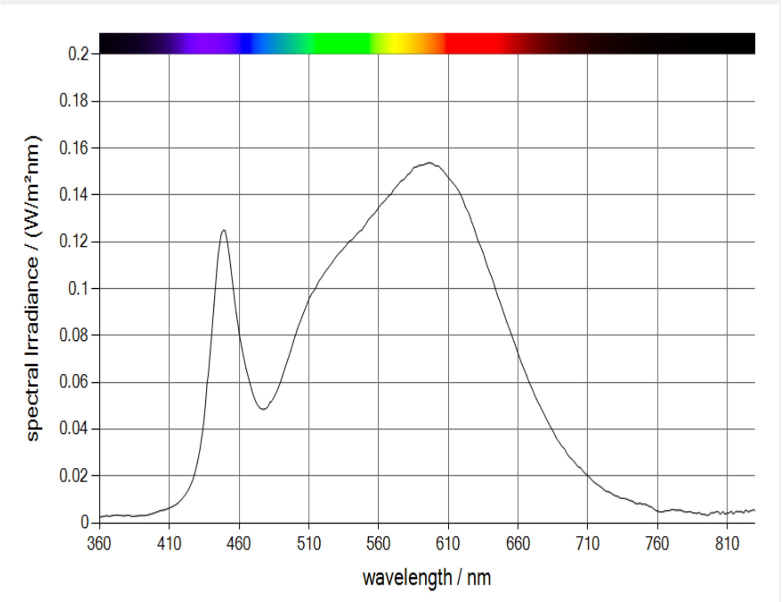


So how do spectral light meters differ from traditional photometers? They still have the same entrance optic requirement but instead of the photometric response matching filter, they employ a wavelength dispersing element, such as a reflectance diffraction grating coupled to an array detector, typically CMOS.

In this way, many narrow wavelength bands can be measured which reveals the spectral composition of the light. Importantly, the perfect photometric curve can be implemented by calculation or 'weighting' of the measured spectrum, thereby eliminating the spectral match error.

Spectral Light Meters

Once we have the absolute spectral data of a light source, we can do so much more than just asses its efficiency in terms of lux level produced or its efficacy in terms of lumens/Watt. We can properly asses its quality, which typically relates to the colour of the source. Additionally, a light source's effectiveness for purposes other than simple general lighting applications can be determined i.e apply other weightings / filter responses than the v-lambda curve.



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

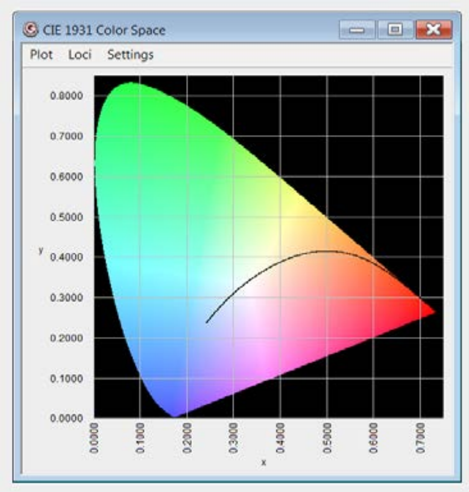
i.e. typically colour

Filter responses other than photometric V(λ)

Colour Measurement

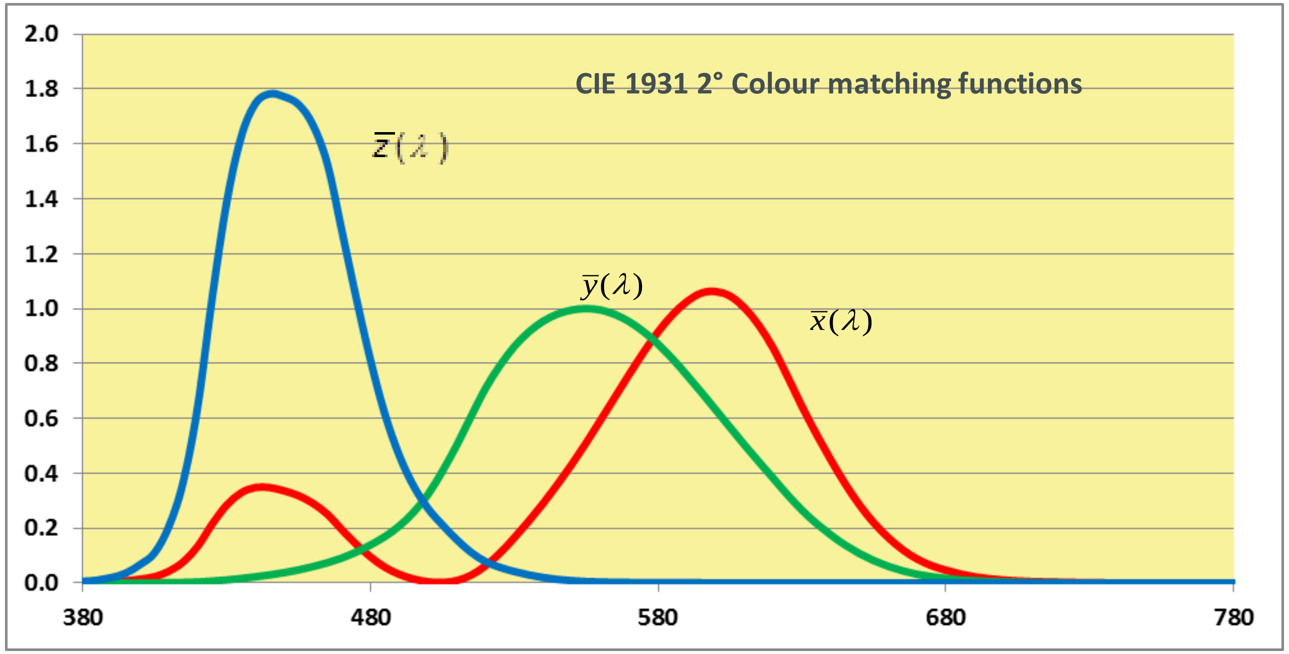
Human eye has two types of photoreceptors for vision – Rods (~120 million) and Cones (~6 million).

