Product Document

Published by
ams OSRAM Group

TAOS Inc.

is now

ams AG

The technical content of this TAOS application note is still valid.

Contact information:

Headquarters:
ams AG
Tobelbaderstrasse 30
8141 Unterpremstaetten, Austria
Tel: +43 (0) 3136 500 0
e-Mail: ams_sales@ams.com

Please visit our website at **www.ams.com**

INTELLIGENT OPTO SENSOR

DESIGNER'S NOTEBOOK

TAOS TEXAS ADVANCED OPTOELECTRONIC SOLUTIONS®

Radiometric and Photometric Measurements with TAOS PhotoSensors

contributed by Todd Bishop
March 12, 2007

ABSTRACT

Light Sensing applications use two measurement systems; Radiometric and Photometric. Radiometric measurements deal with light as a power level, while Photometric measurements deal with light as it is interpreted by the human eye. Both systems of measurement have units that are parallel to each other, but are useful for different applications. This paper will discuss the differences and how they can be measured.

RADIOMETRIC QUANTITIES

Radiometry is the measurement of electromagnetic energy in the range of wavelengths between ~10nm and ~1mm. These regions are commonly called the ultraviolet, the visible and the infrared. Radiometry deals with light (radiant energy) in terms of optical power. Key quantities from a light detection point of view are radiant energy, radiant flux and irradiance.

SI Radiometry Units				
Quantity	**Symbol**	**SI unit**	**Abbr.**	**Notes**
Radiant energy	Q	joule	J	energy
Radiant flux	Φ	watt	W	radiant energy per unit time
Irradiance	E	watt per square meter	$W \cdot m^{-2}$	power incident on a surface

Energy is an SI derived unit measured in joules (J). The recommended symbol for energy is Q.

Power (radiant flux) is another SI derived unit. It is the derivative of energy with respect to time, dQ/dt, and the unit is the watt (W).

Energy is the integral over time of power, and is used for pulsed sources and integrating type detectors. Power is used for continuous sources and non-integrating type detectors.

WWW.TAOSINC.COM

Irradiance (flux density) is another SI derived unit and is measured in W/m^2. Irradiance is power per area incident from all directions in a hemisphere onto a surface that coincides with the base of that hemisphere. The symbol for irradiance is E. Irradiance is the derivative of power with respect to area. The integral of irradiance over area is power. See Figure 1 for an radiometric illustration.

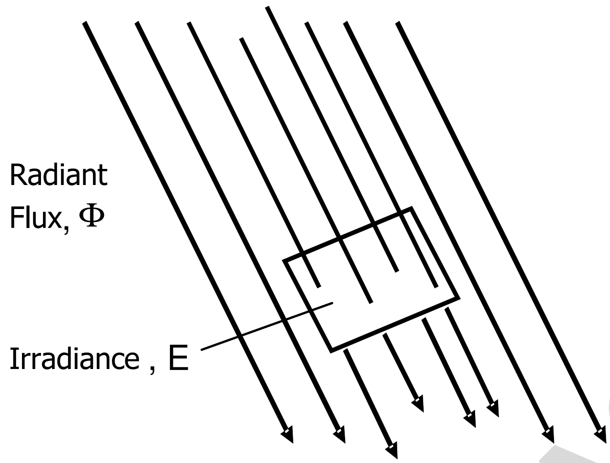

Figure 1. Radiometric Illustration

PHOTOMETRIC QUANTITIES

Photometry is the measurement of light that is detectable by the human eye. Photometry is just like radiometry except that everything is weighted by the spectral response of the eye. The only real difference between radiometry and photometry is that radiometry includes the entire optical radiation spectrum, while photometry is limited to the visible spectrum as defined by the response of the eye which is restricted to electromagnetic radiation in the wavelength range from about 380nm to 780nm. Since photometry uses the eye as a reference, photometric instruments use optical detectors constructed to mimic the spectral response of the eye. Typical photometric units include lumens, lux and candelas. Key quantities from a light detection point of view are luminous energy, luminous flux, and illuminance. These parameters are basically the same as the radiometric units except that they are weighted for the spectral response of the human eye.

The eye does not respond to all wavelengths of visible light with an equal sensitivity. The eye has two general classes of photosensors, which are the cones and rods. Light enters the front of the eye through a lens and is focused on the retina in the back of the eye. The human retina has rods and cones located on it. The rods and cones contain pigments. Pigments absorb light with absorption sensitivities that are wavelength dependent. The pigments allow the rods and cones to react to light in the visible region and pass that information to the optic nerve. See ***"TAOS DN20 Colorimetry Tutorial"*** for more information on the inner eye workings.

