



KONICA MINOLTA

Giving Shape to Ideas

The Language of Light





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The Language of Light

The following resource has been developed to provide readers with an overview into the measurement of light, some of the terminology used and the types of instrumentation that is available to produce accurate and repeatable measurements of light sources, fixtures or environments. The resource cannot be considered in any way exhaustive however if you have a question which is not answered by the following resource please contact your local Konica Minolta office where our experienced product specialists will be happy to help.

WHAT IS LIGHT?

Light is necessary for vision, the world around us is only visible when light reflected or emitted by objects reaches our eye and triggers the sensation of sight.

Light is a form of energy and is part of a broader range of the electromagnetic spectrum. Electrical, radio waves and microwaves to gamma rays form this electromagnetic spectrum. The visible light spectrum is a relatively small portion of this spectrum, between 380 nm and 760 nm. In general, light is often defined as including the infrared and ultraviolet regions too.

There are many applications for measuring and understanding the characteristics of light. Konica Minolta with decades of experience in the technology of light produce a range of market leading instruments to satisfy the many approaches and units used in the industry.

The measurement of light can be a challenge especially in deciding what to measure and how to measure.

WHAT CAN BE MEASURED?

The total light energy emitted from a source or falling on a surface can be measured. This total energy can cover a portion of the visible spectrum including ultraviolet and infrared energy. Energy at an individual wavelength or over a range of wavelengths can be measured.

Another area of interest is colour. Colour is a property of light and can be measured and quantified.

The science of light measurement is known as photometry and is a subset of the broader field of radiometry - the measurement of radiation outside the visible spectrum.

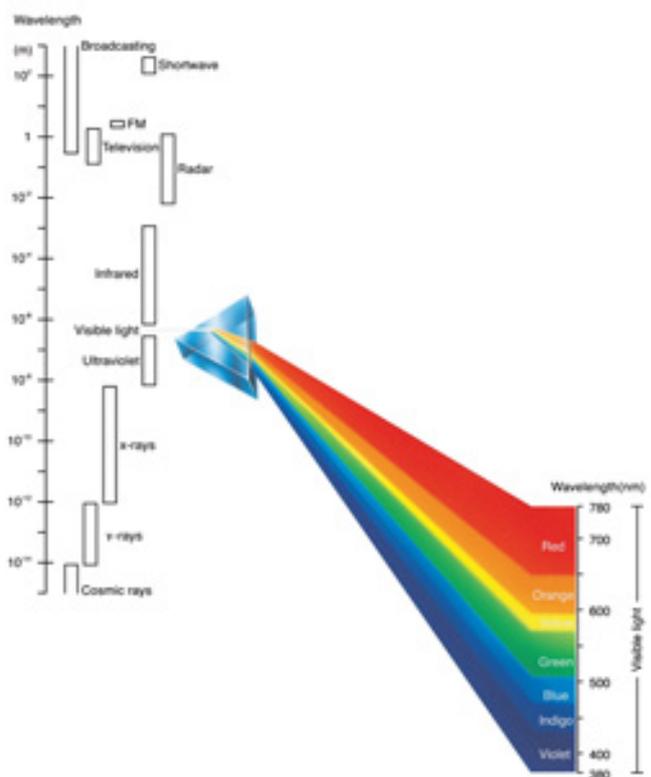


Fig.1 Electromagnetic spectrum including visible light

RADIOMETRY

Radiometry is the science of the measurement of electromagnetic (EM) radiation. The broader spectrum covered by the science of radiometry is based on physical constants.

The properties of concern to us here are radiated power and its spatial and angular distributions. The four basic concepts are:

- Radiant Flux
- Radiant Intensity
- Radiance
- Irradiance

RADIANT FLUX



Radiant Flux
Total Power (watts)

This is the total radiant power emitted from a source or received by a surface. It can also be defined as the rate of flow of radiant energy through a certain area or out of a certain solid angle.

The SI unit of radiant flux is the Watt.

RADIANT INTENSITY



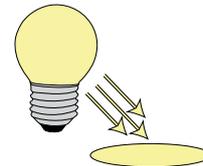
Radiant Intensity
Power/Solid Angle

It is defined as the directed angular density of radiation from a source.

The radiant intensity in a given direction is the sum of the power contained in all the rays (cones) emitted in that direction by the entire source (i.e., power per solid angle).

The SI unit for radiant intensity is Watt/Steradian (Watt/sr).

IRRADIANCE

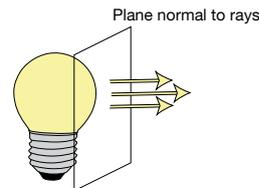


Irradiance
Power/Unit Area

This is a measure of radiant flux incident on an object's surface (radiant flux per unit area).

The SI units for irradiance is Watt/square meter (Watt/m²)

RADIANCE



Radiance
Power/Solid Angle/
Projected Area

This is a measure of the total radiant intensity per unit projected area.

The SI units for radiance is Watt/square meter Steradian (Watt/m² sr)

SPECTRORADIOMETRY

Spectroradiometry is the measurement of light energy at individual wavelengths within the electromagnetic spectrum. It can be measured over the entire spectrum or within a specific band of wavelengths.

SPECTRAL RADIANCE

The radiance of a light source is a single value which is the sum of all energy measured over a spectrum. The individual energy values at a particular wavelength in nanometer (nm) can be determined by a spectral radiance measurement.

The SI units for spectral radiance is Watt/square meter Steradian nanometer (Watt/m² sr nm).

SPECTRAL IRRADIANCE

This is a measure of radiant flux at particular wavelength incident on per unit area.

The SI units for spectral radiance is Watt/square meter nanometer (Watt/m² nm).

PHOTOMETRY

Photometry involves measurement of the psychophysical attributes of electromagnetic energy that is visible to the human eye. The use of the term 'luminous', which refers to visible light, defines photometry in terms of human perception.

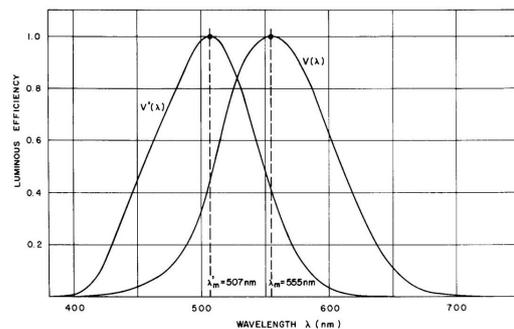


Fig. 2 Approximate relative sensitivity of the average human eye to different wavelengths

Photometry became a modern science in 1942, when the Commission Internationale de l'Eclairage (CIE) met to define the response of the average human eye. CIE measured the light-adapted eyes of a sizeable sample group, and compiled the data into the CIE Standard Luminosity Function (widely known as photopic curve - chromatic perception at normal state, and scotopic curve - achromatic perception at low level of illuminance. – see Fig.2).

The photometric quantities are related to the corresponding radiometric quantities by the CIE Standard Luminosity Function. We can think of the luminosity function as the transfer function of a filter which approximates the behaviours of the average human eye (Fig. 2).

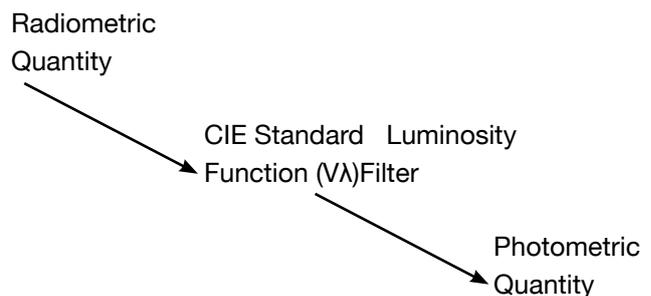


Fig. 3 Relationship between radiometric units and photometric units

Photometry consists of four basic concepts:

- luminous flux
- luminous intensity
- illuminance
- luminance

LUMINOUS FLUX

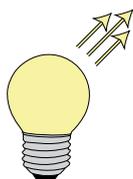


Luminous Flux
Total Power (lumen)
“Light Power”

A source of light radiates energy in the form of electromagnetic waves. We speak of light energy as ‘flux’ and luminous flux is a measure of the flow of light energy emitted by a source, or received by a surface. The quantity is derived from the radiant flux, W (in Watts), by evaluating the radiation in accordance with the relative luminous efficiency of the ‘standard eye’ (CIE Standard Luminosity Function, V_λ).

The unit is lumen (lm).
 $lm = 683 \times W \text{ (Watt)} \times V_\lambda$

LUMINOUS INTENSITY



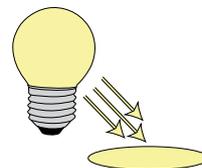
Luminous Intensity
Total Power/Solid Angle
“Candle Power”

This expresses the power of a light source. It is defined as the quantity of luminous flux emitted in a given direction per solid angle (in steradian).