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.



Our colour vision is achieved by the blue, green and red sensitive photoreceptive cones in our eyes. In 1931 the CIE issued colour matching functions for these which are still widely used today. As with a simple photometer, these functions can be implemented by optical filters as used in tri-stimulus meters but the difficulties are compounded by the three responses required. Again, spectral data permits the accurate computation of the necessary colour matching functions.

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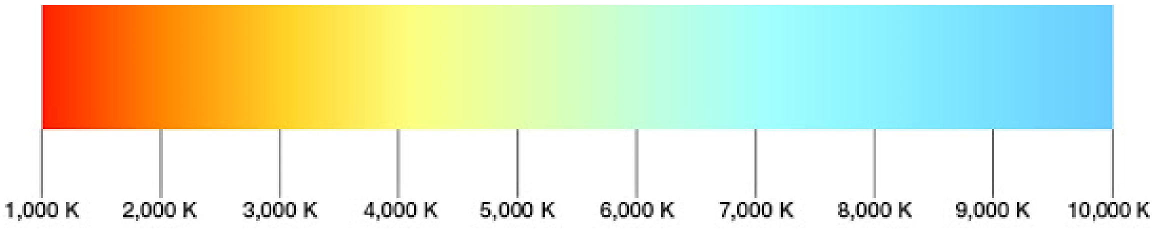
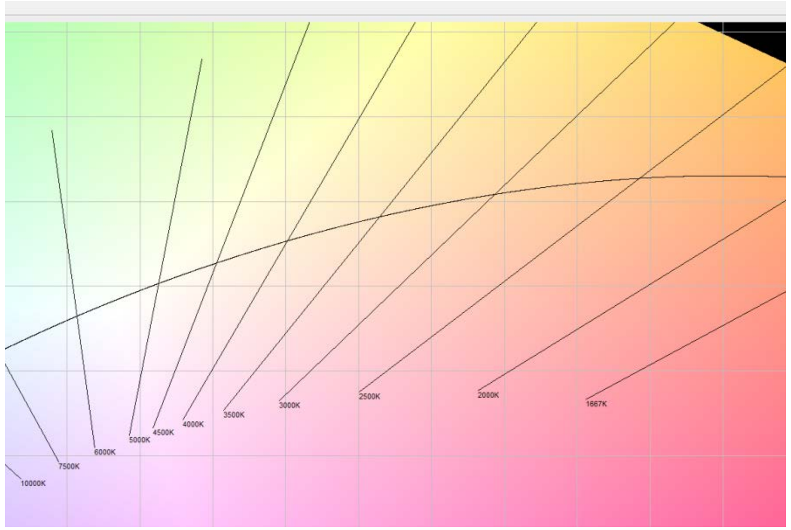
Colour temperature is a widely used 'light quality' indicator. Again this can be determined most accurately with spectral data. However, it's really not an ideal light quality metric as different colour sources can have same CCT.



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

Colour Rendering - CRI

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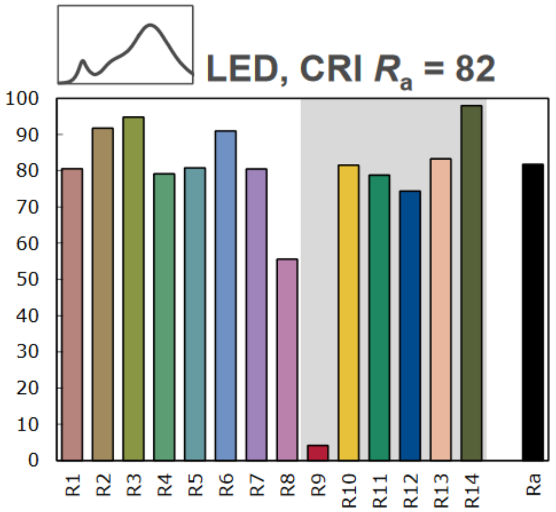
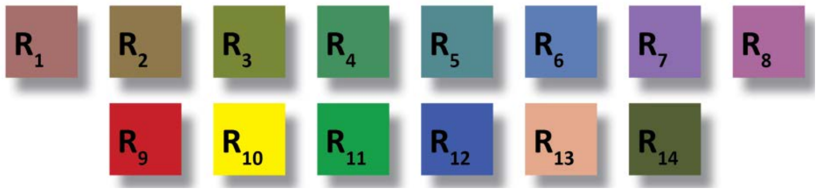


The colour rendering of a light source is a measure of its ability to realistically reproduce the colour of an object. It is a colour fidelity metric only. First released in1965 and updated in 1974, the general index Ra is an average from eight standard colours R_1 - R_8. For general lighting, the general index R_a >80% is generally considered acceptable. The R_9 value for instance is important within medical environments for example.
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.

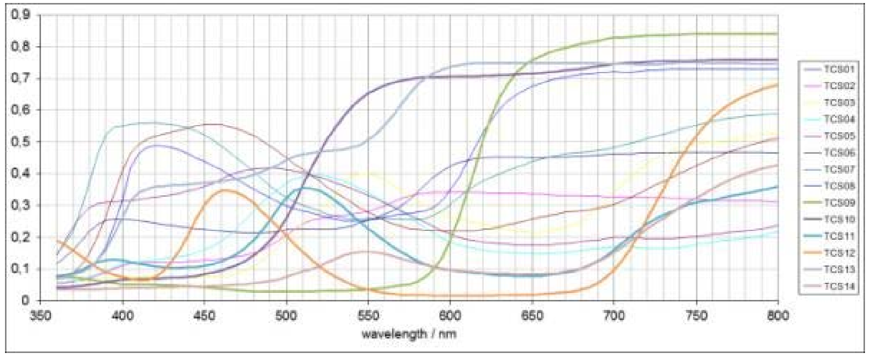
Only possible with spectral data.

