

Lecture 7 - Radiometry, Photometry, the $V(\lambda)$ function

RADIOMETRY

Q. What is radiometry?

A.

Q. What is the difference between radiometry and photometry?

A.

Energy and power

The basic unit of **energy** is the *joule*. **Power** is defined as *energy per unit time*. The basic unit for *power* is the *watt*.

$$1 \text{ watt} = 1 \text{ joule} / 1 \text{ second}$$

A light bulb rated at 60 watts of *radiant power* produces 60 joules of energy each second. If it's left on for 10 seconds it produces 600 joules of energy. This describes the total energy output of the light source.

Radiant intensity

A *point source* emits radiant energy in all directions. If located at the center of a sphere, its energy or power would be distributed across the inside surface of the sphere. In some cases you need to know how concentrated the power is. That is, how much power is contained within a defined volume. The amount of power contained within a defined cone-shaped volume is termed the *radiant intensity*. The more power in the cone, the greater its radiant intensity. The unit for solid angle (cone size) is the *steradian* (Schwartz Fig. 4-5).

$$\text{Steradians} = \text{Area at cone opening} / (\text{cone length})^2$$

To get a feel for the size of one steradian, imagine a fat ice cream cone with an opening that is 6.75" in diameter and has a length of 6". Such a cone has an angular volume of about 1 steradian. Radiant intensity quantifies the concentration of light coming from a *point source only* and is expressed in watts/steradian.

Radiance

An extended source can be thought of as a collection of points. The amount of radiant power *emitted* from an *extended source* is called its **radiance**. Radiance is expressed in units of watts/steradian/m².

Irradiance

The amount of radiant power *falling on a surface* is the **irradiance**. Irradiance is expressed in watts/m². Be careful not to confuse radiance and irradiance. Radiance refers to the energy emitted from a surface (energy off). Irradiance refers to energy falling onto a surface (energy on).

PHOTOMETRY

With this general background on radiometry, we will next study the topic of photometry. Radiometry describes the physical properties of light, but photometry describes light from a *perceptual* frame of reference. Radiometry measures energy; photometry quantifies light as it would be perceived by a **standard human observer**.

In optometry we are usually more interested in photometry than radiometry, but there are certain cases in which radiometry is more relevant. For example, when studying the effect of lasers on ocular tissues, we are not so concerned about how bright it looks, but rather, how much energy is transferred to the tissues. In that case, you would be more interested in radiometric than photometric data.

Photometry is closely related to radiometry, but be careful not to confuse them. Obviously for visible light, more energy or more power will make it appear brighter. That is why a 100-watt light bulb appears brighter than a 60-watt bulb.

Banner from the web site for a company that makes photometers (<http://www.licor.com/env/products/light/photometric.jsp>).

When comparing the apparent brightness of lights of different wavelength, you must take into account the sensitivity of the eye for different wavelengths. For example a 5-mW laser green laser will look brighter than a 5-mW red laser, because the eye is more sensitive to green than red light.

THE CIE LUMINOSITY FUNCTION

For simplicity, let's first consider a monochromatic light source that is visible to the human eye. In order to compute its brightness for a standard observer, that is, the **photometric intensity** of the light, you must know its:

- radiometric power (in watts)
- wavelength
- the eye's sensitivity at that wavelength

The eye's sensitivity to different wavelengths, for a standard observer, was established by the **CIE** (Commission Internationale de l'Eclairage or International Commission on Illumination) in 1924. This standardized data set is fundamental to the field of photometry and is known by several names: The ...

- luminous efficiency function of the human eye
- spectral luminosity function
- **photopic** luminosity function or
- 1924 CIE **$V(\lambda)$** function or V lambda curve for cone (photopic) vision

This function describes the normal relative sensitivity of the eye for different wavelengths under light-adapted conditions. That is, during daylight rather than night viewing conditions. In this case, the cone photoreceptors are working.