The unit is candela (cd).

1 cd = 1 lumen per steradian. (For practical purposes, one candela power.)

ILLUMINANCE



Illuminance
Total Power/Unit Area
“Illumination”

This is a measure of the concentration of luminous flux falling upon a surface. It is expressed in lumens per unit area.

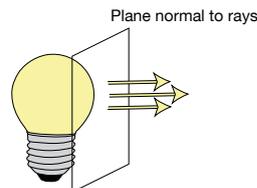
The unit is lux (lx).

1 lx = 1 lumen per square meter (lm/m^2)

The original non-metric British unit is the foot-candle.

1 foot-candle = 1 lumen per square foot (lm/ft^2)

LUMINANCE



Luminance
Total Power/Solid Angle/Projected Area
“Brightness”

Also known as photometric brightness, luminance is a measure of the flux emitted from, or reflected by, a relatively flat and uniform surface. Luminance may be thought of as luminous intensity per unit area.

The unit is candelas per square meter (cd/m^2), or nit. The original non-metric British unit is the footlambert (fL)

1 fL = $(1/\pi)$ 1 candela/ft²

PHOTOPIC AND SCOTOPIC VISION

The human eye adapts to changing brightness and colour conditions, a luxmeter does not. Luxmeters measure light compared to the relative sensitivity of the human eye for daylight conditions (photopic vision) whereas often, particularly for public lighting such as road lighting the sensitivity of the human eye actually shifts toward the blue end of the spectrum as the rods become active (Scotopic vision). If you examine the Peak wavelengths in the diagram in the section on Photometry you will see that the peak wavelength at photopic vision is approximately only half as effective when scotopic vision is active.

Within the human eye, the rods and cones do not work exclusive of one another, indeed, low luminance conditions somewhere between indoor lighting and the light of a full moon will have both rods and cones working together, this is termed mesopic vision occurring from luminances of approximately 0.03 to 3 cd/m².

The human eye uses scotopic vision in the range below 0.03 cd/m², and photopic vision in the range above 3.0 cd/m².

Standards for Public lighting are based on how the human eye reacts in good light (photopic vision), when in fact outside in the evenings when we need streetlights, our eyes are actually using mesopic (low light) or scotopic (no light) vision, with a shift in the peak wavelength from 555nm to 507nm. This shift can actually mean that a large error is noticed between measured values and visual judgement, It is not unheard of for a modern LED light installation to fail inspection when in fact if measured against scotopic vision, would be providing a vastly improved quality of light.

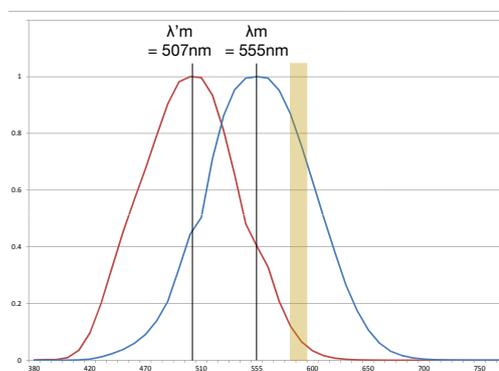


Fig. 4 Photopic (Blue) and Scotopic (Red) luminous efficiency with a bar (yellow) illustrating the Wavelengths at which LPS lamps peak.

Within the near future European Standards will be updated to reflect these requirements and as public installations of newer technologies become increasingly common so too will next generation lux meters (with an F1 Value better than 3%) provide accurate readings to make correct assessments of newer lighting technologies possible.

S/P RATIO

Until Luxmeters with a function to measure scotopic conditions are common place, lighting designers/ inspectors can use the S/P ratio. The manufacturer of the light source should provide the S/P ratio (calculated using a Spectroradiometer) which can then be simply multiplied by the measured photopic value to give a converted reading of the scotopic value.



Fig. 5 A residential street lit by LED street lighting

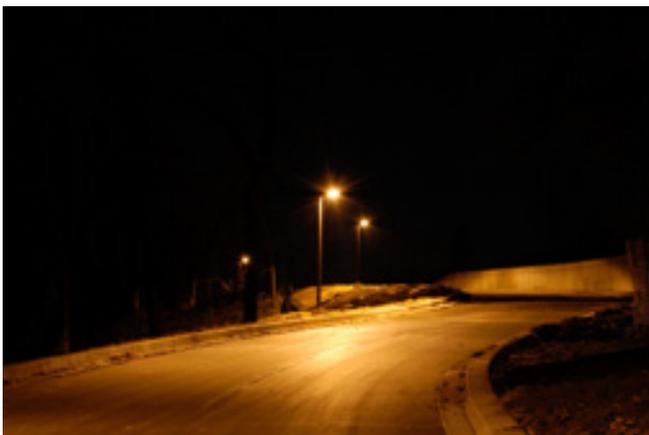


Fig. 6 A road lit by Low Pressure Sodium light

The preceding section has shown how the eye works in different situations and the important knowledge required to measure light correctly. The above photos serve to illustrate an example relating to measurement of light under photopic and scotopic luminous efficiency.

Fig. 6 is a road lit by Low Pressure Sodium lamp, you can see that the colour rendering is not very good, the entire picture looks monotone. If measuring this lighting using a traditional lux meter (that doesn't consider the scotopic luminous efficiency) measurement results would show far higher light levels than correspond with

visual perception. If you consider the photopic and scotopic luminous efficiency curves on page 8 you will see that the wavelengths at which LPS is active fall right at the edge of the scotopic curve. Not only is the relatively narrow bandwidth of the source bad for colour but it also provides reduced perceived brightness.

Whereas fig.5 is a residential street lit by LED streetlight, the range of colours in the picture is far greater, reflecting the broader spectral curve of the light source and higher Colour rendering properties. The perceived brightness is greatly improved but this would not be reflected in the measurements if measured by a lux meter that matches the luminous efficiency of photopic vision, in some cases failing inspection to the contrary of the visual assessment.

COLORIMETRY

Colour is a characteristic of light determined by the light's spectral composition and the interaction with the human eye. Hence, colour is a psychophysical phenomenon, and perception of colour is subjective.

COLOUR PERCEPTION

The eye acts much like a camera, with the lens forming the image of the scene on the light-sensitive retina. There are several kinds of light detectors, called rods and cones. The cones are grouped into three types, each responds to a portion of the spectrum, with peak responses corresponding to blue, green, and red light. The interaction of these groups is then responsible for the stimulus which is interpreted by the brain as colour. This widely accepted theory on colour vision is known as Trichromatic Theory.

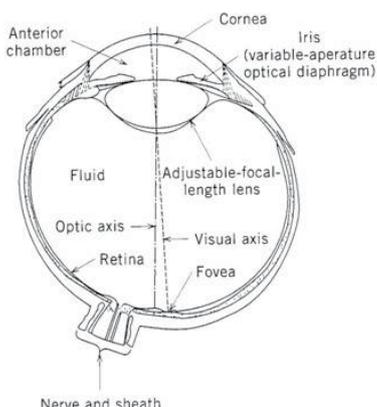


Fig. 7 Human Eye

MIXING OF COLOURS

Isaac Newton first demonstrated and explained the composition of white light, by refracting it through a glass prism into its constituent spectral colours. If coloured lights are added, this implies that different lights with different spectral colours composition are added. The resultant effect on the brain can be any of the spectral colours located in the visible spectrum, for example, yellow, or a non-spectral colour which does not appear in the spectrum as monochromatic light, for example, purple. Creation of colours by addition of coloured lights is known as additive mixing. The human eye behaves as though the 'outputs' of the three types of cones are additive.

Figure 8 illustrates the resultant colour effect of mixing three coloured lights, red, green, and blue. The red, green, and blue can be called the primaries and the resulting yellow, cyan, and magenta the secondaries.

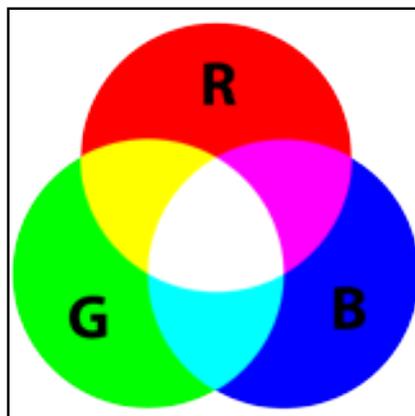


Fig. 8 Additive Mixing

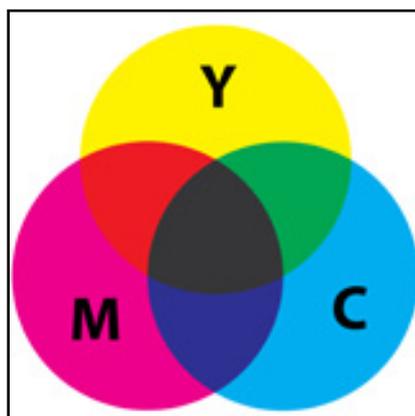


Fig. 9 Simple Subtractive Mixing

The colour of an object is determined by pigments. These are chemicals which create a given colour by subtracting parts of the spectrum of the incident light. The remaining light is reflected and perceived by the observer giving the object its colour characteristic.