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

CIE Colour Rendering Indices, CRI



Test colour samples according to CIE 13.3



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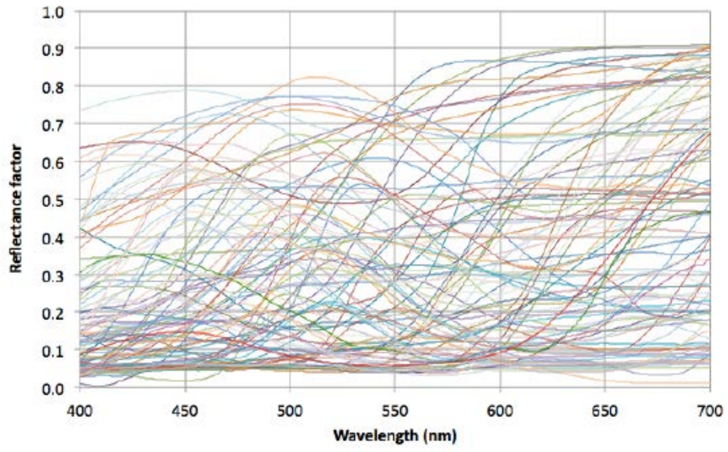
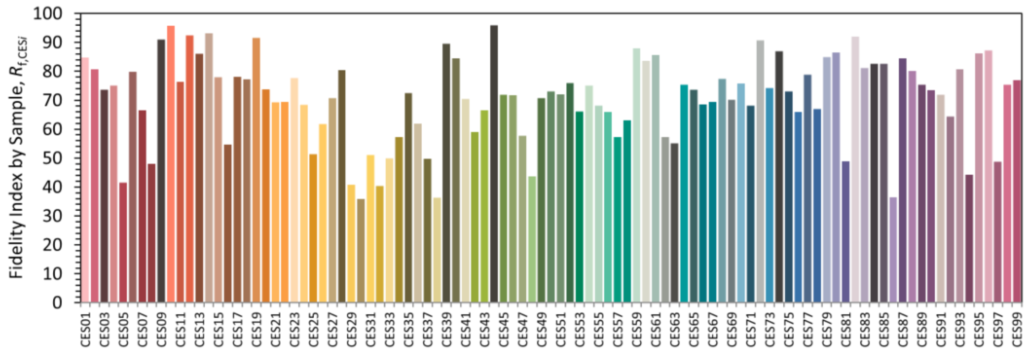
There have been numerous proposed alternatives to the CIE’s CRI system, the latest of which is the IES’s TM30 method which has gained widespread acceptance within the lighting industry (e.g. CIE Report 224:2017). TM-30-15 uses 99 colour samples to characterize the difference between the test source and reference illuminant and uses CIECAM02 (uniform colour space).

TM-30-15 IES *“Method for Evaluating Light Source Color Rendition”*

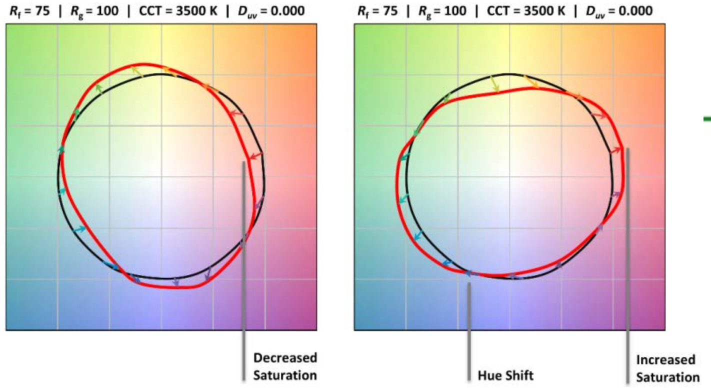
Only possible with spectral data.

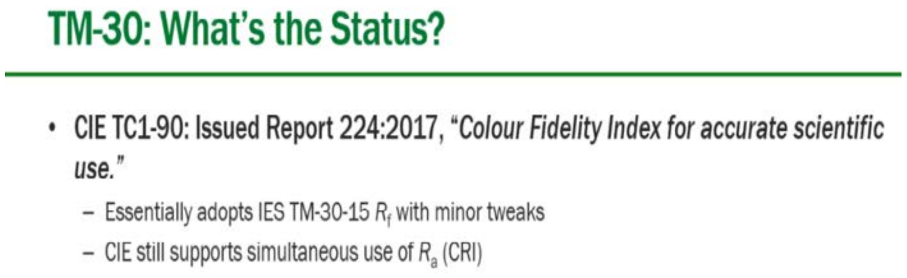


http://www.ies.org



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

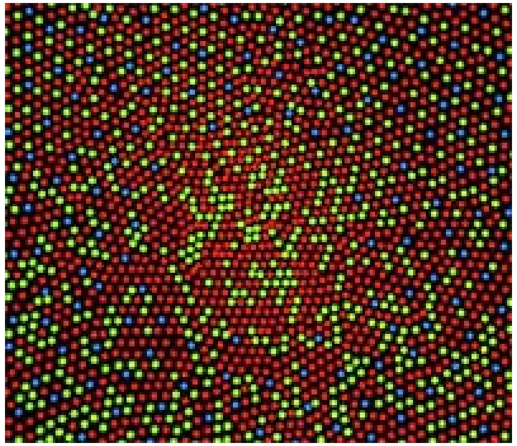




TM-30: What’s the Status?

- CIE TC1-90: Issued Report 224:2017, *“Colour Fidelity Index for accurate scientific use.”*
  - Essentially adopts IES TM-30-15 R_f with minor tweaks
  - CIE still supports simultaneous use of R_a (CRI)

