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Optical Metrology – Photometry

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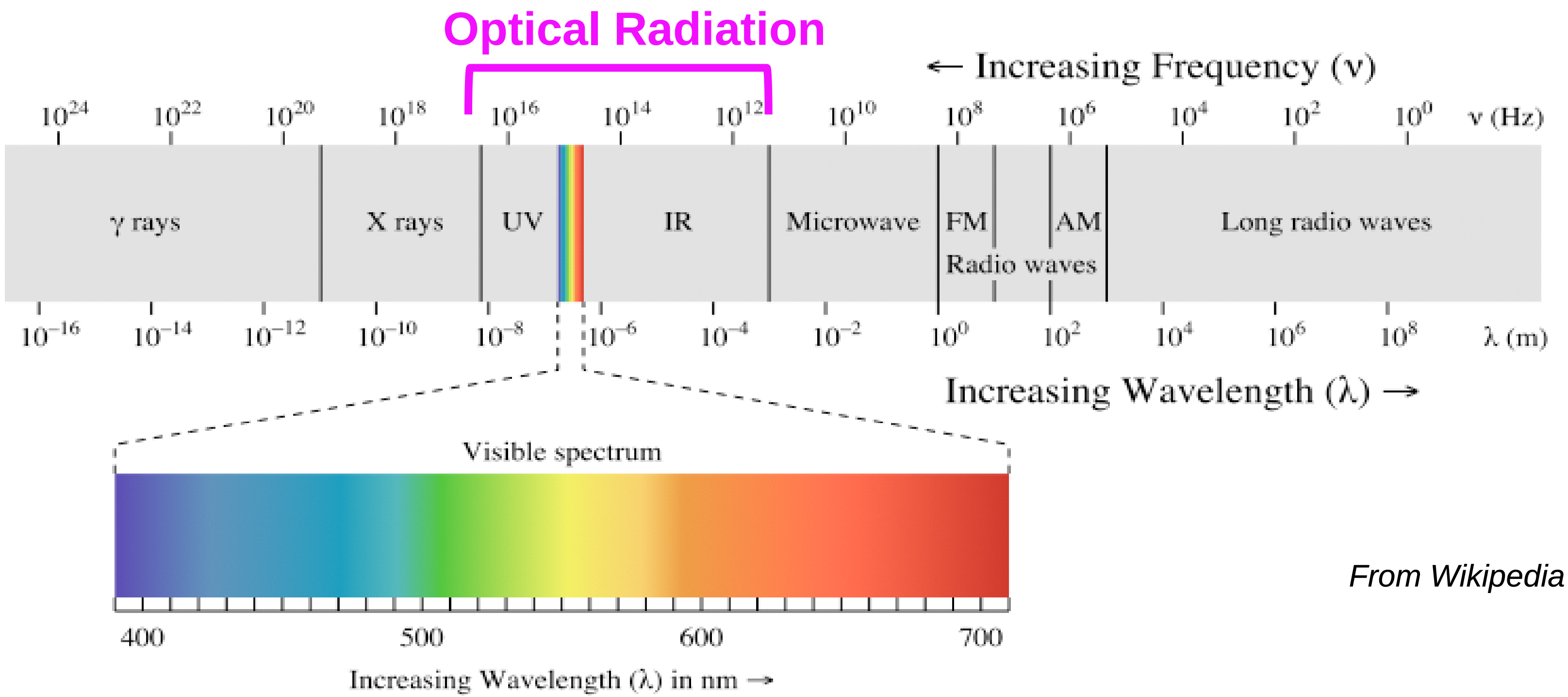
OUTLINE

1. Optical Radiation
2. Radiometry and photometry
3. Quantities and units
4. Human visual response
5. Colorimetry
6. Standards organizations
7. Laboratory Examples

Optical Radiation

Electromagnetic Radiation

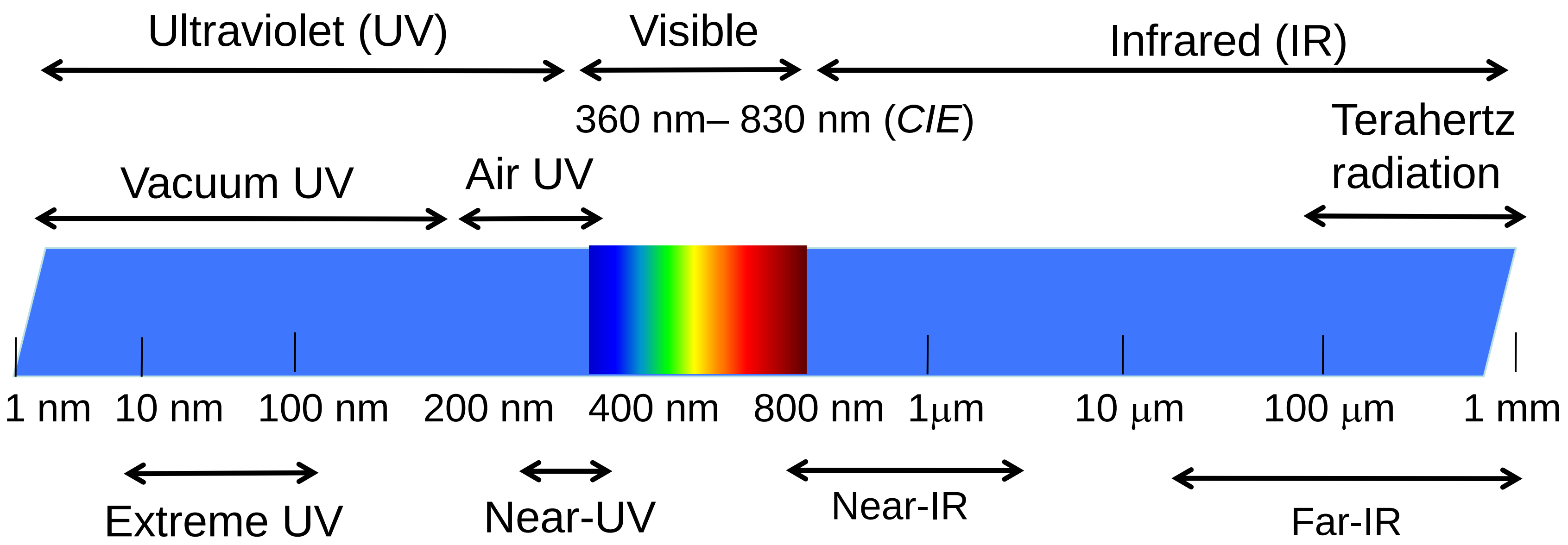


From Wikipedia

Optical Radiation

Electromagnetic radiation at wavelengths between the region of transition to X-rays (λ ≈ 1 nm) and the region of transition to radio waves (λ ≈ 1 mm) *….. International Lighting Vocabulary (CIE 17.4)*

Optical Radiation



UV-A: 315 nm to 400 nm

UV-B: 280 nm to 315 nm

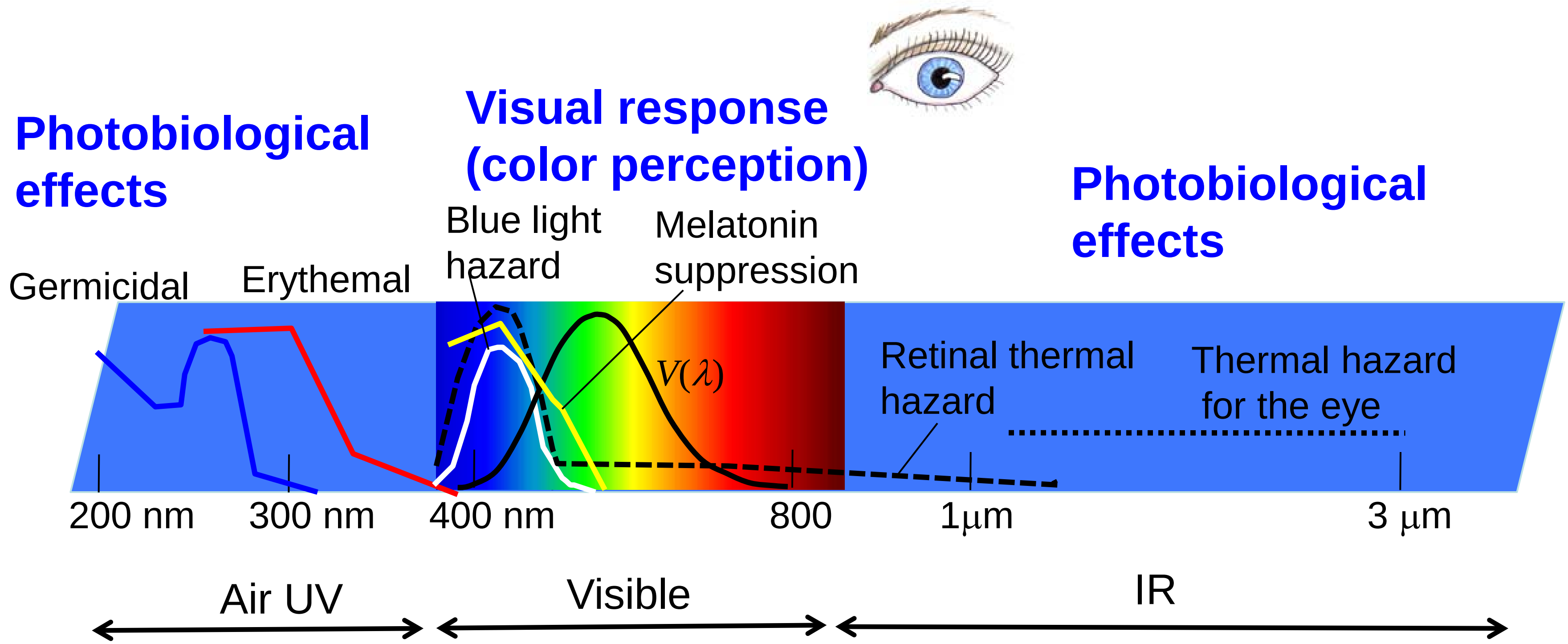
UV-C: 100 nm to 280 nm (*CIE*)

IR-A: 780 nm to 1400 nm

IR-B: 1,4 μm to 3,0 μm;

IR-C: 3 μm to 1 mm. (*CIE*)

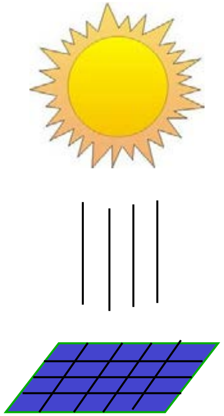
Physiological Effects of Optical Radiation



Action spectrum: Effectiveness of photochemical or biological reaction of optical radiation as a function of wavelength.

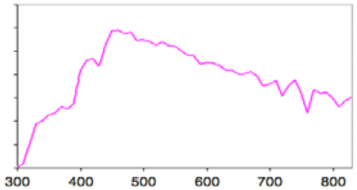
Measurements of Optical Radiation

Radiometry
(all wavelengths, purely pysical)



Radiant power
(radiant flux)
[watt] or [W]
Radiant energy
[joule] or [J]

Irradiance
$[W/m^2]$



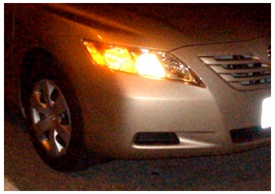
Spectral irradiance
$[W\ m^{-2}\ nm^{-1}]$

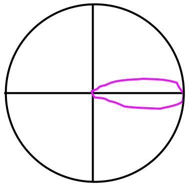
Radiance
$[W\ sr^{-1}\ m^{-2}]$

Photometry
(the visible, based on human visual response)

Luminous flux
[lumen] or [lm]

Illuminance
[lux] or [lx] $(= lm/m^2)$





Luminous intensity
[candela] or [cd]
(= lm/sr)

Luminance
$[cd/m^2]$

The Candela

Unit of luminous intensity

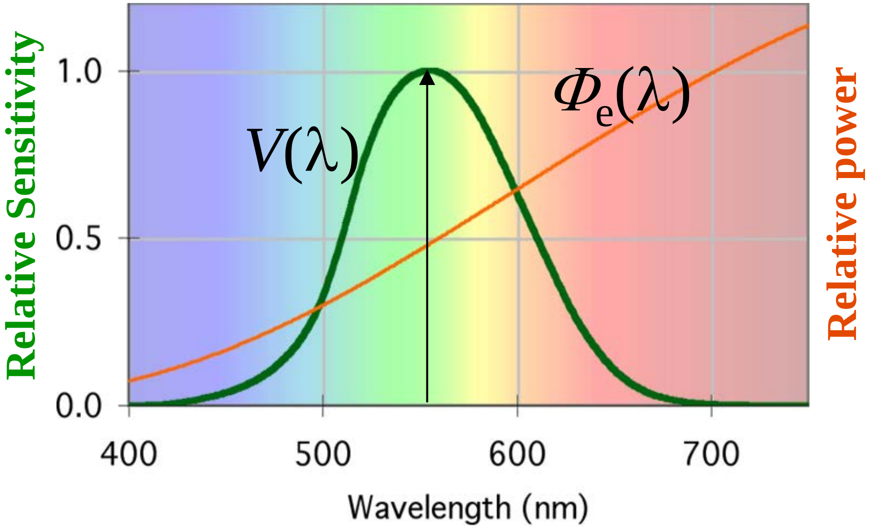
SI-base units

- meter
- second
- kilogram
- ampere
- candela
- kelvin
- mole

"The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 x 10^{12} hertz and that has a radiant intensity in that direction of (1/683) watt per steradian." (CGPM 1979)