Making colours by mixing paint pigments may therefore be described as a process of subtractive mixing (refer to fig. 9), since each pigment that is added subtracts more from the incident light and leaves less to be reflected into the eye. Following are some examples (the incident light in this example is white):

YELLOW = WHITE - BLUE
 MAGENTA = WHITE - GREEN
 CYAN = WHITE - RED

LIGHT SOURCE COLOUR SPECIFICATION

Several methods have been devised to quantify colour so that communication of colour becomes easier and more accurate. These methods attempt to provide a way of expressing colour numerically, in much the same way we express length and weight.

Light source colour specification and measurement can be categorised into three following major colorimetric methods:

- Tristimulus colorimetry
- Colour temperature
- Spectroradiometry
- Dominant Wavelength

TRISTIMULUS COLORIMETRY

Tristimulus colorimetry is based on the three component theory of colour vision, which states that the eye possesses receptors for three primary colours (red, green, blue) and that all colours are seen as mixtures of these three primary colours. The most important system is the CIE (Commission Internationale l'Eclairage) 1931 2° Standard Observer system, which defined the Standard Observer to have colour-matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ as shown in Fig. 10 The XYZ tristimulus values are calculated from the spectral distribution of the lightsource, the spectral reflection of the object and using these three Standard Observer colour matching functions. XYZ tristimulus values and the associated Yxy colour space form the foundation of the present CIE colour space.

Colour-matching functions

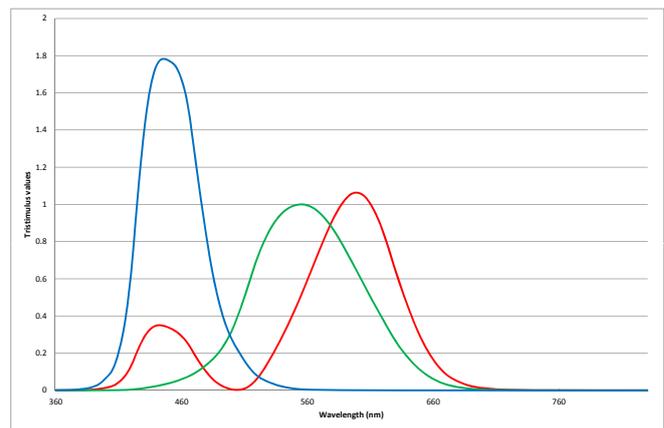


Fig. 10 Colour Matching Functions

CIE 1931 Yxy CHROMATICITY CHART

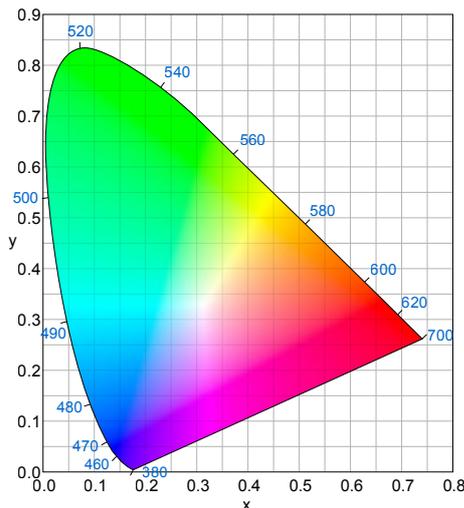


Fig. 11 1931 x,y Chromaticity Diagram

The tristimulus values XYZ are useful for defining a colour, but the results are not easily visualised. Because of this, CIE defined a colour space in 1931 for graphing colour into two dimensions independent of lightness; this is the Yxy colour space, in which Y is the lightness and x and y are the chromaticity coordinates calculated from the tristimulus value XYZ. The x and y chromaticity coordinates are calculated from the XYZ tristimulus values according to the following formulae:

$$x = \frac{X}{X + Y + Z} \quad y = \frac{Y}{X + Y + Z}$$

The principal drawback of the 1931 system is that equal distances on the chart do not represent equal perceived colour differences because of non-linearities in the human eye.

CIE 1976 UCS CHROMATICITY CHART

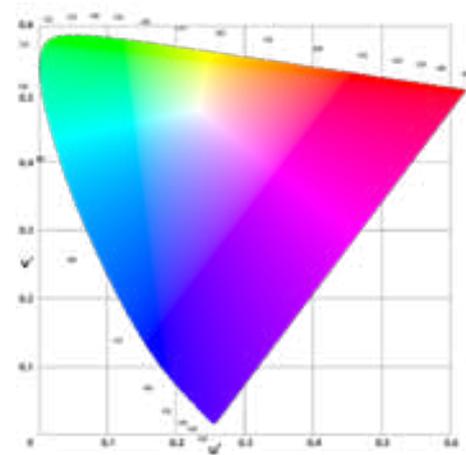


Fig. 12 1976 UCS Diagram

The Uniform Chromaticity Scale (UCS) was developed to minimise the limitations of the 1931 system. It was intended to provide a perceptually more uniform colour spacing for colours at approximately the same luminance. The 1976 CIE- UCS chart uses u' and v' coordinates. The symbols u' and v' were chosen to differentiate from the u and v coordinates of the similar but short lived 1960 CIE-UCS system. The u' and v' chromaticity coordinates are also calculated from the XYZ tristimulus values according to the following formulae:

$$u' = \frac{4X}{X + 15Y + 3Z} \quad v' = \frac{9Y}{X + 15Y + 3Z}$$

HELMHOLTZ COORDINATES

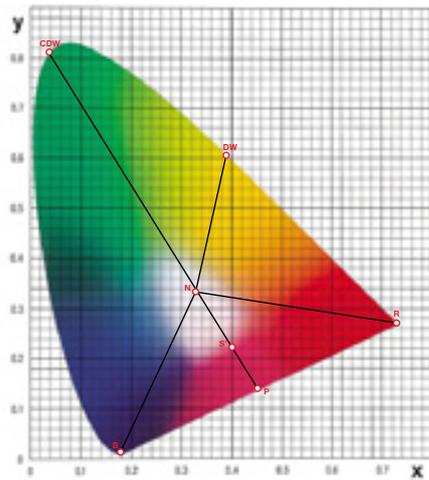


Fig. 13 Helmholtz Coordinates

An alternative set of coordinates in the CIE system, Dominant Wavelength and Purity (also known as Helmholtz coordinates), correlate more closely with the visual aspects of hue and chroma. The dominant wavelength (DW) of a colour is the wavelength of the spectrum colour whose chromaticity is on the same straight line as the sample point (S) and the illuminant point (N) (for light source measurement, the illuminant point is $x=0.333$ and $y=0.333$). Purity, also known as excitation purity, is the distance from the illuminant point (N) to the sample point (S), divided by that from the illuminant point (N) to the spectrum locus (DW).

$$\text{Purity} = (N - S) / (N - DW)$$

The above method is only applicable to spectral colour, that is colour which appears in visible spectrum. When measurement of non-spectral colour, that is colour which does not appear in visible spectrum and is located within the triangle area encompassed by the 3 points N, R and B, is concerned (purple colours), Complementary Dominant Wavelength (CDW) is used. This is because the interception point P, which is sup-

posed to be the Dominant Wavelength has no corresponding wavelength. The line from N to P is extended backward in order to determine the Complementary Dominant Wavelength (CDW). Purity for non-spectral colour is calculated from:

$$\text{Purity} = (N - S') / (N - P)$$

Dominant wavelength and purity are commonly used in LEDs' colour specification.

CL-200A CHROMA METER

Similar in design, features and operation to the popular T-10A illuminance meter, the CL-200A Chroma Meter is an Illuminance meter that can also provide readings of dominant wavelength-colour temperature etc. The CL-200A is a highly portable meter with numerous applications including tests for both amount and ambience of lit environments, inspection and development of projection systems and ensuring uniformity of modules used in LED billboards.

The CL-200A includes Data Management Software CL-S10w which enables users to store, manage and analyse measurement data, determine correlated colour temperature and use the CL-200A in multipoint mode of up to 30 measurement heads.



COLOUR TEMPERATURE

The concept of colour temperature arises from the apparent colour changes that occur when an object is heated. When the temperature of an object increases, the radiation that is emitted changes which results in the change of colour. A special class of incandescent (glows when hot) object emits radiation with 100 percent efficiency when heated; scientists call this ideal full radiator a blackbody radiator.