Observer’s field of view



CIE 1931 2° Standard Observer

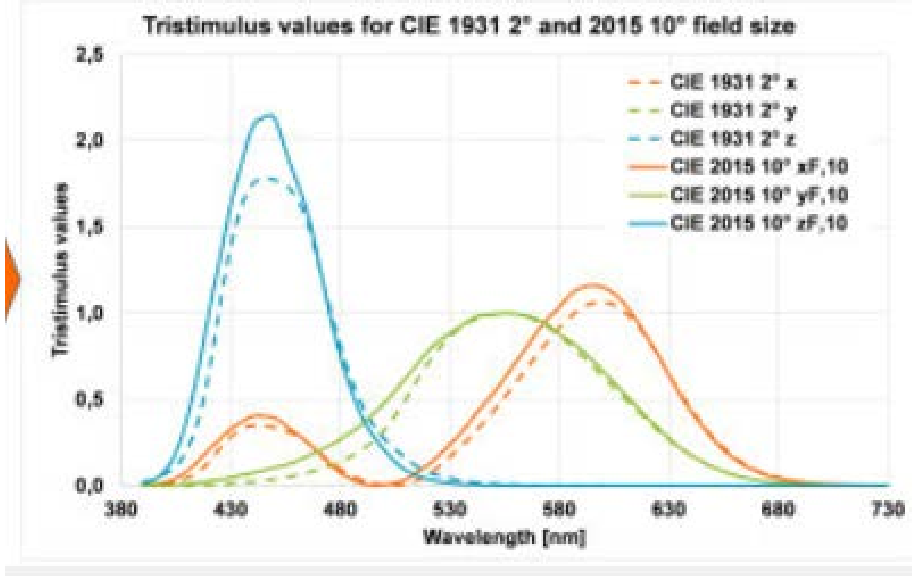
CIE 1964 10° Standard Observer

CIE 170-2:2015

Only with spectral data can these different weighting functions be implemented

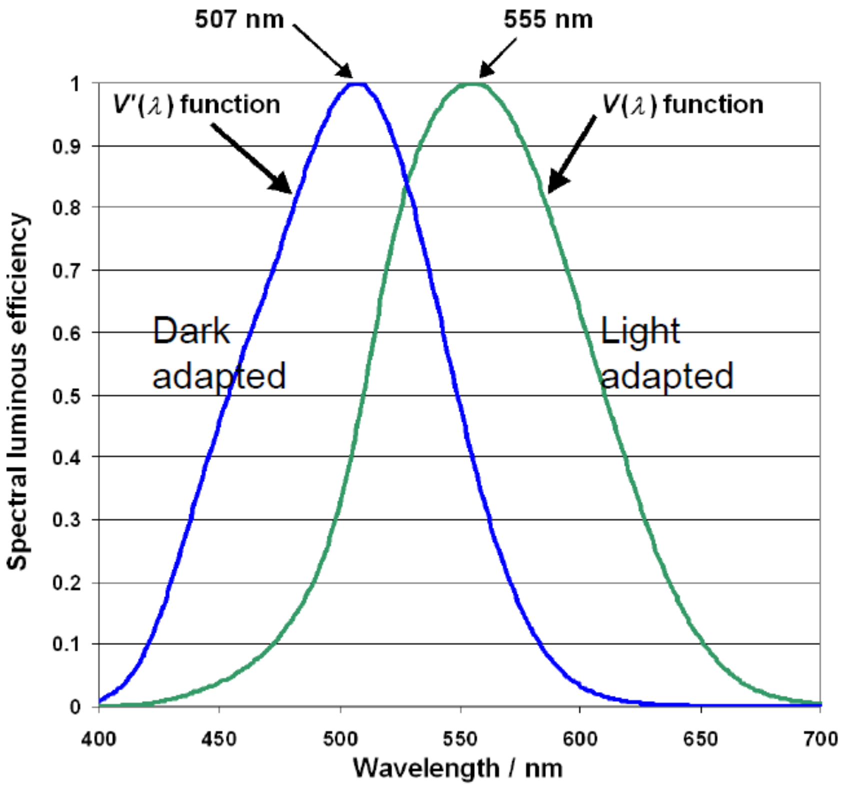
The cones in our eyes are not uniformly distributed – there are far fewer blue cones in the central region. This results in different colour perception as our field of view increases. Accordingly, the CIE offers different colour matching functions for 2 degree and 10 degree FOVs.

Most LEDs manufacturers bin LEDs using the 2 degree observer only, but Osram, for example, have introduced binning with additional match to 10 degree observer.



http://www.osram-os.com/osram_os/en/applications/general-lighting/ten-binning/index.jsp

Scotopic Vision



Scotopic response is simply implemented with spectral meter

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 ~>3cd/m^2 Scotopic lighting condition ~<0.03cd/m^2

The standard scotopic luminosity function or V' (λ) was adopted by the CIE in 1951

Under very low lighting conditions our cones do not produce a signal and our vision depends on the rods only. This is known as scotopic vision and just like our photometric vision it has a CIE defined spectral response, v'(lambda). Note the shift towards the blue end of the spectrum which can be particularly significant for implementing LED lighting for some applications.

Mesopic Vision

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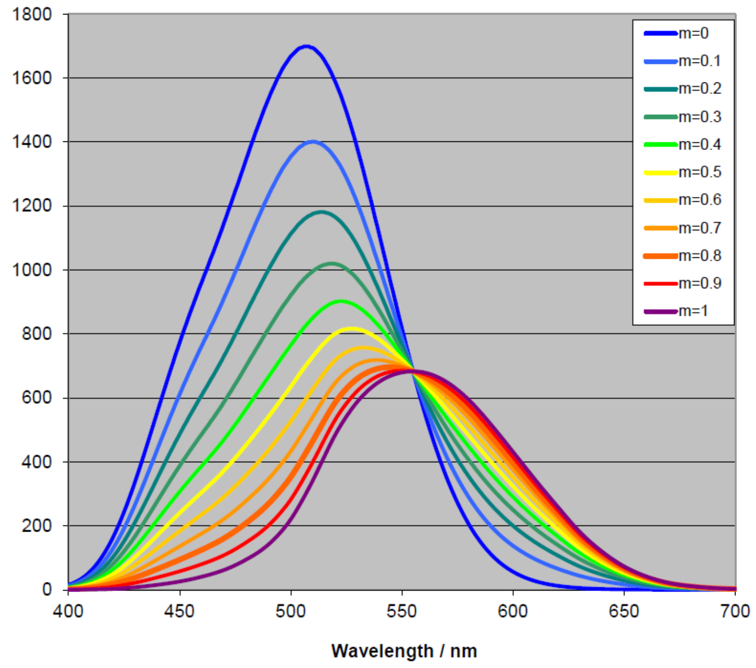
Scotopic Vision	Mesopic Vision	Photopic Vision
Illuminance <0.05 lux to ~3µlux	Illuminance 3µlux to 50 lux	Illuminance levels >50lux
Rods only, no colour perception	Eye not in stable state	Cone receptors yield colour

The eye operates in the mesopic region in many important situations:

- Night time driving;
- Emergency escape lighting;
- Marine signalling.