1 cd = 1/683 [W/sr] at 555.016 nm
(1 W = 683 lm) (in std. air)

Luminous efficiency *V(λ)* **(CIE 1924)**



Photometric quantity

$$\Phi_v = K_m \int_\lambda \Phi_{e,\lambda} V(\lambda) d\lambda$$

$$K_m \approx 683 \text{ [lm/W]}$$

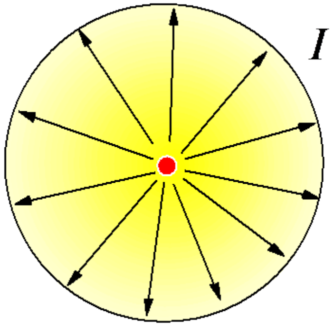
(BIPM 1983)

The Lumen

Unit of (total) luminous flux

Total Luminous Flux [lm]

The geometrically-total luminous flux of a light source. It is given by the spatial integration of luminous intensity *I* [cd]



I (cd)

E (lx)

Integrate over solid angle of 4π

$$\Phi = \int_{\Omega} I \, \mathrm{d}\Omega$$

or the integration of illuminance *E* [lx]:

$$\Phi = \int_{A} E \, \mathrm{d}A$$

(*A*: area of a closed surface on which illuminance is given)

1600 lm / 23W= 70 lm/W

Why photometry so important? (example)

LED lighting products Market

Quality assurance

Certify products

Regulations

ENERGY STAR

Non-standard LED lamps
min. 50 lm/W, 200 lm/lamp

Replacement lamps
a) omnidirectionral lamps
min. 50 lm/W, life 25,000 h
b) Decorative lamps
min. 40 lm/W)

Color rendering requirements
CRI Ra≥80, R9≥0
CCT 2700. 3000. 3500. 4000 K

Nominal wattage of lamp to be replaced (watts)	Minimum initial light output of LED lamp (lumens)
25	200
35	325
40	450
60	800
75	1,100
100	1,600

Product performance data measured

Accredited Manufacturers, testing labs

Test Method Standard (IES LM-79 in USA)

Testing Accreditation Program

Proficiency Testing

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Quantities and Units for Optical Radiation

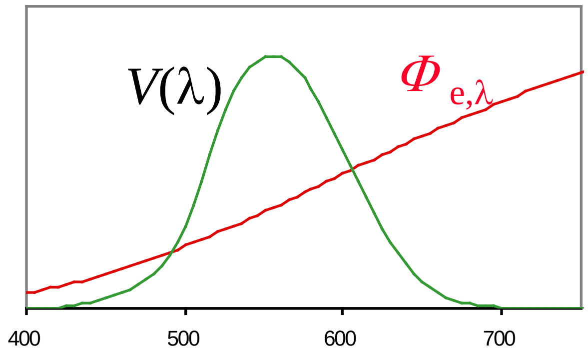
Radiometric quantity	Unit	Photometric quantity	Unit	relationship with lumen
Radiant flux	W (watt)	Luminous flux	lm (lumen)	
Radiant intensity	W/sr	Luminous intensity	cd (candela)	$lm \cdot sr^{-1}$
Irradiance	W/m^2	Illuminance	lx (lux)	$lm \cdot m^{-2}$
Radiance	$W \cdot sr^{-1} \cdot m^{-2}$	Luminance	cd/m^2	$lm \cdot sr^{-1} \cdot m^{-2}$
Radiant exitance	W/m^2	Luminous exitance	lm/m^2	$lm \cdot m^{-2}$
Radiant energy	J (joule)	Luminous energy	lm·s	
Radiant exposure	J/m^2	Luminous exposure	lx·s	$lm \cdot s \cdot m^{-2}$
Total radiant flux	W	Total luminous flux	lm	
Radiance temperature	K (kelvin)	Color temperature	K (kelvin)	

Luminous Flux

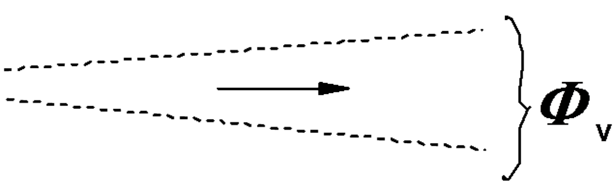
Unit: **lumen**

Symbol for unit: **lm**

Symbol for quantity: Φ, Φ_v



$$\Phi_v = K_m \int_\lambda \Phi_{e,\lambda} V(\lambda)\, d\lambda$$



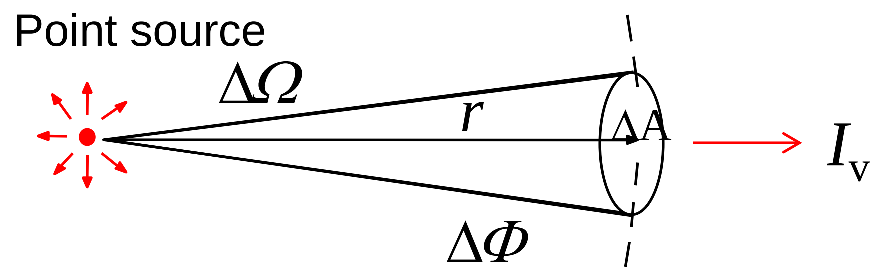
Luminous Intensity

(of a source, in a given direction)

Unit: **candela** = lm/sr

Symbol for unit: **cd**

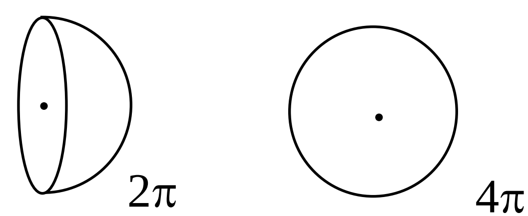
Symbol for quantity: I, I_v



$$I_v = \frac{d\Phi_v}{d\Omega}$$

Solid angle

$$\Delta\Omega = \Delta A / r^2 \quad [\text{sr}]$$

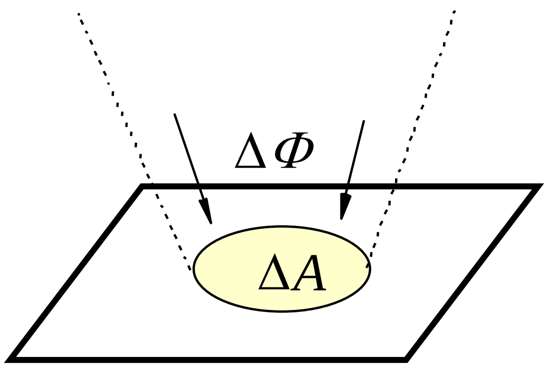


Illuminance (at a point of a surface)

Unit: **lux** = $\mathrm{lm/m^2}$

Symbol for unit: **lx**

Symbol for quantity: $\boldsymbol{E}$, $\boldsymbol{E}_v$



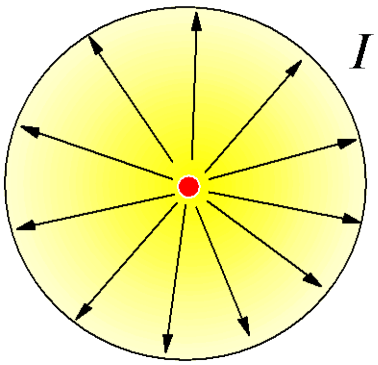
$$E_V = \frac{\mathrm{d}\Phi_V}{\mathrm{d}A}$$

Total Luminous Flux (of a source)

Unit: **lumen**

Symbol for unit: **lm**

Symbol for quantity: $\boldsymbol{\Phi}$, $\boldsymbol{\Phi}_v$



Integrate over solid angle of 4π

$$\Phi = \int_{\Omega} I \, \mathrm{d}\Omega$$

or

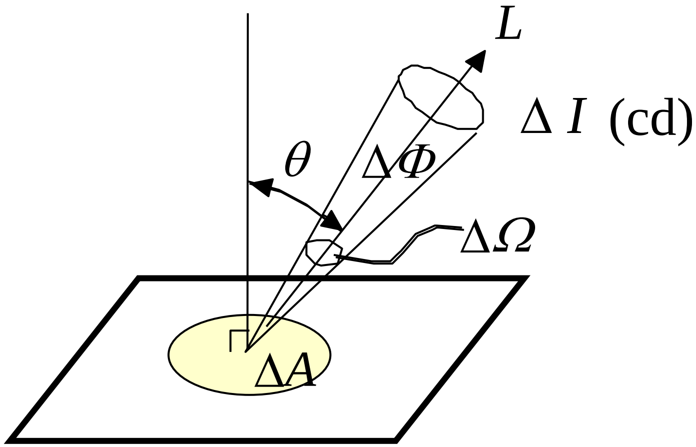
$$\Phi = \int_{A} E \, \mathrm{d}A$$

(A: area of a closed surface on which illuminance is given)

Luminance (at a point of a surface, in a given direction)

Unit: **cd/m²** (= lm sr^{-1} m^{-2})

Symbol for quantity: $\boldsymbol{L}$, $\boldsymbol{L}_v$



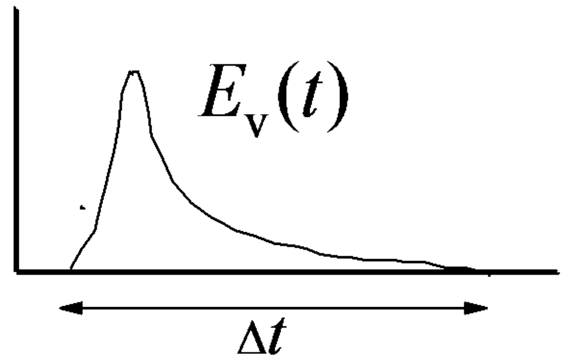
$$L_v = \frac{d\Phi_v}{d\Omega\, dA \cos\theta}$$

$$L_v = \frac{\Delta I}{\Delta A \cos\theta}$$

Luminous exposure

Unit: **lux · second** (lx · s)

Symbol for quantity: $\boldsymbol{H}$, $\boldsymbol{H}_v$



$$H_v = \int_{\Delta t} E_v(t)\,dt$$

Luminous energy

Unit: **lumen · second** (lm · s)

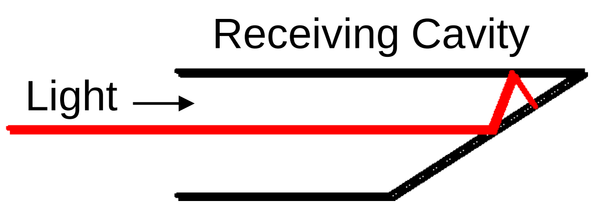
Symbol for quantity: $\boldsymbol{Q}$, $\boldsymbol{Q}_v$

$$Q_v = \int_{\Delta t} \Phi_v(t)\,dt$$

Primary Standards for Optical Radiation

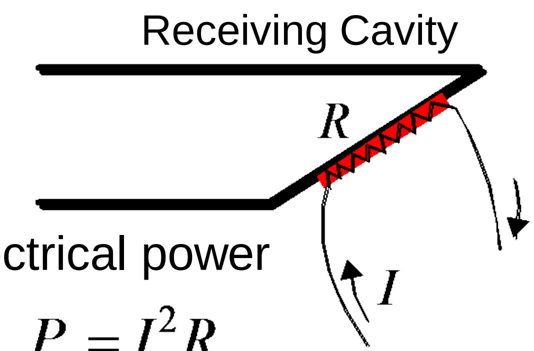
(1) Electrical Substitution Radiometer

Optical Heating



Optical Power P_0

Electrical Heating



Electrical power

$$P_e = I^2 R$$

P_0 creates temperature increase ΔT in the cavity

P_e creates the same ΔT in the cavity

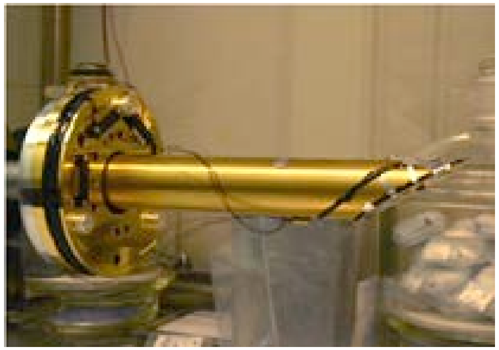
The optical power is measured as equal to the electrical power.

Uncertainty of room-temperature ESR is ~0.1 % (*k*=2)

NIST Cryogenic Radiometer

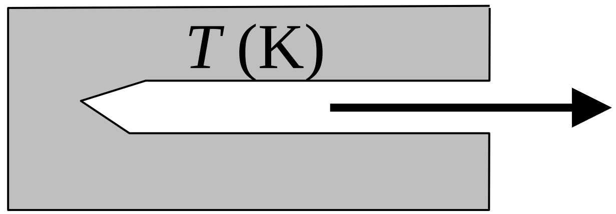
Primary Optical Watt Radiometer (POWR)

- Liquid helium/nitrogen cryostat
- Cavity cooled to 4 K
- Uncertainty ~ 0.01 % (k=2); 200 nm to ~2500 nm
- Basis of all NIST radiometric and photometric units.



