APPENDIX I

THE SI SYSTEM AND SI UNITS FOR RADIOMETRY AND PHOTOMETRY

SI BASE UNITS

BASE QUANTITY	NAME	SYMBOL
length	meter	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	kelvin	K
amount of substance	mole	mol
luminous intensity	candela	cd

SELECTED SI DERIVED UNITS

QUANTITY	NAME	SYMBOL	EQUIVALENT
plane angle	radian	rad	
solid angle	steradian	sr	
energy	joule	J	N-m
power	watt	W	J-s^{-1}
frequency	hertz	Hz	s^{-1}
electric charge	coulomb	C	A-s
luminous flux	lumen	lm	cd-sr
illuminance	lux	lx	lm-m^{-2}
luminance	candela per square meter	cd-m^{-2}	lm-m^{-2}-sr^{-1}
radiant intensity	watt per steradian	W/sr	
radiance	watt per square meter steradian	w/(m^2-sr)	

SI PREFIXES

Factor	Prefix	Symbol	Factor	Prefix	Symbol
10^{24}	yotta	Y	10^{-1}	deci	d
10^{21}	zetta	Z	10^{-2}	centi	c
10^{18}	exa	E	10^{-3}	milli	m
10^{15}	peta	P	10^{-6}	micro	μ
10^{12}	tera	T	10^{-9}	nano	n
10^{9}	giga	G	10^{-12}	pico	p
10^{6}	mega	M	10^{-15}	femto	f
10^{3}	kilo	k	10^{-18}	atto	a
10^{2}	hecto	h	10^{-21}	zepto	z
10^{1}	deka	d	10^{-24}	yocto	y

Complete SI information is available on the World Wide Web at ***www.bipm.fr*** and at ***physics.nist.gov/Pubs/SP811/SP811.html***

The following tables show radiometric and photometric quantities and symbols, definitions and units.

RADIOMETRIC QUANTITIES

QUANTITY	SYMBOL	DEFINITION	UNITS
Radiant energy	Q		joule [J]
Radiant power (flux)	Φ	dQ/dt	watt [W]
Radiant intensity	I	$d\Phi/d\omega$	watt/sr
Radiant exitance	M	$d\Phi/dA$	watt/m^2
Irradiance	E	$d\Phi/dA$	watt/m^2
Radiance	L	$d^2\Phi/(dA \cos\theta \, d\omega)$	watt/m^2-sr

t = time (s), ω = solid angle (sr), A = area (m^2)

PHOTON QUANTITIES

QUANTITY	SYMBOL	DEFINITION	UNITS
Photon power (flux)	Φ_q	dn/dt	/s
Photon intensity	I	$dn/d\omega$	/sr-s
Photon exitance	M	dn/dA	/m^2-s
Photon irradiance	E_q	dn/dA	/m^2-s
Photon radiance	L_q	$d^2n/(dA \cos\theta \, d\omega)$	/m^2-sr-s

n = photon number

SPECTRAL QUANTITIES are derivative, per unit wavelength with the additional dimension m^{-1}, and are indicated by a subscript λ (e.g. spectral radiance L_λ with units W-m^{-3} sr^{-1}.) Non-spectral quantities that are wavelength-dependant are indicated as (λ); e.g. transmission, $\tau(\lambda)$.

PHOTOMETRY is the measurement of light (optical radiant energy as above but weighted by the response function of the human eye). The symbols used are the same as radiometric quantities with the subscript v (for visual) added.

QUANTITY	SYMBOL	UNITS
Luminous Power	Φ_v	Lumen (lm)
Luminous Exitance	M_v	lm /m^2
Luminous Incidance	E_v	lm /m^2
Luminous Intensity (SI base unit)	I_v	lm /sr = candela
Luminance	L_v	lm /m^2-sr = candela /m^2

APPENDIX II

PHYSICAL CONSTANTS, CONVERSION FACTORS AND OTHER USEFUL QUANTITIES

Quantity	**Symbol**	**Value**	**Units**	**Relative uncertainty**
Speed of light (vacuum)	c, c_o	299 792 458	m s^{-1}	exact
Permeability of vacuum	μ_o	$4\pi\times10^{-7}$	N A^{-2}	exact
Permittivity of vacuum	e_o	$1/\mu_o c^2 = 8.854\ 187\ldots\times10^{-12}$	F m^{-1}	exact
Planck constant	h	$6.626\ 068\ 76\ (52)\times10^{-34}$	J s	7.8×10^{-8}
Electronic charge	q, e	$1.602\ 176\ 462\ (63)\times10^{-19}$	C	3.9×10^{-8}
Boltzmann constant	k	$1.380\ 6503\ (24)\times10^{-23}$	J K^{-1}	1.7×10^{-6}
Boltzmann constant	k	$8.617\ 342\ (15)\times10^{-5}$	eV K^{-1}	1.7×10^{-6}
Stefan-Boltzmann constant	σ	$5.670\ 400\ (40)\times10^{-8}$	W m^{-2} K^{-4}	7.0×10^{-6}
First radiation constant ($2\pi hc^2$)	c_1	$3.741\ 771\ 07\ (29)\times10^{-16}$	W m^2	7.8×10^{-8}
First radiation constant for L_λ	c_{1L}	$1.191\ 042\ 722\ (93)\times10^{-16}$	W m^2 sr^{-1}	7.8×10^{-8}
Second radiation constant	c_2	$1.438\ 7752\ (25)\times10^{-2}$	m K	1.7×10^{-6}
Wien displacement law constant	b	$2.897\ 7686\ (51)\times10^{-3}$	m K	1.7×10^{-6}

These are the **1998 CODATA** recommended values of the fundamental physical constants. Adapted in part from P.J. Mohr & B.N. Taylor, "The Fundamental Physical Constants," J. Phys. Chem. Ref. Data **28**, 1713 (1999) and Rev. Mod. Phys. **72**, 351 (2000). These constants are also available in Physics Today, **54** (Part 2), BG6 (2001), reprinted yearly, and from *http://physics.nist.gov/constants*.

Here are some useful conversion factors:

$hc = 1.986\ 445\times10^{-25}$ J-m $= 1.986\ 445\times10^{-19}$ J-μm $= 1.986\ 445\times10^{-16}$ J-nm

$hc/q = 1.23984$ eV-μm

$kT/q = 0.025852$ V at 300K

1 eV $= 1.602\ 176\ 462\times10^{-19}$ J

1 A.U $= 1.495\times10^{11}$ m

$\lambda_{\max}T = c_2/4.965\ 114\ 23\ldots$

APPENDIX III

AN ANTIQUARIANS GARDEN
of
SANE and OUTRAGEOUS TERMINOLOGY

Perhaps the most difficult task in both teaching and learning about radiometry and photometry is learning and conveying an appropriate and sensible system of symbols, units and nomenclature (SUN). This can be a formidable task because of the enormous extent of these found in the literature. I have attempted to be consistent with the current (1986) accepted units in this text, and have addressed the situation with regard to intensity as well. The following is a collection of terms, sysbols and units that I have gathered with little effort. Perhaps you can add some more to this list. Some are still current and some are long obsolete.

UNDER CONSTRUCTION

PHOTOMETRY

Perhaps in no scientific field is the language more obtuse than in photometry. This is in large measure because of the tortuous path of the development of suitable standards.

LUMINOUS INTENSITY: The S.I. base unit of luminous intensity is the candela (cd).

1 Bougie decimale = 1.02 cd
1 Bougie nouvelle = 1 cd
1 International candle = 1.01937 cd
1 new candle = 1 cd
1 carcel = 10 cd
1 Carcel unit = 9.79613 cd
1 Hefnerkerze = 0.903 cd
1 violle = 20.4 cd
1 Pentene candle = 1 cd
1 English sperm candle = 1 cd

LUMINOUS POWER: The (derived) SI unit of luminous flux is the lumen (lm) (= cd-sr).

ILLUMINANCE: The (derived) SI unit of illuminance is the lux (lx = lm/m^2).

1 footcandle (fc or ft-c) = 1 lumen per square foot
1 lux (lx) = 1 lumen per square meter = 1 meter-candle
1 phot (ph) = 1 lumen per square centimeter = 10^4 lx
1 milliphot (mph) = 10^{-3} lm/cm^2
1 nox = 1 millilux = 10^{-3} lux
1 sea-mile candle = 1 cd @ 1 nautical mile (6080 ft) = 2.9×10^{-7} lx
Luminosity (L) lumen-ft^{-2}
Pharosage - lumen-m^{-2}

LUMINANCE: The (derived) SI unit of luminance is the nit (cd/m^2)

1 nit = 1 candela per m^2= π apostilb = 0.2919 foot-lambert
1 stilb (sb) = 1 candela per cm^2
1 nit = 10^4 Bougie-Hectomètre-Carré

NOTE: Several luminance units are related to the illuminance units by assuming a perfect ($\rho = 1$) diffuse (lambertian) reflector. This "simplification" leads to
1 foot-candle of illumination $\Rightarrow$ 1 foot-lambert of luminance
1 lambert = 1 lumen per cm^2= $(1/\pi)$ candela per cm^2
1 footlambert (ft.L.) = $(1/\pi)$ candela per ft^2
1 apostilb (asb) = $(1/\pi)$ candela per m^2 = $(1/\pi)$ nit
1 skot = 10^{-3} $(1/\pi)$ candela per m^2= 10^{-3} apostilb
1 millilambert ≈ 1 foot-lambert
1 equivalent phot = 1 lambert
1 equivalent lux = 1 blondel = 1 apostilb
1 equivalent footcandle = 1 footlambert

LUMINOUS ENERGY: The (derived) SI unit of luminous energy is the talbot (lm-sec).

