Farbe

Units of Light
Overview

- radiometric units
- photometric units
- material properties
Radiometric Units

inconsistent & confusing varied notations!

- **radiant flux** [Strahlungsfluss]
- **irradiance** [Einstrahlung]
- **spectral irradiance**
- **radiance** [Abstrahlung]
- **spectral radiance**
Radiometric Units: **Radiant Flux**

**Radiant Flux**  
[Strahlungsfluss]

- also called radiant power [Strahlungsleistung]
- measure of the total power (energy per unit time) of electromagnetic radiation of a (light) beam
- measured in Watt (W)
- notation: $\Phi_e$
- includes visible, infrared and ultraviolet light
Radiometric Units

- **radiant flux** \([\text{Strahlungsfluss}]\)

- **irradiance** \([\text{Einstrahlung}]\)
- **spectral irradiance**

- **radiance** \([\text{Abstrahlung}]\)
- **spectral radiance**
**Radiometric Units: Irradiance**

**Irradiance** [Einstrahlung]

- measure of the total integrated radiant flux for all wavelengths per unit area falling on an illuminated body
- measured in Watt per m² (W/m²)
- notation: \( E \)

\[
E = \frac{\text{radiant flux}}{\text{area}} = \frac{d\Phi_e}{dA}
\]
**Radiometric Units: Spectral Irradiance**

**Spectral Irradiance**

- defined as irradiance per unit wavelength interval
- notation: $E(\lambda)$
- related to irradiance by:

$$E = \int_{0}^{\infty} E(\lambda) \, d\lambda$$
Radiometric Units

- **radiant flux** [Strahlungsfluss]
- **irradiance** [Einstrahlung]
- **spectral irradiance**

- **radiance** [Abstrahlung]
- **spectral radiance**
Reminder: What is a Steradian?

- **Steradian** = unit of solid angle
- symbol: $\text{sr}$
- a single unit of sr is defined as the solid angle subtended at the center of a sphere of radius $r$ by a portion of the surface of the sphere having an area $r^2$
- maximum = $4\pi \text{ sr}$
Reminder: Projection of a Polygon

\[ a \cdot \cos \theta \]
Radiometric Units: *Radiance*

**Radiance**  
*Abstrahlung*

- measure of the total integrated radiant flux for all wavelengths per steradian, per unit of perceived area of a luminous surface
- measured in Watt per m² per sr (W/m²/sr)
- notation: \( L \)

\[
L = \frac{\text{radiant flux per steradian}}{\text{perceived area}} = \frac{1}{\cos \theta} \frac{d^2 \Phi_e}{dA \, d\Omega}
\]
Radiometric Units: **Spectral Radiance**

**Spectral Radiance**
- defined as radiance per unit wavelength interval
- notation: \( L(\lambda) \)
- related to radiance by:

\[
L = \int_{0}^{\infty} L(\lambda) \, d\lambda
\]
Photometric Units

inconsistent & confusing varied notations!

- **luminous flux** \([\text{Lichtfluss}]\)
- **luminance** \([\text{Leuchtdichte}]\)
- **spectral luminance**
- **luminous efficiency** \([\text{Lichtausbeute}]\)
- **brightness** \([\text{Helligkeit}]\)
**Photometric Units: Luminous Flux**

**Luminous Flux**  
[Lichtfluss]

- also called luminous power  
  [Leuchtleistung]
- magnitude of the luminous stimulus of a light beam
- measured in *lumen* (lm)
- notation: $\Phi_v$
- only visible light
Photometric Units

- **luminous flux**  \([\text{Lichtfluss}]\)

- **luminance**  \([\text{Leuchtdichte}]\)
- **spectral luminance**

- **luminous efficiency**  \([\text{Lichtausbeute}]\)
- **brightness**  \([\text{Helligkeit}]\)
Photometric Units: **Luminance**

**Luminance**  
[Leuchtdichte]

- measure of the total integrated luminous flux for all wavelengths emitted per steradian, per unit of perceived area of a luminous surface

- measured in **candela** per m² (cd/m²)
  - cd = lm/sr

- notation: \( L_v \)

\[
L_v = \frac{\text{luminous flux per steradian}}{\text{perceived area}} = \frac{1}{\cos \theta} \frac{d^2 \Phi_v}{dA \ d\Omega}
\]
Photometric Units: **Spectral Luminance**

**Spectral Luminance**

- defined as luminance per unit wavelength interval
- notation: $L_v(\lambda)$
- related to luminance by the relation:

$$L_v = \int_0^\infty L_v(\lambda) \, d\lambda$$
Candela & Lumen

- **Definition**: 1 *candela* is the luminous intensity, in a given direction, of a monochromatic radiation source of frequency $540 \times 10^{12}$ hertz that has a radiant intensity in that direction of $1/683$ Watt per steradian.

- $540 \times 10^{12}$ hertz $\equiv$ 555 nm in air.

- “683” is to make the value identical to the previous version of the unit: the emission from 1 cm² of glowing, solidifying platinum (2042 K).

