



KONICA MINOLTA

# The Language of Light

The essentials of imaging



From perception  
to instrumentation



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# 1

# Introduction

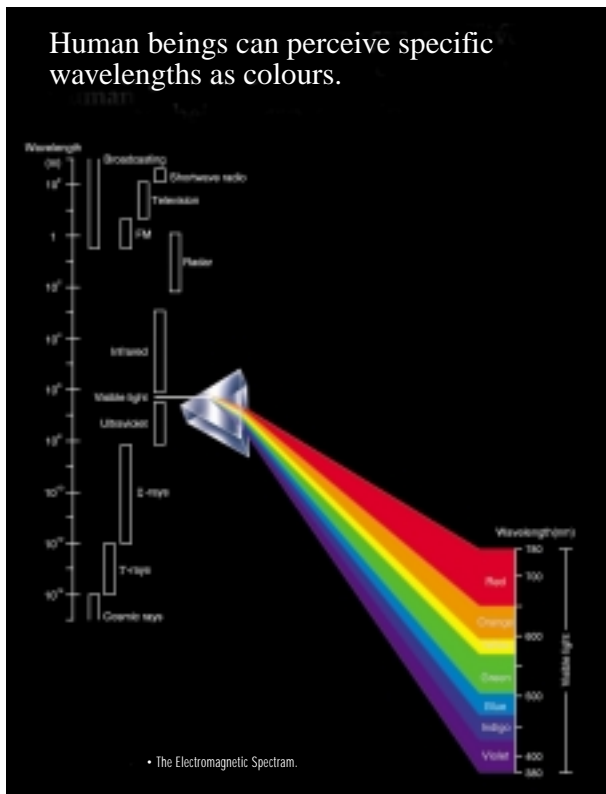
Light is necessary for vision. To most of us, it provides a world of visual information. The forms and colours around us are visible only when light from objects around us reaches our eye and triggers the sensation of sight.

## 1.1 WHAT IS LIGHT?

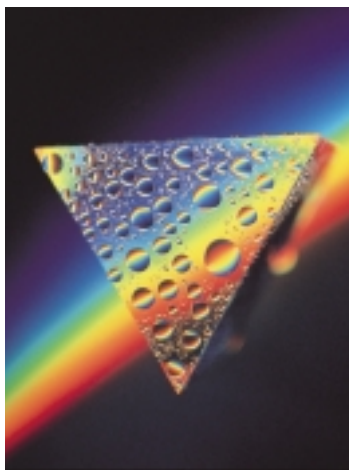
Light is a form of energy and is part of a broader range of the electromagnetic spectrum. Electrical, radio waves and microwaves to gamma rays form this electromagnetic spectrum. The visible light spectrum is a relatively small portion of this spectrum, between 380 nm and 760 nm. In general, light is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

The detection of light is a fundamental process and to measure it requires great understanding. A least understood subject in the field of optics, a probable reason is the introduction of new terminology and concepts.

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



Sources of Light



## 1.2 WHAT CAN BE MEASURED?

Generally, 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 individual wavelength or over a range of wavelength 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.

## 2.1 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.

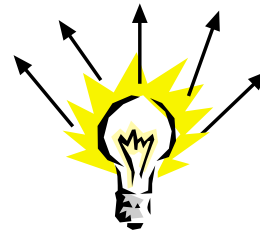
The properties of concern to us here are radiated power and its spatial and angular distributions. The four basic concepts are:

- Radiant Flux
- Radiant Intensity
- Radiance
- Irradiance

### 2.1.1 RADIANT FLUX

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.

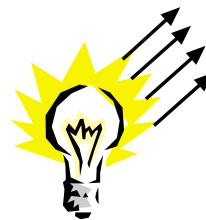


*Radiant Flux  
Total Power (Watts)*

### 2.1.2 RADIANT INTENSITY

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).

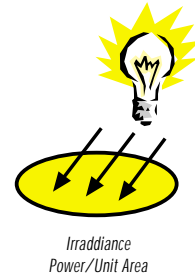


*Radiant Intensity  
Power/Solid Angle*

### 2.1.3 IRRADIANCE

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

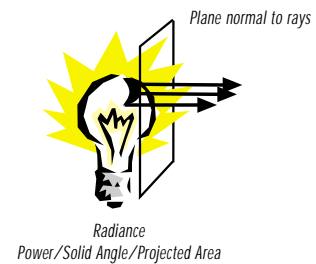
The SI units for irradiance is Watt/square meter ( $\text{Watt}/\text{m}^2$ )



### 2.1.4 RADIANCE

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

The SI units for radiance is Watt/square meter Steradian ( $\text{Watt}/\text{m}^2 \text{sr}$ )