1 talbot = 10^7 lumergs (c.g.s)
10^7 erg = 1 watt-sec
Phos - lumen-sec

1 light-watt = $1/V(\lambda)$ lumen = K_m lumen (683 at λ_p = 555 nm)
Pharos - lumen
Helios - blondel
Heliosent - blondel-m^{-1}
Radiant heliosent = path radiance (hershel-m^{-1})

luminous efficiency is luminous flux / radiant flux
luminous efficacy is luminous flux / electrical input power
mechanical equivalent of light is 1/683 watts/lumen

VISION RESEARCH

troland - retinal illuminance produced by luminance of 1 cd/m^2 if entrance pupil of eye is 1 mm^2, corrected for Stiles-Crawford effect; formerly called the *photon*

troland - also defined as the external illuminance that produces retinal illumination of 0.002 lux

ULTRAVIOLET

E-viton - erythemal effectiveness equivalent to 10 microwatts @ 296.7nm.
1 Finsen = 1 E-viton/cm^2
1 erythemal watt = 10^5 E-vitons
1 EU = 1 E-viton = 1 erytheme
floren - UV flux equivalent to 1 mW between 320 and 400 nm
bactericidal microwatt - weighted by bactericidal action spectrum
ultraviolet microwatt or UV watt - evaluated at 253.7 nm
MPE (minimum perceptible erythema) = 0.025 erythemalwatt/cm^2
1 MPE = 2500 finsens
1 MPE = 2.5×10^5 erg/cm^2 @ 296.7 nm
1 MED (minimum erythemal dose) =

ASTRONOMY

1 Jansky (Jy) = 10^{-26} W-m^{-2}-Hz^{-1} (spectral irradiance
1 W/cm^2-µm = $3\times10^{16}/\lambda^2$ Jy
1 solar flux unit (s.f.u.) = 10^4 Jy
1 µJy = 1.509×10^{-3} keV cm^{-2}-s^{-1} keV^{-1}
1 Jy = 2.42×10^{-6} erg cm^{-2} s^{-1} keV^{-1}
visual magnitude zero = 2.65×10^{-6} lux outside atmosphere (IR Handbook, p. 3-23)
visual magnitude zero = 2.54×10^{-6} lux outside atmosphere (Radiometry and photometry in astronomy, *hotel04.ausys.se/pausch/comp/radfaq.html*)
visual magnitude zero = 2.09×10^{-6} lux outside atmosphere (Optronic Laboratories)
1 rayleigh = 10^6 photons-cm^{-2}-s^{-1}
1 rayleigh = $(1/4\pi)\times10^6$ photons-cm^{-2}-s^{-1}-sr^{-1}
1 S_{10} = 1.23×10^{-12} W/cm^2-sr-µm @ 0.55 µm - equivalent to the number of 10th magnitude stars per square degree
1 S_{10} = 1.899×10^6 photons/s-cm^2-sr-µm @ 0.55 µm

COLOR, APPEARANCE

reciprocal megakelvin (MK)$^{-1}$ = $10^6/T_c$ where T_c is color temperature, also known as mirek or mired (microreciprocal Kelvin or microreciprocal degree)

MISCELLANEOUS

1 microeinstein (μE) = 6.022×10^{17} photons = 1 micromole
angstrom (Å) obsolete unit of wavelength = 10^{-10}m
Kayser - waves per centimeter
gillette - measure of laser energy, sufficient to penetrate one standard razor blade
microflick - unit of spectral radiance - μW-cm^{-2}-sr^{-1}-μm^{-1}
Spectral lamprosity - young per watt
Lamprosity (y) youngs per radiated watt
Actance - lumens per input watt
Radiant phos = exposure (W-sec)
Radiant helios = radiance (hershel)

following are CIE 106/8
PPFD (photosynthetic photon flux density) measured in mol m^{-2} sec^{-1}
SPPFD (spherical photosynthetic photon flux density) measured in mol m^{-2} sec^{-1}
PAP (photosynthetically active photons) measured in mol-m^{-2}
SPAP (spherical photosynthetically active photons) measured in mol-m^{-2}

Irradiation = radiant pharosage = radiant incidance (W-m^{-2})
Radiosity = radiant pharosage = radiant exitance (W-m^{-2})
Phengosage = spectral pharosage
Radiant pharos = radiant power (W)
1 W/m^2 = 0.317 BTU/ft^2-hr
1 langley = 1 gm-cal/cm^2

APPENDIX IV

SOLID ANGLE RELATIONSHIPS

Θ (deg)	Θ (rad)	ω (sr)	Ω (sr)	ω/Ω	$F/\#$	NA/n*
0.573	.0100	.00031	.00031	1.000	50.00	0.010
1.000	.0175	.00096	.00096	1.000	28.65	0.017
1.146	.0200	.00126	.00126	1.000	25.00	0.020
1.719	.0300	.00283	.00283	1.000	16.67	0.030
2.000	.0349	.00383	.00383	1.000	14.33	0.035
2.292	.0400	.00503	.00502	1.000	12.50	0.040
2.865	.0500	.00785	.00785	1.001	10.00	0.050
3.000	.0524	.00861	.00861	1.001	9.554	0.052
4.000	.0698	.0153	.0153	1.001	7.168	0.070
5.000	.0873	.0239	.0239	1.002	5.737	0.087
5.730	.1000	.0314	.0313	1.003	5.008	0.100
10.00	.1745	.0955	.0947	1.008	2.880	0.174
11.46	.2000	.1252	.1240	1.010	2.517	0.199
15.00	.2618	.2141	.2104	1.017	1.932	0.259
17.19	.3000	.2806	.2744	1.023	1.692	0.296
20.00	.3491	.3789	.3675	1.031	1.462	0.342
22.92	.4000	.4960	.4764	1.041	1.284	0.389
25.00	.4363	.5887	.5611	1.049	1.183	0.423
28.65	.5000	.7692	.7221	1.065	1.043	0.479
30.00	.5236	.8418	.7854	1.072	1.000	0.500
34.38	.6000	1.097	1.002	1.096	0.886	0.565
40.11	.7000	1.478	1.304	1.133	0.776	0.644
45.00	.7854	1.840	1.571	1.172	0.707	0.707
45.84	.8000	1.906	1.617	1.179	0.697	0.717
51.57	.9000	2.377	1.928	1.233	0.638	0.783
57.30	1.000	2.888	2.224	1.298	0.594	0.841
60.00	1.047	3.142	2.356	1.333	0.577	0.866
71.63	1.250	4.269	2.830	1.521	0.527	0.949
85.95	1.500	5.839	3.126	1.868	0.501	0.997
90.00	1.571	6.283	3.142	2.000	0.500	1.000

* To obtain the numerical aperture *NA*, numbers in this column must be multiplied by the index of refraction n of the local media.

Adapted from Nicodemus, F.E., et.al., Self-Study Manual on Optical Radiation Measurements, NBS Technical Note 910-01. National Institute of Standards and Technology, Washington, DC (1976).

APPENDIX V

Radiometry vs. photometry FAQ

by

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> ***"When I use a word, it means just what I choose it to mean - neither more nor less."***
>
> Lewis Carroll (Charles Lutwidge Dodgson)

Effective technical communication demands a system of symbols, units and nomenclature (SUN) that is reasonably consistent and that has widespread acceptance. Such a system is the International System of Units (SI). There is no area where words are more important than radiometry and photometry. This document is an attempt to provide necessary and correct information to become conversant.

1. What is the motivation for this FAQ?
2. What is radiometry? What is photometry? How do they differ?
3. What is projected area? What is solid angle?
4. What are the quantities and units used in radiometry?
5. How do I account for spectral quantities?
6. What are the quantities and units used in photometry?
7. What is the difference between lambertian and isotropic?
8. When do the properties of the eye get involved?
9. How do I convert between radiometric and photometric units?
10. Where can I learn more about this stuff?

1. What is the motivation for this FAQ?

There is so much misinformation and conceptual confusion regarding photometry and radiometry, particularly on the WWW by a host of "authorities", it is high time someone got it straight. So here it is, with links to the responsible agencies.

Background: It all started over a century ago. An organization called the General Conference on Weights and Measures (CGPM) was formed by a diplomatic treaty called the Metre Convention. This treaty was signed in 1875 in Paris by representatives from 17 nations (including the USA). There are now 48 member nations. Also formed were the International Committee for Weights and Measures (CIPM) and the International Bureau of Weights and Measures (BIPM). The CIPM, along with a number of sub-committees, suggests modifications to the CGPM. In our arena, the subcommittee is the CCPR, Consultative Committee on Photometry and Radiometry. The BIPM is the physical facility responsible for dissemination of standards, the international metrology institute.

The SI was adopted by the CGPM in 1960. It currently consists of seven base units and a larger number of derived units. The base units are a choice of seven well-defined units that by convention are regarded as independent. The seven are: metre, kilogram, second, ampere, kelvin, mole and **candela**. The derived units are those formed by various combinations of the base units.

International organizations involved in the promulgation of SUN include the International Commission on Illumination (CIE), the International Union of Pure and Applied Physics (IUPAP), and the International Standards Organization (ISO). In the USA, the American National Standards Institute (ANSI) is the primary documentary (protocol) standards organization. Many other scientific and technical organizations publish recommendations concerning the use of SUN for their learned publications. Examples are the International Astronomical Union (IAU) and the American Institute of Physics (AIP).

Read all about the SI, its history and application, at physics.nist.gov/cuu/ or at www.bipm.fr.

This FAQ was in essence the first draft (modified to actually look like a FAQ) of Chapter 7, Radiometry and Photometry: Units and Conversions in the Handbook of Optics III, McGraw-Hill (2001).

2. What is radiometry? What is photometry? How do they differ?

Radiometry is the measurement of optical radiation, which is electromagnetic radiation within the frequency range between 3×10^{11} and 3×10^{16} Hz. This range corresponds to wavelengths between 0.01 and 1000 micrometres (μm), and includes the regions commonly called the ultraviolet, the visible and the infrared. Two out of many typical units encountered are watts/m^2 and photons/sec-steradian.