In particular, an ideal blackbody glows with a colour which depends on its temperature. The range of hues may be shown on the CIE diagram by a line which is referred to as a blackbody locus (or, Planckian locus). The colour progresses from a very deep red through orange, yellow, white and finally bluish-white as the temperature increases. Most natural light sources, such as the sun, stars, and fire fall very close to the Planckian locus.

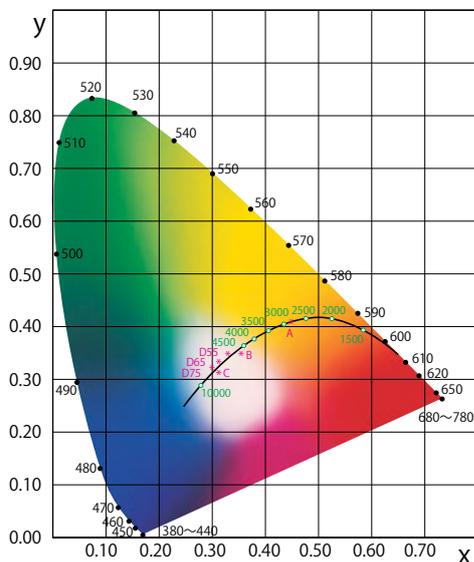


Fig. 14 Planckian locus plotted on the CIE x,y Chromaticity Diagram.

The colour of some light sources corresponds to that of a full radiator when the latter is held at a particular temperature. For some purposes, it is convenient to classify a light source by quoting its colour temperature (measured in Kelvins). As long as the light being measured closely approximates a blackbody source, the results are quite accurate. Hence, the locus is particularly useful in the classification of 'whites'. Colour

temperature is widely used among lamp and display manufacturers.

CORRELATED COLOUR TEMPERATURE

Colour temperature is strictly applicable to light sources which may be precisely matched by a full radiator. The concept is extended to include sources which emit light that can be closely - but not exactly - matched by a full radiator. The expression Correlated Colour Temperature (CCT) is used to describe the light from such sources. This is the temperature at which a full radiator produces a light that most nearly matches the light from the given source. CCT is calculated by determining the isothermperature line on which the colour of the light source is positioned. Isothermperature lines are straight lines for which all colours on the line appear visually equal. Δuv is used to specify the deviation from the blackbody locus. The maximum deviation for Δuv is set at $\pm 0.02 \Delta uv$.

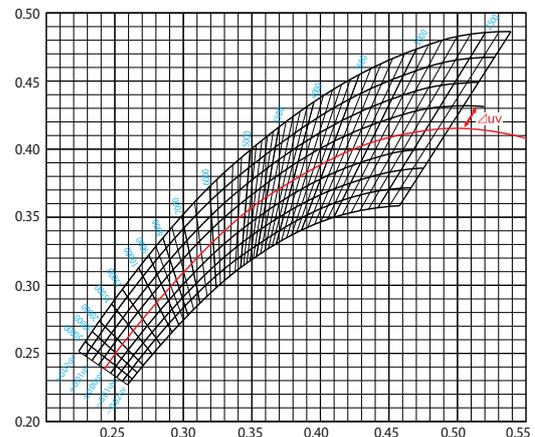


Fig. 15 xy chromaticity chart indicating the blackbody locus, the isothermperature lines and equal Δuv lines.

CCT is not suitable for measuring light sources which have narrow-band spectral emittance curves that do not approximate any blackbody curve (for example, LED).

COLOUR TEMPERATURE MEASURED USING A PHOTOGRAPHIC COLORIMETER

Photographic colorimeters function differently from industrial-grade measuring instruments. Although they claim to measure colour temperature, the purpose is to determine the appropriate filter values for taking pictures. The colour temperature taken with photographic colorimeters is called “photographic colour temperature.” The sensors used in the industrial instruments are intended to closely match the sensitivity of the human eye, the sensors of photographic colorimeters are similar to the sensitivity of colour photographic film.

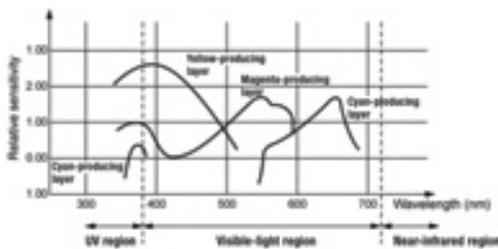


Fig.16 Colour sensitivity of photo film

Fig. 10 on page 11 shows the sensitivity of the human eye, and Fig. 16 above shows the sensitivity of colour photographic film. Due to these differences between the two instruments, if the colour temperature of a light source was measured with a Chroma Meter and a photographic colorimeter, the result would be two completely different values.

SPECTRORADIOMETRY

The colour of a light source does not tell us the nature of its spectral power distribution, two

different light sources which have the same colour in x,y or colour temperature might not exhibit the same spectral power distribution. The reverse, however, is true: knowledge of spectral power distribution of light will enable us to describe the colour (see below different spectral power distribution curves of some common CIE illuminants).

The spectroradiometric method is the most accurate and complete method of specifying colour. The spectral data can be analysed visually and/or compared to data from another light source. However, the best use of spectral data is to calculate the CIE tristimulus values by mathematically integrating the data with the CIE colour-matching function. The tristimulus values are then used to compute CIE chromaticity coordinates and luminosity, which provide a complete description of the colour.

Standard Illuminant D65: Average daylight (including ultraviolet wavelength region) with a correlated colour temperature of 6504K.

Standard Illuminant C: Average daylight (not including ultraviolet wavelength region) with a correlated colour temperature of 6774K.

Standard Illuminant A: Incandescent light with a correlated colour temperature of 2856K.

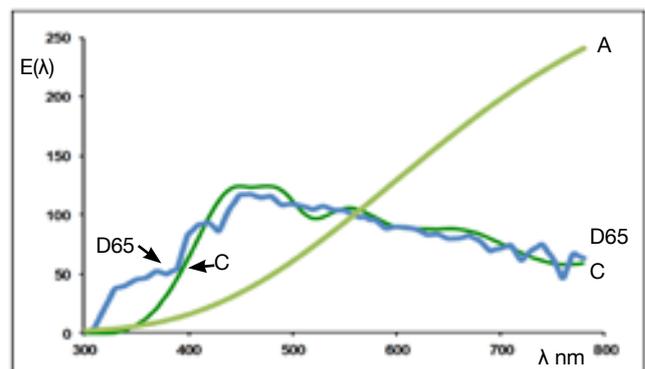


Fig. 17 Spectral Distribution of CIE illuminants

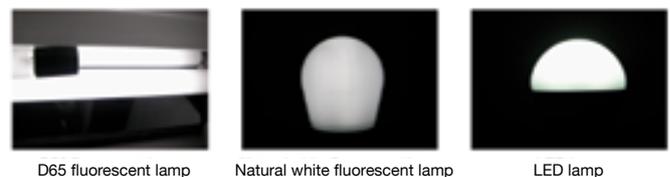
COLOUR-RENDERING PROPERTIES

Illumination can be provided by hundreds of different types of light source, both natural and man-made. For assessment or comparison of colour it has always been standard practice to compare colours under natural light, either genuine or simulated using fluorescent lamps. In addition to fluorescent lamps, next generation light sources such as LEDs (light emitting diodes) are increasingly being adopted as illuminating lamps. When comparing how objects look under different lamps against how they look under natural light, how closely they match is called the “colour-rendering property.” A lamp that produces a hue similar to that of natural light is said to have a good (high) colour-rendering property.

There are many types of lamps commercially available (incandescent, fluorescent, LED, etc), each labelled with descriptions such as “white,” “warm white,” etc.

In the following examples, an object has been illuminated with a D65 fluorescent lamp with good colour-rendering property, a fluorescent lamp that was labelled as “Natural white” and an LED lamp.

To the eye, a D65 fluorescent lamp, a natural white fluorescent lamp and a white LED lamp all seem white. However, the natural white fluorescent lamp actually has a slightly higher colour temperature and may appear slightly bluer than the others.



D65 fluorescent lamp Natural white fluorescent lamp LED lamp

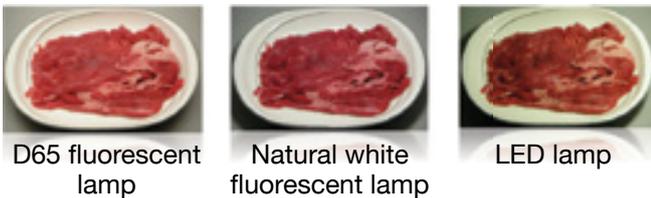
We measured the three different light sources by mounting a luminance adapter on the Konica Minolta CS-2000 Spectroradiometer. If you compare the Blue and Green measured points on the xy chromaticity diagram to the right, you can see that the tones are similar to the D65 and in the visible range.