## 2.2 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.

### 2.2.1 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 ( $\text{Watt}/\text{m}^2 \text{sr nm}$ ).

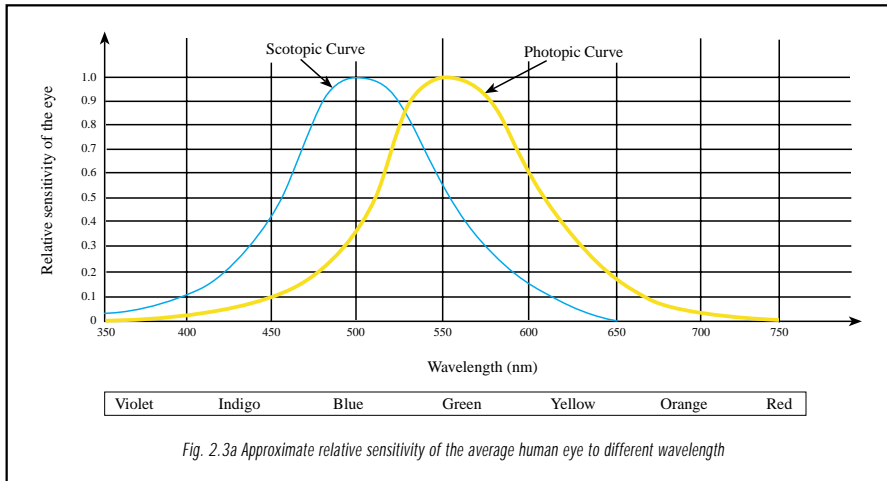
### 2.2.2 SPECTRAL IRRADIANCE

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 ( $\text{Watt}/\text{m}^2 \text{nm}$ ).

## 2.3 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.



Photometry becomes a modern science in 1942, when 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 compile 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.2.3a).

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. 2.3b).

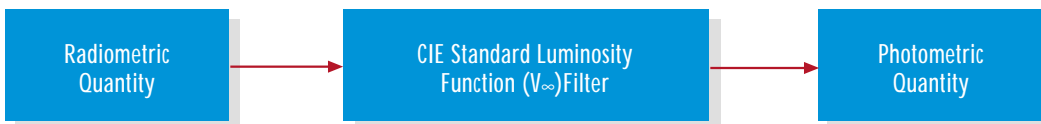


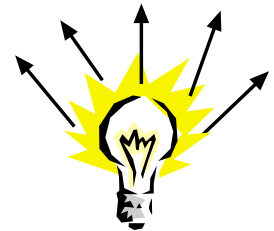
Fig. 2.3b - Relationship between radiometric units and photometric units

Photometry consists of four basic concepts, namely the luminous flux, luminous intensity, illuminance, and luminance.

### 2.3.1 LUMINOUS FLUX

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,  $V_\lambda$ ).

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

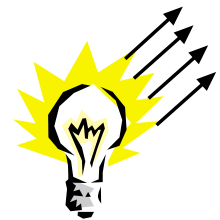


*Luminous Flux  
Total Power (lumen)  
"Light Power"*

### 2.3.2 LUMINOUS INTENSITY

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.)

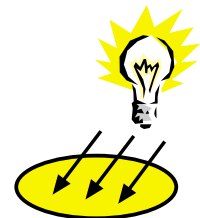


*Luminous Intensity  
Total Power/Solid Angle  
"Candle Power"*

### 2.3.3 ILLUMINANCE

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 ( $lm/ft^2$ )



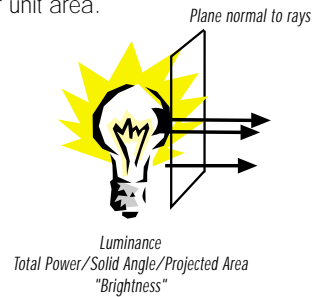
*Illuminance  
Total Power/Unit Area  
"Illumination"*



## 2.3.4 LUMINANCE

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 ( $\text{cd}/\text{m}^2$ ), or nit.  
The original non-metric British unit is the footlambert (fL)  
 $1 \text{ fL} = 1 \text{ candela}/\pi \text{ ft}^2$



## 2.4 COLORIMETRY

### 2.4.1 COLOUR

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.

### 2.4.2 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.

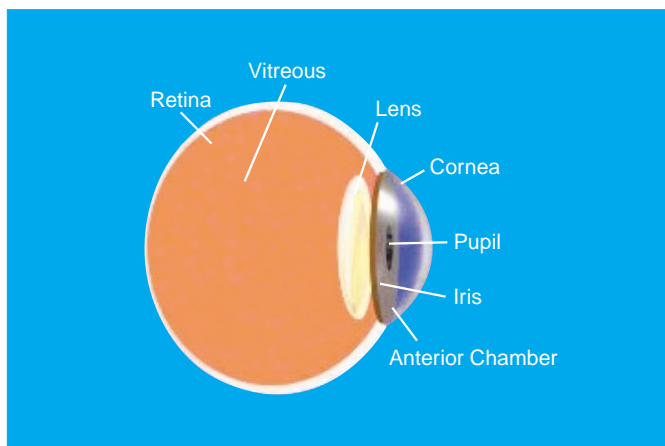


Fig. 2.4.2 - Human Eye

### 2.4.3 MIXING OF COLOURS

Issac 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. It is found that the eye behaves as though the 'outputs' of the three types of cones are additive.