Photometry is the measurement of light, which is defined as electromagnetic radiation detectable by the human eye. It is thus restricted to the wavelength range from about 360 to 830 nanometers (nm; 1000 nm = 1 μm). Photometry is just like radiometry except that everything is weighted by the spectral response of the eye. Visual photometry uses the eye as a comparison detector, while physical photometry uses either optical radiation detectors constructed to mimic the spectral response of the eye, or spectroradiometry coupled with appropriate calculations to do the eye response weighting. Typical photometric units include lumens, lux, candelas, and a host of other bizarre ones.

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. In my forty years of experience, photometry is more difficult to understand, primarily because of the arcane terminology, but is fairly easy to do, because of the limited wavelength range. Radiometry, on the other hand, is conceptually somewhat simpler, but is far more difficult to actually do.

3. What is projected area? What is solid angle?

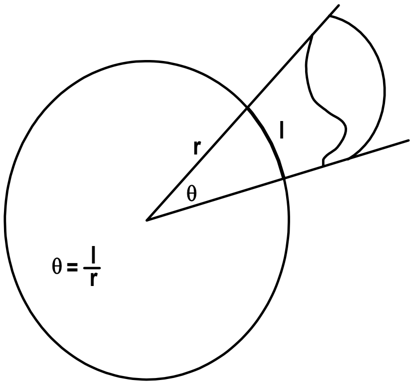
Projected area is defined as the rectilinear projection of a surface of any shape onto a plane normal to the unit vector. The differential form is $dA_{proj} = \cos(\beta)\, dA$ where β is the angle between the local surface normal and the line of sight. We can integrate over the (perceptible) surface area to get

$$A_{proj} = \int_A \cos\beta \, \mathrm{d}A$$

Some common examples are shown in the table below:

SHAPE	**AREA**	**PROJECTED AREA**
Flat rectangle	$A = L\times W$	$A_{proj} = L\times W \cos\beta$
Circular disc	$A = \pi r^2 = \pi d^2 / 4$	$A_{proj} = \pi r^2 \cos\beta = \pi d^2 \cos\beta / 4$
Sphere	$A = 4 \pi r^2 = \pi d^2$	$A_{proj} = A/4 = \pi r^2$

Plane angle and solid angle are two derived units on the SI system. The following definitions are from NIST SP811.

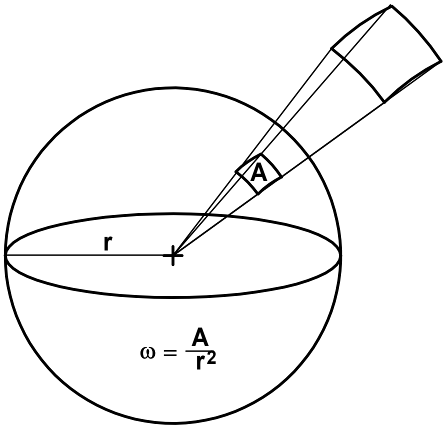


> ***"The radian is the plane angle between two radii of a circle that cuts off on the circumference an arc equal in length to the radius."***

The abbreviation for the radian is **rad**. Since there are 2π radians in a circle, the conversion between degrees and radians is 1 rad = (180/π) degrees.

A solid angle extends the concept to three dimensions.

> ***"One steradian (sr) is the solid angle that, having its vertex in the center of a sphere, cuts off an area on the surface of the sphere equal to that of a square with sides of length equal to the radius of the sphere."***



The solid angle is thus ratio of the spherical area to the square of the radius. The spherical area is a projection of the object of interest onto a unit sphere, and the solid angle is the surface area of that projection. If we divide the surface area of a sphere by the square of its radius, we find that there are 4π steradians of solid angle in a sphere. One hemisphere has 2π steradians.
The symbol for solid angle is either **ω**, the lowercase Greek letter omega, or **Ω**, the uppercase omega. I use ω exclusively for solid angle, reserving Ω for the advanced concept of projected solid angle (ω cosθ).

Both plane angles and solid angles are dimensionless quantities, and they can lead to confusion when attempting dimensional analysis.

4. What are the quantities and units used in radiometry?

Radiometric units can be divided into two conceptual areas: those having to do with power or energy, and those that are geometric in nature. The first two are:

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

Power (a.k.a. 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). The recommended symbol for power is Φ (the uppercase Greek letter theta). An acceptable alternate is **P**.

Energy is the integral over time of power, and is used for integrating detectors and pulsed sources. Power is used for non-integrating detectors and continuous sources. Even though we patronize the power utility, what we are actually buying is energy in watt-hours.

Now we become more specific and incorporate power with the geometric quantities area and solid angle.

Irradiance (a.k.a. flux density) is another SI derived unit and is measured in W/m^2. Irradiance is power per unit area incident from all directions in a hemisphere onto a surface that coincides with the base of that hemisphere. A similar quantity is **radiant exitance**, which is power per unit area leaving a surface into a hemisphere whose base is that surface. The symbol for irradiance is ***E*** and the symbol for radiant exitance is ***M***. Irradiance (or radiant exitance) is the derivative of power with respect to area, $d\Phi/dA$. The integral of irradiance or radiant exitance over area is power.

Radiant intensity is another SI derived unit and is measured in W/sr. Intensity is power per unit solid angle. The symbol is ***I***. Intensity is the derivative of power with respect to solid angle, $d\Phi/d\omega$. The integral of radiant intensity over solid angle is power.

Radiance is the last SI derived unit we need and is measured in W/m^2-sr. Radiance is power per unit projected area per unit solid angle. The symbol is ***L***. Radiance is the derivative of power with respect to solid angle and projected area, $d\Phi/d\omega\ dA\cos(\theta)$ where θ is the angle between the surface normal and the specified direction. The integral of radiance over area and solid angle is power.

A great deal of confusion concerns the use and misuse of the term *intensity*. Some folks use it for W/sr, some use it for W/m^2 and others use it for W/m^2-sr. It is quite clearly defined in the SI system, in the definition of the base unit of luminous intensity, the candela. Some attempt to justify alternate uses by adding adjectives like *optical* (used for W/m^2) or *specific* (used for W/m^2-sr), but this practice only adds to the confusion. The underlying concept is (quantity per unit solid angle). For an extended discussion, I wrote a paper entitled "Getting Intense on Intensity" for

Metrologia (official journal of the BIPM) and a letter to OSA's "Optics and Photonics News", with a modified version available on the web.

Photon quantities are also common. They are related to the radiometric quantities by the relationship $Q_p = hc/\lambda$ where Q_p is the energy of a photon at wavelength λ, h is Planck's constant and c is the velocity of light. At a wavelength of 1 μm, there are approximately 5×10^{18} photons per second in a watt. Conversely, also at 1 μm, 1 photon has an energy of 2×10^{-19} joules (watt-sec). Common units include $\mathrm{sec}^{-1}\text{-}\mathrm{m}^{-2}\text{-}\mathrm{sr}^{-1}$ for photon radiance.

5. How do I represent spectral quantities?

Most sources of optical radiation are spectrally dependent, and just radiance, intensity, etc. give no information about the distribution of these quantities over wavelength. Spectral quantities, like spectral radiance, spectral power, etc. are defined as the quotient of the quantity in an infinitesimal range of wavelength divided by that wavelength range. In other words, spectral quantities are derivative quantities, per unit wavelength, and have an additional (λ^{-1}) in their units. When integrated over wavelength they yield the total quantity. These spectral quantities are denoted by using a subscript λ, e.g., L_λ, E_λ, Φ_λ,, and I_λ.

Some other quantities (examples include spectral transmittance, spectral reflectance, spectral responsivity, etc.) vary with wavelength but are not used as derivative quantities. These quantities should **not** be integrated over wavelength; they are only weighting functions, to be included with the above derivative quantities. To distinguish them from the derivative quantities, they are denoted by a parenthetical wavelength, i.e. $\Re(\lambda)$ or $\tau(\lambda)$.

6. What are the quantities and units used in photometry?

They are basically the same as the radiometric units except that they are weighted for the spectral response of the human eye and have funny names. A few additional units have been introduced to deal with the amount of light reflected from diffuse (matte) surfaces. The symbols used are identical to those radiometric units, except that a subscript "v " is added to denote "visual. "The following chart compares them.

QUANTITY	RADIOMETRIC	PHOTOMETRIC
power	watt (W)	lumen (lm)
power per unit area	$\mathrm{W/m^2}$	$\mathrm{lm/m^2}$ = lux (lx)
power per unit solid angle	W/sr	lm/sr = candela (cd)
power per unit area per unit solid angle	$\mathrm{W/m^2\text{-}sr}$	$\mathrm{lm/m^2\text{-}sr} = \mathrm{cd/m^2}$ = nit

Now we can get more specific about the details.

Candela (unit of luminous intensity). The candela is one of the seven base units of the SI system. It is defined as follows:

> ***The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian.***

The candela is abbreviated as **cd** and its symbol is I_v. The above definition was adopted by the 16th CGPM in 1979.

The candela was formerly defined as the luminous intensity, in the perpendicular direction, of a surface of 1/600 000 square metre of a black body at the temperature of freezing platinum under a pressure of 101 325 newtons per square metre. This earlier definition was initially adopted in 1946 and later modified by the 13th CGPM (1967). It was abrogated in 1979 and replaced by the current definition.

The current definition was adopted because of several reasons. First, the freezing point of platinum (≈2042K) was tied to another base unit, the kelvin. If the best estimate of this point were changed, it would then impact the candela. The uncertainty of the thermodynamic temperature of this fixed point created an unacceptable uncertainty in the value of the candela. Second, the realization of the Pt blackbody was extraordinarily difficult; only a few were ever built. Third, if the temperature were slightly off, possibly because of temperature gradients or contamination, the freezing point might change or the temperature of the cavity might differ. The sensitivity of the candela to a slight change in temperature is significant. At a wavelength 555 nm, a change in temperature of only 1K results in a luminance change approaching 1%. Fourth, the relative spectral radiance of blackbody radiation changes drastically (some three orders of magnitude) over the visible range. Finally, recent advances in radiometry offered new possibilities for the realization of the candela.