- *lumen*: $\text{lm} = \text{cd} \cdot \text{sr}$ ( cd = lm/sr )
Luminous Units

- **candela** is a unit of intensity (in a direction)
  - measures the intensity of a lamp viewed from a defined direction
- **lumen** is a unit of power (from a source)
  - measures the total luminous flux emitted by a lamp independent of its direction
- **lux** is a unit of illuminance (on a surface)
  - measures the illumination flux arriving on a surface
  - \( 1 \text{ lx} = 1 \text{ lm} / \text{m}^2 \)
Example: Description of a Lamp

- **yellow area** = lumen
- **brown curve** = candela
- **green area** = lux
Photometric Units

- **luminous flux**  
  [Lichtfluss]

- **luminance**  
  [Leuchtdichte]

- **spectral luminance**

- **luminous efficiency**  
  [Lichtausbeute]

- **brightness**  
  [Helligkeit]
Luminous Efficacy  

[Lichtausbeute]

- describes, how much lumen of light are produced by 1 Watt of energy
- notation: $\eta$

$$\eta = \frac{\Phi_v}{\Phi_e}$$

[Leuchtleistung]  [Strahlungsleistung]

- measured in lumen/Watt
Luminous Efficiency [Wirkungsgrad]

- defined as ratio of the luminance to the radiance
- notation: $\eta_L$
- has no dimension (is a percentage value)
- describes „how much of the power we see“
Spectral Luminous Efficiency

- looking at any specific wavelength \( \lambda \),
  \[
  L_v(\lambda) / L(\lambda) \quad [\text{Leuchtdichte / Abstrahlung}]
  \]
  is dependent only on the eye!

- dividing this curve by its peak value at 555 nm, we get \( V(\lambda) \)

- also called the *luminous sensitivity function* of the eye
Luminous Sensitivity Function

- 1 W of radiant flux at 555 nm produces 683 lm.
- Spectral luminous efficacy of a light source with wavelength $\lambda$ is: $683 \cdot V(\lambda) \cdot \text{lm/W}$.

Luminance $L_v$ of a polychromatic light is the sum of energy in each wavelength, multiplied by luminous efficacy of that wavelength:

$$L_v = \int_{0}^{\infty} 683 \cdot V(\lambda) \cdot L(\lambda) \, d\lambda = 683 \cdot \int_{0}^{\infty} V(\lambda) \cdot L(\lambda) \, d\lambda$$
Remarks on Luminance Efficiency

1 W of radiant flux at 555 nm produces 683 lm

1 W “ideally white“ radiant flux (5800 K black body truncated to 400-700 nm) can produce 251 lm of light (36% efficiency)

all valid for photopic conditions!

different values for scotopic conditions (eye adapted to the dark in dark environment)
**Brightness**  [„Leuchtwirkung“]

- is the actual perceived luminance for a given observer (subjective!)
- includes environment etc.
- e.g. Mach bands

*constant luminance but not constant brightness!*
Reflectance

- **reflectance** $\bar{\rho}$ of a diffuse object

\[
\bar{\rho} = \frac{\text{radiance (total radiant flux reflected in all directions)}}{\text{irradiance (total radiant flux incident on the object)}}
\]

- **spectral reflectance** $\rho(\lambda)$ is the reflectance per unit wavelength:

\[
\bar{\rho} = \int_{0}^{\infty} \rho(\lambda) \, d\lambda
\]

- **reflectance spectrum** describes color of an opaque object:
Transmittance

- **transmittance** $\overline{\tau}$ of a transparent object
  
  $$\overline{\tau} = \frac{\text{radiance (total radiant flux transmitted by the object)}}{\text{irradiance (total radiant flux incident on the object)}}$$

- **spectral transmittance** $\tau(\lambda)$ is the transmittance per unit wavelength:
  
  $$\overline{\tau} = \int_{0}^{\infty} \tau (\lambda) \, d\lambda$$

- **transmittance spectrum** describes color of a transparent object:
Luminous Reflectance & Transmittance

- **luminous reflectance** $\overline{R}$
  - luminous transmittance $\overline{T}$
  - by measuring *luminous* flux
    - (assuming a standard illuminant)

- **spectral luminous reflectance** $R(\lambda)$
  - **spectral luminous transmittance** $T(\lambda)$
  - defined per unit wavelength:

\[
\overline{R} = \int_0^\infty R(\lambda) \, d\lambda \quad \text{and} \quad \overline{T} = \int_0^\infty T(\lambda) \, d\lambda
\]
## Summary

### Radiometric Units
- **Radiant Flux**: $\Phi_e$
- (spectral) Irradiance: $E, E(\lambda)$
- (spectral) Radiance: $L, L(\lambda)$

### Photometric Units
- **Luminous Flux**: $\Phi_v$
- (spectral) Luminance: $L_v, L_v(\lambda)$
- Luminous Efficacy, Efficiency: $\eta, \eta_L$
- Luminous Sensitivity Function: $V(\lambda)$

### Luminous Units
- **Candela**: Intensity $\text{cd}$
- **Lumen**: Energy $\text{lm}$
- **Lux**: Illuminance $\text{lx}$

### Material Properties
- (spectral) Reflectance: $\bar{\rho}, \rho(\lambda)$
- (spectral) Transmittance: $\bar{\tau}, \tau(\lambda)$
- (spectral) Luminous Reflectance: $\bar{R}, R(\lambda)$
- (spectral) Luminous Transmittance: $\bar{T}, T(\lambda)$