Figure 2.4.3a 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.

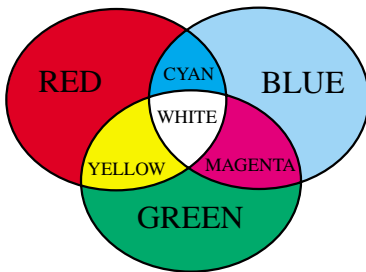


Fig. 2.4.3a - Additive Mixing

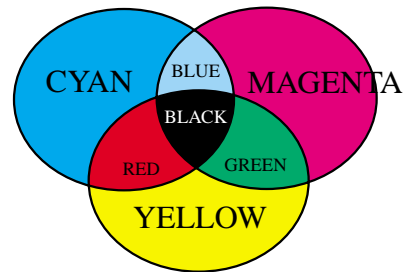
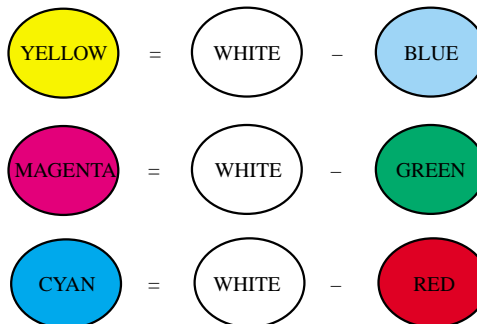


Fig. 2.4.3b - Simple Subtractive Mixing

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 this gives the object its colour characteristic.

Making colours by mixing paint pigments may therefore be described as a process of subtractive mixing (refer to fig. 2.4.3b), since each added pigment 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):



## 2.4.4 LIGHT SOURCE COLOUR SPECIFICATION

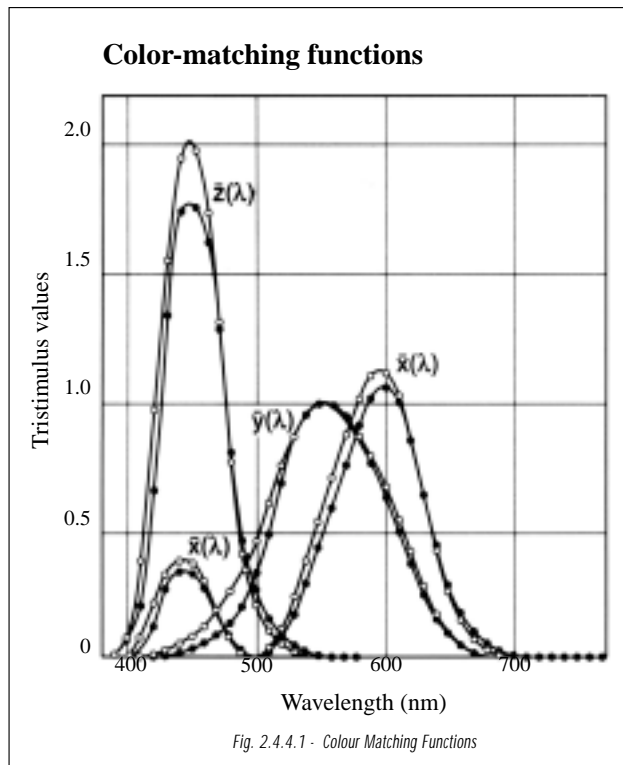
In the past, various people have devised methods to quantify colour so that communication of colour becomes easier and more accurate. These methods attempt to provide a way of expressing colour numerically, in much the same way we express length and weight.

Light source colour specification and measurement can be categorised into three major colorimetric methods. They are:

- Tristimulus colorimetry
- Colour temperature
- Spectroradiometry

### 2.4.4.1 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 1931 Commission Internationale l'Eclairage (CIE) 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. 2.4.4.1. The XYZ tristimulus values are calculated 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.



### 2.4.4.1.1 CIE 1931 Yxy CHROMATICITY CHART

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.