The value 683 lm/W was selected based upon the best measurements with existing platinum freezing point blackbodies. It has varied over time from 620 no nearly 700 lm/W, depending largely upon the assigned value of the freezing point of platinum. The value of 1/600 000 square metre was chosen to maintain consistency with prior standards. Note that neither the old nor the new definition say anything about the spectral response of the human eye. There are additional definitions that include the characteristics of the eye, but the base unit (candela) and those SI units derived from it are “eyeless.”

Also note that in the definition there is no specification for the spatial distribution of intensity. Luminous intensity, while often associated with an isotropic point source, is a valid specification for characterizing highly directional light sources such as spotlights and LEDs.

One other issue before we press on. Since the candela is now defined in terms of other SI derived quantities, there is really no need to retain it as an SI base quantity. It remains so for reasons of history and continuity.

Lumen (unit of luminous flux). The lumen is an SI derived unit for luminous flux. The abbreviation is lm and the symbol is Φ_v. 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 analogous to the unit of radiant flux (watt), differing only in the eye response weighting. If a light source is isotropic, the relationship between lumens and candelas is 1 cd = 4π lm. In other words, an isotropic source having a luminous intensity of 1 candela emits 4π lumens into space, which just happens to be 4π steradians. We can also state that 1 cd = 1 lm/sr, analogous to the equivalent radiometric definition.

If a source is not isotropic, the relationship between candelas and lumens is empirical. A fundamental method used to determine the total flux (lumens) is to measure the luminous intensity (candelas) in many directions using a goniophotometer, and then numerically integrate over the entire sphere. Later on, we can use this “calibrated” lamp as a reference in an integrating sphere for routine measurements of luminous flux.

Lumens are what we get from the hardware store when we purchase a light bulb. We want a high number of lumens with a minimum of power consumption and a reasonable lifetime. Projection devices are also characterized by lumens to indicate how much luminous flux they can deliver to a screen.

Lux (unit of luminous flux density, or illuminance). **Illuminance** is another SI derived unit that denotes luminous flux density. It has a special name, **lux**, and is lumens per square metre, or lm/m^2. The symbol is E_v. Most light meters measure this quantity, as it is of great importance in illuminating engineering. The IESNA Lighting Handbook has some sixteen pages of recommended illuminances for various activities and locales, ranging from morgues to museums. Typical values range from 100 000 lx for direct sunlight to 20-50 lx for hospital corridors at night.

Nit (unit of luminance). Luminance should probably be included on the official list of derived SI units, but is not. It is analogous to radiance, differentiating the lumen with respect to both area and direction. It also has a special name, **nit**, and is cd/m^2 or lm/m^2-sr if you prefer. The symbol is L_v. It is most often used to characterize the “brightness “ of flat emitting or reflecting surfaces. A typical use would be the luminance of your laptop computer screen. They have between 100 and 250 nits, and the sunlight readable ones have more than 1000 nits. Typical CRT monitors have between 50 and 125 nits.

Other photometric units

We have other photometric units (boy, do we have some strange ones). Photometric quantities should be reported in SI units as given above. However, the literature is filled with now obsolete terminology and we must be able to interpret it. So here are a few terms that have been used in the past.

Illuminance:

1 metre-candle = 1 lux
1 phot = 1 lm/cm^2 = 10^4 lux
1 foot-candle = 1 lumen/ft^2 = 10.76 lux
1 milliphot = 10 lux

Luminance: Here we have two classes of units. The first is conventional, easily related to the SI unit, the cd/m^2 (nit).

1 stilb = 1 cd/cm^2 = 10^4 cd/m^2 = 10^4 nit
1 cd/ft^2 = 10.76 cd/m^2 = 10.76 nit

The second class was designed to "simplify" characterization of light reflected from diffuse surfaces by including in the definitions the concept of a perfect diffuse reflector (lambertian, reflectance ρ= 1). If one unit of illuminance falls upon this hypothetical reflector, then 1 unit of luminance is reflected. The perfect diffuse reflector emits $1/\pi$ units of luminance per unit illuminance. If the reflectance is ρ, then the luminance is ρ times the illuminance. Consequently, these units all have a factor of $(1/\pi)$ built in.

1 lambert = $(1/\pi)$ cd/cm^2 = $(10^4/\pi)$ cd/m^2
1 apostilb = $(1/\pi)$ cd/m^2
1 foot-lambert = $(1/\pi)$ cd/ft^2 = 3.426 cd/m^2
1 millilambert = $(10/\pi)$ cd/m^2
1 skot = 1 milliblondel = $(10^{-3}/\pi)$ cd/m^2

Photometric quantities are already the result of an integration over wavelength. It therefore makes no sense to speak of spectral luminance or the like.

7. What is the difference between lambertian and isotropic?

Both terms mean "the same in all directions" and are unfortunately sometimes used interchangeably.

Isotropic implies a spherical source that radiates the same in all directions, i.e., the intensity (W/sr) is the same in all directions. We often hear about an "isotropic point source." There can be no such thing; because the energy density would have to be infinite. But a small, uniform sphere comes very close. The best example is a globular tungsten lamp with a milky white diffuse envelope, as used in dressing room lighting. From our vantage point, a distant star can be considered an isotropic point source.

Lambertian refers to a flat radiating surface. It can be an active surface or a passive, reflective surface. Here the intensity falls off as the cosine of the observation angle with respect to the surface normal (Lambert's law). The radiance (W/m^2-sr) is independent of direction. A good example is a surface painted with a good “matte” or “flat” white paint. If it is uniformly illuminated, like from the sun, it appears equally bright from whatever direction you view it. Note that the flat radiating surface can be an elemental area of a curved surface.

The ratio of the radiant exitance (W/m^2) to the radiance (W/m^2-sr) of a lambertian surface is a factor of π and not 2π. We integrate radiance over a hemisphere, and find that the presence of the factor of cos(θ) in the definition of radiance gives us this interesting result. It is not intuitive, as we know that there are 2π steradians in a hemisphere.

A lambertian sphere illuminated by a distant point source will display a radiance which is maximum at the surface where the local normal coincides with the incoming beam. The radiance will fall off with a cosine dependence to zero at the terminator. If the intensity (integrated radiance over area) is unity when viewing from the source, then the intensity when viewing from the side is 1/π. Think about this and consider whether or not our Moon is lambertian. I'll have more to say about this at a later date in another place!

8. Where do the properties of the eye get involved?

We know that the eye does not see all wavelengths equally. The eye has two general classes of photosensors, cones and rods.

Cones: The cones are responsible for light-adapted vision; they respond to color and have high resolution in the central foveal region. The light-adapted relative spectral response of the eye is called the spectral luminous efficiency function for photopic vision, V(λ). 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 370 and 785 nm. The 50% points are near 510 nm and 610 nm, indicating that the curve is slightly skewed. The V(λ) curve looks very much like a Gaussian function; in fact a Gaussian curve can easily be fit and is a good representation under some circumstances. I used a non-linear regression technique to obtain the following equation:

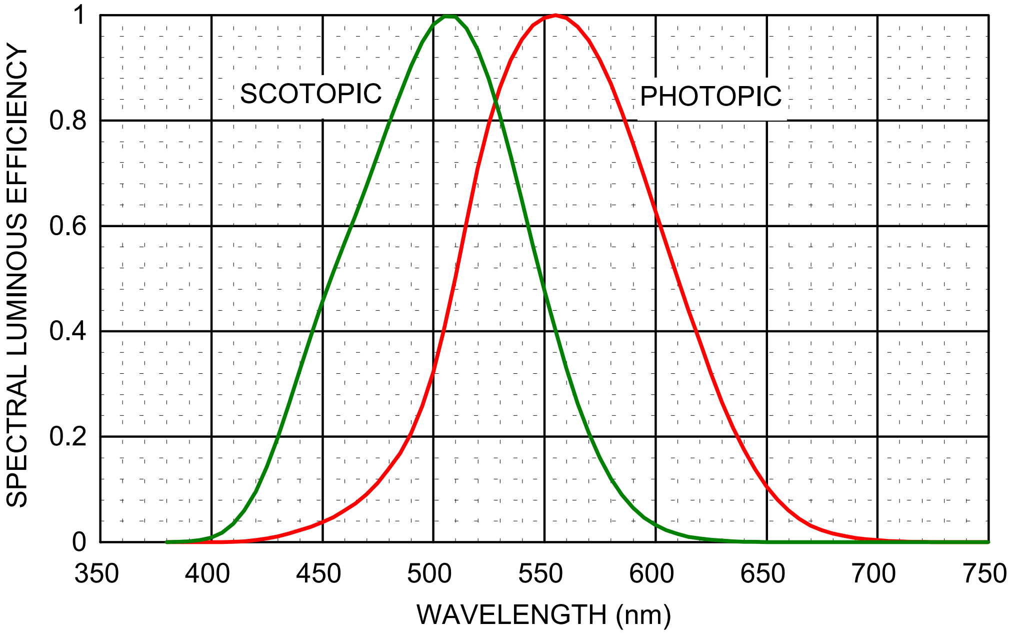
$$V(\lambda) \cong 1.019 e^{-285.4(\lambda - 0.559)^2}$$

More recent measurements have shown that the 1924 curve may not best represent typical human vision. It appears to underestimate the response at wavelengths shorter than 460 nm. Judd (1951), Vos (1978) and Stockman and Sharpe (1999) have made incremental advances in our knowledge of the photopic response.