Rods are optimal at low light levels (scotopic vision), such as night vision, and provide the brain with information about light and dark which is good for seeing motion at night. At luminance levels below approximately 0.034 cd/m2, vision is classified as scotopic and is completely lacking in color. The rods have a peak responsivity to light around 510 nm in the blue-green region, and have little to no effect on color vision. See Figures 2 and 3.

The cones are what give humans the ability to distinguish colors at higher light levels (photopic vision). At luminance levels above approximately 3.4 cd/m2, vision is classified as photopic. The light-adapted relative spectral response of the eye is called the spectral luminous efficiency function for photopic vision, $V(\lambda)$. This empirical curve, first adopted by the international commission on illumination (CIE) in 1924, has a peak of unity at 555 nm, and decreases to levels below 10^{-5} at about 380nm and 780nm.

There is a region of vision between low light levels (scotopic) and high light levels (photopic) called mesopic where both rods and cones contribute to vision. An example of mesopic vision is when the sun starts to set. During this time, reddish colors fade to grey shades, followed by greens, and finally blues. Mesopic vision is not fully understood and is still a subject of much research. See Figure 2 for the three levels of vision and corresponding luminance levels of common sources.

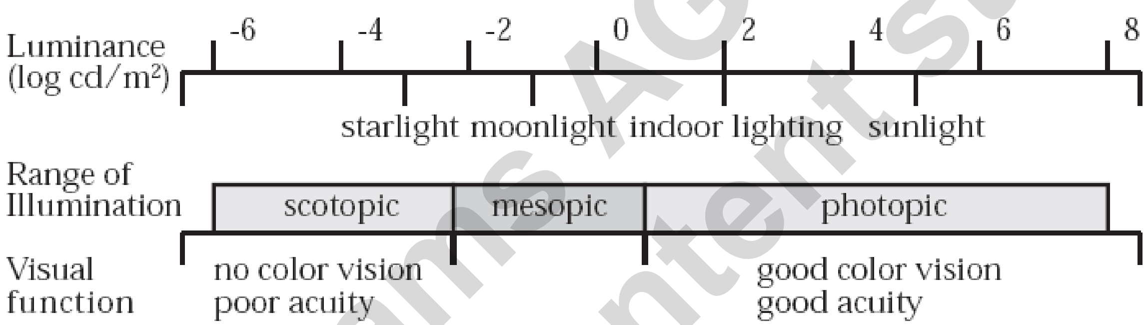

Figure 2. Types of Vision

SI Photometry units				
Quantity	**Symbol**	**SI unit**	**Abbr.**	**Notes**
Luminous energy	Q_v	lumen second	lm·s	units are sometimes called talbots
Luminous flux	F	lumen (= cd·sr)	lm	also called *luminous power*
Illuminance	E_v	lux (= lm/m^2)	lx	Used for light incident on a surface
Luminous efficacy		lumen per watt	lm/W	ratio of luminous flux to radiant flux; maximum is 683 Lm/W @ 555nm