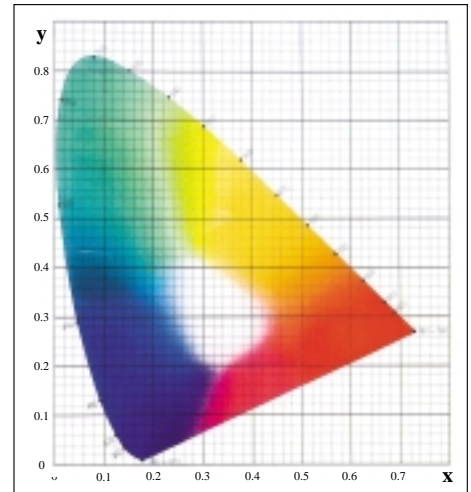


Fig. 2.4.4.1.1 - 1931 x,y Chromaticity Diagram

### 2.4.4.1.2 CIE 1976 UCS CHROMATICITY CHART

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:

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

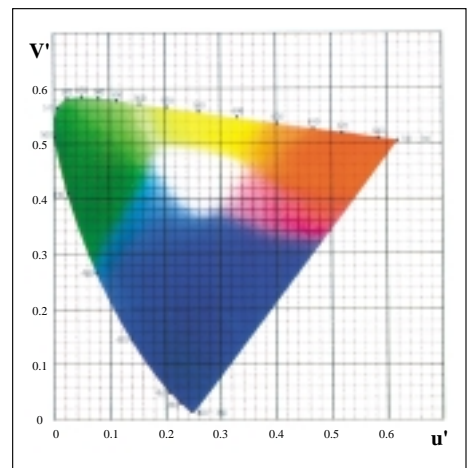
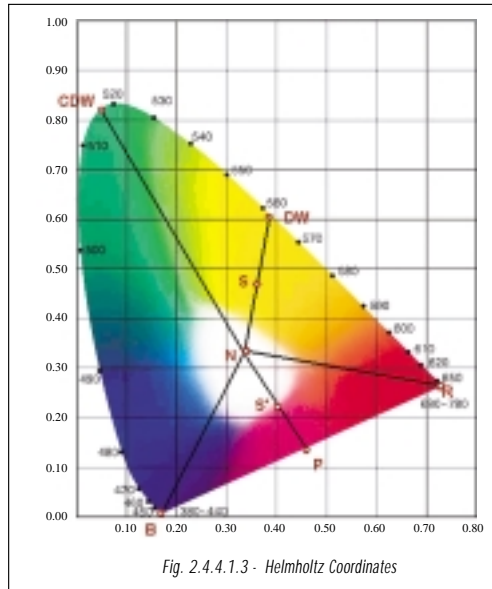


Fig. 2.4.4.1.2 - 1976 UCS Diagram

### 2.4.4.1.3 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, Complementary Dominant Wavelength (CDW) is used. This is because the interception point P, which is supposed 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.

## 2.4.4.2 COLOUR TEMPERATURE

The concept of colour temperature arises from the apparent colour changes of an object when it is heated to various temperatures. When the temperature of an object increases, the emitted radiation changes which result in the change of colour. A special class of incandescent (glow when hot) object emits radiation with 100 percent efficiency when heated; scientists call this ideal full radiator as 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 of the natural light sources, such as the sun, star, and fire fall very close to the Planckian locus.

Some light sources have colour which corresponds to that of a full radiator when the latter is held at a particular temperature. For some purposes, it is convenient to classify such a light source by quoting its colour temperature (measured in Kelvins). Colour Temperature curves from 1,500K to 10,000K can be supplied. 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.

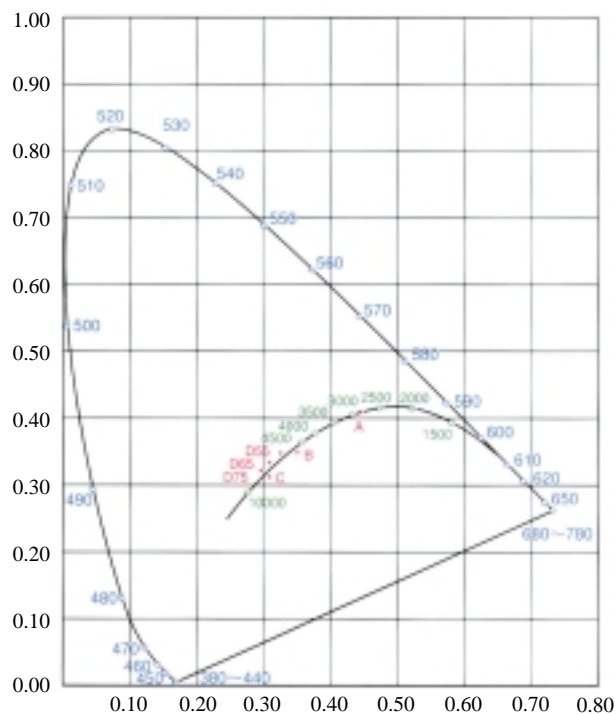


Fig. 2.4.4.2 - Planckian locus plotted on the CIE x,y Chromaticity Diagram.

### 2.4.4.2.1 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 give 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.  $\Delta uv$  is used to specify the deviation from the blackbody locus. The maximum deviation for  $\Delta uv$  is set at  $\pm 0.02$ .

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).