Rods: The rods are responsible for dark-adapted vision, with no color information and poor resolution when compared to the foveal cones. The dark-adapted relative spectral response of the eye is called the spectral luminous efficiency function for scotopic vision, V'(λ). This is another empirical curve, adopted by the CIE in 1951. It is defined between 380 nm and 780 nm. The V'(λ) curve has a peak of unity at 507 nm, and decreases to levels below 10^{-3} at about 380 and 645 nm. The 50% points are near 455 nm and 550 nm. This scotopic curve can also be fit with a Gaussian, although the fit is not quite as good as the photopic curve. My best fit is

$$V'(\lambda) \cong 0.992e^{-321.9(\lambda-0.503)^2}$$

Photopic (light adapted cone) vision is active for luminances greater than 3 cd/m². Scotopic (dark-adapted rod) vision is active for luminances lower than 0.01 cd/m². In between, both rods and cones contribute in varying amounts, and in this range the vision is called mesopic. There are currently efforts under way to characterize the composite spectral response in the mesopic range for vision research at intermediate luminance levels.



The Color Vision Lab at UCSD has an impressive collection of the data files, including V(λ) and V'(λ), that you need to do this kind of work.

9. How do I convert between radiometric and photometric units?

We know from the definition of the candela that there are 683 lumens per watt at a frequency of 540THz, which is 555 nm (in vacuum or air). This is the wavelength that corresponds to the maximum spectral responsivity of the human eye. The conversion from watts to lumens at any other wavelength involves the product of the power (watts) and the V(λ) value at the wavelength of interest. As an example, we can compare laser pointers at 670 nm and 635 nm. At 670 nm, V(λ) is 0.032 and a 5 mW laser has 0.005W×0.032×683 lm/W = 0.11 lumens. At 635 nm, V(λ) is 0.217 and a 5 mW laser has 0.005W×0.217×683 lm/W = 0.74 lumens. The shorter wavelength (635 nm) laser pointer will create a spot that is almost 7 times as bright as the longer wavelength (670 nm) laser (assuming the same beam diameter).

In order to convert a source with non-monochromatic spectral distribution to a luminous quantity, the situation is decidedly more complex. We must know the spectral nature of the source, because it is used in an equation of the form:

$$X_v = K_m \int_0^\infty X_\lambda V(\lambda)\, d\lambda$$

where X_v is a luminous term, X_λ is the corresponding **spectral** radiant term, and V(λ) is the photopic spectral luminous efficiency function. For X, we can pair luminous flux (lm) and spectral power (W/nm), luminous intensity (cd) and spectral radiant intensity (W/sr-nm), illuminance (lx) and spectral irradiance (W/m^2-nm), or luminance (cd/m^2) and spectral radiance (W/m^2-sr-nm). This equation represents a weighting, wavelength by wavelength, of the radiant spectral term by the visual response at that wavelength. The constant K_m is a scaling factor, the maximum spectral luminous efficiency for photopic vision, 683 lm/W. The wavelength limits can be set to restrict the integration to only those wavelengths where the product of the spectral term X_λ and V(λ) is non-zero. Practically, this means we only need integrate from 360 to 830 nm, limits specified by the CIE V(λ) table. Since this V(λ) function is defined by a table of empirical values, it is best to do the integration numerically. Use of the Gaussian equation given above is only an approximation. I compared the Gaussian equation with the tabulated data using blackbody curves and found the differences to be less than 1% for temperatures between 1500K and 20000K. This result is acceptable for smooth curves, but don't try it for narrow wavelength sources, like LEDs.

There is nothing in the SI definitions of the base or derived units concerning the eye response, so we have some flexibility in the choice of the weighting function. We can use a different spectral luminous efficacy curve, perhaps one of the newer ones. We can also make use of the equivalent curve for scotopic (dark-adapted) vision for studies at lower light levels. This V'(λ) curve has its own constant K'm, the maximum spectral luminous efficiency for scotopic vision. K'_m is 1700 lm/W at the peak wavelength for scotopic vision (507 nm) and this value was deliberately chosen such that the absolute value of the scotopic curve at 555 nm coincides with the photopic curve, at the value 683 lm/W. Some workers are referring to "scotopic lumens", a term which should be discouraged because of the potential for misunderstanding. In the future, we can also expect to see spectral weighting to represent the mesopic region.

The International Commission on Weights and Measures (CGPM) has approved the use of the CIE V(λ) and V'(λ) curves for determination of the value of photometric quantities of luminous sources.

Now about converting from lumens to watts. The conversion from watts to lumens that we saw just above required that the spectral function X_λ of the radiation be known over the spectral range from 360 to 830 nm, where V(λ) is non-zero. Attempts to go in the other direction, from lumens to watts, are far more difficult. Since we are trying to back out a quantity that was weighted and placed inside of an integral, we must know the spectral function X_λ of the radiation over the entire spectral range where the source emits, not just the visible. There are a few tricks which appear in Chapter 7, Radiometry and Photometry: Units and Conversions in the Handbook of Optics III, McGraw-Hill (2001).

10. Where can I learn more about this stuff?

Books, significant journal articles:

DeCusatis, C., "Handbook of Applied Photometry," AIP Press (1997).
Authoritative, with pertinent chapters written by technical experts at BIPM, CIE and NIST. Skip chapter 4!

Rea, M., ed. "Lighting Handbook: Reference and Application," 8th edition, Illuminating Engineering Society of North America (1993).

"Symbols, Units and Nomenclature in Physics," International Union of Pure and Applied Physics (1987).

"American National Standard Nomenclature and Definitions for Illuminating Engineering," ANSI Standard ANSI/IESNA RP-16 96.

"The Basis of Physical Photometry," CIE Technical Report 18.2 (1983)

Publications available on the World Wide Web

All you ever wanted to know about the SI is contained at BIPM and at NIST.
Available publications (highly recommended) include:

"The International System of Units (SI)" 7th edition (1998), direct from BIPM. The official document is in French; this is the English translation). Available in PDF format.

NIST Special Publication SP330 "The International System of Units (SI)" The US edition of the above BIPM publication. Available in PDF format.

NIST Special Publication SP811 "Guide for the Use of the International System of Units (SI)," available in PDF format.

Papers published in recent issues of the NIST Journal of Research are also available on the web in PDF format.

Useful Web sites

BIPM International Bureau of Weights and Measures - www.bipm.fr/

NIST National Institute of Standards and Technology - physics.nist.gov/cuu/

ISO International Standards Organization - www.iso.ch/

ANSI American National Standards Institute - www.ansi.org/

CIE International Commission on Illumination - www.cie.co.at/cie/

IESNA Illuminating Engineering Society of North America - www.iesna.org/

IUPAP International Union of Pure and Applied Physics -

www.physics.umanitoba.ca/iupap/

Color Vision Lab at UCSD - cvision.uscd.edu/

AIP American Institute of Physics - www.aip.org

SPIE - International Society for Optical Engineering - www.spie.org

OSA Optical Society of America - www.osa.org

CORM Council of Optical Radiation Measurements - www.corm.org

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APPENDIX VI

GLOSSARY

1/f Noise	Weird, ubiquitous noise from many familiar and strange sources, inversely proportional to frequency (pink or red noise). An approximation is $\overline{i^2_{1/f}} = \frac{const \cdot I^{\alpha}_{dc} B}{f^{\beta}}$ where α is between 1.25 and 4 (typically 2) and ß is between 0.8 and 3 (typically 1). Also called flicker, contact, excess, modulation, etc. A major pain!
AΩ product	symbol **T**, units m^2-sr; geometrical term relating to amount of power that can get through a system a.k.a. throughput, etendue
Bandwidth normalization	Determination of an equivalent responsivity using a rectangle; the areas under the curve and rectangle are set equal.
Blackbody radiation simulator	An object that simulates blackbody (Planckian) radiation via careful cavity design and temperature measurement.
BLIP	**B**ackground-**L**imited **I**nfrared **P**hotodetector, one whose noise is predominantly due to the noise in the incident photon stream, not intrinsic to the detector
Bode plot	Plotting log(signal or noise) vs log(frequency) - shows many orders of magnitude, asymptotes of linear plots map to straight lines on Bode plot
BRDF	**B**idirectional **R**eflectance **D**istribution **F**unction. A directional quantity that denotes output radiance as a function of direction and irradiance. A perfectly diffusing reflector has a BRDF of ρ/π, while a perfectly specular reflector has a BRDF ρ/Ω; ρ is reflectance and Ω is the PSA of the source. Units: sr^{-1}.
Brightness temperature	The brightness temperature of an object is the temperature of blackbody radiation that has the same spectral radiance as the object.
BTDF	**B**idirectional **T**ransmission **D**istribution **F**unction. The angular distribution of transmitted radiance around the normal transmitted beam. Units: sr^{-1}.
Charge transfer efficiency	Fraction of charge that is successfully transferred from one CCD charge storage element (potential well) to the adjacent charge storage element
Chopping factor	Ratio of the rms amplitude of the fundamental