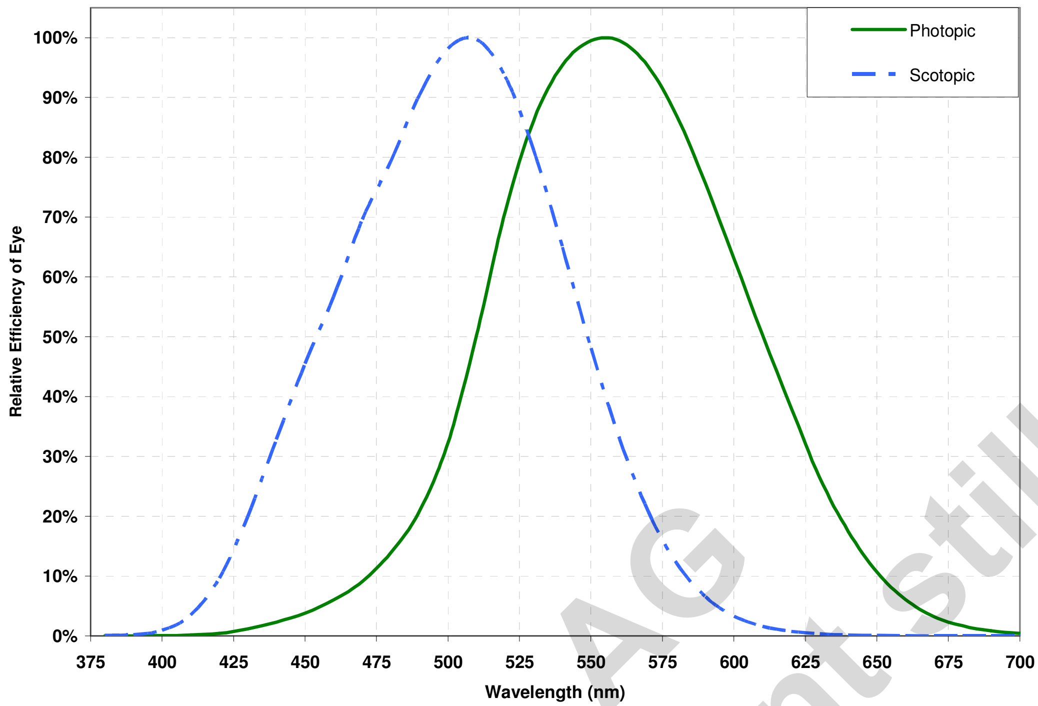

Figure 3. Scotopic and Photopic Vision

The lumen is an SI derived unit for luminous flux. The abbreviation is lm and the symbol is F. The lumen is derived from the candela and is the luminous flux emitted into unit solid angle (1 sr) by an isotropic point source having a luminous intensity of 1 candela. The lumen is the product of luminous intensity and solid angle, cd-sr. It is similar to the unit of radiant flux (watt) adjusted for how the eye responds to the light.

Illuminance is another SI derived quantity which denotes luminous flux density . It has a special name, lux, and is lumens per square meter, or lm/m2. The symbol is Ev. Most light meters measure this quantity. Typical values range from 50,000 to 100,000 lux for direct sunlight to 20 to 50 lux for low level interior lighting. See Figure 4 for an photometric illustration.

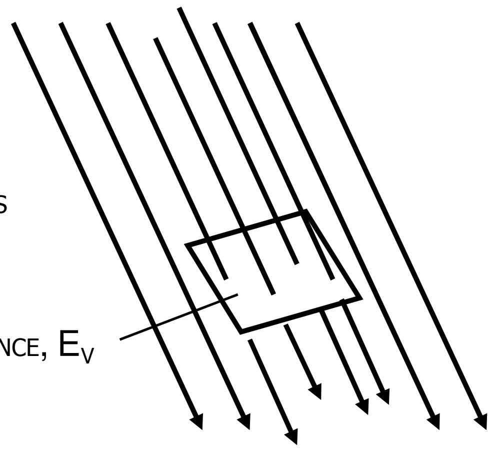

Figure 4. Photometric Illustration

Conversion between Radiometric and Photometric units

It can be seen that there is parallel terminology used between radiometric and photometric terms, and that the spectral range and weighting is really the only difference.

QUANTITY	RADIOMETRIC	PHOTOMETRIC
power	watt (W)	lumen (lm)
power per unit area	W/m^2	lm/m^2 = lux (lx)

The maximum luminous efficacy of 683 lumens per watt occurs at a wavelength of 555 nm (in the green region) for the eye. This is the wavelength that corresponds to the maximum spectral responsivity of the human eye as shown in Figure 3. The conversion from watts to lumens at any other wavelength involves the product of the power (watts) and the value of the spectral luminous efficiency function $V(\lambda)$ at the wavelength of light applied. In order to convert a source with non-monochromatic spectral distribution to a luminous quantity, the problem is more complex. For a broadband light source the spectral power distribution (SPD) of the source must be known because the energy in the visible region will be integrated according to how sensitive the eye is at each wavelength. The equation to convert from radiometric to photometric values can be found in Equation 1.