Our vision doesn't suddenly switch from photopic to scotopic mode as light levels fall, but gradually changes. This is known as the mesopic region and applies in some important situations like night time driving, emergency escapes and maritime navigation. A range of spectral weightings are required depending on the adaptation of the eye.

CIE 191: System for mesopic photometry



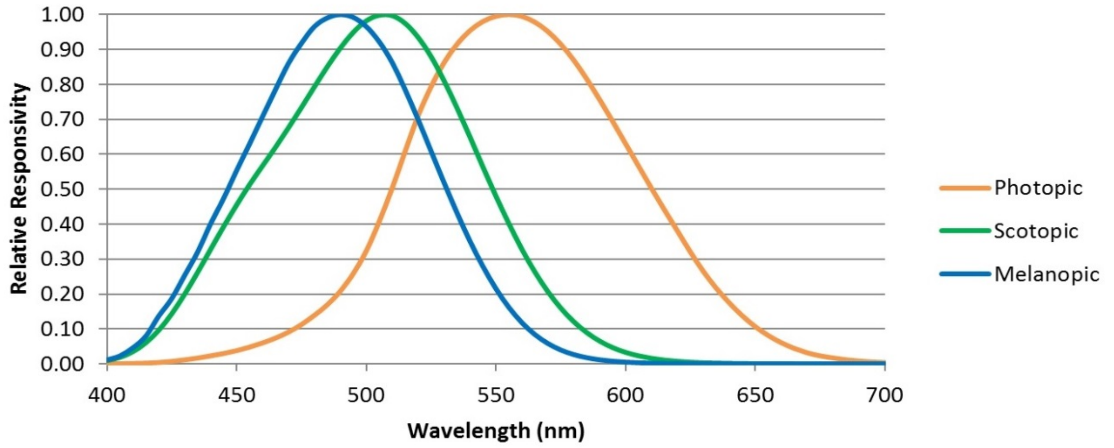
Spectral weighting function depends on visual adaptation (determines value of *m*)

Human Centric Lighting / Circadian Lighting / Biodynamic lighting

Contemporary scientific research has shown that as well as the rod and cones responsible for our vision, our retinas also have non-image forming photoreceptors, intrinsically photosensitive retinal ganglion cells (ipRGCs), that play a major role in entraining our circadian rhythms

Of particular interest is the spectral responsivity of ipRGCs which contain a photopigment called melanopsin which have their own ‘melanopic’ spectral responsivity with peak sensitivity in the blue spectral region, around 480nm.

Modern insights into human chronobiology combined with the possibilities of SSL lighting offer many new opportunities to improve health and wellbeing through appropriate lighting, most commonly referred to as ‘human centric lighting’ (HCL), but other terms such ‘circadian lighting’, ‘biodynamic lighting’ or ‘biologically-effective lighting’ are also regularly used.



Ev : illuminance
Ee,z : melanopic irradiance
Ev,z : melanopic illuminance (equivalent melanopic lux)
Ev,mel : melanopic daylight equivalent illuminance

Human Centric Lighting – research & standards

α-optic	*BTS256-update new measurands*	*unit*
Ez	melanopic illuminance	z-lx
Ee,z	melanopic irradiance	W/m^2
Ev,mel	melanopic daylight equivalent illuminance	lx
Esc	cyanopic illuminance	sc-lx
Ee,sc	cyanopic irradiance	W/m^2
Emc	chloropic illuminance	mc-lx
Ee,mc	chloropic irradiance	W/m^2
Elc	erythropic illuminance	lc-lx
Ee,lc	erythropic irradiance	W/m^2
Er	rhodopic illuminance	r-lx
Ee,r	rhodopic irradiance	W/m^2

CIE Technical Note CIE TN 003:2015 Report on the First International Workshop on Circadian and Neurophysiological Photometry.
http://files.cie.co.at/785_CIE_TN_003-2015.pdf

For research purposes, CIE (CIE TN 003:2015) now recommends reporting the 5 α-opic equivalent illuminances for s-cones, m-cones, l-cones, rods and ipRGC. These are all provided by suitable specytal light meters such as the BTS256-EF.

Standards are being developed.

The WELL Building Standard https://www.wellcertified.com/
(specifies lighting conditions in terms of Equivalent Melanopic Lux)

DIN SPEC 67600:2013-04 (E) Biologically effective illumination - Design guidelines
(recommendations based on melanopic illumination)

prEN 16791 Quantifying irradiance for eye-mediated non-image forming effects of light in humans

EN 12464-1:2011 Lighting of indoor work places (gives some guidance only)

DIN SPEC 5031-100 Melanopic effects of ocular light on human beings - Quantities, symbols and action spectra

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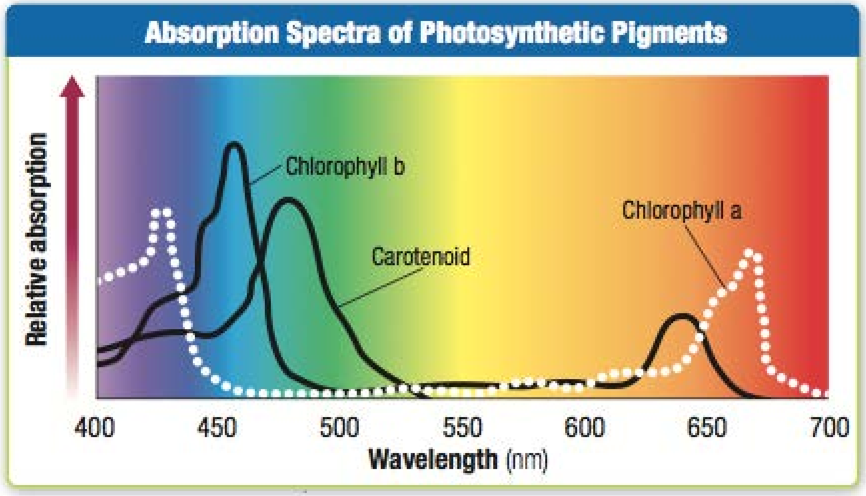
LED lighting offers horticulturalists energy efficiency and many further benefits such as increased crop yields, improved product quality, and control of particular plant characteristics.