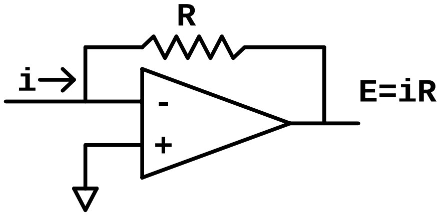
	frequency component of a modulated signal to the peak-to-peak amplitude of the unmodulated signal. Equal to $\sqrt{\pi}/2 = 0.45$ for square wave chopping.
CIE chromaticity diagram	A horseshoe shaped diagram showing the gamut of all possible colors in terms of hue and saturation. The horseshoe is the spectrum locus and white is at the center where $x = y = z = 1/3$.
Cold filter	A filter that passes desired bandpass and is cooled to minimize self-radiation at other wavelengths
Cold stop	An aperture placed in front of a detector to limit the field of view and cooled to minimize the stop radiance. Improves SNR.
Collimator	An optical system designed to make a near small source appear as if it were located at infinity
Color temperature	The color temperature of an object is the temperature of blackbody radiation that has the same chromaticity (color) as the object.
Conduction calorimeter	A device to measure laser power and energy by calorimetric means, i.e., heating of an absorber.
Contrast sensitivity function	The visual acuity of the eye as a function of both spatial frequency and contrast. Determined by looking at variable frequency $\cos^2$ wave patterns that have contrast decreasing from bottom to top.
Correlated color temperature	The temperature of a blackbody having a chromaticity (colour) as close as possible to the chromaticity of the source in question.
Cosine response	The response curve desired for an instrument designed to measure irradiance from a hemisphere. Related to projected area.
D	Detectivity , the reciprocal of NEP. It is the SNR per watt for a 1 detector. Unit: W^{-1}
D*	Specific or normalized detectivity. It is detectivity $D = NEP^{-1}$ normalized for bandwidth and area. $D^{*}=(AB)^{1/2}/NEP$. Unit: cm-$Hz^{1/2}$-W^{-1}. It is the SNR per watt for a 1 cm^2 detector with a bandwidth of 1 Hz. Allows a fair comparison between detector types.
D** **more here**	A normalized detectivity, taking into account detector area, noise bandwidth and FOV. It's the SNR per incident watt for a 1 cm^2 area, 1 Hz noise bandwidth and π sr of projected solid angle. $D^{**}=(AB\Omega/\pi)^{1/2}/NEP$. Unit: cm-$Hz^{1/2}$-$W^{-1}$ a further normalization for field of view; $D^{*}(\Omega/\pi)^{1/2}$
D^{*}_{BLIP}	Background-limited infrared photodetector, the best SNR you can get when photon noise from the

	background limits
Decade, octave	Frequency ratio of 10 and 2, respectively.
Decibel	(dB) a ratio of two voltages, currents or powers. $dB = 20\log_{10}\frac{V_2}{V_1} = 20\log_{10}\frac{I_2}{I_1} \quad dB = 10\log_{10}\frac{P_2}{P_1}$ It is a relative measure. There are several ways of denoting absolute values. dBv referred to 1 volt rms dBm referred to 1 mW with stated impedance (75Ω, 600Ω) To compare unlike waveforms, such as a sine wave to gaussian noise, use the power formulation.
Detective quantum efficiency (DQE)	A relative measure of the amount of noise added by a detector. Detective quantum efficiency, like RQE but includes noise, $(SNR_{out})^2/(SNR_{in})^2$, unitless, $0<DQE<1$
Diffuse reflectance	Ratio of radiation reflected into a hemisphere (whose base is the reflector) to the incident radiation. Excludes specular component.
Distribution temperature	The distribution temperature of an object is the temperature of a blackbody radiator that has the same (or nearly the same) relative spectral distribution over a substantial portion of the spectrum as the object.
Effective noise bandwidth	The equivalent square-band power bandwidth, used for evaluation of noise. Given for "white" noise by $ENB = \frac{1}{\left\|A_o\right\|^2}\cdot\int_0^\infty \left[A(f)\right]^2 df$ The equivalent “brick-wall” rectangular passband. Alternate symbols are B and Δf, units are Hz.
Electrical substitution radiometer	A radiometer based upon a thermal detector with provisions for injecting a known power via electrical means for the purpose of calibration.
Full well capacity	The number of electrons (signal + noise + dark current) that a potential well in a CCD structure can hold.
Generation-recombination noise	Noise due to the generation of carriers by photon absorption and by recombination random motion of carriers (electrons) in a resistive material. Spectral power density depends on frequency
H-D curve	The characteristic curve of photographic film (named after Hurter and Driffield) which plots density (log(1/t) vs log of the exposure (product of irradiance and time).
Hemispherical reflectance	Directional emittance integrated over an entire hemisphere.
Iluminance	Luminous flux per unit incident on a surface from a

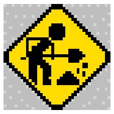
	hemisphere; units lm/m^2 = lux. Analagous to irradiance in W/m^2.
Intensity	Symbol **I**; watts per unit solid angle, often from an isotropic "point" source W-sr^{-1}
Irradiance	symbol **E**, units W-m^{-2}, watts per unit area incident on a surface
Isotropic point source	Small (relative to distance) source where intensity is independent of direction
Johnson noise	Noise due to random thermal agitation of carriers (electrons) in a resistive material. Spectral power density independent of frequency (i.e., white) $\overline{v_n^2} = 4kTRB \qquad or \qquad \overline{i_n^2} = 4kTB/R$
Jones calibration configuration	Also known as near small source. The radiometer is focussed at infinity. A small calibration source is placed within a cone whose base is the entrance aperture and whose half-angle is the chief ray angle. It fills a fraction of the entrance aperture. The calibration equation is $\Re = \frac{SIG}{L} \cdot \frac{A_a}{A_s}$
Lambertian source	Source where radiance is independent of direction
Laser calorimeter	A device to measure laser energy, particularly for short pulses, by calorimetric means, i.e., heating of an absorber. Output proportional to time integral of power, i.e., energy.
Luminance	Photometric equivalent of radiance. Measure of visible power per unitprojected area per unit solid angle. Unit: candela/m^2 = lumen/m^2/sr.
Luminous intensity	Measure of visible power per unit solid angle. Unit: candela (cd) = lumen/sr. One of the seven SI base units. Analogous to radiant intensity, W/sr.
Measurement equation	An equation that relates the output signal from a detector or radiometer to a function of the receiver and source spectral parameters. An example: $SIG = A\Omega \int_0^\infty L_\lambda \Re(\lambda) d\lambda$
Moments normalization	A normalization based on a moments analysis of a spectral responsivity. The center wavelength is the centroid and the bandwidth and cut-on and cut-off wavelengths are computed from the variance.
Noise Equivalent Photon Flux	The photon phlux incident on a detector which gives rise to a signal-to-noise ratio of one. Units: sec^{-1}
Noise Equivalent Power	The power incident on a detector which gives rise to a

NEP	signal-to-noise ratio of one. Units: watt
Noise Equivalent Temperature Difference **NETD, NEΔT**	The temperature difference between the target and the background that produces an r.m.s. signal equal to the r.m.s. noise
Passband normalization	Normalization method wherein the band limits of the equivalent rectangle are assigned at fixed response points (50%, 10%, 1/e, etc.). The normalized responsivity is then related to the area under the response curve.
Peak normalization	A normalization where the band responsivity is set to the peak of the actual response curve. The bandwidth is calculated by matching the area of the equivalent rectangle to the area under the response curve.
Photoconductive gain	The ratio of the transit time to the carrier lifetime for a photoconductive detector. A measure of the number of electrons a single absorbed photon can generate.
Photon noise	Noise due to the random arrival of photons; manifest as shot noise or the g- component of g-r noise.
Photopic	Pertaining to light-adapted vision
Photopic visibility curve	The relative spectral responsivity of the standardized light-adapted human eye (cones). Symbol is $V(\lambda)$, dimensionless.
Precision	A measure of the repeatability of a measurement. Comes from granularity, noise, etc. Determined and enhanced by repeated measurements.
Projected solid angle	Solid angle $\times \cos\theta$, projected onto flat surface $d\Omega = d\omega \cos\theta$. Symbol $\mathbf{\Omega}$, units (sr)
Quantum efficiency	see Responsive Quantum Efficiency
Quantum trap detector	A multiple detector array where detectors are placed in series optically and in parallel electrically. Has a quantum efficiency approaching unity.
Radiance	Fundamental unit of radiometer, directional. Symbol **L**, units W-m^{-2}-sr^{-1}
Radiance temperature	The radiance (a.k.a brightness) temperature of an unknown object is the temperature of a blackbody that has the same **spectral** radiance as the unknown object
Radiant exitance	Radiant power per unit area leaving a source into a hemisphere. Symbol **M**, units W-m^{-2}
Radiant intensity	Radiant power per unit solid angle - W-sr^{-1}
Radiation reference	A comparison source for a radiometer; zero-based for short-wave radiometers, a known thermal source for long-wave radiometers.

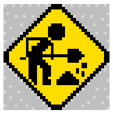
Radiation temperature	The radiation temperature of an object is the temperature of blackbody radiation that has the same total (integrated over all wavelengths) radiance as the object.
Range equation	An equation that gives the distance from a source that one can detect with a stated SNR.
Ratio temperature	The ratio temperature of an object is the temperature of blackbody radiation that has the same ratio of spectral radiances at two wavelengths as the object.
Reflectance factor	Ratio of flux reflected from a sample to the flux that would be reflected from a perfect diffuse reflector (lambertian, $\rho = 1$).
Responsive quantum efficiency **RQE**	The number of independent output events per incident photon. Dimensionless, between 0 and 1. Symbols: η, RQE
Responsivity	Ratio of the output of a detector to its input. Units: usually A/W or V/W. Symbol is $\Re$. The result of an integral over wavelength. $\Re = \frac{\int \Re(\lambda)\Phi_\lambda \, d\lambda}{\int \Phi_\lambda \, d\lambda}$
Retroreflectance	Wherein the reflected beam retraces the path from the source back to the source
rms (root mean square)	A measure of the equivalent heating effect of a voltage or current $V_{rms} = \sqrt{\frac{1}{T}\int_0^T v^2(t)dt}$ where T is time, usually a single or integer multiple of periods for periodic waveforms. For a sine wave, the rms voltage is 1/√2 times the peak voltage (measured from 0) or 1/2√2 times the peak-to-peak voltage. Electric power companies deliver $117V_{rms}$ which is $330V_{p\text{-}p}$. For a square wave, the rms amplitude is the same as the peak amplitude.
Saturation exposure	The exposure (product of irradiance and time) necessary to saturate an integrating detector. Used for CCD, CID and CMOS array detectors. Unit: watt-s/m^2.
Scotopic visibility curve	The relative spectral responsivity of the standardized dark-adapted human eye (rods). Peaks at 507 nm. Dimensionless, symbol is $V'(\lambda)$
Shot noise	Noise associated with current flow across a potential barrier, due to discreet nature of electrons. Power spectral density is independent of frequency (i.e.,