- X = LED lamp
- X = Natural White Fluorescent lamp



Fig.18 xy chromaticity diagram comparing the colour temperature of an LED white and Natural White Fluorescent

	D65 Fluorescent Lamp	Natural white fluorescent lamp	LED lamp
x	0.3128	0.3372	0.3465
y	0.3290	0.3496	0.3662
Correlated colour temperature (k)	6504	5308	5004



The photographs above show a plate of meat under the three light sources .

Under the D65 fluorescent lamp, the meat and the plate look like they would under natural light. Under the natural white fluorescent lamp, the colour temperature is slightly higher and both the meat and the plate look slightly paler. Under the LED lamp, the meat and plate look darker.

- The luminance at the sample surface was adjusted to be about 1600 lux for all three light sources.
- When a sample is illuminated with different light sources, the colour may look different.
- The difference in colour rendering performance is called “colour-rendering index” or CRI
- The CRI indicates how 15 test colours look under a particular light.
- When comparing a light source against a stipulated reference light source, an index of 100 is the best.

* Because of its low colour-rendering index, the LED lamp used this time made the meat and plate look dark, but the meat would look fresher with an LED lamp having a higher colour- rendering index.

THE CL-500A

The CL-500A Illuminance Spectrophotometer from Konica Minolta Sensing is designed for measurement of illuminance and colour rendering index particularly suited to ‘next generation’ light sources such as LED and EL Lighting.



- The first illuminance spectrophotometer that conforms to both JIS and DIN standards
- Two standard tripod mounting sockets
- Free SDK (Software Development Kit) gives you control of the software
- Excel® software add-in as standard provides user friendly analysis functions
- Spectral irradiance waveform display to facilitate grading and classification of light sources
- Can perform CRI, CCT, peak wavelength etc without PC connection
- LED binning function

We obtained the following colour-rendering indexes using the Konica Minolta CL-500A Illuminance Spectrophotometer. You could also measure these indexes using an illuminance adapted CS-2000A and the Data Management Software CS-S10w. With D65 being the standard, below are the two other light sources.

	Ra	R1	R2	R3	R4	R5	R6	R7
Natural white fluorescent lamp	79	89	89	54	82	81	72	86
LED lamp	68	65	74	79	68	65	62	81

	R8	R9	R10	R11	R12	R13	R14	R15
Natural white fluorescent lamp	76	16	40	63	55	92	70	92
LED lamp	54	-39	36	61	31	66	88	59

Fig.19 Values for each of the CRI tones (R1-R8) and special CRI tones (R9-R15) under LED White and Natural White Fluorescent

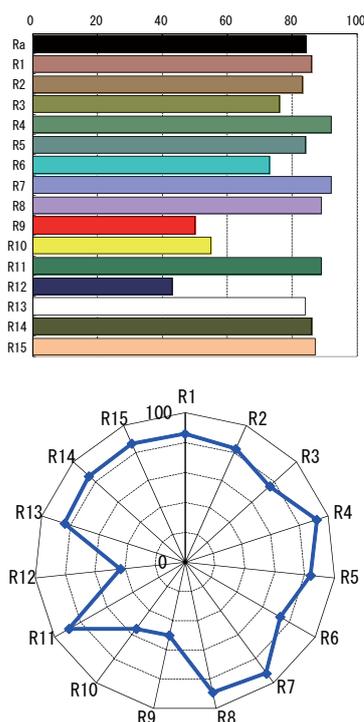


Fig. 20 Graphical Representations of Colour Rendering Index generated by the CL-500A and standard software CL-S10w

Ra is the “mean colour-rendering index.” It is the average of indexes R1 ~ R8 and is a representative value of colour-rendering indexes.

R9 ~ R15 are termed “special colour-rendering indexes,” with particular interest often being shown in R9 (highly vivid red) and in R15.

R9 is used for evaluation of the reproduction of red, and the big differences in values between the three types of light sources also give an indication of how much the colour of the meat seen under the different light sources will vary.

The graphics to the left are visual representations of colour rendering index measured using a Konica Minolta CL-500A.

ADDRESSING THE WEAKNESSES OF CRI

CRI (Ra) only uses the R1-R8 tones not the special CRI tones from R9-R15, it covers only non saturated colours and is weak on Red Colours (colour space U*V*W* used for CRI is not Uniform in red). It is therefore possible for a lamp to have a high CRI but due to this deficiency the visual assessment actually shows that colour rendering is poor, LED lighting can be particularly susceptible to this phenomenon.

There are several alternative approaches to replacing CRI under consideration by the CIE including CQS (Colour quality Scale), MCRI (Memory Colour Rendering Index), CAM02UCS (Colour Appearance Model Universal Colour Space), CCI (Colour Category Index) etc. At this stage none of these alternatives have been adopted, however the most likely scenario as things stand is that CQS will be implemented into standards in the medium term future.

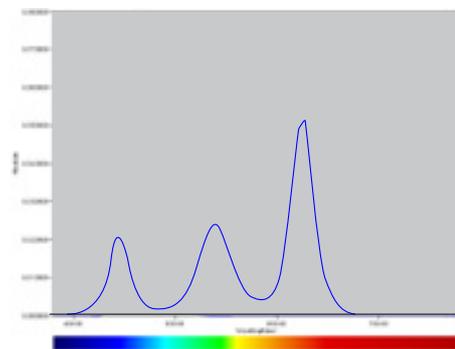
CQS was developed by NIST and functions in a similar way to CRI, providing an overall average figure (Qa) based on relative evaluation with differences between a test and reference light source. However, CQS uses the L*a*b* Colour space and 15 highly saturated colours and the addition of a saturation factor.

The Konica Minolta CL-500A will be suitable for assessing colour rendering by whatever method is eventually adopted as it measures the full spectral curve of any light source. A simple firmware update can be made by the user, making the CL-500A a future proof instrument for lighting designers or inspectors.

Example

The spectral power curve of an RGB LED with the following information is displayed below:

Tcp = 3300K
 $\Delta uv = 0.000$
 CRI (Ra) = 80



However when you include R9-R15, the score for R9 is -114 meaning that skin tones under this light source would appear pale and unhealthy.

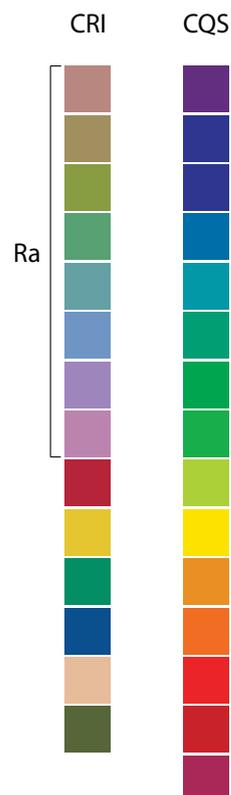


Fig. 21 A comparison of CRI and CQS Tones

PHOTOMETER

A photometer can be defined as an instrument for measurement of visible light. Luminance and illuminance meters are the most common photometers and are easily available as turnkey systems. Luminous flux meters and luminous intensity meters are not widely available and usually have to be customised to the specific light measurement application due to the geometry of measurement involved.

The basic difference between radiometer and photometer, is that the latter must respond to light as the CIE standard observer. In other words, the spectral response of the photometer must follow the CIE Standard Luminosity Function V_λ curve.

SENSORS

The sensor of the photometer, which decides the conformity to the CIE V_λ curve, is critical to the accurate performance of the photometer.

Non-filtered sensors, such as the selenium and cadmium sulfide, inherit a natural spectral response which approximate the V_λ curve. However, its deviation from the V_λ curve makes it impractical for accurate photometry measurement and it is more commonly used in automatic light switches and other similar applications. Most modern filtered photometers use silicon

photodiodes which incorporate optical filters in front of the sensor so that the transmission of the filter and the spectral response of the sensor can be combined to closely match the CIE V_λ curve.

CIE recognised the need for a meaningful and internationally applicable method of specifying the quality of a photometric sensor and developed the f_1 value. The f_1 value, specified in percentage error, represents the degree to which the relative spectral responsivity matches CIE V_λ curve.