$$Q_v = 683 \int_{380}^{780} Q_\lambda \bullet V(\lambda) \bullet d\lambda$$

Equation 1. Photometric conversion formula

Where Q_V is a luminous term, Q_λ is the corresponding spectral radiant term at the wavelength of interest, and $V(\lambda)$ is the photopic spectral luminous efficiency function. For the conversion from photopic to radiometric quantities of Q, we can match luminous flux (lm) and spectral power (W/nm), illuminance (lx) and spectral irradiance (W/m^2-nm), luminous intensity (cd) and spectral radiant intensity (W/sr-nm), or luminance (cd/m^2) and spectral radiance (W/m^2-sr-nm). This equation represents a weighting of each wavelength of the radiant spectral term by the visual response of the eye at that wavelength. The constant in front of the integral is a scaling factor, which is the maximum spectral luminous efficiency for photopic vision of 683 lm/W. The wavelength limits can be set to restrict the integration to only those wavelengths where the product of the spectral term Q_λ and $V(\lambda)$ is non-zero. This means we only need to integrate from 380nm to 780nm which are the limits specified by the $V(\lambda)$ table. What this formula implies is that to convert a radiometric unit of light to a photometric one requires the energy spectrum of the light source to be biased to how the human eye perceives the brightness of light in the visible region, because the eye does not see light with wavelengths shorter than ~ 380nm or longer than ~ 780nm. If a purely infrared light source were used (such as a 880nm IR LED), it could have a large radiometric power output, but it would have a zero photometric light output. Since the $V(\lambda)$ function is defined by a table of empirical values, it is best to do the integration numerically.

Converting from radiometric to photometric values can be accomplished as long as the SPD of the light source is known, but if the reverse conversion is attempted from photometric to radiometric values the results could likely be incorrect. This occurs because the conversion to photopic values results in a loss of information outside the integration range of visible light. A conversion from photopic to radiometric could only be correct if the light source's SPD emitted no energy outside of the visible region. With these restrictions it would be difficult to have a meaningful conversion without a complete history of the light source SPD under investigation.

AMBIENT LIGHT MEASUREMENT

Ambient light measurement, or measurement of surrounding light intensity, is useful in applications such as display brightness control, streetlamp / lighting control, camera exposure controls, daylight harvesting, etc. where human-eye response is desired. In general the procedure to make an ambient light measurement with a TAOS photosensor would consist of placing the detector in a radiant flux of energy, then measuring the output that corresponds to the detectors sensitivity to energy at a certain wavelength as well as the amount of energy (light) available per area. See Equation 2.

$Ev = S / (Re*A)$
where: S = sensor Signal, Re = responsivity, A = area
Equation 2. PhotoSensor Irradiance Output function

The sensor output will vary greatly depending on the type of light source used. This is because every light source tends to have its own shape of SPD. A few common types of light sources are the Sun, a Tungsten filament incandescent lamp emitting light when heated to 2000°K to 3500°K, Fluorescent lamps containing phosphors that are excited by ultraviolet light emitted from ionized gas, LEDs (material bandgap determines color) and White LEDs (Blue LED with Phosphor Overcoat). The typical SPD of these common light sources can be found in Figure 5 and 6.