Detector module

(2) Blackbody radiation



Spectral radiance

$$L_e(\lambda, T)$$

Planck's Law

$$L_e(\lambda, T) = c_1 n^{-2} \pi^{-1} \lambda^{-5} \left[\exp\left(\frac{c_2}{n \lambda T} \right) - 1 \right]^{-1}$$

$c_1 = 2\pi hc^2 = 3.74177153 \times 10^{-16}$ W·m^2

$c_2 = hc/k = 1.438770 \times 10^{-2}$ m·K

(2010 CODATA)

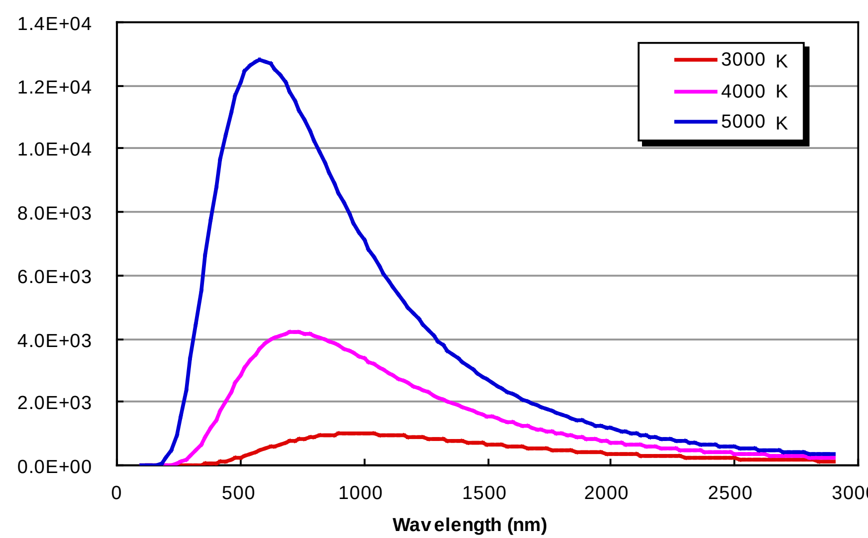
h: Planck constant

c: speed of light in vacuum

k: Boltzmann constant

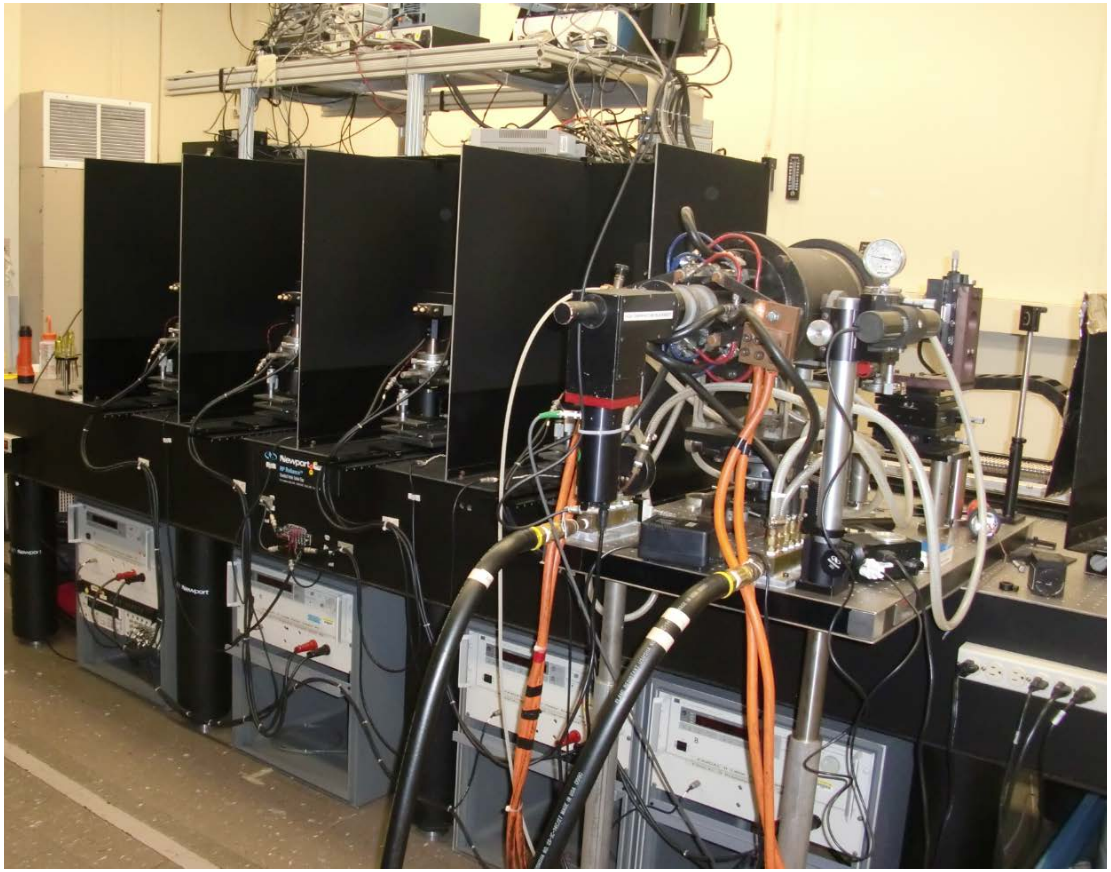
n (=1.00028): the refractive index of standard air

λ: wavelength



NIST Blackbody Radiation Facility

FASCAL 2 (Facility for Automated Spectral Irradiance Calibrations)

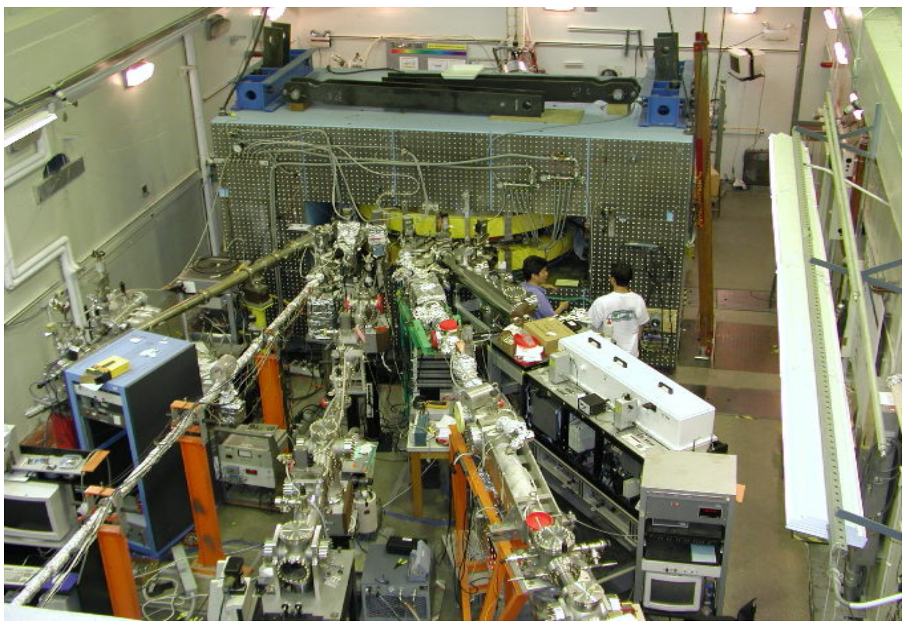


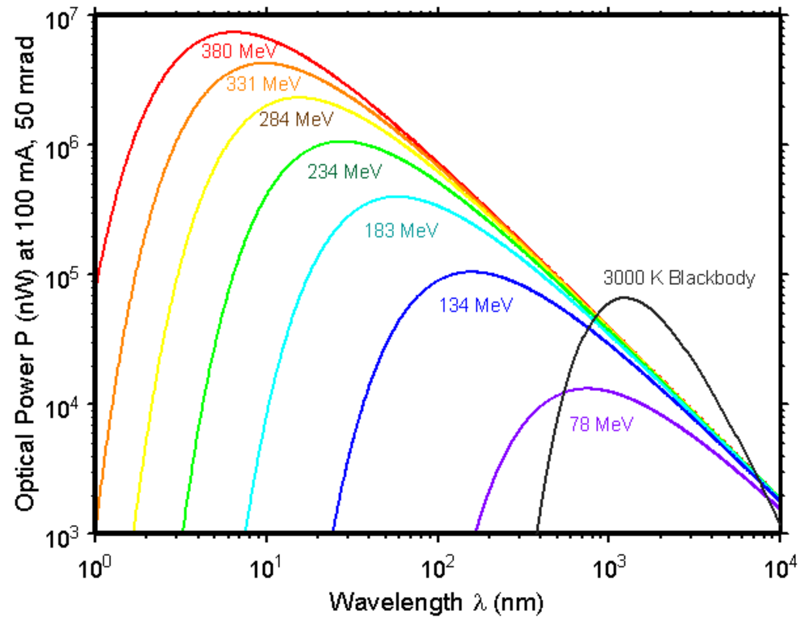
- Basis for NIST spectral irradiance scale 250 nm to 2400 nm.
- High temperature blackbody 2950 K.
- 1000 W FEL lamps issued.
- The scale provided to NMIs worldwide.

(3) Synchrotron radiation

Spectral radiant flux from a beam line is given by Schwinger equation.
Synchrotron radiation is used primarily for UV metrology.

NIST SURF III
Synchrotron Ultraviolet Radiation Facility





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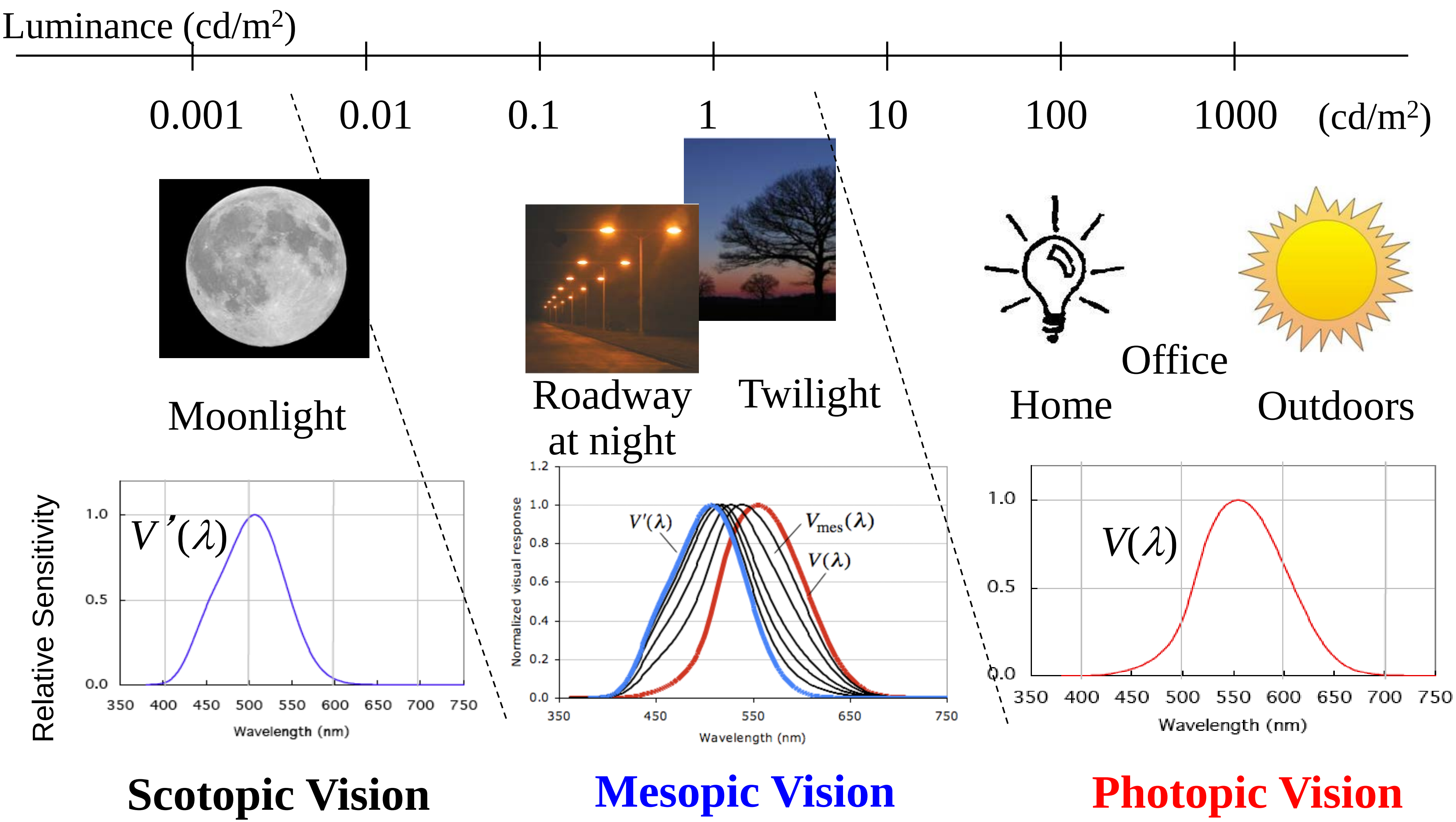
Human Visual Response



Photometric Quantities

CIE 18.2 The Basis of Physical Photometry (1983)
BIPM Monographie – Principles Governing Photometry (1983)

Luminous flux

For photopic vision:

$$\Phi_v = K_m \int_\lambda \Phi_{e,\lambda} V(\lambda) d\lambda$$

K_m = 683 lm/W (approx.)