During dark adaptation, the eye's maximum sensitivity shifts toward shorter wavelengths, when the rods are working. The corresponding sensitivity function under dark adapted conditions is the **scotopic** luminosity function or the 1951 CIE $V'(\lambda)$ function (V -prime lambda function). We will usually work with the photopic $V(\lambda)$ function, but you should be aware that there is a different spectral luminosity function for scotopic (dark adapted) vision.

Figure 1 shows the $V(\lambda)$ and $V'(\lambda)$ functions on the same graph. Note that both are bell-shaped curves. The $V(\lambda)$ curve peaks at about 555 nm (peak cone sensitivity), therefore the luminous efficiency of the human eye at this wavelength is given a value of 1.0 $V(\lambda_{555}) = 1.0$. (Schwartz Figs. 4-1, 2, 8B)

The $V'(\lambda)$ (scotopic) curve is shifted toward shorter wavelengths and peaks at about 507 nm (peak rod sensitivity). The luminous efficiency under scotopic conditions, at this wavelength, is given a value of 1.0. $V'(\lambda_{507}) = 1.0$. (Schwartz Fig. 4-8A)

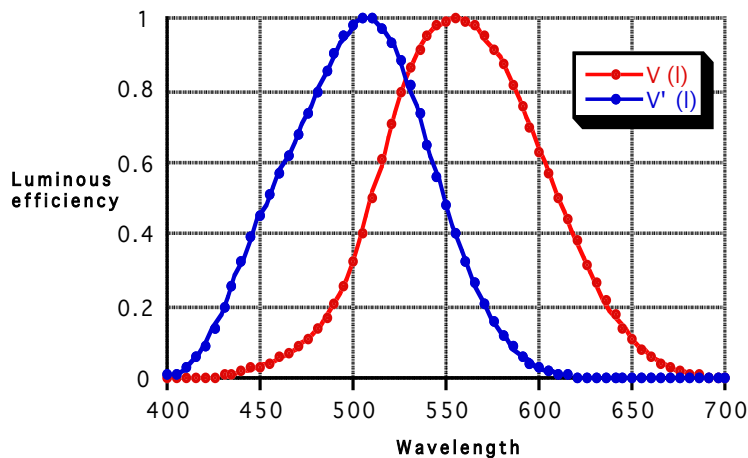


Figure 1. The CIE $V(\lambda)$ (right, red) and $V'(\lambda)$ (left, blue) curves

Derivation of the photopic luminosity function

How can you experimentally determine the photopic luminosity function? That is, how bright do different wavelengths appear to the human eye? One way (Schwartz Fig. 4-9) would be to compare a reference light with fixed wavelength and radiance, with another light of different wavelength. The subject would adjust the radiance of the test light until it appears the same brightness as the reference light (Fig. 2, below). Unfortunately this procedure gives variable results because it is difficult to match the brightness of stimuli that have different wavelengths.

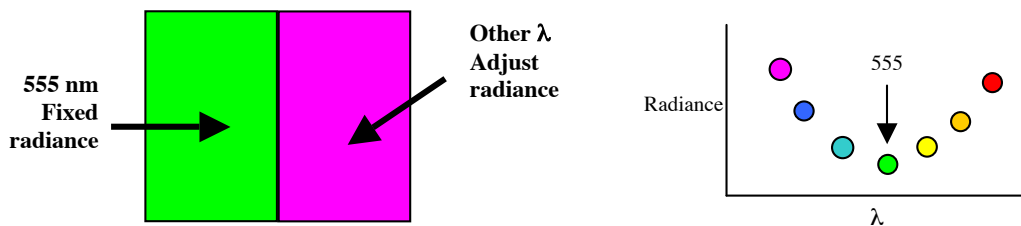


Figure 2. Experiment to compare relative luminous efficiency for different wavelengths.