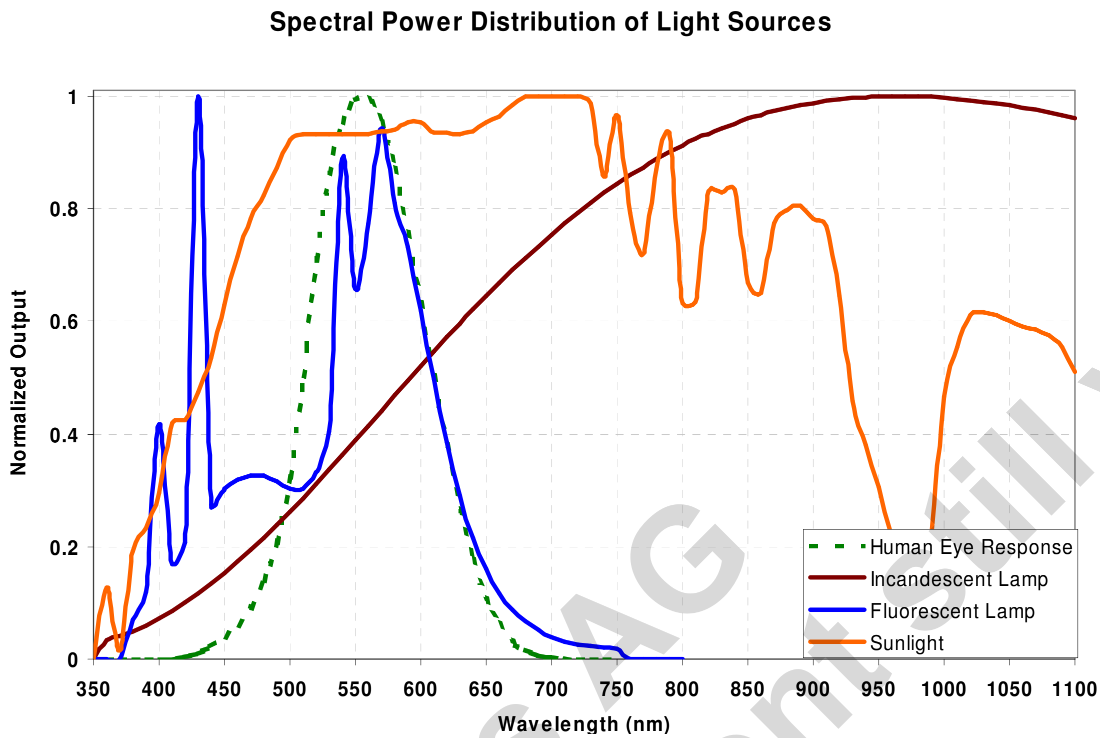

Figure 5. SPD of Sunlight, Incandescent 2800K, and typical Fluorescent

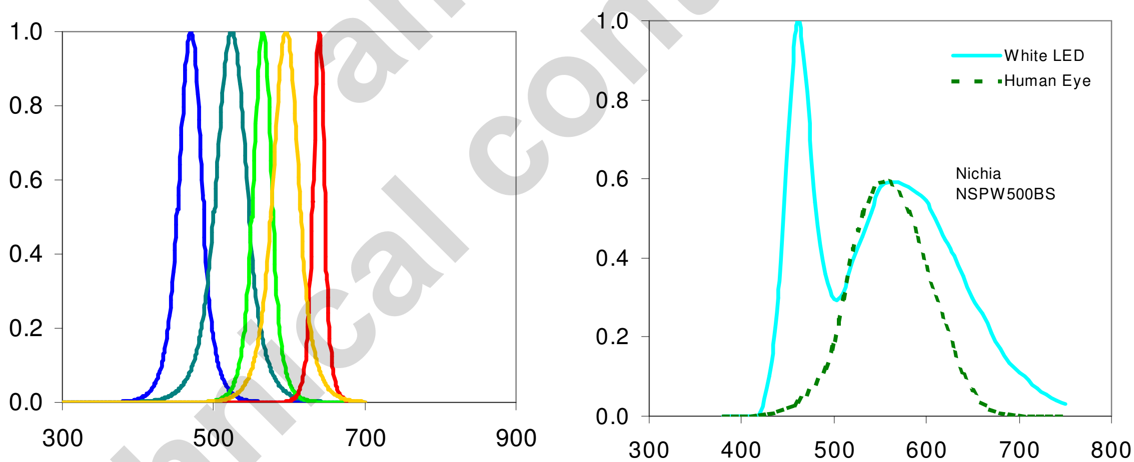

Figure 6. SPD of Monochromatic LED, and typical White LED

It can be seen from the charts that all these common light sources have dramatically different energy spectrums. It was shown in the *Photometric conversion Formula* in Equation 1, that the eyes only see light in the visible region from ~380nm to ~780nm when determining the perception of brightness. Silicon photosensors on the other hand react to light outside the sensitivity range of the eye.

Silicon PhotoSensors

TAOS photosensors, and Silicon photosensors in general, have a spectral response from approximately 300nm to 1100nm. See Figure 7 for a typical silicon detector spectral response. This means that Silicon photodiodes have response to light where the human eye does not respond. Using Silicon based photodiodes to replicate the way the eye sees can be difficult for this reason.

