Radiometry

Radiometry is the measurement of optical radiation, corresponding to wavelengths between 0.01 and 1000 µm, and includes the regions commonly called the ultraviolet, the visible and the infrared.

Energy & Power

Energy, Q, is measured in joules (J). Think of this as the number of photons in a beam of em radiation since each photon is a discrete packet of energy.

Power, Φ, is the derivative of energy with respect to time, dQ/dt, and the unit is the watt (W = J / s).

Energy is the integral over time of power, and is used for pulsed sources.

Power is used for continuous sources

Radiometric Quantities

Irradiance, E, is measured in W/m^2. Irradiance is power per unit area incident from all directions onto a surface.

Radiant exitance, M, which is power per unit area leaving a surface. This also has the units of W/m^2.

Radiant intensity, I, is measured in W/sr. Intensity is power per unit solid angle.

Radiance, L, is measured in W/m^2-sr. Radiance is power per unit projected area per unit solid angle.

Safety Standards

- ANSI Z136.1 American National Standard for Safe Use of Lasers. Laser safety associated with eye and skin.
- Sometimes Z136.1 used for non-laser sources (e.g. superluminescent diodes) due to stricter guidelines.
- ICNIRP non-ionizing radiation safety e.g. radio waves, microwaves, UV, infrared.
- ICNIRP covers lasers, but also considers incoherent broadband sources such as lamps, LEDs, etc.

Laser Classes

CLASS	Maximum Power	Comment
I	<0.38 μW	No ocular hazard
II	<1 mW	No retinal burns <0.25 sec, aversion
IIIa	<5 mW	1 sec burn threshold
IIIb	<500 mW	No skin burns < 1.0 sec
IV	>500 mW	Ocular, skin and fire hazard

Types of Hazards

- Photochemical – Chemical changes to molecules induced by the absorption of incident photons. Exhibits *reciprocity* which means a short intense exposure causes the same damage as long weak exposures.
- Thermal – Damage to tissue due to heating. No reciprocity.

Maximum Permissible Exposure

Somewhat self-explanatory. This is the amount of energy or power that can be safely viewed with the eye without damage. It is an order of magnitude below damage threshold.

The following constants are defined for MPE:

$$C_A = \begin{cases} 1 & 0.4 \le \lambda < 0.7\mu m \\ 10^{2(\lambda-0.7)} & 0.7 \le \lambda < 1.05\mu m \\ 5 & 1.05 \le \lambda < 1.4\mu m \end{cases}$$

$$C_B = 10^{15(\lambda-0.55)} \quad \text{for } 0.55 \le \lambda \le 0.77$$

$$C_C = \begin{cases} 1 & \lambda < 1.15\mu m \\ 10 & 1.15 \le \lambda < 1.20\mu m \\ 8 & 1.20 \le \lambda < 1.40\mu m \end{cases}$$

$$T1 = 10 \times 1010^{20(\lambda-0.450)}$$

MPE Calculations (Point Source)

Wavelength (µm)	Exposure Duration, t (s)	MPE ($J\cdot cm^{-2}$)	MPE ($W\cdot cm^{-2}$)
Ultraviolet			
Dual Limits for λ between 0.180 and 0.400 *µm*			
Thermal			
0.180 to 0.400	10^{-9} to 10	$0.56\ t^{0.25}$	
Photochemical			
0.180 to 0.302	10^{-9} to 3×10^{4}	3×10^{-3}	
0.302 to 0.315	10^{-9} to 3×10^{4}	$10^{200(\lambda-0.295)} \times 10^{-4}$	
0.315 to 0.400	10 to 3×10^{4}	1.0	
Visible			
0.400 to 0.700	10^{-13} to 10^{-11}	1.5×10^{-8}	
0.400 to 0.700	10^{-11} to 10^{-9}	$2.7\ t^{0.75}$	
0.400 to 0.700	10^{-9} to 18×10^{-6}	5.0×10^{-7}	
0.400 to 0.700	18×10^{-6} to 10	$1.8\ t^{0.75} \times 10^{-3}$	
0.500 to 0.700	10 to 3×10^{4}		1×10^{-3}
Thermal			
0.450 to 0.500	10 to T_1		1×10^{-3}
Photochemical			
0.400 to 0.450	10 to 100	1×10^{-2}	
0.450 to 0.500	T_1 to 100	$C_B \times 10^{-2}$	
0.400 to 0.500	100 to 3×10^{4}		$C_B \times 10^{-4}$