	white). Mean square shot noise current $\overline{i_n^2} = 2qI_{dc}B$.
Solid angle	Projected area ÷ (distance)^2 , given by $2\pi(1-\cos\theta_{1/2})$ for right circular cone. Symbol ω, units (sr)
Spectral directional emissivity	The ratio of radiance at a specified wavelength in a particular direction to that of a blackbody at the same wavelength and in the same direction.
Spectral radiance	Symbol L_λ,, watts per unit area per unit projected solid angle per unit wavelength interval; fundamental unit of radiometry.
Spectral radiant intensity	Symbol $\mathbf{I}_\lambda$, units W-sr^{-1}-µm^{-1}; watts per steradian per unit wavelength, often from an isotropic "point" source
Spectral reflectance	Ratio of reflected power at a specific wavelength to the incident power, at the same wavelength.
Spectral responsivity	Responsivity as a function of wavelength. Symbol $\Re(\lambda)$. Units: amps (or volts, etc.) per watt. Not a derivative quantity, per unit wavelength interval.
Specular reflectance	Ratio of radiation reflected in the mirror direction to the incident radiation. Excludes diffuse (scattered) component.
Throughput	Symbol **T**, units m^2-sr; geometrical term relating to amount of power that can get through a system. The product of area and projected solid angle AΩ.
Time constant	A measure of the speed of response of a device. The time required to reach (1-1/e) or 0.632 of the final value in response to a step input.. Symbol τ, units are sec. For a simple RC circuit, τ=RC
Total hemispherical emissivity	Integral of spectral directional emissivity over the entire spectrum and over an entire hemisphere.
Transimpedance amplifier	a.k.a. current-to-voltage converter, used to interface with current sources. 
Trap detector	A multiple detector array where detectors are placed in series optically and in parallel electrically. Has a quantum efficiency approaching unity.
Type A error	Older term: Precision. A.k.a random error. A measure of the repeatability of a measurement. Comes from granularity, noise, etc. Determined by repeated

	measurements.
Type B error	Older term: Accuracy. A.k.a. systematic error or bias. A measure of the difference between the mean reading and “truth.” May b e corrected by careful calibratioon and characterization.
Uncertainty	The total estimated difference between a measurement and “truth”; includes both random and systematic error terms and a confidence parameter.
Wien’s displacement law	Product of wavelength and temperature a constant.
Wien approximation	An equation representing blackbody radiation at short wavelengths and/or low temperatures. Form is: $$M_\lambda = \frac{c_1}{\lambda^5} e^{-c_2/\lambda T}$$



APPENDIX VII



SUPPLEMENTARY NOTES

1. Effective noise bandwidth
2. Full derivation of moments bandwidth normalization
3. Jones NSS calibration configuration original derivation

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EFFECTIVE NOISE BANDWIDTH OF RC FILTERS AND THE SELECTION OF FILTER PARAMETERS TO OPTIMIZE SNR

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ABSTRACT

1. Introduction

Engineering calculations involving noise and signal-to-noise ratio need to use the effective noise bandwidth (ENB) in order to calculate noise properly. Often the conventional (-3dB voltage, -6dB power) bandwidth is used, leading to erroneous results. When the difference between -3dB bandwidth and ENB is recognized, it is often oversimplified by attempting to relate ENB to the -3dB bandwidth. Table 1 shows several of these relationships I found in the open and corporate literature.

Table 1. Ratio of ENB to (-3dB) bandwidth for low-pass filters

SECTIONS	A, B	C, D	E
1	1.57	1.57	1.57
2	1.22	1.11	1.12
3	1.15	1.05	1.08
4	1.13	1.025	1.06
5	1.11		1.05

A - C.D. Motchenbacher & J.A. Connelly, “Low Noise Electronic System Design,” Wiley, NY (1993), sec 1-4. **B** - H.W. Ott, “Noise Reduction Techniques in Electronic Systems,” Wiley, NY (1976), Table 8-2. **C** - P. Horowitz & W. Hill, “The Art of Electronics,” Cambridge, NY (1989), sec 7.21. **D** - Ithaco, “Measuring Noise Spectra with Variable Electronic Filters,” Ithaco Application Note IAN-102, Ithaco Corp, Ithaca NY (7/83), Appendix 1. **E** - E.L. Dereniak & G.D. Boreman, “Infrared Detectors and Systems,” Wiley, NY (1996), Table 5.1.

These discrepancies, while not extremely serious, are disconcerting, particularly for the two-section filter, which is readily realizable with a single operational amplifier and a handful of R and C components. So I set off to find out which values are correct. This was accomplished by means of simple spreadsheet analysis and BASIC computer programs to do the necessary integrations.

There are many multiple-pole filter types in the literature. This paper is limited to simple Butterworth RC filters, where each section has the same R and C and therefore cutoff frequency. The primary emphasis is limited to “white” noise, with a uniform power spectral density. We conclude with a simple bandwidth optimization to maximize the SNR of a single-frequency signal in the presence of white noise.

2. Definitions

The signal bandwidth of a low-pass filter is defined as the frequency where the signal voltage falls to -3dB (1/√2=0.707) of the transmission at DC (typically unity). This frequency is also referred to as the half-power point, where the power transmission has dropped to -6dB (0.5). For a bandpass filter, the same terms are used relative to the peak transmission of the filter. The bandwidth is often referred to as FWHM (full-width at half-maximum) for power. Figures 1 and 2 show these terms for a simple low-pass and bandpass filters, respectively.

The signal bandwidth is not appropriate for characterization of noise. The effective noise bandwidth (ENB, more often seen as B or Δf) is defined as the equivalent brick-wall (rectangular) filter, having the same area under the **power** transmission curve. The equation is

$$B = \frac{1}{G(f_0)\,\overline{v_0^2}} \int_0^\infty G(f)\,\overline{v(f)^2}\,df \tag{1}$$

where *G(f)* is the power gain as a function of frequency and f_o is the frequency where *G(f)* is a maximum. $\overline{v(f)^2}$ is the power spectrum for the noise under consideration, and $\overline{v_o^{\,2}}$ is the noise power at the peak frequency. For "white" (spectrally flat) noise, equation (1) simplifies to:

$$B = \frac{1}{G(f_0)} \int_0^\infty G(f)\,df \tag{2}$$

and this format is most often seen. In electro-optical systems, this bandwidth may be limited by the frequency response of a detector or its associated electronics, or by the insertion of an electrical filter operating in the audio to low radio frequency range, 20 Hz to several Mhz. Figures 1 and 2 also show the ENB (white noise) for low-pass and bandpass filters.

The signal-to-noise ratio (SNR, S/N) of a system is the ratio of the r.m.s. signal current i_{sig} to the r.m.s. noise current i_n. Voltage may be substituted for current. SNR is dimensionless. Use of r.m.s. is indicated as it is the only measure appropriate for the characterization of random noise.

3. Low-pass filters

The voltage transmission of a single-section RC low-pass filter is

$$A = \frac{1}{\sqrt{1+\omega^2\tau^2}} \tag{3}$$

where ω is the radian frequency, equal to $2\pi f$ in Hz, and τ is the circuit time constant, the RC product. At low frequencies ($\omega\tau << 1$), A is unity. The transmission curve drops to -3dB in amplitude at the point where $\omega\tau = 1$, and falls at 6dB/octave (20 dB/decade) at higher frequencies ($\omega\tau >>1$). The cutoff frequency is defined as the -3dB (0.707) point, although there is substantial transmission for higher frequencies. The -3dB point is at $1/\tau$ radians/sec or $1/(2\pi\tau)$ Hz. The ENB of this simple filter is readily found by integrating the square (power transmission) of equation (3) in closed form; the result is $\pi/(2\tau)$ in radians/sec, or $1/(4\tau) = (\pi/2)f_o$ expressed in Hz. The ENB is therefore $\pi/2$ or 1.571 times the -3dB bandwidth, and everybody in Table 1 agrees!

For higher order filters, the closed-form integration becomes more complex, so I chose numerical techniques by writing a simple BASIC program and using a spreadsheet. It must be noted that whenever two or more RC sections are cascaded, the -3dB point for the new composite filter shifts to lower frequencies; one does <u>not</u> use the -3dB point for a single RC section. In addition, multiple sections are buffered (isolated from each other) so that subsequent sections present no loading to preceeding sections). The results of the integrations are shown in Table 2.

Table 2. Low pass filter characteristics, matched sections

SECTIONS	**ω_{-3dB} (rad/sec)**	**f_{-3dB} (Hz)**	**ENB (rad/sec)**	**ENB (Hz)**	**RATIO ENB/B_{-3b}**
1	$1/\tau$	$1/2\pi\tau$	$\pi/2\tau$	$1/4\tau$	$\pi/2 = 1.571$
2	$0.644/\tau$	$0.102/\tau$	$\pi/4\tau$	$1/8\tau$	1.220
3	$0.510/\tau$	$0.081/\tau$	$0.589/\tau$	$0.094/\tau$	1.155
4	$0.435/\tau$	$0.069/\tau$	$0.492/\tau$	$0.078/\tau$	1.130
5	$0.386/\tau$	$0.061/\tau$	$0.430/\tau$	$0.068/\tau$	1.115
6	$0.350/\tau$	$0.056/\tau$	$0.387/\tau$	$0.062/\tau$	1.106

These results confirm that the values given by Motchenbacher & Connelly and by Ott in Table 1 are correct.