For scotopic vision:

$$\Phi_v = K'_m \int_\lambda \Phi_{e,\lambda} V'(\lambda) d\lambda$$

K'_m = 1700 lm/W (approx.)

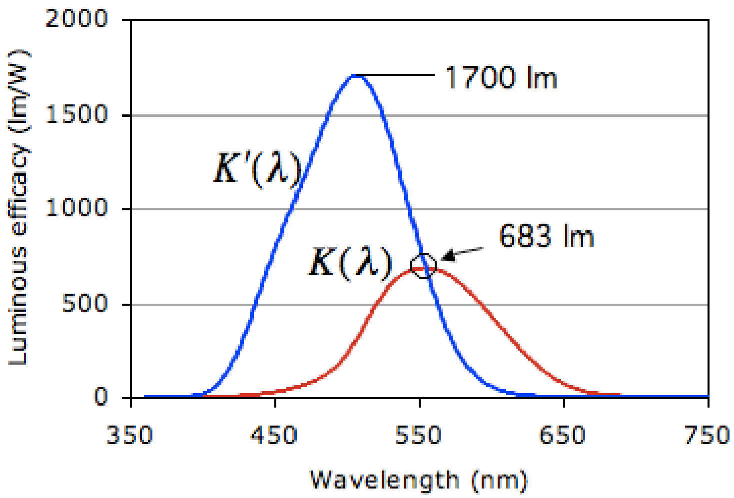
(Scotopic vision is rarely used.)

Spectral luminous efficacy

$K(\lambda) = K_m V(\lambda)$ for photopic

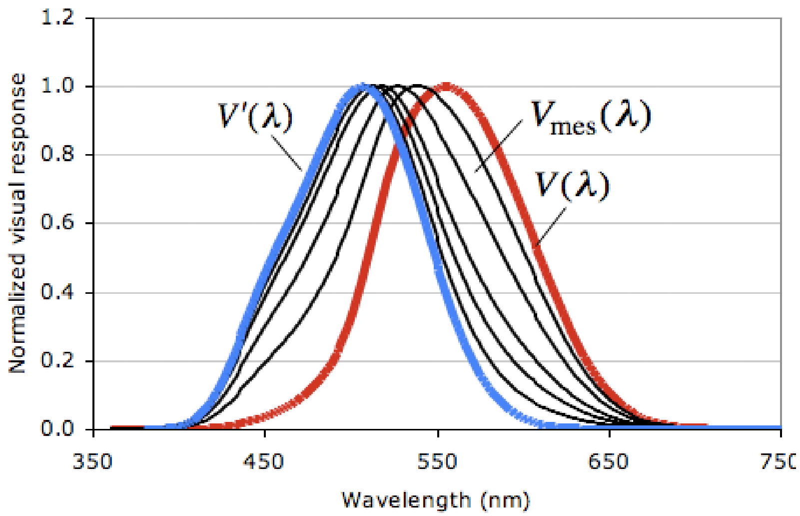
$K'(\lambda) = K'_m V(\lambda)$ for scotopic

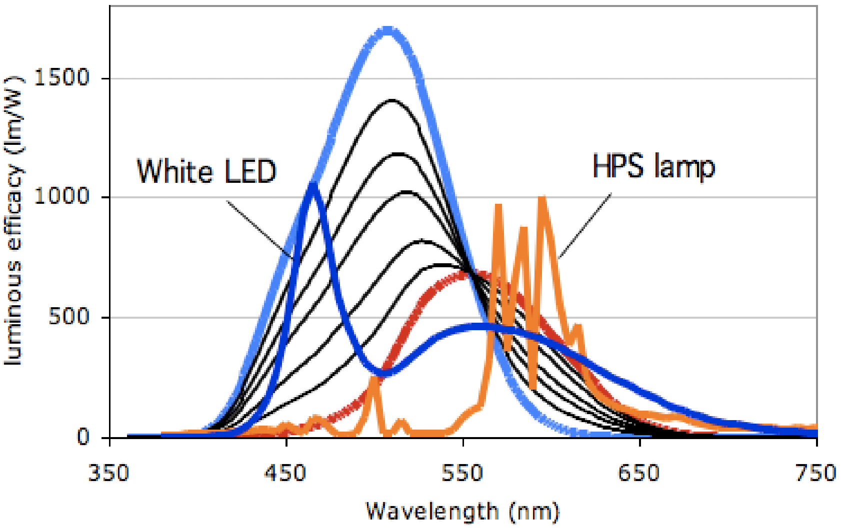
$K(\lambda)=K'(\lambda)=683$ lm/W at the frequency 540×10^{12} Hz



Mesopic Photometry

CIE 191:2010: Recommended System for Mesopic Photometry based on Visual Performance

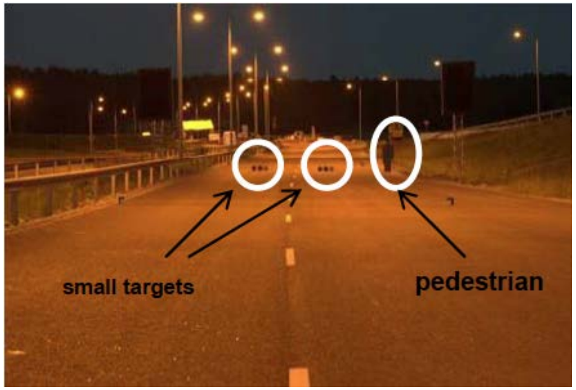




$$M(m)V_{mes}(\lambda) = m\,V(\lambda) + (1-m)V'(\lambda) \qquad for\ 0 \le m \le 1$$

and $$L_{mes} = \frac{683}{V_{mes}(\lambda_0)} \int V_{mes}(\lambda)\, L_e(\lambda)\, d\lambda$$

m is determined by adaptation luminance of the filed.



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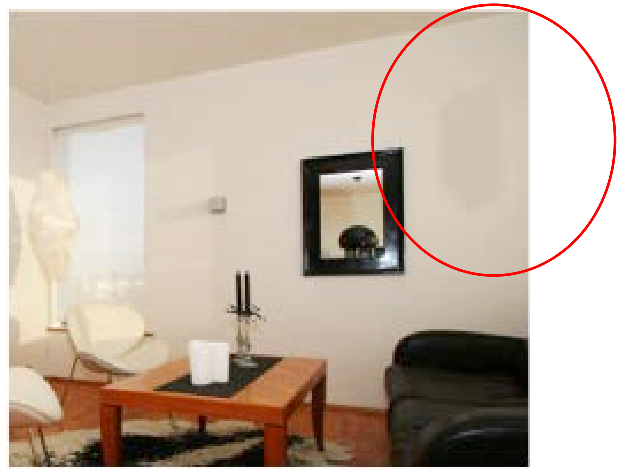
Why accurate color so important?

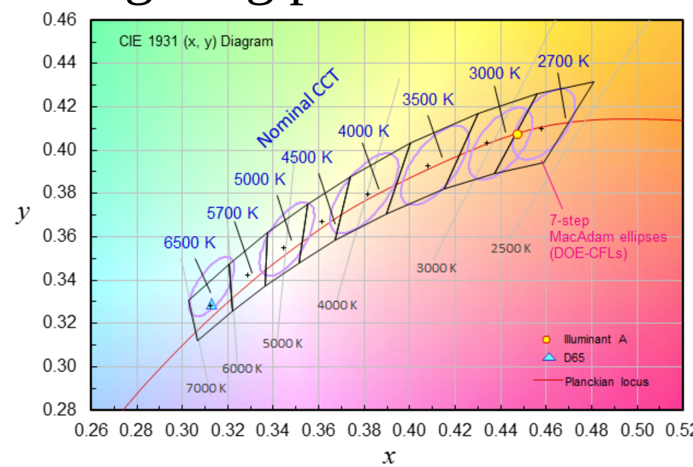
Colors of parts do not match



Color of paint does not match though same spec.

Skin tone does not appear right.

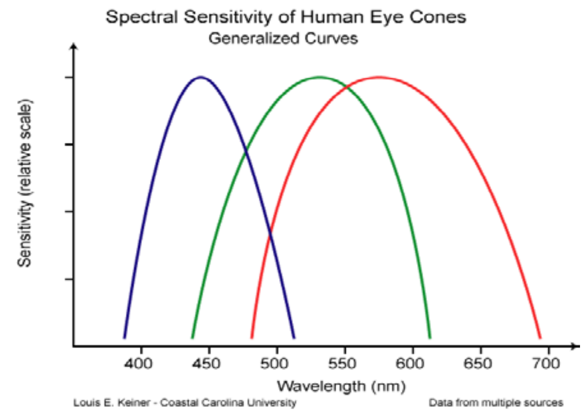
ANSI standard on LED lighting products



Color Vision

Trichromacy theorty (Young, 1800’s)

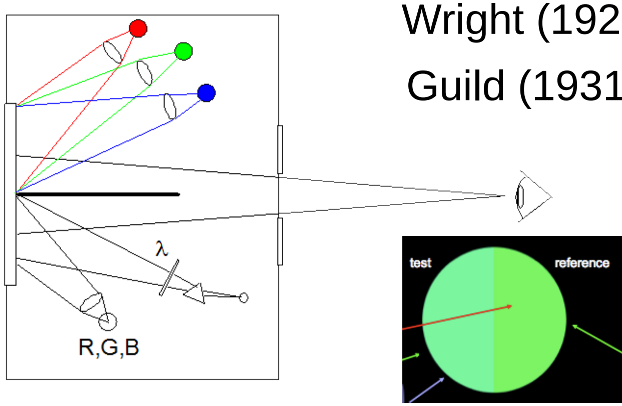
3 cone photopigments in retina



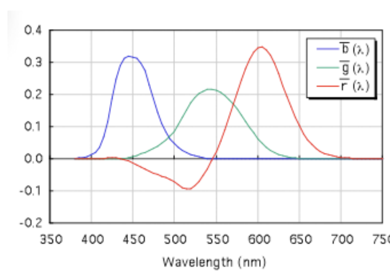
Color matching experiments

Wright (1929)

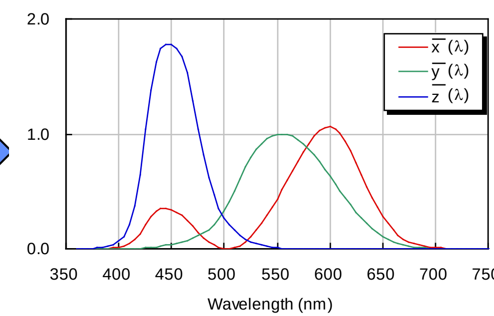
Guild (1931)