Another clever method, known as **heterochromatic flicker photometry** (HFP), was developed to overcome this problem. A single illuminated stimulus is designed so that it alternately flickers between two wavelengths (in Fig. 3, Light A) at a rate of about 15 cycles/sec (~ 15 Hz). For example, one wavelength may be 555 nm with a fixed radiance (Light B), while the other wavelength is variable, and its radiance can be adjusted (Light C). The alternating colors will appear to fuse into another in-between color, but if their perceived brightnesses are not equal the light will still flicker. The *radiance* of the test wavelength is adjusted until the flicker disappears or is minimized. At that point, the *luminances* (perceived brightness for a standard human observer) are equal. The procedure is repeated for many test wavelengths. The CIE 1924 data is based on experiments using this method.

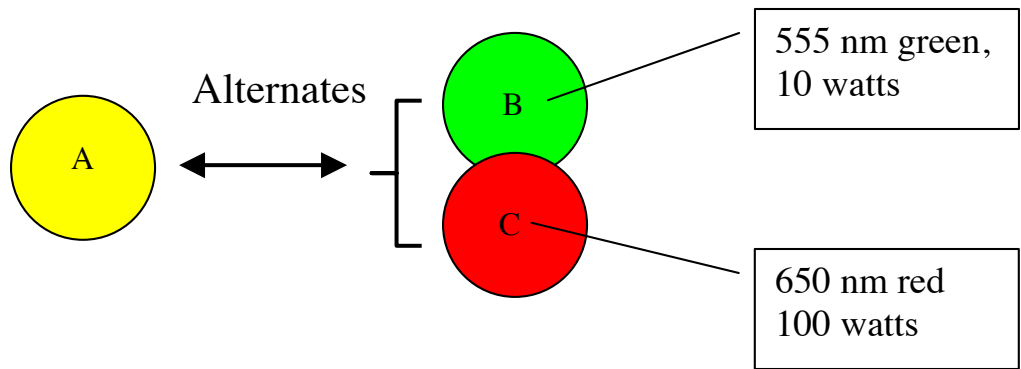


Figure 3. Heterochromatic flicker photometry. The yellow spot, whose color is seen as a fusion of the two alternating colors, appears to flicker until the luminances of the two colors become equal (equal perceived brightnesses). In this example, red must be set to ten times the radiant power of the reference green light, therefore the eye must be 1/10th as sensitive at 650 nm; hence the $V(\lambda)$ value at 650 nm is 0.1.

Minimally Distinct Border method is shown in Schwartz Fig. 4-11. The standard wavelength and test wavelength stimuli occupy two halves of a square patch (similar to the stimulus shown in Fig. 2) and share a common border. The radiances are adjusted until the border becomes minimally distinct. At that radiance the brightnesses appear to be equal, so luminances are equal. The results agree well with HFP results.

BASIC QUANTITIES MEASURED IN PHOTOMETRY

Luminous power

Whereas radiant power is simply a function of how much energy is present, *luminous power* indicates perceived brightness (for a standard human observer). 10 watts at 555 nm is much brighter than 10 watts at 400 nm. Even though the radiant power is the same, the *luminous power* at 400 nm is different. Luminous power at one particular wavelength is expressed in *lumens*, where one lumen is defined as:

$$\text{lumens} = (\text{radiant power in watts})V_{\lambda}(680)$$

This equation appears in Schwartz and uses a constant that has been rounded to 680. Other references may use 683 or 685. Note that this formula is for *photopic lumens*. See the examples in Schwartz Fig. 4-2.

The $V(\lambda)$ curve refers to the photopic luminosity function. Since rods are more sensitive to light, that is, they can see dim lights better than cones, the perceived brightness of a light in the scotopic system is different, and there is a different formula for *scotopic lumens*.

$$\text{scotopic lumens} = (\text{radiant power in watts})V'_{\lambda}(1700)$$

It turns out that at 555 nm, the scotopic luminous efficiency is 0.4, so for a 1-watt light source at that wavelength, there are 680 scotopic lumens. We won't use scotopic lumens much in this course. In the photopic system, luminous efficiency at 555 nm is 1.0, so for a 1-watt source at that wavelength, there are 680 photopic lumens.