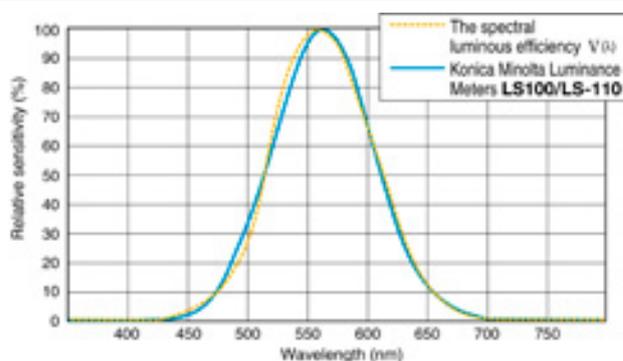


Fig.22 Relative Spectral Response

CALIBRATION METHOD

Beside f_1 value, the calibration method of the photometer is also an important factor when deciding its suitability to a specific application. For example, a photometer with a relative large f_1 value can still achieve good accuracy when the measured light source and the standard lamp used during the calibration process is similar.

There are two basic methods of calibrating photometers. The first and the most common method is using a standard lamp (usually tungsten). These lamps are certified and traceable to national standard laboratories/institutions. The photometers will be adjusted until the measurement reading matches the certified output of the standard lamp. The second calibration method is to use standard detectors. Such detectors have built-in sensors where the

spectral responses perfectly match the CIE $V\lambda$ curve. In such calibrations, a lamp is still required but output can be varied but must be stable. The standard detector first measures the output of the lamp, and is substituted by the photometer and will be adjusted until the measurement give similar readings as the standard detector. Such detectors can also be certified and traceable to national standards.

COLOUR CORRECTION FACTOR

The correction of the detector-filter combination to the CIE $V\lambda$ curve is generally poor at the end of the visible spectral range. Hence, the colour temperature of the lamp used during calibration is critical. As most of the photometers are calibrated by a tungsten lamp, measurement of incandescent, halogen searchlights and sunlight generally give good accuracy. However, these photometers are not suitable for measurement of monochromatic light or narrowband emitters, e.g., blue and white LEDs. Measurement error will also be significant in discharge lamps, e.g., luminescent tubes, which show clear peaks (i.e. spectral lines) in the visible spectrum.

Modern photometers utilise a Colour Correction Factor feature to compensate the error caused by this spectral response difference between the sensor and the CIE $V\lambda$ curve. The CCF value can be calculated when both the spectral response of the sensor and the spectral power distribution of the light source is known. An alternate and easier method is to transfer the measurement data of a primary standard (for example, data taken from a spectroradiometer) to the photometer by varying the CCF value. CCF can also be used as a user-calibration feature, which is particularly useful if traceability of in-house standards' is necessary.

APPLICATIONS OF PHOTOMETERS

Not surprisingly, misapplication of photometric instruments by the user is a common source of error. For many users, the main obstacle to effective light measurement is a lack of understanding of the characteristics of the type of measurement required. Attempts to convert between units will lead to gross errors. For example, the most common mistake encountered is attempting to use an illuminance meter (lumen/m²) to determine luminous flux (lumen), or, to use a luminance meter (candela/m²) to determine the luminous intensity (candela).

There are four main photometric instruments, namely the luminance meter, illuminance meter, luminous flux meter, and luminous intensity meter.

LUMINANCE METER

The visible energy output of a light source can be determined with a luminance measurement. Luminance is a directional quantity and in order to communicate measurements effectively we must specify the acceptance angle, measured area and measurement geometry. These factors are important as most light sources are not perfect lambertian sources (luminance is the same in all direction).

Since measurement is targeted at the source, such measurement can be achieved by using a optical lens system. Both the angular field of view and the angle subtended by the objective lens should be limited to avoid collecting light from parts of the display at slightly different angles.

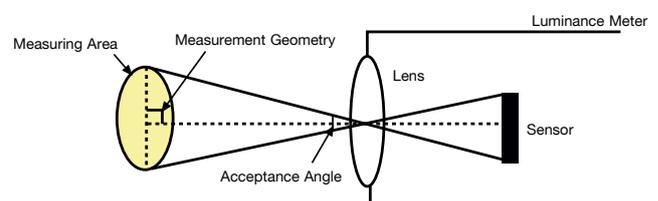


Fig. 23 Luminance measurement technique involving the use of lens.

Luminance measurement are important for products, such as traffic lights, televisions, and tail lights of automobiles.

THE LS-100,110 AND CS-100A

The LS-100 and 110 are portable luminance meters designed with a user friendly SLR design, and narrow acceptance angles to allow users to accurately measure even small specimen areas (LS-100 1° areas down to Ø1.3mm and LS-110 1/3° down to Ø0.4mm). The LS-100 and LS-110 provide a close match to CIE spectral luminous efficiency $V(\lambda)$ the human eye under photopic vision conditions.



The CS-100A is a luminance meter that also provides measurements of chromacity, the CS-100A can also be used to make non contact colour measurements or assess colour difference by non contact methods where the surface is distant, just painted or cannot be touched for sanitary reasons. Similar to the LS-100 and 110 the CS-100A features a narrow measurement angle of 1° to measure subjects as small as Ø14.4mm (at a distance of 1014mm) or Ø1.3mm using optional close up lenses. The CS-100A is ideal for measuring CRT displays, projectors and the luminance and chromacity of all manner of light sources including for example signal lamps.

ILLUMINANCE METER

Illuminance is a measure of visible energy falling upon an object's surface. Illuminance measurements are particularly susceptible to errors caused by off-axis light. By definition, light at the measurement plane should be proportional to the cosine of the angle at which the light is incident. However, due to total integration of the sensor into the detector head or the illuminance meter itself, many illuminance meters do not naturally collect light correctly according to the cosine law.

Cosine correction feature is included in the illuminance meter by means of a cosine diffuser which is placed over the sensor and filter. It is important to note that different systems will generate different cosine responses which result in different cosine errors at different incident angles due to the nature of the system geometry. Therefore, it is important to understand the system cosine response when comparing illuminance measurements from different illuminance meters, especially when off-axis light measurement is concerned.

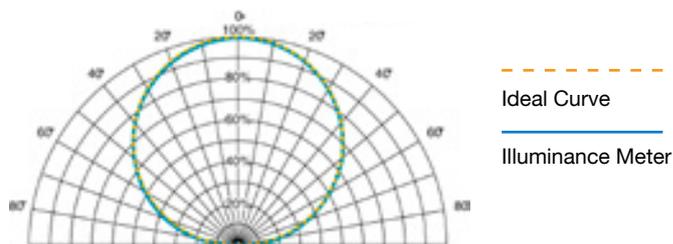


Fig. 24 An example of the cosine response of an illuminance meter

Illuminance measurement is widely used in ambient lighting measurement to determine how well the room is lit for ease of reading or working. For example, the standard in Europe for a comfortably lit desk is 500 lx.

PWM CONTROLLED LIGHTING

A white LED is produced by a short wavelength LED (blue) and a phosphor which absorbs some of the blue light and emits a broader spectrum of visible light.

The current supplied can have a significant effect on the Correlated Colour Temperature produced by an LED lamp, with low current producing a more yellow light and high current a blue cast. This shift in colour is noticeable to the human eye which is why analog dimming is considered unsuitable for use in LED lamps.

PWM (pulse-width modulation) control is used to provide a dimming facility to LED lamps, largely to prevent shifts in colour temperature. Current is suppressed during portions of each cycle of the AC line voltage. The fluctuation happens faster than the human eye can notice, perceiving only the average intensity of the lamp.

To achieve a lower light intensity, the 'off' periods are extended, and the average brightness perceived is reduced but the current at the LED is constant.

PWM controlled lighting is an invaluable tool for Lighting Designers to control CCT and achieve reliable dimming to lower levels.

The imperceptible flicker relies on the human flicker fusion threshold, (a psychophysical threshold) which makes it difficult to measure the illuminance of these light sources with a conventional illuminance meter.

T-10A ILLUMINANCE METER

The T-10A is the successor to the popular T-10 Illuminance meter with the addition of USB connectivity and the ability to measure PWM controlled lighting. Conventional Illuminance meters are not designed to compensate for the flicker fusion threshold, and therefore may not provide accurate measurements of PWM controlled lamps.

The T-10 A conforms to both JIS AA Class and DIN Class B and is available with a range of options including a waterproof receptor and mini receptor for measurement in narrow or hard to access areas. The T-10A can also be used in a cost effective multi-point system for measurement of Illuminance distribution (for example street lighting, architectural lighting or projectors)

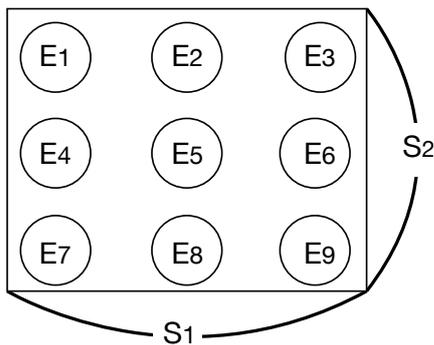


The Konica Minolta T-10A

ANSI

An Illuminance meter is sometimes used to measure ANSI lumen. ANSI Standards IT7.227 & IT7.228-1997 specify 3 methods for evaluation of surface illuminance: ANSI lumen, uniformity and contrast. For evaluation of the performance of a LCD projector etc., the illuminance on the projector screen is measured by a matrix of receptor heads and a calculation is performed on the measured data using mathematical formula detailed below.