LEDs allow control of the amount and spectral composition of light which can be used to govern a plant's growth rate, shape and flowering. Therefore, spectral light meters offer many advantages over traditional PAR sensor technology which offer no spectral information.

Photosynthetically Active Radiation, PAR, 400-700nm

Lux and lumens are not meaningful for plants.



Photosynthesis depends on the amount of photons. Planck–Einstein relation, $E = hc/\lambda$, allows us to determine this from the spectral data.

PAR is a much misused term – it's not quantitative, it's just descriptive. It describes Photosynthetically Active Radiation which is generally understood to mean light in the 400-700nm region. A manufacturer of a lighting product is likely to specify it in terms of photosynthetic photon flux, PPF in micro-moles per second whereas the grower will be most interested in the photosynthetic photon flux density, PPFD, the actual micro-moles per square meter per second arriving on the plant.

Photosynthetic Photon Flux (PPF) : measurement of the total number of photons emitted by a light source each second within PAR wavelength range. Measured in **µmol/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 **µmol/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**.

The mole is the SI base unit (symbol **mol**) for the amount of a substance i.e. photons in this context.
1 mol = 6.0221415×10^{23} ("Avogadro's number")

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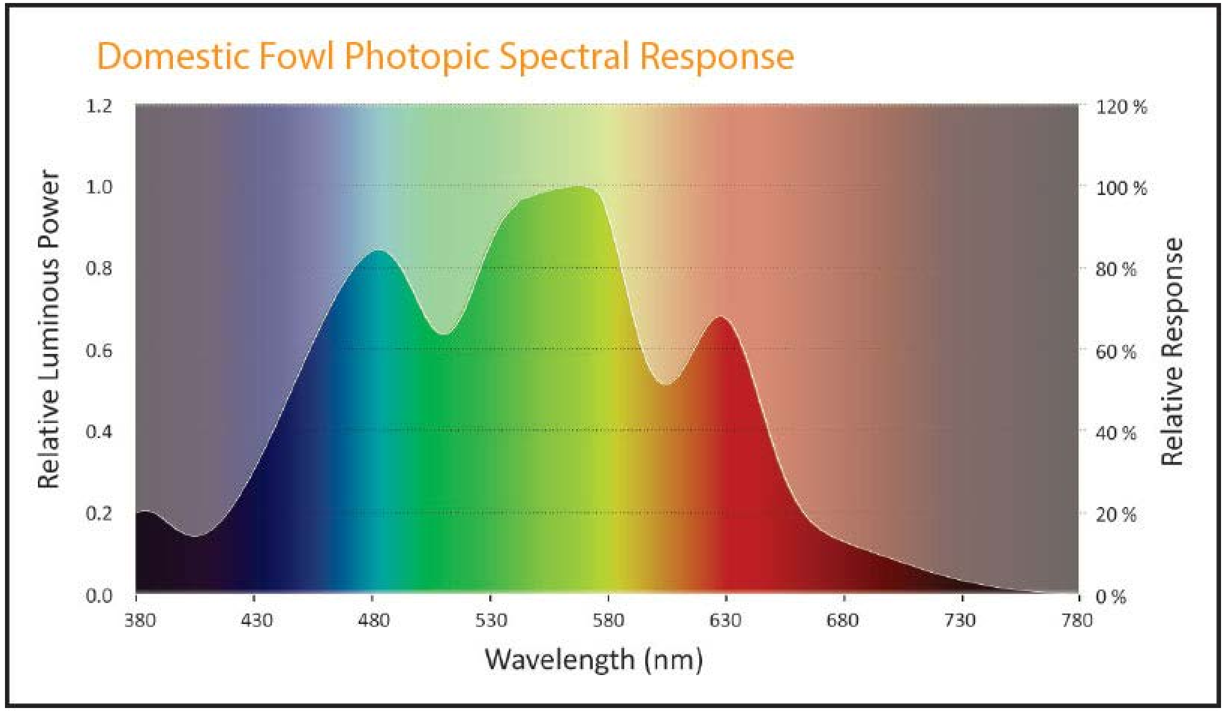
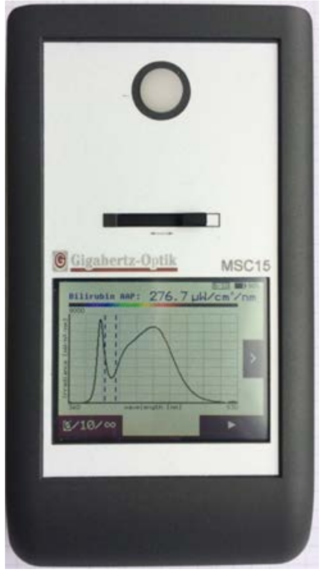


Data source: "Spectral sensitivity of the domestic fowl (Gallus g. domesticus)" N. B. PRESCOTT AND C. M. (1999)

Both livestock and fish rearing can also benefit from appropriately spectrally tuned and controlled lighting. Each species has their own spectral responses for vision and circadian rhythms which often varies significantly from human vision.