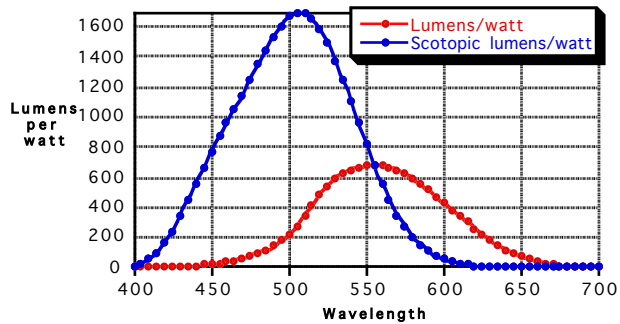


Figure 4 Photopic & scotopic lumens compared

Figure 4 shows the number of photopic and scotopic lumens at each wavelength, assuming a radiant power of 1 watt. Schwartz mentions that at 555 nm, both the number of photopic and scotopic lumens is equal to 680. At 507 nm there are 1699 scotopic lumens per watt. Schwartz rounds it to 1700.

If the light source is polychromatic (that is it has multiple wavelengths), the total luminous power is equal to the sum of the luminous power computed separately for each wavelength. The additivity of luminous power at each wavelength is called **Abney's law of additivity**. (Schwartz Fig. 4-3)

Luminous intensity

This photometric term is similar to radiant intensity (watts/steradian). It is used for a *point source* only and the unit for luminous intensity is the candela.

$$1 \text{ candela} = 1 \text{ lumen} / 1 \text{ steradian}$$

Luminance

The perceived brightness of an extended source (for the standard observer) is referred to as the **luminance** and is similar to radiance in that it quantifies light given off by an extended surface area. The basic metric unit for luminance is the **nit**.

$$1 \text{ nit} = 1 \text{ candela} / 1 \text{ m}^2$$

Another metric unit for luminance is the **apostilb** and the similar English unit is the **footlambert**. These are specifically used with *Lambertian surfaces*, which we will discuss in the next lecture. They are defined as follows:

$$1 \text{ apostilb} = (\text{candela} / \text{m}^2) / \pi = (1/\pi)\text{nits}$$

$$1 \text{ footlambert} = (\text{candela} / \text{ft}^2) / \pi$$

Illuminance

This term is similar to irradiance in that it quantifies light falling onto a surface. The metric unit for illuminance is the **lux**. The English unit for illuminance is the **foot-candle**.

$$1 \text{ lux} = 1 \text{ lumen} / \text{m}^2$$

$$1 \text{ foot-candle} = 1 \text{ lumen} / \text{ft}^2$$

Schwartz Table 4-1 lists recommended illuminance values for various sites or activities, and may be a useful reference for you someday when you are in practice. The field of photometry can be confusing because there are so many photometric units in both the English and metric systems. In this course we are mainly interested in metric photometric units, primarily the units for luminance and illuminance. The main units you need to know are

- luminance in nits
- luminance in apostilbs
- illuminance in lux

We will discuss one more specialized photometric, the troland, in the next lecture.

Be careful not to confuse *luminance* and *illuminance*. Luminance refers to the brightness of light coming off a surface. Illuminance refers to the brightness of the light falling on a surface.

Table 1, below, shows the parallel between radiometric and photometric units. Photometry is concerned with how bright a light looks and that depends both on the radiant power and the $V(\lambda)$ value for each particular wavelength considered.

Table 1 Comparison of radiometric and photometric units

| Description | Radiometry | Unit | Photometry | Unit |
|--|-------------------|--------------------------|--------------------|--|
| energy | energy | joule | | |
| energy/time (power) | radiant power | joules/sec (watt) | luminous power | lumen |
| intensity from a point source | radiant intensity | watts/steradian | luminous intensity | lumens/steradian (candela) |
| energy emitted from an extended source | radiance | watts/str/m ² | luminance | lum/str/m ² (candela/m ²) (nit) |
| energy falling on a surface | irradiance | watts/m ² | illuminance | lumens/m ² (lux) |