Results

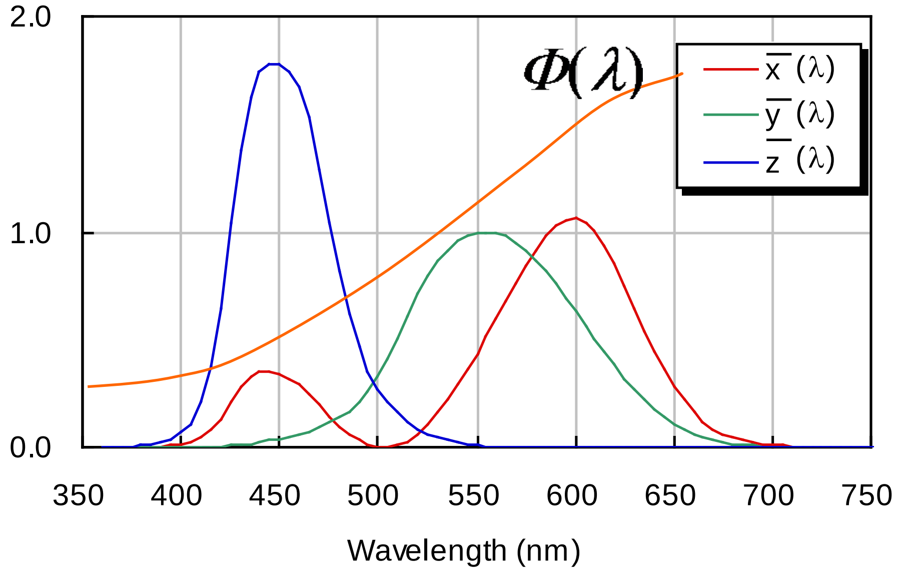


CIE 1931 Color Matching Functions



1931 CIE System of Colorimetry

CIE 1931 Color Matching Functions



Tristimulus Values

$$X = k\int_{\lambda} \Phi(\lambda)\,\bar{x}(\lambda)\,\mathrm{d}\lambda$$

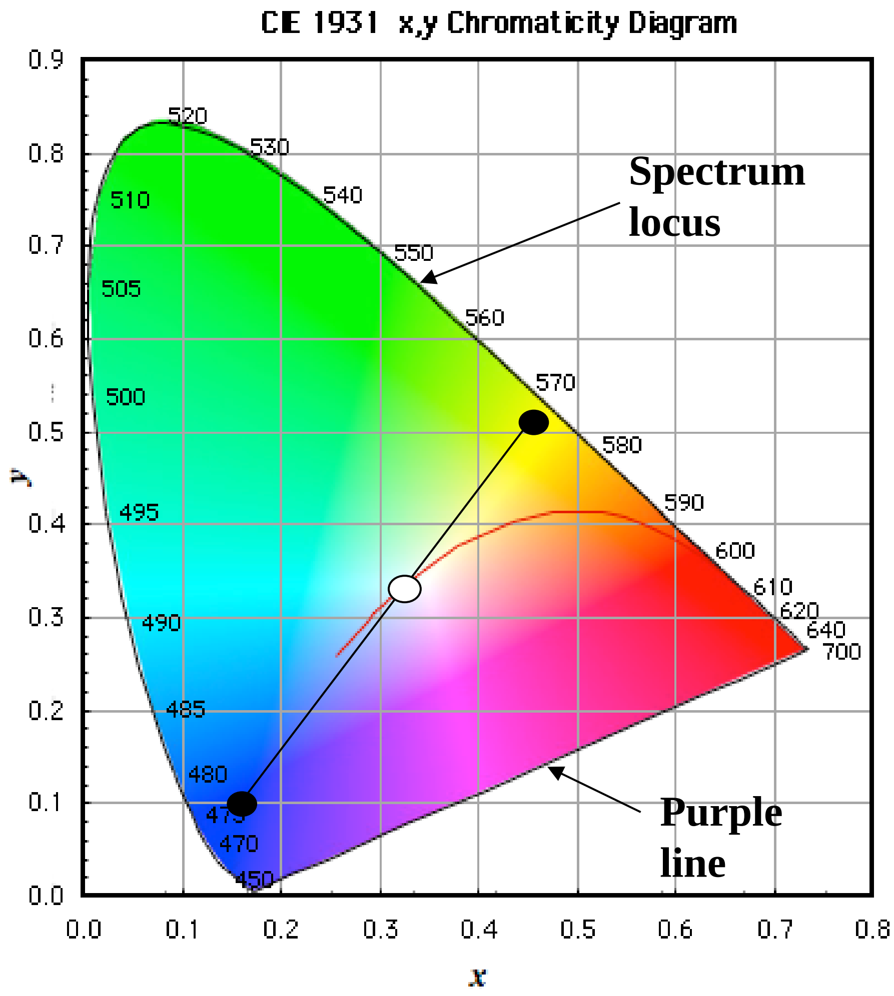
$$Y = k\int_{\lambda} \Phi(\lambda)\,\bar{y}(\lambda)\,\mathrm{d}\lambda$$

$$Z = k\int_{\lambda} \Phi(\lambda)\,\bar{z}(\lambda)\,\mathrm{d}\lambda$$

$$\bar{y}(\lambda) \equiv V(\lambda)$$

CIE 15:2004 Colorimetry, 3^{rd} ed.
ISO 11664-1:2008(E)/CIE S 014-1/E:2006 Standard Colorimetric Observer
BIPM Monographie – Principles Governing Photometry (1983)

Chromaticity Coordinates



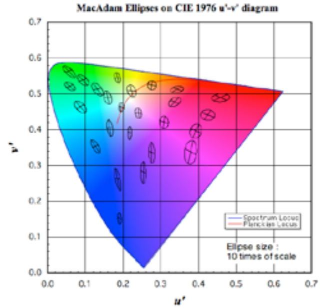
Chromaticity Coordinate (*x*, *y*)

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

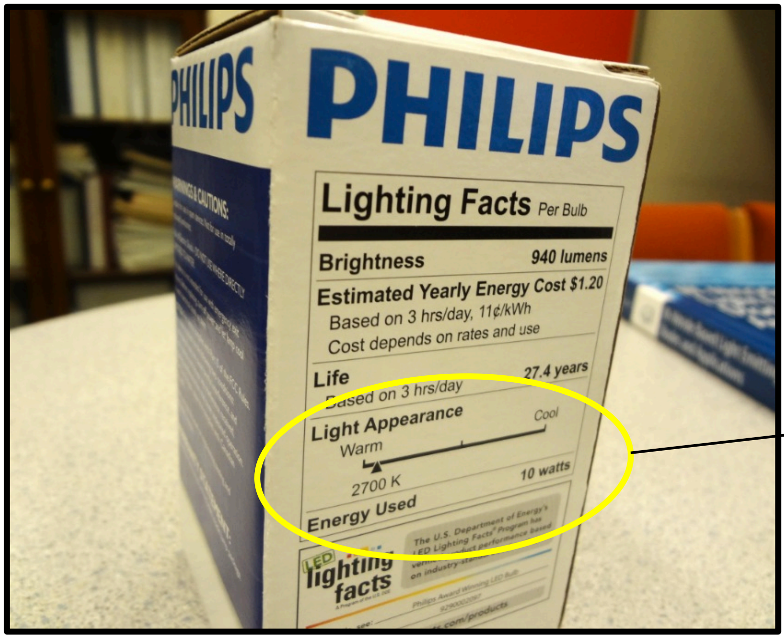
$$y = \frac{Y}{X+Y+Z}$$

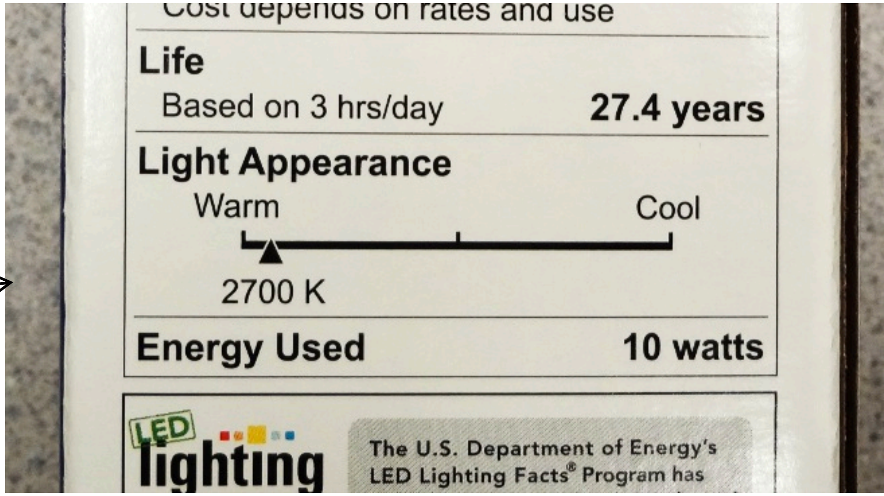
CIE 1931 (*x*, *y*) diagram

CIE 1976 (*u'*, *v'*) diagram



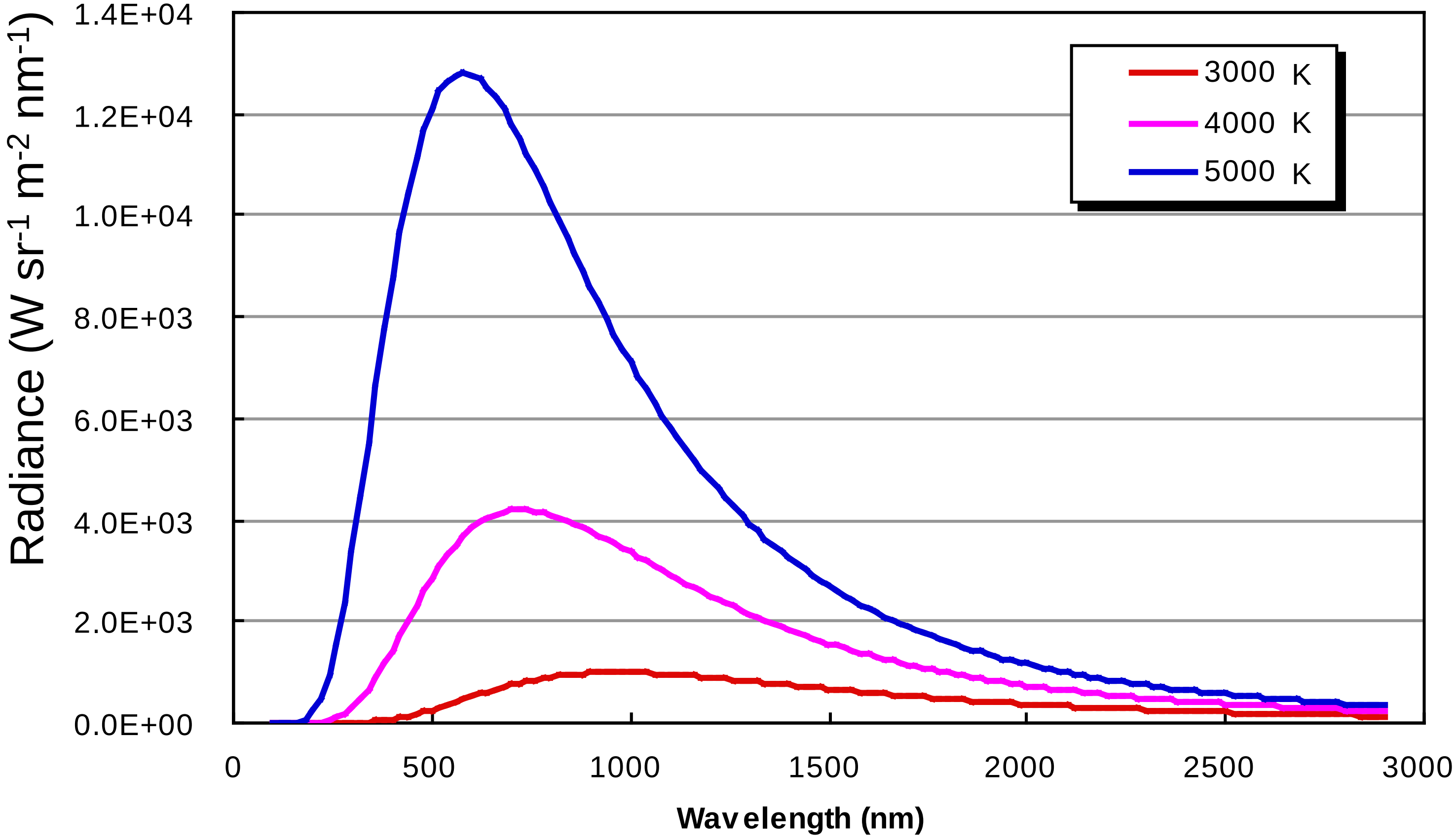
Color specification in products



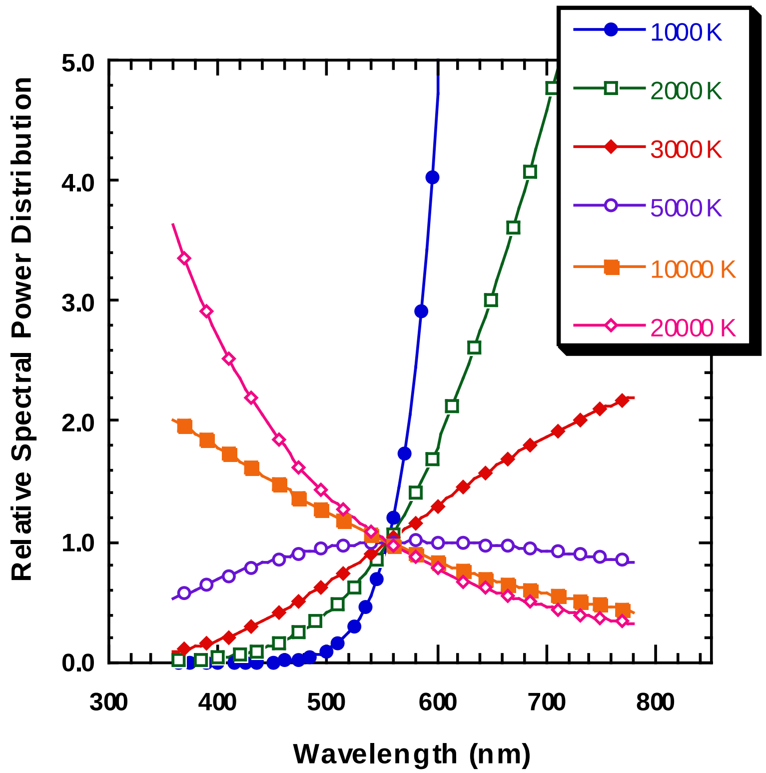


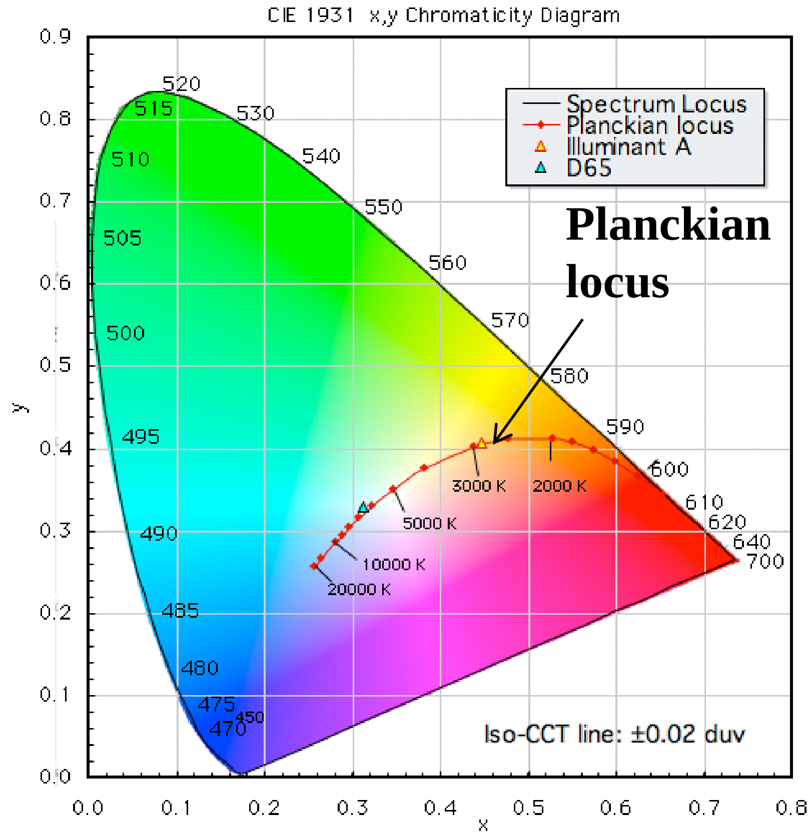
Spectral Radiance of a Planckian radiator (blackbody)

$$L_e(\lambda, T) = c_1 n^{-2} \pi^{-1} \lambda^{-5} \left[\exp\left(\frac{c_2}{n \lambda T} \right) - 1 \right]^{-1}$$