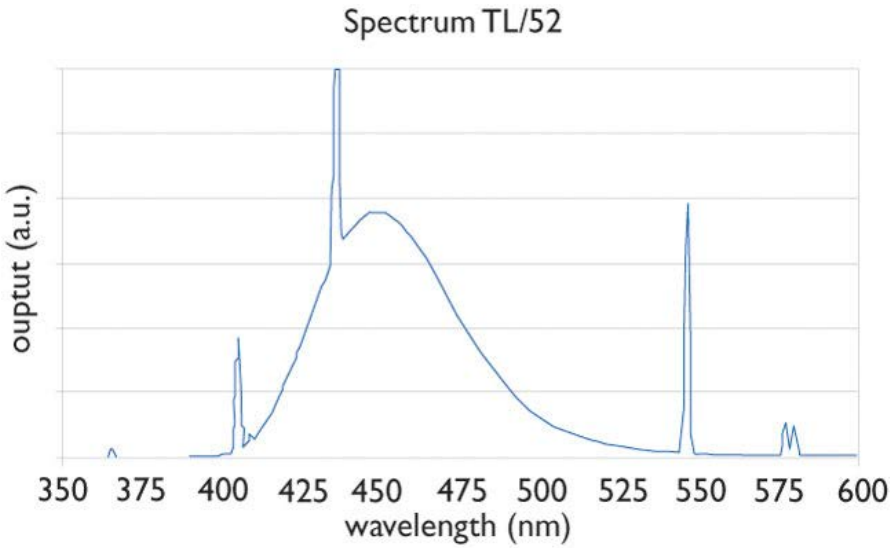
Phototherapy - bilirubin



One of the most common uses of phototherapy is the use of ‘blue light’ to treat jaundice in new born babies. Photometers are of no use whatsoever and the variety of radiometers used in this field has led to great confusion, inappropriate measurements and inaccuracy. Different standards also exist. However, a spectral light meter can overcome all these difficulties.
Using a suitable spectral light meter such as the MSC15 enables neonatal phototherapy lamps can be accurately measured in accordance with the latest standards and guidance, irrespective of the lamp type or manufacturer.

The European market specifies:
Total irradiance for bilirubin, E_{bi} in accordance with IEC 60601-2-50:2009+A1:2016
E_{bi} = integrated irradiance 400 to 550nm, 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 $\mu W/cm^2/nm$



Blue Light Hazard

X1-3 + XD-45-HB

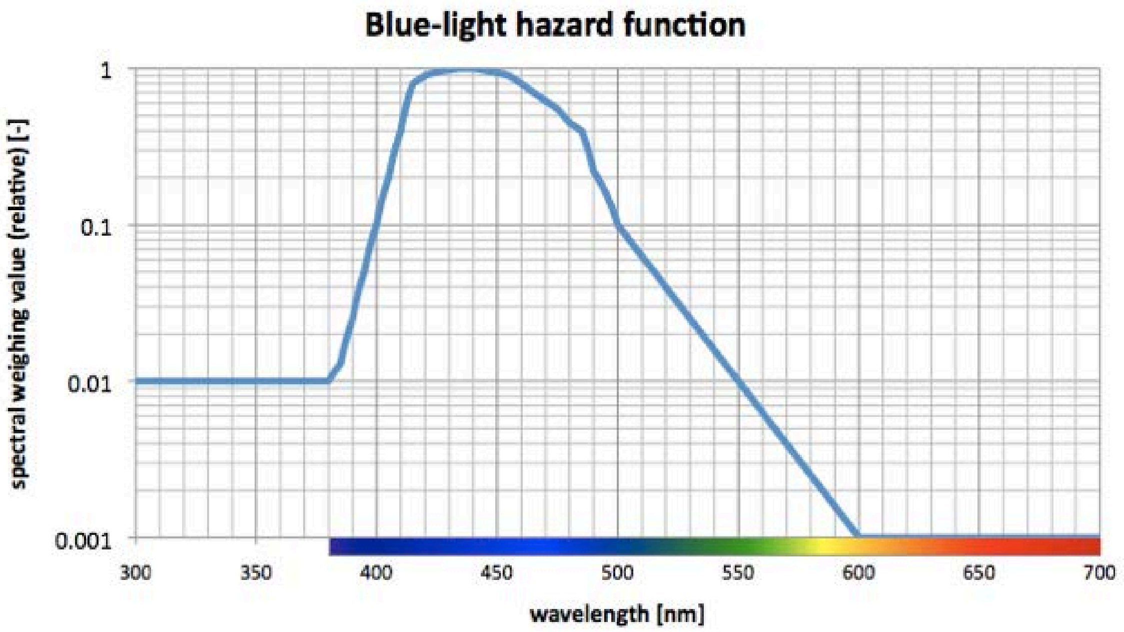
IEC TR 62778:2014 Application of IEC 62471 for the assessment of blue light hazard to light sources and luminaires

2006/25/EC Guideline and **DIN EN 14255** for Safety of Workplaces

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

IEC 62471:2006 Photobiological safety of lamps and lamp systems

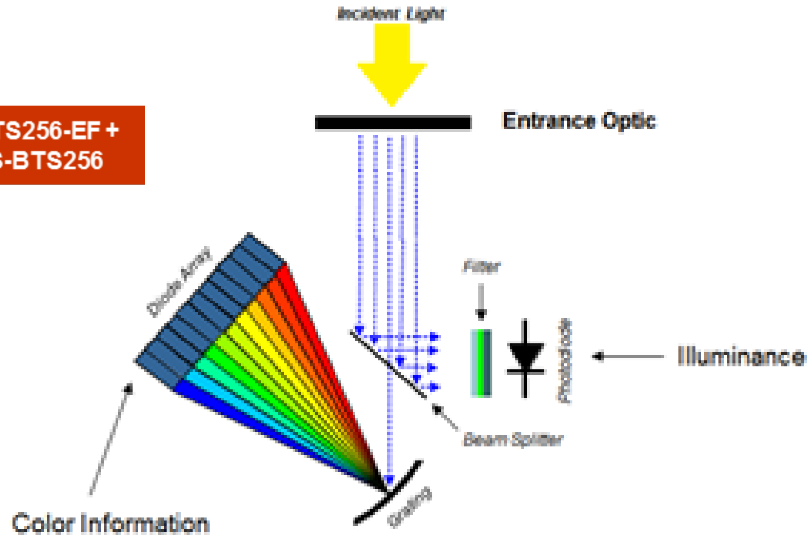
Includes UV and IR hazards too, 200-3000nm



Too much light passing through the eye's lens and reaching the retina can cause damage. In particular, the higher energy blue light is potentially most hazardous hence the term 'blue light hazard'. The relatively high blue content of most phosphor-conversion white LED products has created particular interest in this matter. Proper measurement of blue light hazard requires an extended wavelength range to 300nm in the UV and also requires particular measurement geometries. It therefore requires specialist instrumentation such as the Gigahertz-Optik X1-3 meter.