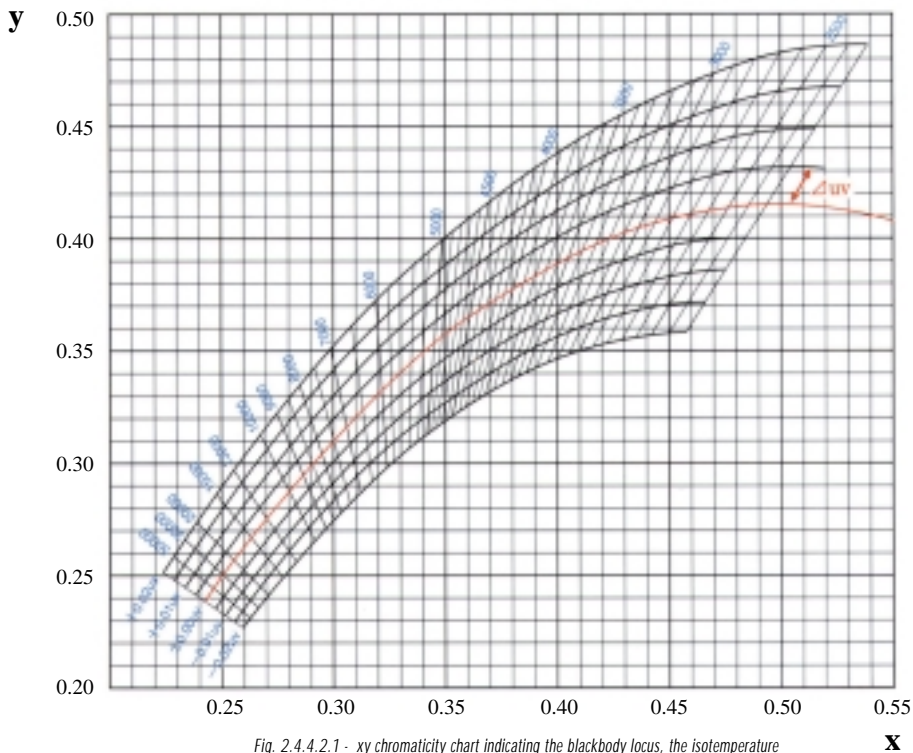


Fig. 2.4.4.2.1 - xy chromaticity chart indicating the blackbody locus, the isothermperature lines and equal  $\Delta uv$  lines.

### 2.4.4.3 SPECTRORADIOMETRY

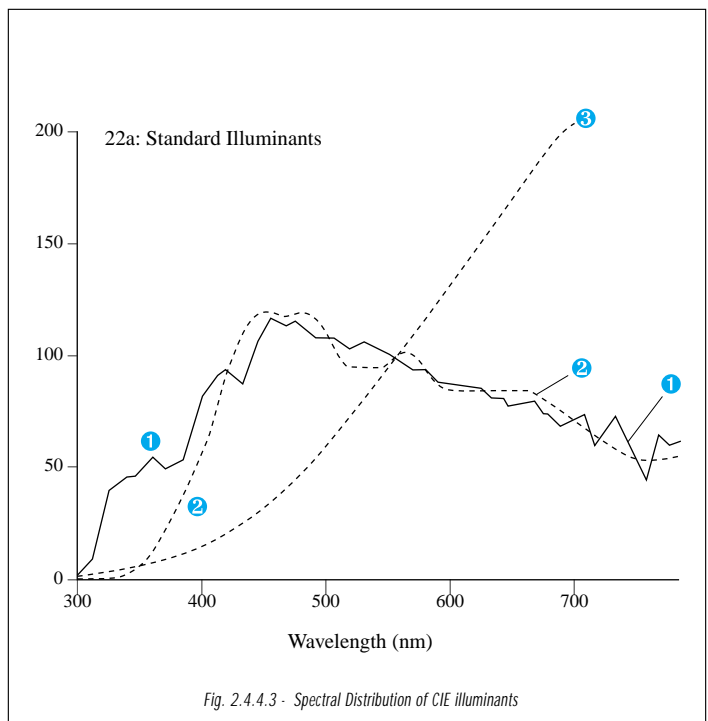
Many different spectral power distribution curves can yield the same visual effect which we call colour. It means that the colour of a light source does not tell us the nature of its spectral power distribution. In other words, two different light sources which have the same colour in x,y or colour temperature 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 (refer to Fig. 2.4.4.3 for the types of spectral power distribution curve of some common CIE illuminants).

Hence, 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 complete description of the colour.

① Standard Illuminant D65: Average daylight (including ultraviolet wavelength region) with a correlated colour temperature of 6504K.

② Standard Illuminant C: Average daylight (not including ultraviolet wavelength region) with a correlated colour temperature of 6774K.

③ Standard Illuminant A: Incandescent light with a correlated colour temperature of 2856K.





## 3.1 RADIOMETER

Radiometer is a device used to measure the intensity of radiant energy. A majority of radiometers use only single photocell sensors. In order to measure radiation emitted from a specific spectrum or to incorporate the radiometer within a certain spectral response, an optical filter is normally used. Such optical filtering offers a simpler and more cost effective solution.