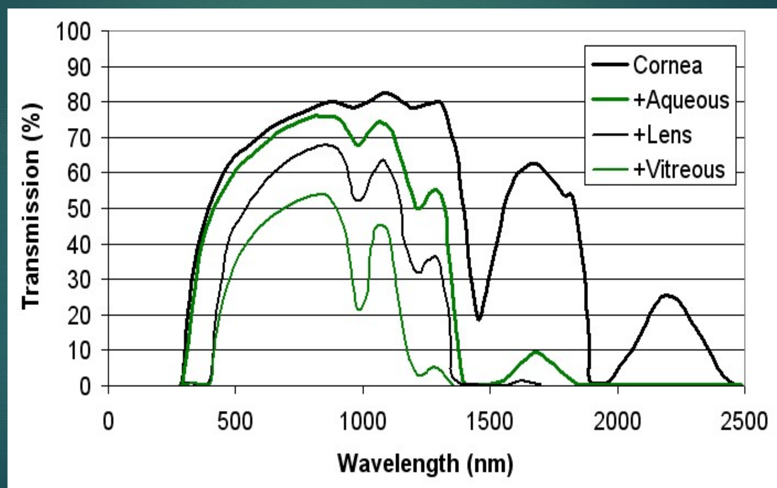
MPE Calculations (Point Source)

Wavelength	Exposure Duration, t	MPE	
(μm)	(s)	($J \cdot cm^{-2}$)	($W \cdot cm^{-2}$)
Near Infrared			
0.700 to 1.050	10^{-13} to 10^{-11}	$1.5\ C_A \times 10^{-8}$	
0.700 to 1.050	10^{-11} to 10^{-9}	$2.7\ C_A\ t^{0.75}$	
0.700 to 1.050	10^{-9} to 18×10^{-6}	$5.0\ C_A \times 10^{-7}$	
0.700 to 1.050	18×10^{-6} to 10	$1.8\ C_A\ t^{0.75} \times 10^{-3}$	
0.700 to 1.050	10 to 3×10^4		$C_A \times 10^{-3}$
1.050 to 1.400	10^{-13} to 10^{-11}	$1.5\ C_C \times 10^{-7}$	
1.050 to 1.400	10^{-11} to 10^{-9}	$27.0\ C_C\ t^{0.75}$	
1.050 to 1.400	10^{-9} to 50×10^{-6}	$5.0\ C_C \times 10^{-6}$	
1.050 to 1.400	50×10^{-6} to 10	$9.0\ C_C\ t^{0.75} \times 10^{-3}$	
1.050 to 1.400	10 to 3×10^4		$5.0\ C_C \times 10^{-3}$
Far Infrared			
1.400 to 1.500	10^{-9} to 10^{-3}	0.1	
1.400 to 1.500	10^{-3} to 10	$0.56\ t^{0.25}$	
1.400 to 1.500	10 to 3×10^4		0.1
1.500 to 1.800	10^{-9} to 10	1.0	
1.500 to 1.800	10 to 3×10^4		0.1
1.800 to 2.600	10^{-9} to 10^{-3}	0.1	
1.800 to 2.600	10^{-3} to 10	$0.56\ t^{0.25}$	
1.800 to 2.600	10 to 3×10^4		0.1
2.600 to 1000	10^{-9} to 10^{-7}	1×10^{-2}	
2.600 to 1000	10^{-7} to 10	$0.56\ t^{0.25}$	
2.600 to 1000	10 to 3×10^4		0.1

Ocular Tissue Absorption

Wavelength	Absorbing Structure	Effects
180 nm - 315 nm	Cornea	Photokeratitis (Welder's Flash)
315 nm - 400 nm	Lens	Cataracts
400 nm -780 nm	Retina	Retinal Lesions
780 nm -1.4 µm	Lens & Retina	Glassblower's Cataracts & Retinal Lesions
1.4 µm - 3.0 µm	Cornea & Lens	Glassblower's & Thermal damage
3.0 µm - 1.0 mm	Cornea	Thermal damage

Ocular Transmission



Ultraviolet Hazards

Different regions of the ultraviolet spectrum have different damage mechanisms.

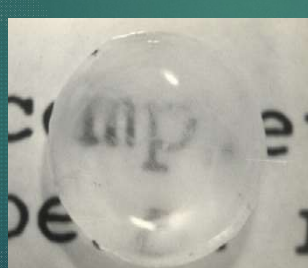
Label	Wavelength Band (nm)
UV-A	315-400
UV-B	280-315
UV-C	100-280

Photokeratitis

- Also, known as welder's flash and snow blindness.
- Front surface of cornea is covered by thin layer of epithelial cells that regenerate on a weekly basis.
- UV-B damages these cell and pain and poor vision can result.
- Typically, only lasts a couple of days until new epithelial cells resurface the cornea.