Color Temperature



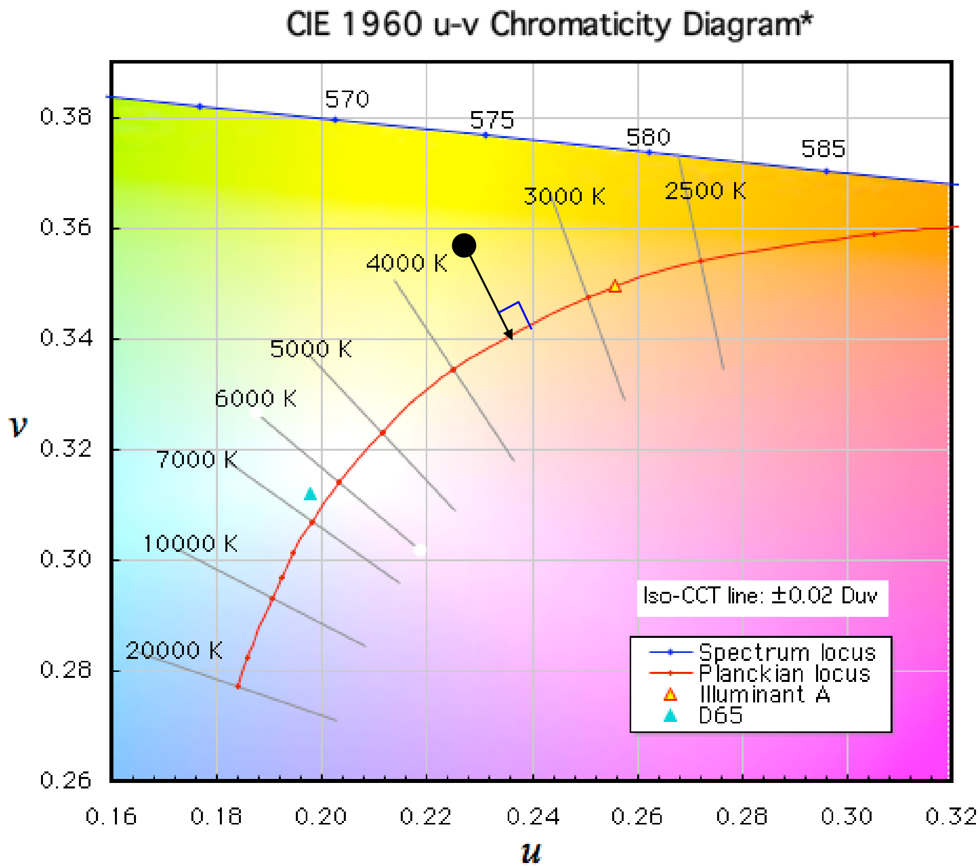


Colors along the Planckian locus are expressed by the temperature (K) of the blackbody.

Correlated Color Temperature (CCT)

Color of a light source can be expressed by the color temperature of the closest point on the Planckian locus on a uniform chromaticity diagram*.

* CIE 1960 (*u*,*v*) diagram



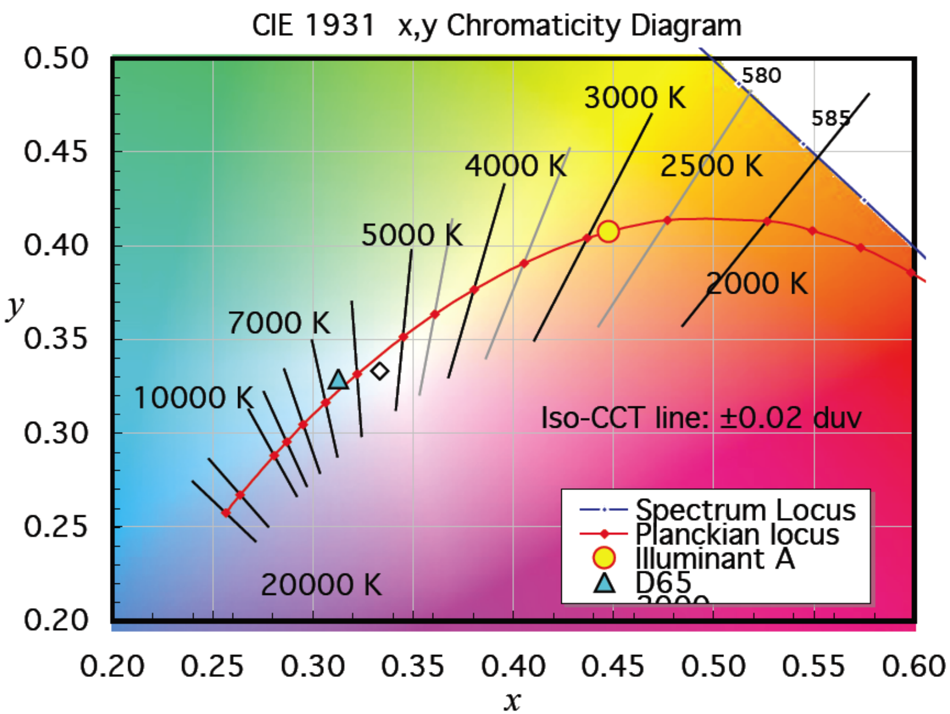
Symbol: T_{cp}

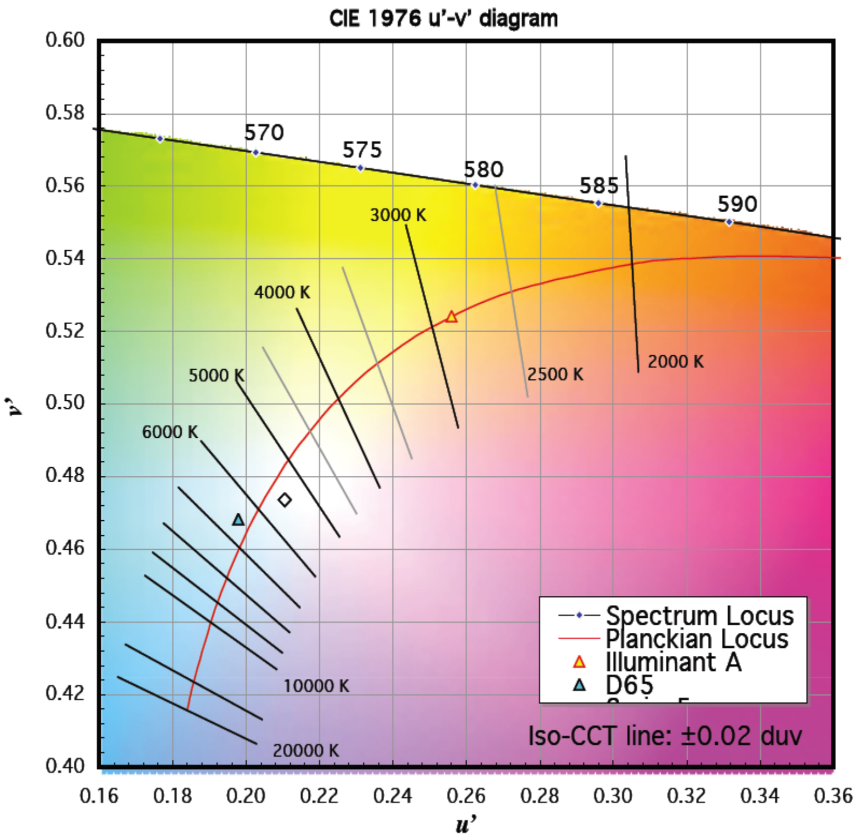
Applicable to white light sources only

CCT is based on the CIE 1960 (u, v) diagram, which is now obsolete.

CCT is valid within distance 0.05 from the Planckian locus on the (u' , $2/3 \cdot v'$) coordinate. (CIE 15:2004)

iso-CCT lines





OUTLINE

1. Optical Radiation
2. Radiometry and photometry
3. Quantities and units for optical radiation
4. Human visual response
5. Colorimetry
6. **Standards organizations**
7. Laboratory Examples

COMMISSION INTERNATIONALE DE L'ECLAIRAGE
INTERNATIONAL COMMISSION ON ILLUMINATION
INTERNATIONALE BELEUCHTUNGSKOMMISSION

CIE Central Bureau Kegelgasse 27 A-1030 Wien Austria

CIE: International Commission on Illumination

Established in 1913.

CIE defines quantities in optical metrology, publishes standards in light and lighting

CIE Central Bureau in Vienna, Austria
A. Webb (UK), President
Y. Ohno (USA), Vice President-Technical

Divisions

Division 1 Vision and Color
Division 2 Physical measurement of Light and Radiation
Division 3 Interior Environment and Lighting Design
Division 4 Lighting and Signalling for Transport
Division 5 Exterior Lighting and Other Applications
Division 6 Photobiology and Photochemistry
Division 8 Image Technology

The Meter Convention

CIPM (International Committee for Weights and Measures)

CCPR (Consultative Committee for Photometry and Radiometry)

CCPR defines units in optical metrology

Chair: T. Usuda (Japan)

WG on Key Comparisons (Y. Ohno, chair)
WG on Strategic Planning (J. Zwinkels, chair)
WG on CMC (rotates)

CCPR Key Comparisons

K1 (a,b,c) spectral irradiance
K2 (a,b,c) spectral responsivity
K3 luminous intensity
K4 luminous flux
K5 spectral diffuse reflectance
K6 spectral regular transmittance

Inter-American Metrology System (SIM)

Technical Committee of Photometry and Radiometry (TC-PR)

Chair: Maria Nadal (NIST, USA)

Key Comparisons
- SIM.PR-K4: luminous flux
- SIM.PR-K6: spectral regular transmittance (in preparation)
- SIM.PR-S3: cryogenic radiometer, bilateral (NIST-INMETRO)

Planned
- K3 luminous intensity
- more

OUTLINE

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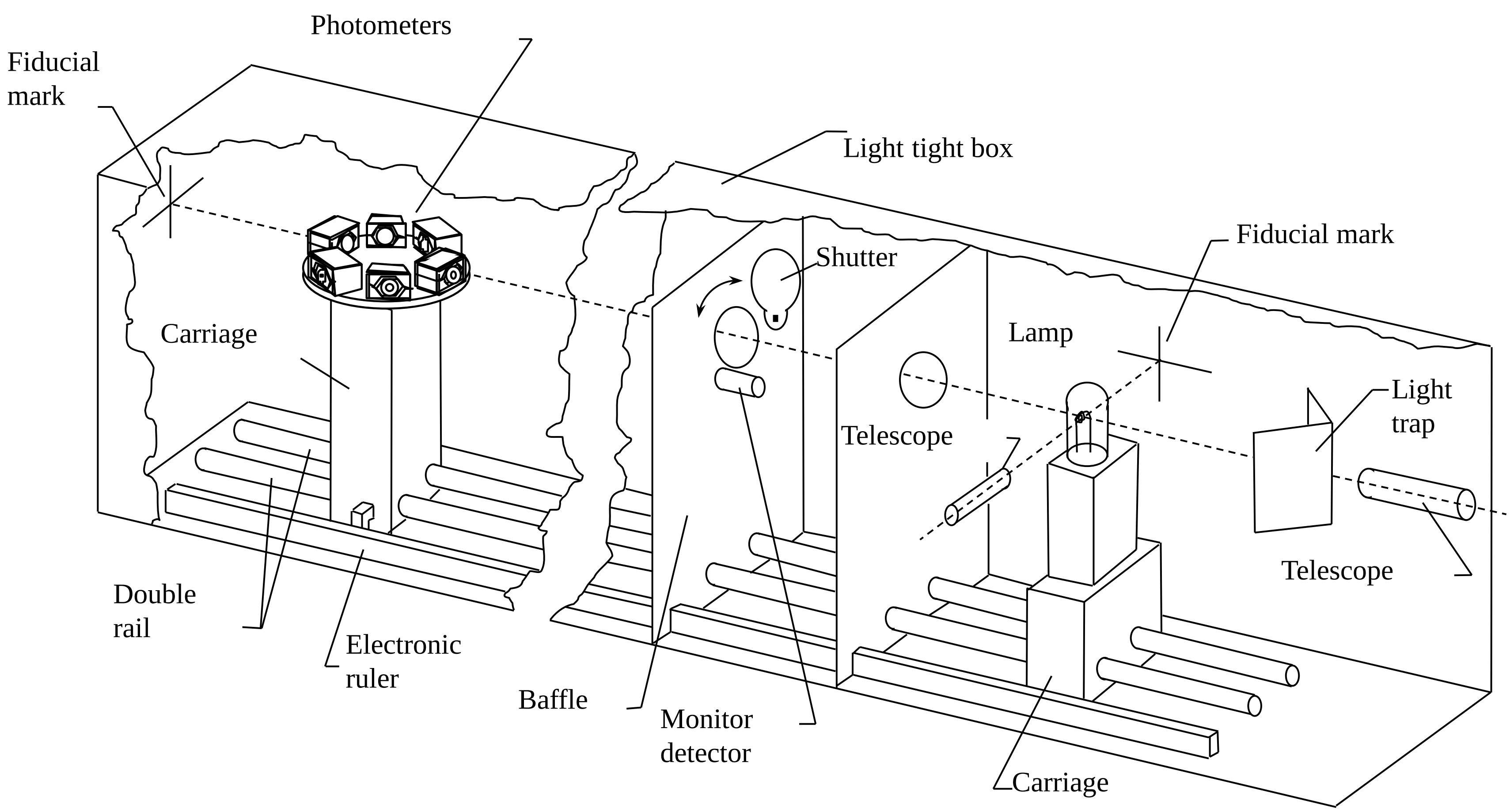
Example 1: Measurement of Luminous Intensity