The industrial applications of radiometer mainly involve irradiance and radiance measurement. In order to quantify the radiation emission from source, radiance measurement is normally used. On the other hand, when the level of exposure is of concern, the irradiance or the integrated irradiance measurement is then carried out.

### 3.1.1 APPLICATIONS OF RADIOMETER

Radiometer is commonly used in industry to quantify light which is outside the visible spectrum, i.e., ultraviolet and infrared. Ultraviolet (UV) light is widely used in the industry for various applications, for example,

- Curing of photoresists in semiconductor manufacturing
- Curing of emulsions for printing or plate-making
- Colour-fastness testing
- Biological application

To conduct UV measurement by radiometer, either radiance or irradiance measurement, the spectral response (wavelength range and peak wavelength) should be specified to match the specific application.

Beside UV, infrared energy is also a common parameter in the field of radiometric measurement. Infrared measurement is useful as all material emits infrared radiation according to their thermal energies. Infrared thermometer utilises the principle of infrared radiance measurement to determine the temperature of object by non-contact means. Hence, such infrared radiometer is also commonly known as "Radiation Thermometer". Different filters with specific spectral responses are used for different applications and temperature ranges. For more details about temperature measurement by infrared detection, please refer to our publication on 'The Wonders of Temperature'.

## 3.2 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  $V_\lambda$  curve.

### 3.2.1 SENSORS

The sensor of the photometer, which decides the conformity to the CIE  $V_\lambda$  curve, is critical to the accurate performance of the photometer. Non-filtered and filtered sensors have been used in photometers.

Non-filtered sensors, such as the selenium and cadmium sulfide, inherit a natural spectral response which approximate the  $V_\lambda$  curve. However, its deviation from the  $V_\lambda$  curve makes it impractical for accurate photometry measurement and it is more commonly used in automatic light switches 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  $V_\lambda$  curve.

CIE recognised the need for a meaningful and internationally applicable method of specifying the quality of a photometric sensor. Hence,  $f_1$  value is developed for this purpose. The  $f_1$  value, specified in percentage error, represents the degree to which the relative spectral responsivity matches CIE  $V_\lambda$  curve.

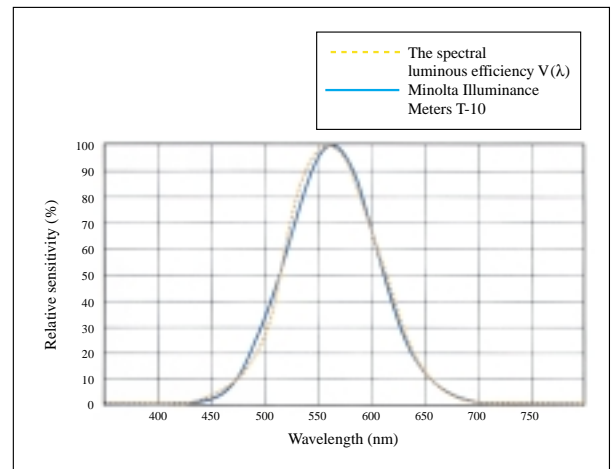


Fig. 3.2.1 - Relative spectral response

## 3.2.2 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 lamp). 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.

### 3.2.2.1 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.

For this reason, modern photometers have incorporated 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 is by varying the CCF value. CCF can also be used as a user-calibration feature, which is particularly useful if in-house standards' traceability is necessary.

### 3.2.3 APPLICATIONS OF PHOTOMETERS

There are a multitude of light measurements to be made. Not surprisingly, misapplication of photometric instrument by user can become a common source of error. For many users, the main obstacle to effective light measurement is the 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 illuminance meter ( $\text{lumen}/\text{m}^2$ ) to determine luminous flux (lumen), or, to use luminance meter ( $\text{candela}/\text{m}^2$ ) 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.

#### 3.2.3.1 LUMINANCE METER

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

Since measurement is targeted at the source, such measurement can be achieved by using an 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.

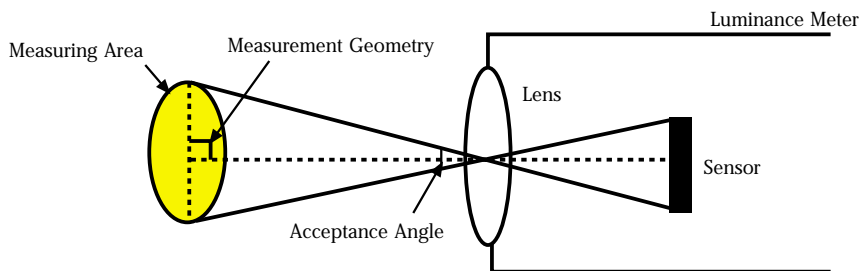


Fig. 3.2.3.1 - Luminance measurement technique involving the use of lens.