Enhanced Spectral Light Meters

BTS256-EF + S-BTS256



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

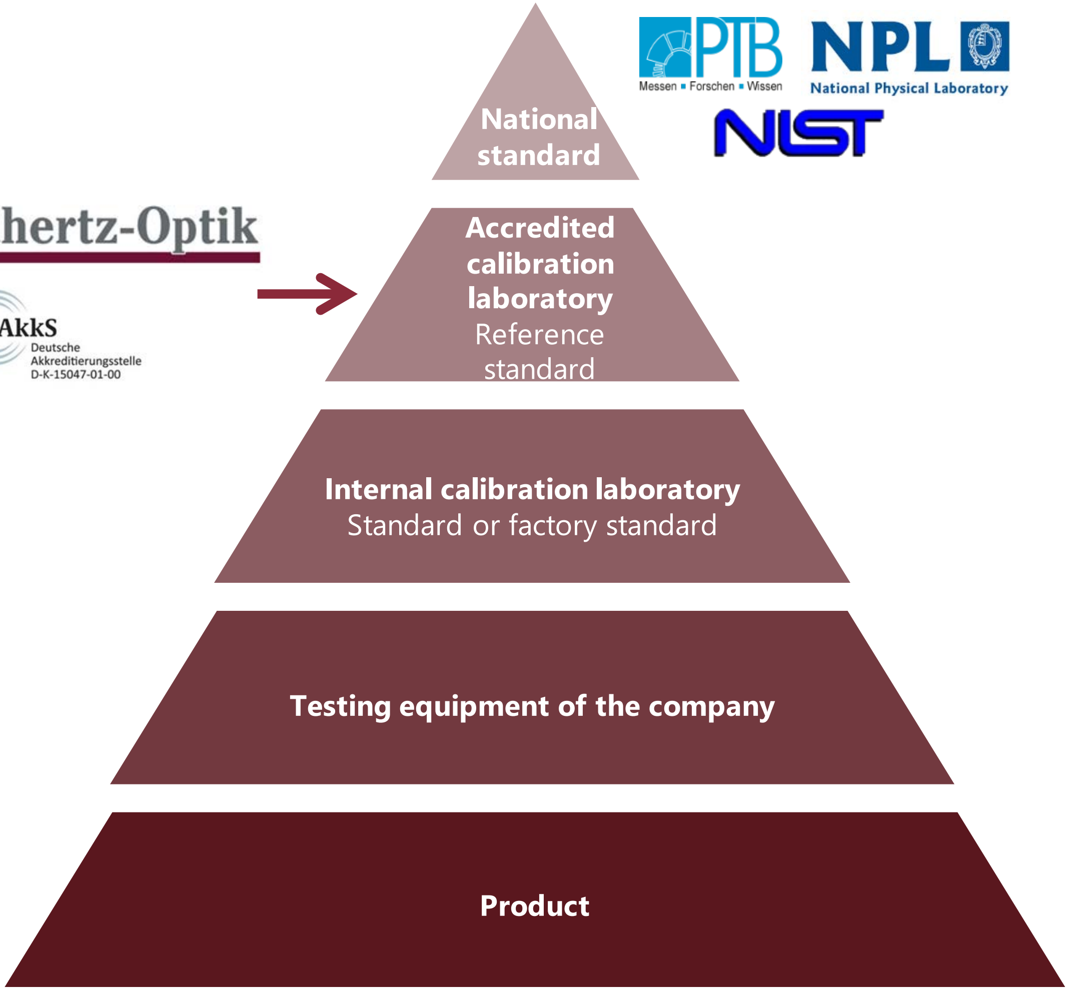
Ev (t)	Illuminance over time graph	lx
Ev,min	Minimum illuminance	lx
Ev,max	Maximum illuminance	lx
	Flicker Percent	%
	Flicker Index	a.u.
f_dom	Dominant flicker frequency	Hz
FFT	FFT flicker frequencies	Hz - %
P_{st}^{LM}	Short term flicker	
SVM	Stroboscopic Visibility Measure	
M_p	ASSIST flicker perceptibility	

Some spectral light meters, such as the BTS256-EF, are available with additional functionality and technologies to further enhance their accuracy and applicability. For example, the inclusion of a high speed photometric detector enables flicker measurement

CIE TN 006:2016 Visual Aspects of Time-Modulated Lighting Systems – Definitions and Measurement Models http://files.cie.co.at/883_CIE_TN_006-2016.pdf

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***

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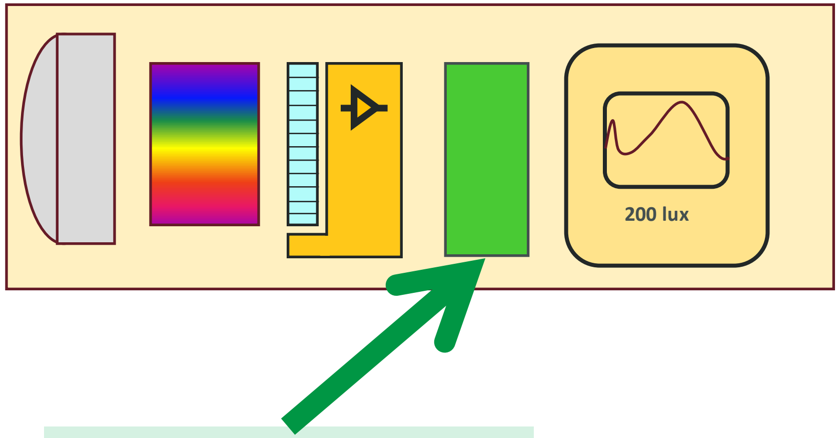

Spectral matching to:

- Photometric curve V(λ)
- Scotopic curve V’(λ)
- Colour matching
- Mesopic
- Melanopic
- PAR
- Bilirubin
- Blue light hazard
- Chicken vision
- Etc, etc …

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.**

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Thank you for your attention.

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