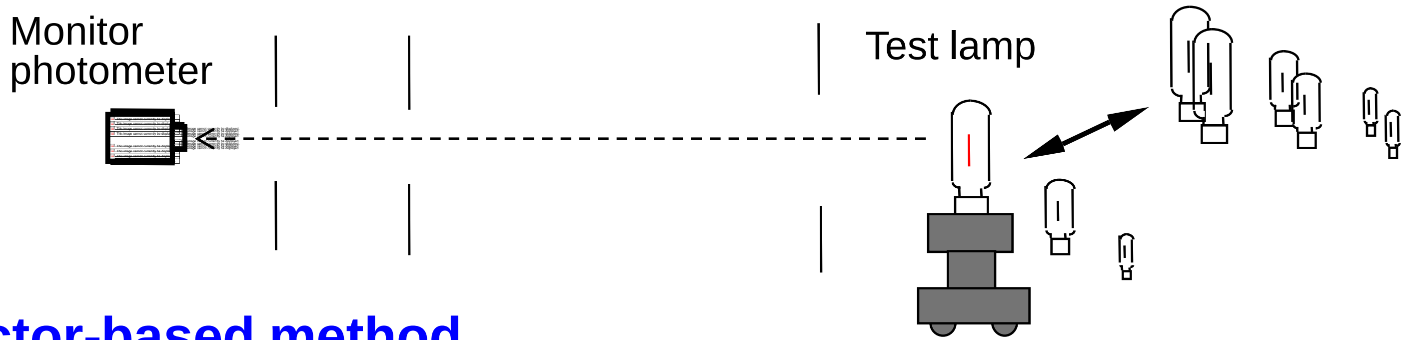
NIST photometry bench

NIST photometry bench

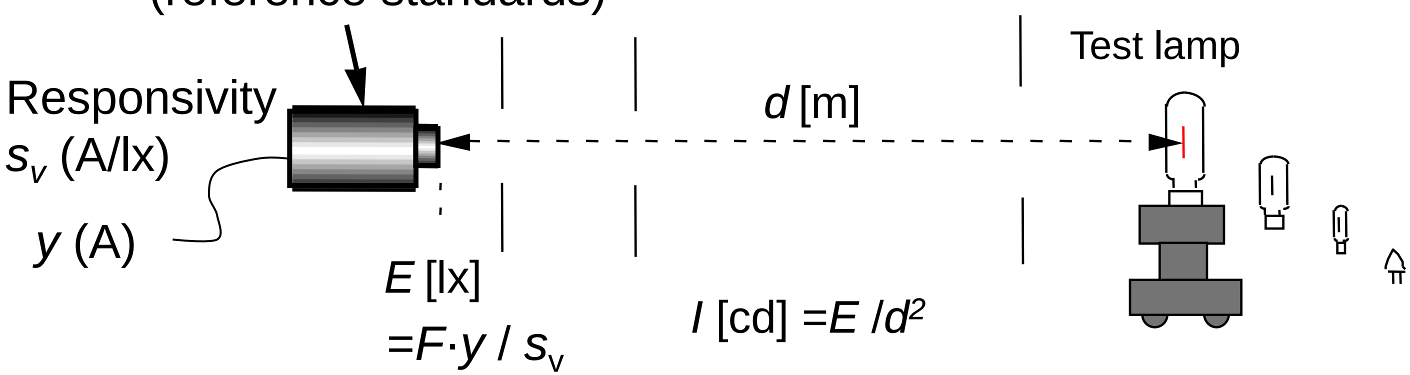


Example 1: Measurement of Luminous Intensity

Source-based method (substitution method)

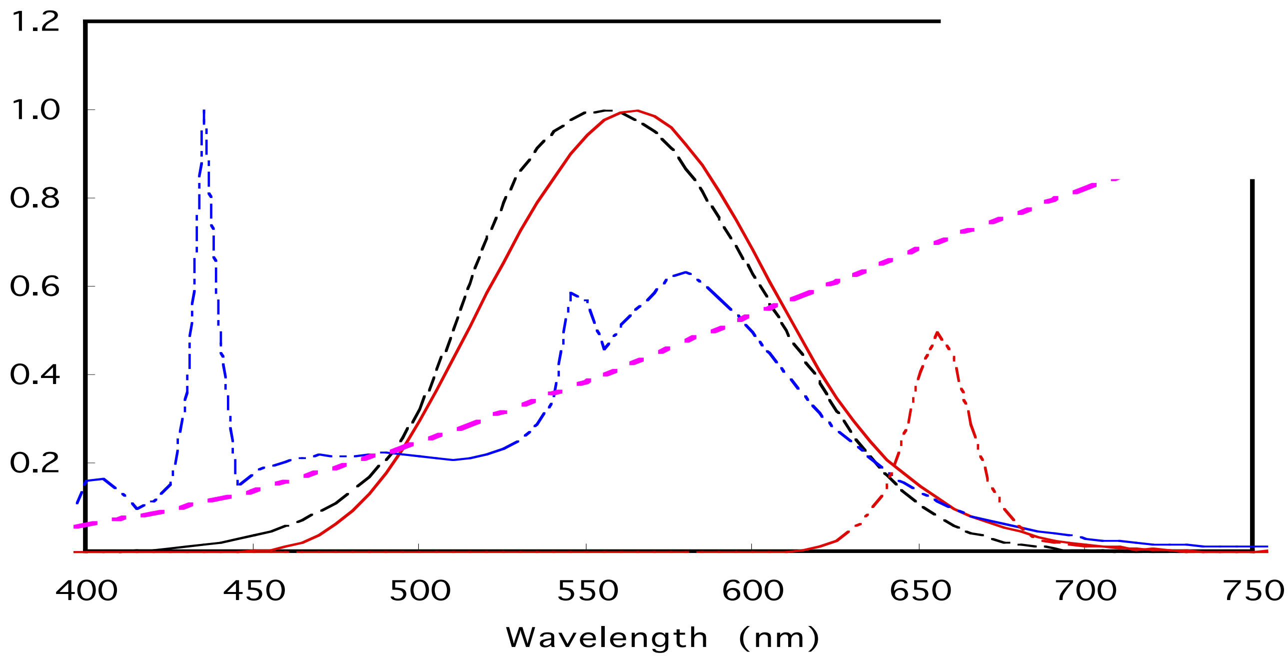


Detector-based method



F: spectral mismatch correction factor

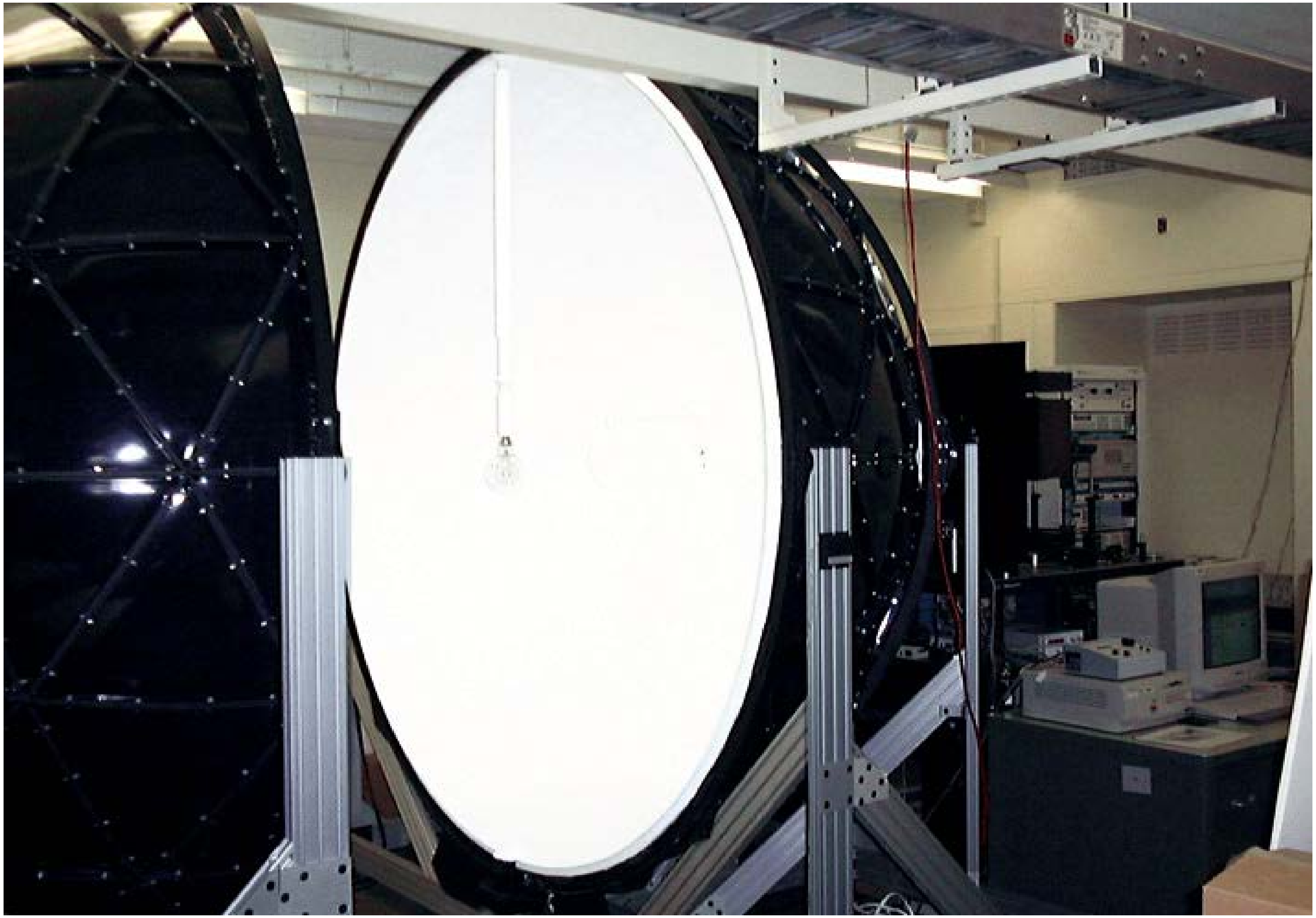
Spectral mismatch correction



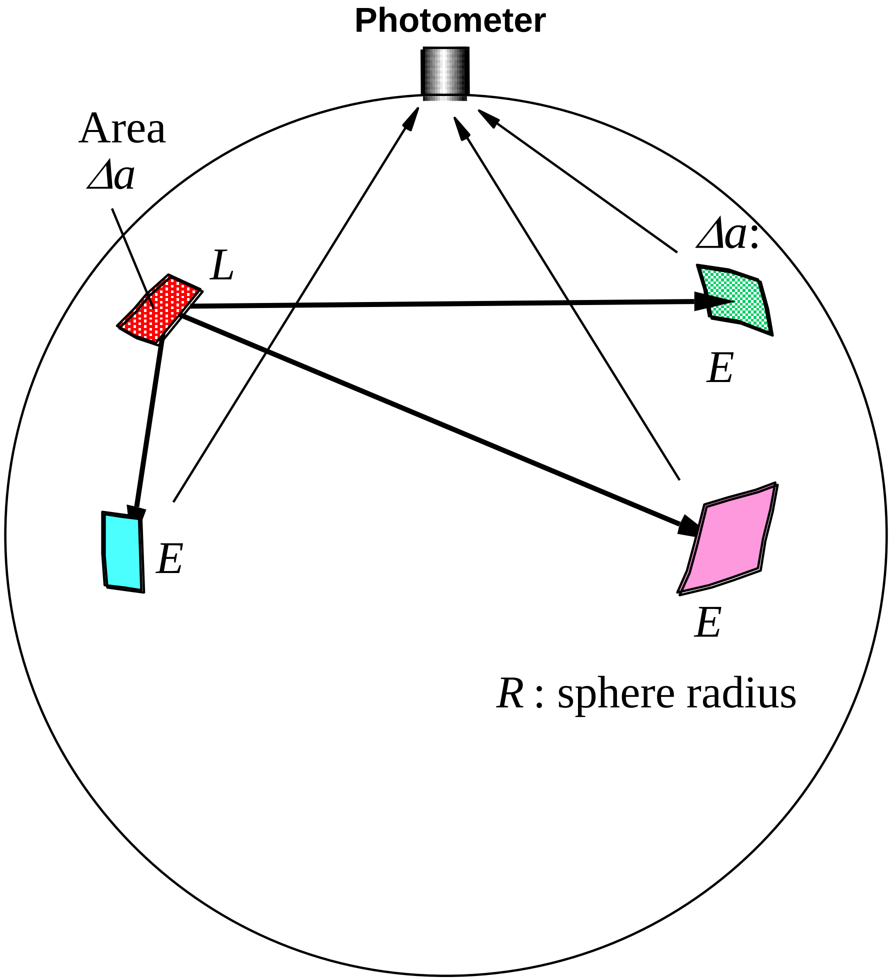
$$F(S_t,S_s) = \frac{\int_\lambda S_s(\lambda)\, R_s(\lambda)\, d\lambda \int_\lambda S_t(\lambda)\, V(\lambda)\, d\lambda}{\int_\lambda S_s(\lambda)\, V(\lambda)\, d\lambda \int_\lambda S_t(\lambda)\, R_s(\lambda)\, d\lambda}$$