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

### 3.2.3.2 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.

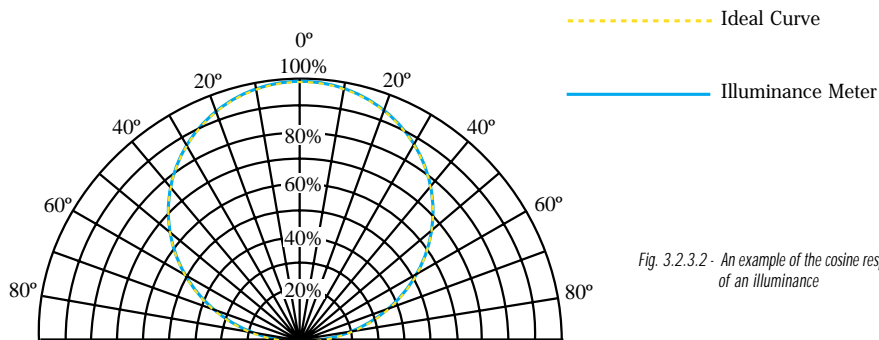


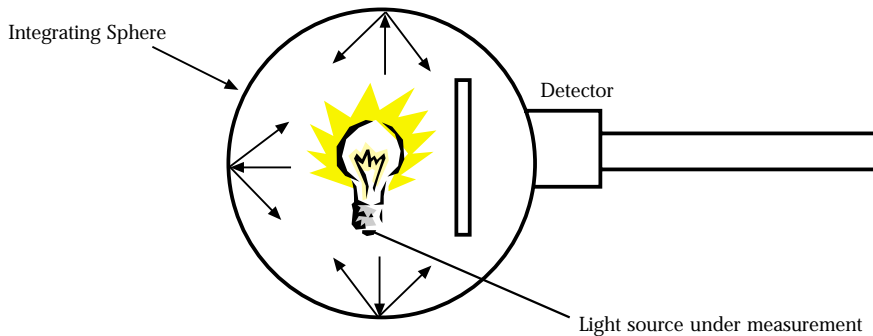
Fig. 3.2.3.2 - An example of the cosine response of an illuminance

Illuminance measurement is widely used in ambient lighting measurement to determine how well the room is lighted up for ease of reading or working. For example, a comfortably lit desk should be illuminated at 300 lx.

Illuminance meter is sometime used to compute measurement in term of ANSI lumen (especially in projection system measurement), by simply averaging the nine points illuminance measurement in lux and multiply by the measurement area in square meter encompassed by the nine points measurement.

### 3.2.3.3 LUMINOUS FLUX METER

Luminous flux measurement is 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. 3.2.3.3 - 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 the same lamp in a 2m sphere. Calibration of such 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 have to be customised to the light measurement application. Hence, the existence of a general purpose luminous flux meter is very limited.

### 3.2.3.4 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.

Hence, 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 an 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 serve no purpose, unless their measurement geometries are identical.

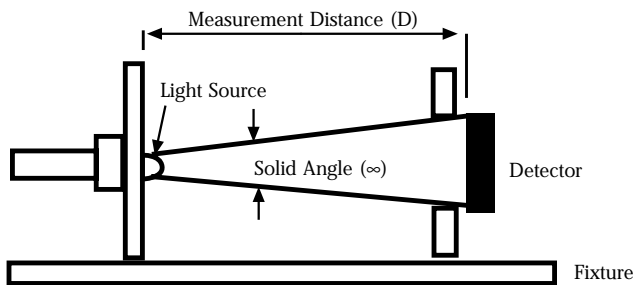


Fig. 3.2.3.4 - An example of luminous intensity meter set-up

**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.

### 3.3 THREE-FILTER COLORIMETER

Instruments designed for measuring coloured light, which make use of three filters whose spectral sensitivity are matched to the CIE tri-stimulus 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.3.2.3.5a), or with narrow spectral energy distributions, e.g., LEDs (refer to Fig.3.2.3.5b).