ANSI lumen multiplies the average illuminance of 9 units by the measuring area.



Measuring area $S (m^2) = S_1 \times S_2$

ANSI lumen $E = (1/9 \sum_{i=1}^9 E_i) \times S$

ANSI uniformity finds the brightest and darkest units from the average illuminance of 9 units and illuminance at each point and corner.

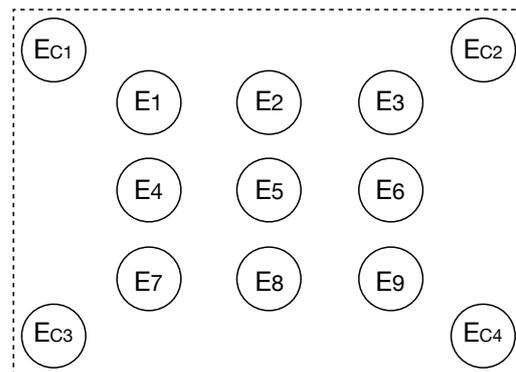
Average illuminance of nine units $E (lx) = 1/9 \sum_{i=1}^9 E_i$

$A_i (%)$: Ratio of illuminance E_{ii} at each point to the average illuminance E

$A_i (%) = ((E_{ci} - E)/E) \times 100$

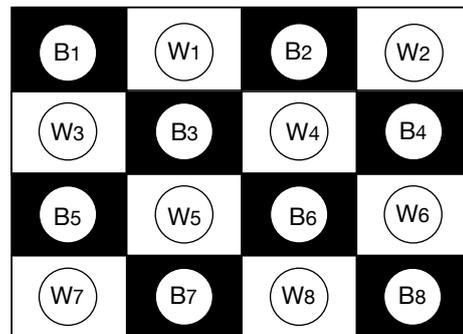
$B_i (%)$: Ratio of illuminance E_{Ci} at each corner to the average illuminance E

$B_i (%) = ((E_{ci} - E)/E) \times 100$



A_i and B_i are calculated for every 9 point and 4 corner to obtain the maximum and minimum values.

ANSI contrast calculates the ratio to the black background (as "1") using the average illuminance of units in the black and white areas as shown below.



Average illuminance of 8 units in the black ground $B(lx) = 1/8 \sum_{i=1}^8 B_i$

Average illuminance of 8 units in the white ground $W(lx) = 1/8 \sum_{i=1}^8 B_i$

The results are expressed in the ratio W:B (B as 1). for example when $W=1000(lx)$ and $B=5(lx)$:
ANSI contrast = 200:1

LUMINOUS FLUX METER

Luminous flux measurement is used to determine the total visible energy emitted by a light source. An integrating sphere is often used to converge all the power emitted by the source to the detector head.

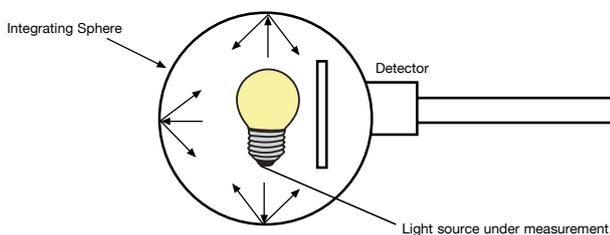


Fig. 25 Total luminous flux measurement using an integrating sphere

The integrating sphere has to be large enough to encompass the light source being measured, and as a general rule, the larger the sphere, the smaller the errors in measuring luminous flux for different light sources. As a rough example, calibrating a 1.5m tubular lamp in a 2.5m diameter sphere against a small incandescent standard will produce half the error that would result from calibration of the same lamp in a 2m sphere. Calibration of an integrating sphere can be carried out by means of transfer lamp standards which are traceable to recognised national standards. A good quality integrating sphere which postulates the performance of an ideally spherical, evenly coated interior requires a huge investment and usually has to be customised to the light measurement application. Hence, the existence of general purpose luminous flux meters is very limited.

LUMINOUS INTENSITY METER

Luminous intensity represents the flux flowing out of a source in a given direction per solid angle and it is used to quantify the power

of a light source. As the definition implies, luminous intensity measurement involves several geometrical intricacies, such as measurement direction and amount of solid angle. Light sources are rarely spatially homogeneous, leading to the questions on which direction and how much solid angle should be used to carry out the measurement.

To measure the luminous intensity of a light source meaningfully, an agreed-upon fixture that defines the solid angle encompassed by the measurement and that orients the light source repeatably in a specified direction must be used. In other words, such meters have to be configured for the geometry of the source under test.

Basically, there are no off-the-shelf luminous intensity meters and comparison of measured data from two different luminous intensity meters serves no purpose, unless their measurement geometries are identical.

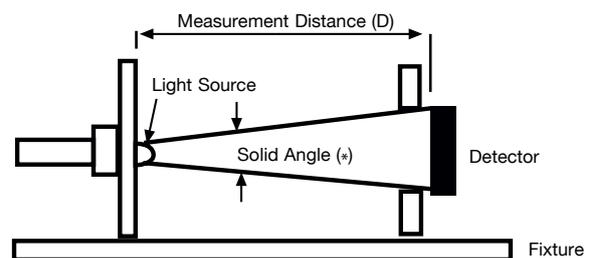


Fig.26 An example of luminous intensity meter set-up

Note: Solid angle can be calculated from the known detector's area and measurement distance. Detector is used to measure the flux reading in lumen.

THREE-FILTER COLORIMETER

Instruments designed for measuring coloured

light, which make use of three filters whose spectral sensitivity are matched to the CIE tristimulus colour matching functions, are known as three-filter colorimeters. Besides chromaticity measurement, these meters usually include one of the four basic photometric measurements, i.e., luminance, illuminance, luminous intensity, or luminous flux measurement.

These instruments use detectors which comprise high quality photodiodes with series-connected filters. The incident light is converted by the detector into signals which directly yield the standard XYZ tristimulus values.

Nevertheless, matching to the standard CIE tristimulus curves can be achieved only with finite accuracy. Deviations will occur in the defined CIE curves and in the sensitivity curves of the measuring instrument. These differences are negligible as long as the light to be measured exhibits a continuous energy output over the entire visible spectrum. However, the error may be significant if steep edges or spectral lines occur in the spectrum. Hence, three-filter colorimeters are not usually suited to measure light sources with spectral lines, e.g., discharge lamps (refer to Fig.28), or with narrow spectral energy distributions, e.g., LEDs (refer to Fig.29).

THE CS-200 LUMINANCE CHROMAMETER

The CS-200 is a tristimulus chromameter that uses a spectral fitting method to provide luminance and chromacity measurement, the CS-200 uses 40 sensors to calculate spectral response closely corresponding to human eye sensitivity and provides accuracy comparable to some spectroradiometers.

The CS-200 can measure luminances ranging from 0.01 cd/m² to 20,000,000 cd/m² (with a

measuring angle of 0.1°) and can be used for measurement of displays and light sources. The instrument can be used to measure either 1°, 0.2°, 0.1° covering everything from full displays down to individual pixels or distant light sources such as signal lights.



The CS-200 offers users a cost effective solution for measurement in an instrument that is portable and can be used with batteries or power chord as a standalone meter or partnered with a PC and software. Multiple CS-200 units could also be used in conjunction with a reference instrument such as a CS-2000A.

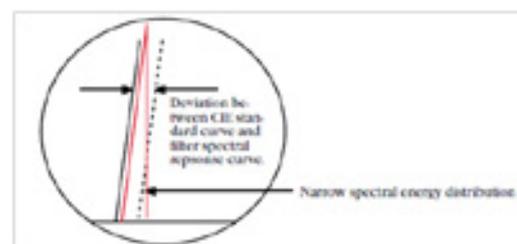


Fig. 27 Error in measurement caused by deviation between CIE tristimulus curve and instrument's spectral response.