$S_s(\lambda)$: SPD of standard lamp
$S_t(\lambda)$: SPD of test lamp
$R_s(\lambda)$: spectral responsivity of sphere system

Example 2: Measurement of Total Luminous Flux



Integrating Sphere Theory



Luminance *L* on a surface element creates equal illuminance *ΔE* all around the sphere surface

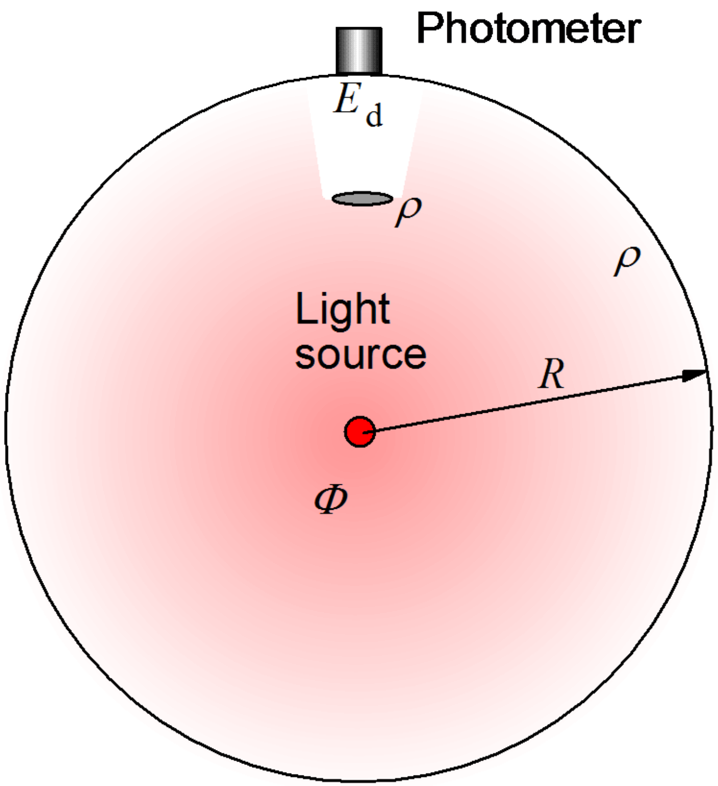
$$E = L \ \Delta a / 4R^2$$

The same amount of flux incident anywhere on the surface on the wall creates an equal illuminance on the photometer port.

Premise

* Sphere wall is perfectly Lambertian.

Measurement of total luminous flux with an integrating sphere



Direct illumination from the source to the detector must be shielded so that the detector measures only the flux from the sphere wall.

Flux created by interreflections:

$$\Phi\,(\rho + \rho^2 + \rho^3 \ldots\ldots) = \Phi \frac{\rho}{1-\rho}$$

Illuminance E_d created by interreflections

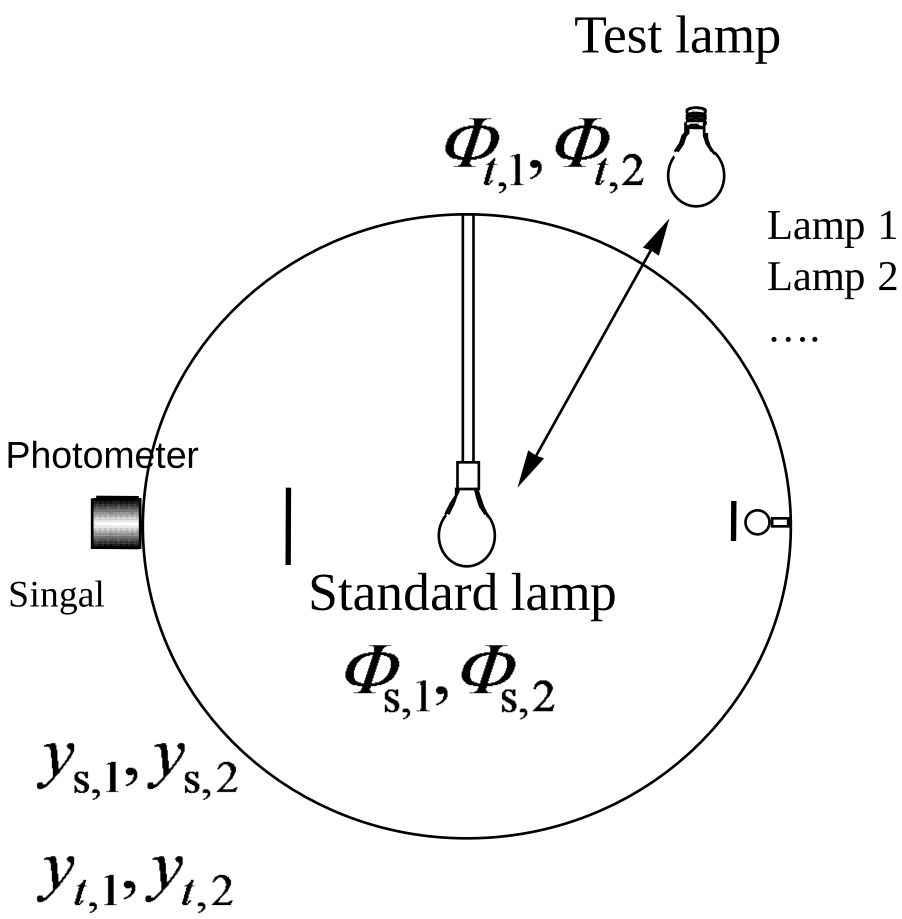
$$E_d = \frac{\Phi\,\rho}{1-\rho} \cdot \frac{1}{4\pi R^2}$$

This equation indicates:

1. The sphere throughput (E_d/Φ) is strongly dependent on ρ .
   (E_d at ρ=0.98 is 10 times larger than at ρ= 0.8)

2. The sphere throughput will be very sensitive to ρ when ρ is close to 1.
   (0.1 % change of ρ at ρ=0.98 causes 5 % change of the signal.)

Substitution Method



The sphere responsivity is calibrated as

$$R_s = \mathrm{ave}\left(\frac{y_{s,i}}{\Phi_{s,i}}\right) \quad [\mathrm{A/lm}]$$

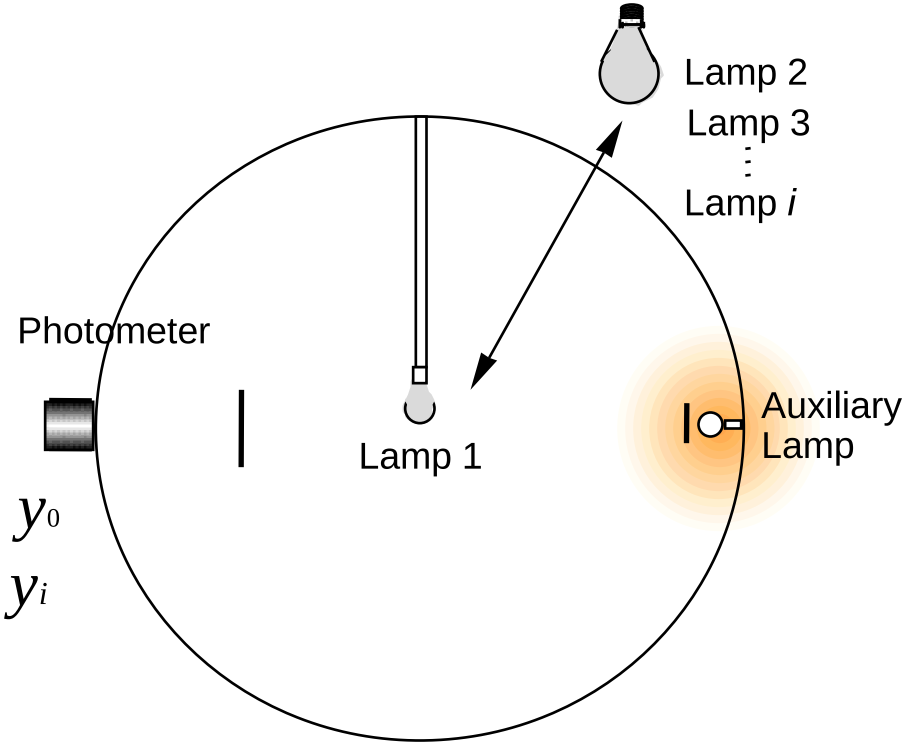
Luminous flux of test lamp $\Phi_{t,i}$ is obtained by

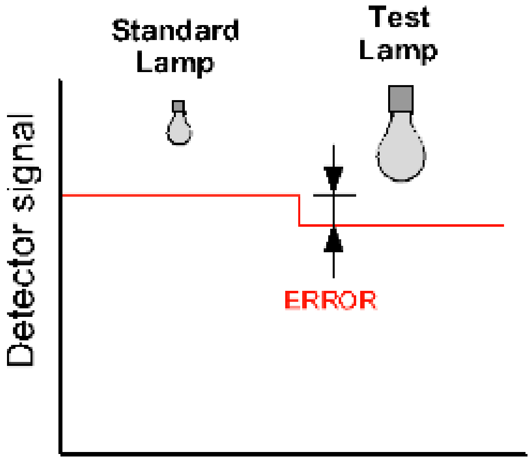
$$\Phi_{t,i} = \frac{y_{t,i}}{R_s} \cdot \frac{F}{\alpha} \quad [\mathrm{lm}]$$

α : self-absorption factor

F: spectral mismatch correction factor

Self-absorption Correction





With the auxiliary lamp turned on, measure the detector signals :

y_0 : Signal with standard lamp

y_i : Signal with test Lamp

Self-absorption Factor α_i for Lamp i is obtained by

$$\alpha_i = \frac{y_i}{y_0}$$

References

- ISO 80000 Quantities and Units, Part 7 Light (2008).
- SI brochure (8th edition) http://www.bipm.org/en/si/si_brochure
- CIE S 017/E:2011: ILV: International Lighting Vocabulary http://eilv.cie.co.at.
- *IES Lighting Handbook,* 10th Edition, Illuminating Engineering Society of North America (2011).
- BIPM Monographie, *Principles Governing Photometry* (1983).
- ISO 23539:2005(E)/CIE S 010/E:2004: Joint ISO/CIE Standard: Photometry - The CIE System of Physical Photometry
- OSA/AIP, *Handbook of Applied Photometry* (1997).
- Y. Ohno, NIST SP250-37, *Photometric Calibrations* (July 1997).
- B. N. Taylor, NIST Special Publication 811, *Guide for the use of the International System of Units (SI)* (1995).

- CIE 15:2004: Colorimetry, 3rd ed.
- ISO 11664-1:2007(E)/CIE S 014-1/E:2007: Joint ISO/CIE Standard: Colorimetry — Part 1: CIE Standard Colorimetric Observers
- ISO 11664-2:2007(E)/CIE S 014-2/E:2006: Joint ISO/CIE Standard: Colorimetry — Part 2: CIE Standard Illuminants for Colorimetry.
- CIE S 014-3/E:2011: Colorimetry - Part 3: CIE Tristimulus Values
- ISO 11664-4:2008(E)/CIE S 014-4/E:2007: Joint ISO/CIE Standard: Colorimetry — Part 4: CIE 1976 L*a*b* Colour Space
- CIE 13.3-1995: Method of measuring and specifying colour rendering of light sources New edition (including Disk D008)
- G. Wyszecki and W. S. Stiles, "Color Science: Concepts and Methods, Quantitative Data and Formulae," John Wiley and Sons, New York, 1982.
- Y. Ohno, Practical Use and Calculation of CCT and Duv, LEUKOS, 10:1, 47-55, DOI: 10.1080/15502724.2014.839020 (2013).

Questions

Are the following statements correct or not (Yes/No)?

1. The visible region is 360 nm to 830 nm (Yes/No).
2. Radiant energy in radiometry corresponds to luminous flux in photometry. (Yes/No)
3. Luminance of a surface is the same at any distance it is measured. (Yes/No)
4. Integrating sphere is used for luminous intensity measurement. (Yes/No)
5. Incandescent lamps have a correlated color temperatures of about 5000 K. (Yes/No)