Glassblower's Cataract

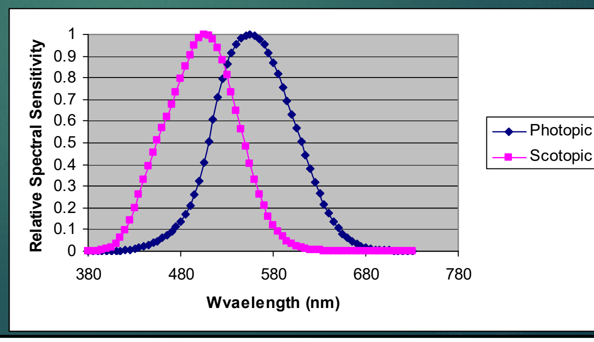
- Intensely heated glass gives off lots of infrared radiation (think of blackbody sources).
- Chronic exposure to these wavelengths (10-15 years) can cause premature cataracts



Photometry

Photometry is the measurement of light, which is defined as electromagnetic radiation which is detectable by the human eye. It is thus restricted to the wavelength range from about 360 to 830 nanometers.

Photometry is just like radiometry except that everything is weighted by the spectral response of the eye.

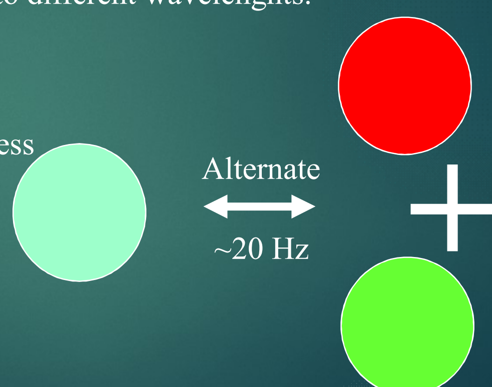


Measuring Response Curves

Heterochromic flicker photometry is a technique for measuring the sensitivity of the eye to different wavelenghts.

At this frequency, the spot will appear to flicker. The observer adjusts the brightness of the red spot until flicker is gone.

Brightness of red spot to brightness of green spot is the relative sensitivity.



Radiometric vs. Photometric Units

Radiometric	Photometric
Watt(W)	Lumen(lm)
W/m^2	lm/m^2 = lux
W/sr	lm/sr = candela (cd)
W/m^2-sr	lm/m^2-sr = cd/m^2

Luminous Flux

Luminous Flux (think Power), Φ_v, is in units of Lumens (lm) and is given by

$$\Phi_v = 683\int \Phi(\lambda)V(\lambda)d\lambda$$

for photopic vision, where V(λ) is the photopic response curve. There are 683 lm per W at a wavelength of 555 nm. For scoptic vision

$$\Phi_v = 1700\int \Phi(\lambda)V'(\lambda)d\lambda$$

where V'(λ) is the scotopic response curve.

Photometric Quantities

Illuminance, E_v, is measured in lm/m^2 (aka lux). Irradiance is the photopically weighted power per unit area incident from all directions onto a surface. Most light meters measure this quantity.

Luminous intensity, I_v, is measured in lm/sr (aka candela, cd). Intensity is spectrally weighted power per unit solid angle. Typically, only for small sources.

Luminance, L_v, is measured in lm/m^2-sr (aka cd/m^2). Luminance is the spectrally weighted power per unit projected area per unit solid angle. It gives the "brightness" of an source.

Luminance

Scene	Luminance (cd/m^2)
Clear Day	10^4
Overcast Day	10^3
Heavily Overcast Day	10^2
Sunset Overcast Day	10
15 Minutes After Sunset, Clear	1
30 Minutes After Sunset, Clear	10^{-1}
Bright Moonlight	10^{-2}
Moonless Clear Night	10^{-3}
Moonless Overcast Night	10^{-4}

Retinal Illuminance

A common unit for measuring Retinal Illuminance is the Troland, instead of lux.

Troland = (Luminance in cd/m^2)x(Pupil Area in mm^2)

Retinal Illuminance (Trolands) = 278 E_v (lux)

Example: A piece of paper in sunlight has a luminance of about 10000 cd/m^2. Typical pupil sizes in bright sum are 2 mm

(10000 cd/m^2)($\pi 1^2$) = 31400 Trolands