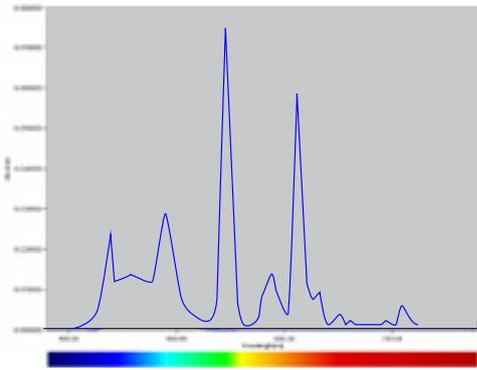


Fig. 28 Spectral energy distribution of a light source with spectral lines

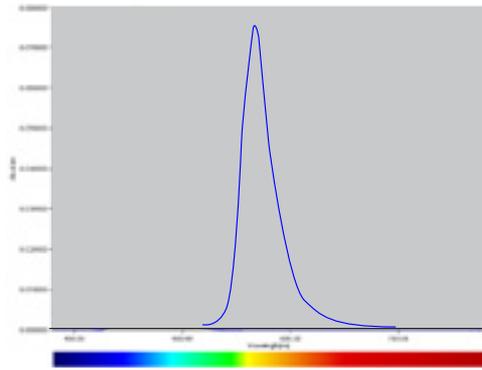
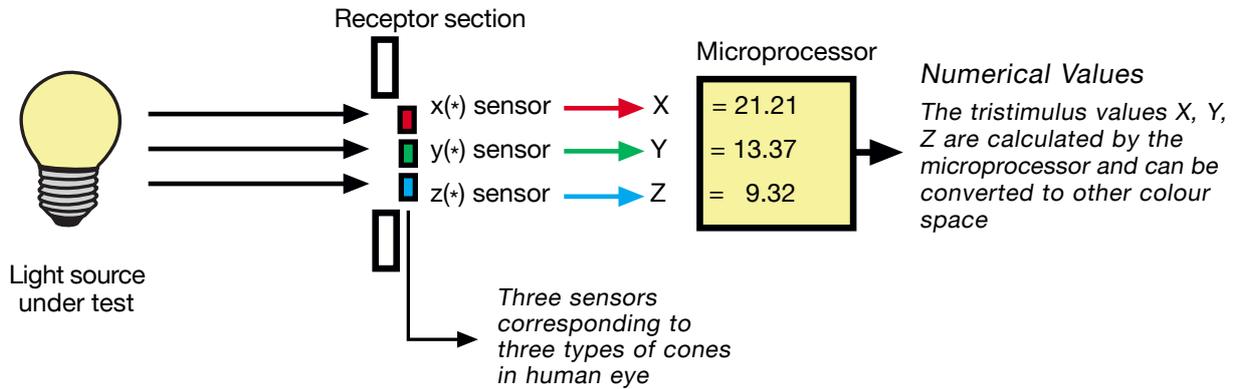


Fig. 29 Spectral energy distribution of a narrow-band emitter

Tristimulus Method



Spectroradiometric Method

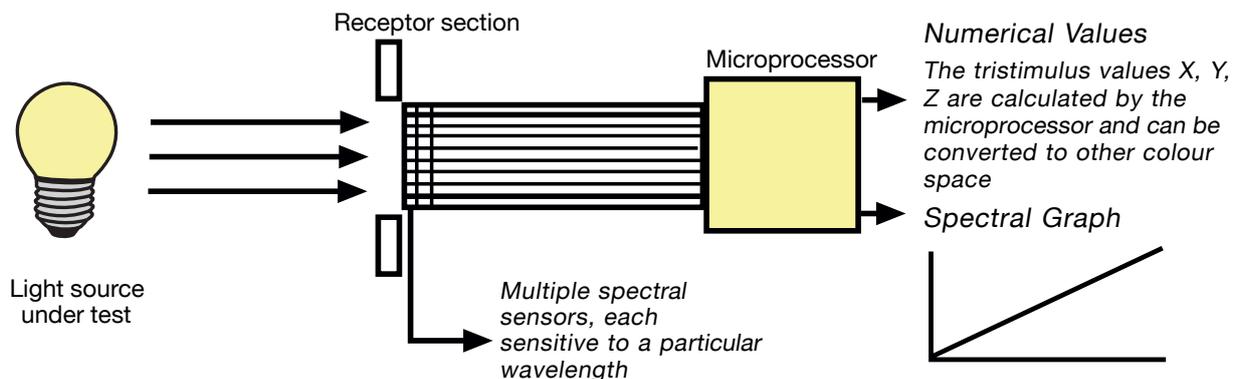


Fig. 30 Comparison between tristimulus colorimetric method and spectroradiometric methods

SPECTRORADIOMETER

Spectroradiometers are used to measure the spectral energy distribution of the light source, measuring both the radiometric and photometric quantities and the colorimetric quantities of light. These instruments record the radiation spectrum of the light source and calculate the desired parameters, such as chromaticity and luminance. Dispersion of light is usually accomplished in a spectroradiometer by means of prisms or diffraction gratings.

The exact CIE V_{λ} curve and CIE colour matching curves are stored in the software and are used to process the data from the measured spectral energy distribution of the light source under test. Hence, the measurement error associated with photometers and filter colorimeters is avoided in spectroradiometers. However, adequate sensitivity, high linearity, low stray light, low polarisation error, and a spectral bandpass resolution of 5 nm or less are essential for obtaining good accuracy.

Non-thermal radiators, such as discharge lamps (which can be characterised by their non-continuous spectral energy distribution), and narrow-band emitters can only be measured with precision by a spectroradiometer or illuminance spectrophotometer.

When compared to three-filter colorimeters, spectroradiometers do have their limitations, in terms of speed of measurement, price and portability.

CS-2000A SPECTRORADIOMETER

The CS-2000A is an advanced Spectroradiometer capable of measuring extremely low luminance levels (down to 0.0005 cd/m^2) can take measurements in as little as 2 seconds over a wavelength range of 380-

780nm the CS-2000A is the ideal instrument for measuring optical displays where contrast ratio (the CS-2000A can measure to 1,000,000:1) is a key criteria.

For assessment of light sources where accurate spectral data is required the CS-2000A maintains less than 5nm half bandwidth throughout the entire measurement wavelength range and can also be used with an optional adapter to take illuminance measurements. In terms of Scotopic luminous efficiency discussed earlier in this resource (page 8).

The CS-S10W software included with the CS-2000A includes the data for the spectral luminous efficiency of spectral vision, enabling the user to take highly accurate measurements corresponding to Scotopic vision. The software also enables the user to measure dominant wavelength, ideal for quality control of LEDs.



SUMMARY

If precise measurement of light is required, the spectroradiometric method is the most ideal and comprehensive method as it records the spectral characteristics of light and further processes them mathematically to obtain radiometric, spectroradiometric, photometric, and colorimetric data.

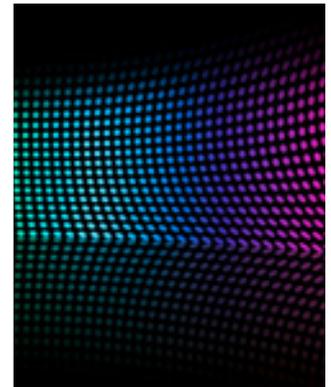
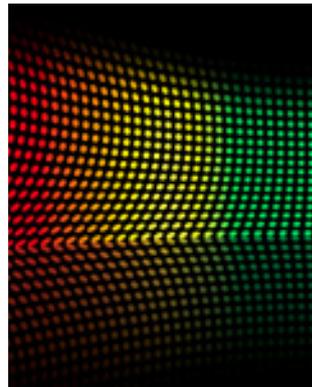
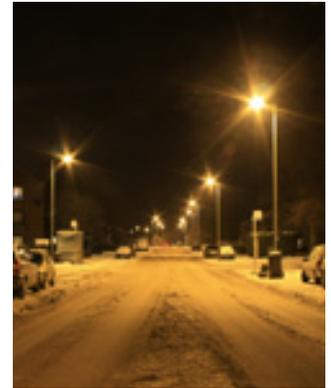
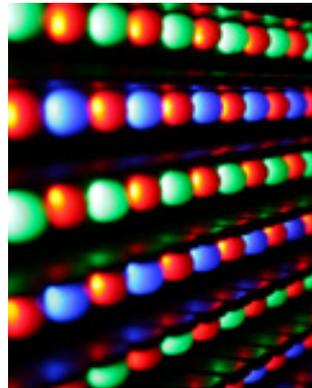
When portability, speed of measurement, and cost of investment, is of priority, filter photometers are still preferred. However, one should have a good understanding of the $f1'$ value of the photometer and its calibration method. This information is important to ascertain whether the photometer is appropriate to measure the light source under test, considering its spectral energy distribution.

Finally, one should choose an instrument which can make direct measurements of light characteristics, such as luminance, illuminance, luminous intensity, luminous flux and should not attempt any form of conversions across measurement geometries.

CONCLUSION

A good understanding of the measurable characteristics of light, and exactly which of those characteristics of light need to be quantified for a particular situation, will ensure that the radiometric and/or photometric characteristics of an application are described correctly.

This publication makes no claim to completeness but simply describes what the user needs to know about measurement of light. The pointers described are based on problems which are frequently mentioned in discussion between suppliers and customers.



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