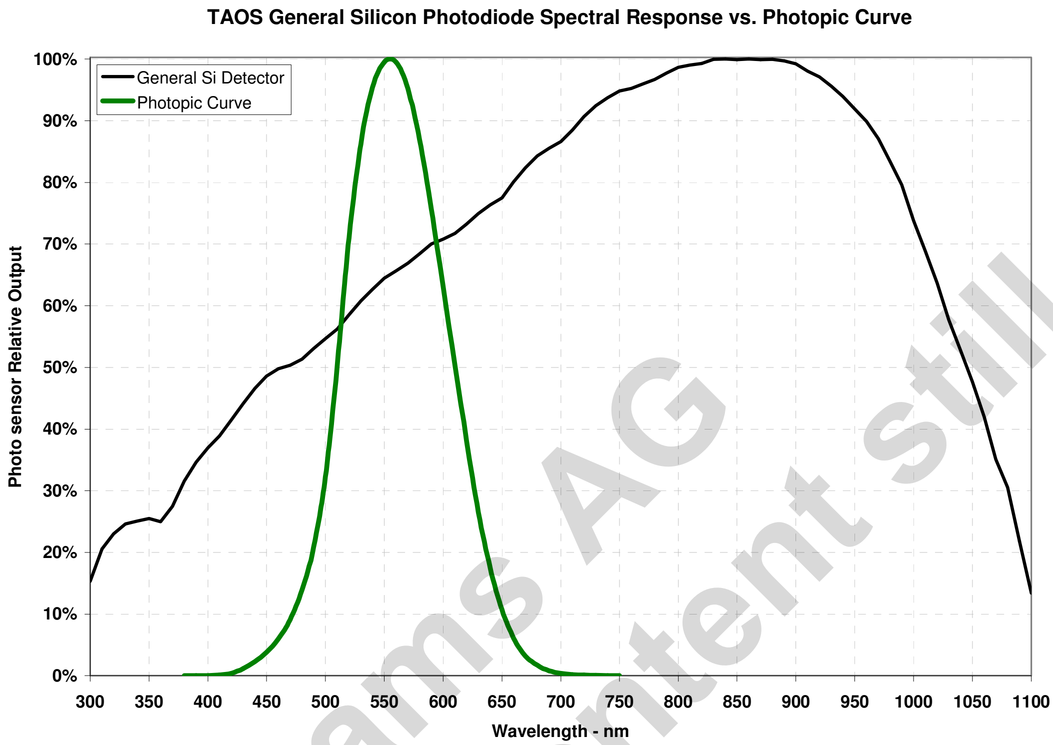

Figure 7. Typical silicon detector normalized spectral response vs. Photopic response

Earlier it was stated that an 880nm IR LED with some radiometric power output would have a zero photometric light output. A photodiode in this case would have some sensitivity to light in the near infrared range from 780nm to 1100nm that the eye does not see. As a result, the photodiode would have produced a nonzero output. In this instance if we were trying to use the photodiode to give an indication of a photometric output, the result would have been incorrect.

TAOS offers a group of ambient light sensors (ALS) that are specially designed to be used as photometric sensors.

If a non-photopic filtered photodiode is used to measure light for a photopic measurements, the results will vary largely based on the type of light source used because of the different SPD shape of light sources.

It may be possible through empirical measurements to get a correlation between a photodiode sensor output and a photometric quantity for a specific light source, but in general the results will have large errors, and this method is not recommended.

CONCLUSION

This paper has discussed the differences between Radiometric and Photometric measurements taken with Silicon Photo detectors. Results were shown that for a sensor to have a truly photometric response it has to have a sensor that mimics the sensitivity to light of the human eye. Since different types of light sources emit energy in different spectral wavelengths, the light source type will greatly affect the way humans perceive the light's photometric value. For a photosensor to produce a proportional photopic output it has to be designed with photopic measurements in mind. TAOS offers a line of products for ambient light sensing (ALS) that produce a digital output that can be used to calculate a corresponding photopic result. Please visit www.taosinc.com for more information on this family of ALS products.

REFERENCES

ANSLG. 2001. Specifications for the Chromaticity of Fluorescent Lamps, ANSI C78.376-2001. Rosslyn, VA: American National Standards Lighting Group – National Electrical Manufacturers Association

Borbély, A., A. Sámson, and J. Schanda. 2001. *The Concept of Correlated Color Temperature Revisited*, Color Research & Application 26(6):450–457

CIE, 1986. Colorimetry, Second Edition. Technical Report CIE 15.2-1986. Vienna, Austria: CIE Central Bureau

Ferwerda, James A., *Fundamentals of Spatial Vision*, Internet http://www.graphics.cornell.edu/~jaf/publications/notes_final.pdf

Malacara, Daniel*, Color Vision and Colorimetry Theory and Applications,* SPIE Press, Bellingham WA, 2002

McCamy, C. S. 1992. *Correlated Color Temperature as an Explicit Function of Chromaticity Coordinates*, Color Research & Application 17:142–144

McGuire*,* Kevin "Daylight: Is it in the eye of the beholder?", Internet http://www.solux.net/edu13.htm

Palmer, James, "Radiometry and Photometry FAQ", Internet http://www.optics.arizona.edu/Palmer/rpfaq/rpfaq.htm

Poynton, Charles, "The Color FAQ", Internet www.poynton.com/ColorFAQ.html

Walker, John, "Color Rendering of Spectra", Internet http://www.fourmilab.ch/documents/specrend/