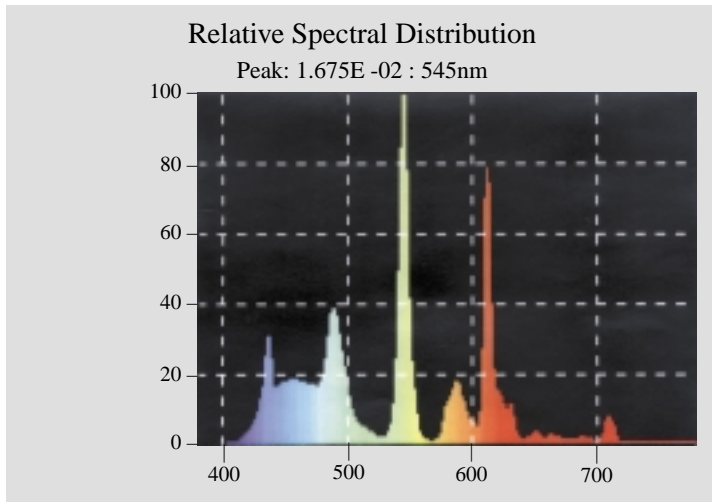


Fig. 3.2.3.5a - Spectral energy distribution with spectral lines

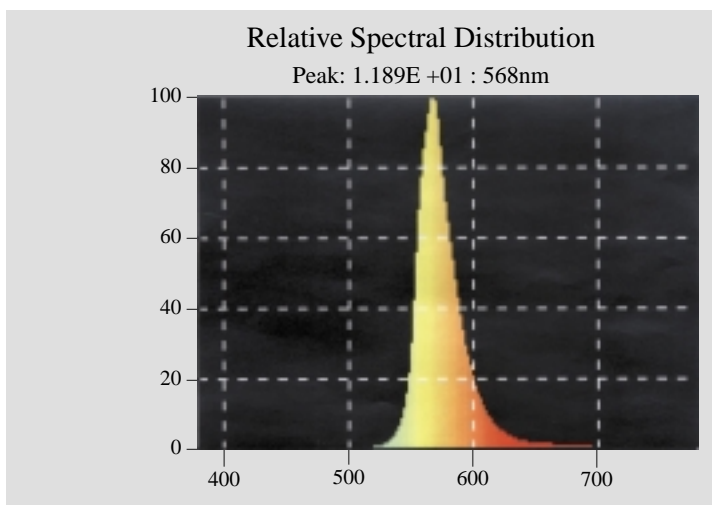


Fig. 3.2.3.5b - Spectral energy distribution of a narrow-band emitter

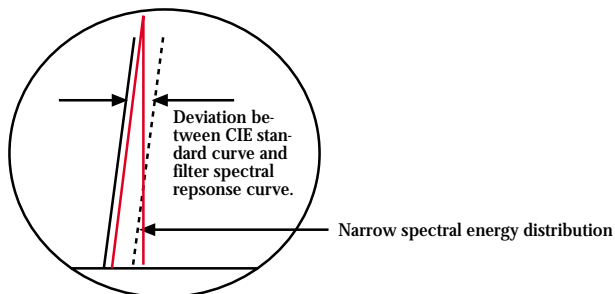
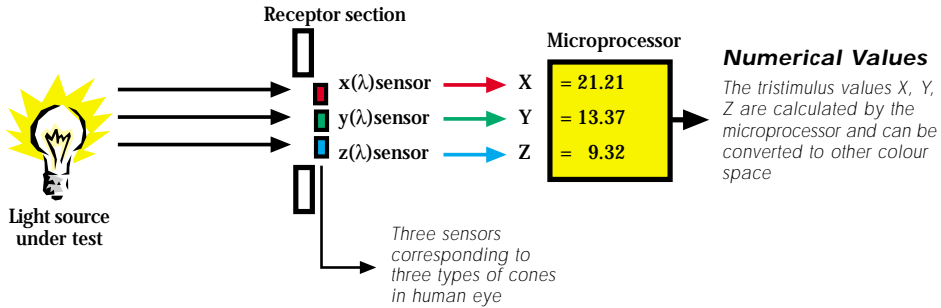


Fig. 3.2.3.5c - Error in measurement caused by deviation between CIE tristimulus curve and instrument's spectral response.



### Tristimulus Method



### Spectroradiometric Method

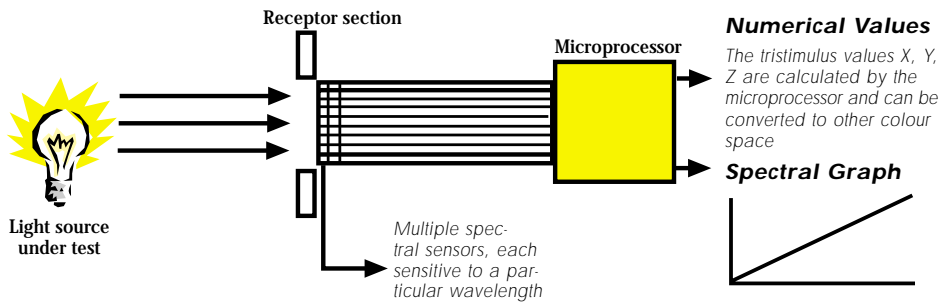


Fig. 3.2.3.6 - Comparison between tristimulus colorimetric method and spectroradiometric methods

## 3.4 SPECTRORADIOMETER

Spectroradiometers are most ideal for measuring spectral energy distribution of the light source, which determine not only the radiometric and photometric quantities, but also 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 spectroradiometer by means of prisms or diffraction gratings.

The exact CIE  $V_\lambda$  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 means of the spectral procedure.

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

### **3.5** 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 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.

## **4** C o n c l u s i o n

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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