4. Bandpass filters with matched time constants

The simple RC bandpass filter with matched time constants adds a single hi-pass filter to a single lo-pass filter, each with the same time constant $\tau = RC$. The voltage transmission of a single-section RC hi-pass filter is

$$A = \frac{\omega\tau}{\sqrt{1+\omega^2\tau^2}} \tag{4}$$

where ω is the radian frequency, equal to $2\pi f$ in Hz, and τ is the circuit time constant, the RC product, in seconds. At high frequencies, A approaches unity, and the curve falls at 6dB/octave (20 dB/decade) at lower frequencies. The cutoff frequency is defined as the -3dB (0.707) point, even though there is substantial transmission at lower frequencies. The -3dB point, where $\omega^2\tau^2 = 1$, is $1/\tau$ radians/sec or $1/(2\pi\tau)$ Hz. The peak transmission for these simple bandpass filters is no longer unity, and the -3dB bandwidth points must be evaluated with respect to the peak transmission of the composite filter, not unity. For the single section bandpass filter, a peak transmission of 0.5 (-6dB) is found, located at the coincidence of the -3dB points of the hi-pass and lo-pass sections. The -3dB passband of the bandpass filter is determined at 3dB below this level, or at -9dB = 0.3535. The closed form integration of this single-stage bandpass filter gives an ENB of πf_C. Results for filters with one to four sections are shown in Table 3.

Table 3. Band-pass filter characteristics, matched sections

SECTIONS	**1**	**2**	**3**	**4**
Peak trans	0.5	0.25	0.125	0.0625
$B_{-3dB}/f_C = 1/Q$	2	1.287	1.019	0.871
f_{LP}/f_C	0.414	0.546	0.613	0.655
f_{HP}/f_C	2.414	1.833	1.632	1.526
ENB/f_C	π	$\pi/2$	1.177	0.982
f_{LP}/f_C	0.291	0.486	0.572	0.623
f_{HP}/f_C	3.432	2.057	1.749	1.605
ENB/B_{-3dB}	$\pi/2$	1.220	1.155	1.127

It should be noted that the cut-on and cut-off frequencies are disposed about the center frequency in a geometric sense, i.e., $f_{LP} \times f_{HP} = f_C^2$ where f_C is the center frequency of the filter. The location of f_{LP} is given by

$$f_{LP} = \frac{f_C}{2}\left[\sqrt{B^2+4} - B\right] \tag{5}$$

where B is either the -3dB bandwidth or the ENB. f_H is then f_C^2/f_L.

5. Bandpass filters with different time constants

Here we discuss bandpass filters constructed using a single hi-pass section in series with a single lo-pass section. Each section has a different time constant. Figures 3 and 4 shows a typical bandpass filter, voltage and power transmissions, with the bandwidths superimposed. First we note that the minimum bandwidth is achieved with the lo-pass cutoff and hi-pass cuton frequencies matched. If the lo-pass cutoff is chosen at a lower frequency than the hi-pass cuton frequency, the resulting bandwidth remains the same as the case where the two frequencies are identical. The only thing achieved is a reduction in filter transmission.

A simple BASIC program was written to find the ENB, the peak transmission, the -3dB points and the -3dB bandwidth for these filters. Again the integrations were done for several selections of lo-pass cutoffs and hi-pass cuton frequencies, and the -3dB points were located with respect to the composite transmission. The results are shown in Table 4 for a single-section bandpass filter. These calculations were done holding f_{HP} constant at unity.

Table 4. ENB for bandpass filters where $f_{LP} \geq f_{HP}$.

f_{LP}/f_{HP}	T_{peak}	B_{-3dB}	ENB
1	0.5	2	3.14
1.5	0.6	2.5	3.91
2	0.667	3	4.70
3	0.75	4	6.26
4	0.8	5	7.82
5	0.833	6	9.39
6	0.857	7	10.96
10	0.909	11	17.20
20	0.952	21	32.78

From these data we find some surprisingly simple relationships. The maximum transmission is given by

$$T_{peak} = \frac{f_{LP}}{f_{LP} + f_{HP}} \tag{6}$$

and if $f_{LP} >> f_{HP}$, the peak transmission approaches unity as expected. The -3dB bandwidth is given by

$$B_{-3db} = f_{LP} + f_{HP} \tag{7}$$

so that if $f_{LP} >> f_{HP}$, the -3dB bandwidth approaches that of the lo-pass filter alone. The effective noise bandwidth is given by

$$\text{ENB} = \frac{\pi}{2} B_{-3db} \tag{8}$$

Figure 7.63 in Horowitz and Hill shows a simple equation to relate the ENB for this case to the individual cut-on and cut-off frequencies:

$$ENB = \left(\frac{\pi}{2}\right)\frac{f_{LP}^2}{f_{LP} + f_{HP}} \tag{9}$$

If we were to use equation (9) to determine the ENB in the special case where $f_{LP} = f_{HP}$, it shows that the ENB is π/4 times the 3dB bandwidth, which is less than the -3dB bandwidth, a surprising result. This analysis shows that the ENB is (π/2) times the 3dB bandwidth. It can be seen than when $f_L \gg f_H$, the results of equation (9) converge to the correct solution, just that of the low-pass filter alone. A comparison between these new calculations for ENB and the results predicted using equation (9) is given in Table 5. It is apparent that equation (9) gives erroneous results.

Table 5. Comparison with Horowitz and Hill.

f_L/f_H	ENB	Equation (9)	RATIO
1	π	π/4	4
2	4.70	2.09	2.24
5	9.39	6.55	1.43
10	17.20	14.28	1.2
20	32.78	29.9	1.1

6. Filter selection to optimize SNR

We now address the selection of the optimum filter to maximize the signal-to-noise ratio. For many applications, we can ignore preservation of the signal waveform to achieve better SNR. We shall recover just the fundamental with maximum SNR. Our discussion will be limited to "white" noise (uniform power spectral density).

For the low-pass filter, the choice of cut-off frequency f_c was determined using a short BASIC program to iterate f_c for a fixed signal frequency of 100 (arbitrary units). The results are shown in Figures 5 and 6 for single- and multiple-section lo-pass filters, respectively. In the second case, the frequencies are adjusted to place the -3dB point of the composite filters at the same frequency as the single-section filter. These results show that for the single-section filter, the best SNR is obtained when f_c is equal to the signal fundamental frequency.

The results differ little for multi-section lo-pass filters. The double-section filter achieves its peak SNR at a frequency slightly higher (1.11 times the composite -3dB point) than for the single-section filter. If we choose the composite -3dB point, the SNR is 0.991 times the maximum achievable SNR. Three- and four-section filters showed similar results: the peak SNR was realized at about a 15% higher cutoff frequency, but the SNR at the composite -3dB point was within 1% of the maximum SNR. Satisfactory results will be achieved by using the composite -3dB frequency for 1 to 4 section lo-pass filters.

For the simple bandpass filter, where the hi-pass and lo-pass sections are set to the same frequency, the optimum SNR is achieved by setting both -3dB points at the signal frequency, as that will maximize signal transmission. It was hypothesized that if the bandpass were increased somewhat, the transmission at the peak may increase faster than the noise, which is proportional to the square root of the ENB. To test this hypothesis, further spreadsheet work was done to implement the calculations. I again chose to keep the geometric mean of the lo-pass and hi-pass sections equal to the center frequency, i.e., $f_{LP} \times f_{HP} = f_C^2$. The results are shown in Figure 7. It can be seen that the optimum SNR is achieved when the passband is defined where $f_L = f_H$. It can also be seen that setting the lo-pass section to a lower frequency than the hi-pass section is futile, yielding the same SNR, with both signal and noise attenuated equally. These above results are valid only for “white” noise.

Every practical circuit has at a minimum a single RC time constant associated with it, defining an ENB and a corresponding SNR. If additional noise filtering is necessary, we can add a simple active filter using a single operational amplifier with two RC sections. It is then interesting to consider the simple bandpass filter (one section each matched hi-pass and lo-pass) and one- and two-section low-pass RC filters. The bandpass filter has an ENB of π and a peak gain of 0.5, whereas a single section low-pass filter has an ENB of $\pi/2$ and a gain of unity. The noise transmission, the product of the peak transmission and $ENB^{1/2}$, is 1.253 for the lo-pass filter and 0.886 for the bandpass filter. The signal transmission for the lo-pass filter is 0.707 whereas it is 0.5 for the bandpass filter. The SNR for each is therefore the same. However, for a two-section low-pass filter with the signal at the (composite) -3dB frequency, the ENB is $1.220 \times f_C$, the noise transmission is 1.105, the signal transmission is 0.707 and the SNR is therefore improved by some 13.5% over the simple bandbass and single-section filters.

7. Conclusions

Several recommendations can be made.

(1) A double-section lo-pass filter is sufficiently better in the reduction of white noise to warrant the use of two additional components.

(2) In the absence of 1/f noise, a two-section lo-pass filter will outperform a bandpass filter with the same number of components.

BANDWIDTH NORMALIZATION BY MOMENTS

General measurement equation:

$$I = \int_0^\infty \Re(\lambda)\,\Phi_\lambda\,\mathrm{d}\lambda \tag{1}$$

If $\Re(\lambda)$ can be represented as a rectangle

$$I = \Re_n \int_{\lambda_1}^{\lambda_2} \Phi_\lambda \mathrm{d}\lambda \tag{2}$$

Let the source function Φ_λ be described as a second-degree polynomial:

$$\Phi_\lambda = A + B\lambda + C\lambda^2 \tag{3}$$

Substitute (3) into (1), divide both sides by $\int\Re(\lambda)\,\mathrm{d}\lambda$ and multiply both sides by $(\lambda_2 - \lambda_1)$ to get:

$$\frac{I\cdot(\lambda_2-\lambda_1)}{\int_0^\infty \Re(\lambda)\mathrm{d}\lambda} = \left[A + B\frac{\int_0^\infty \lambda\Re(\lambda)\mathrm{d}\lambda}{\int_0^\infty \Re(\lambda)\mathrm{d}\lambda} + C\frac{\int_0^\infty \lambda^2\Re(\lambda)\mathrm{d}\lambda}{\int_0^\infty \Re(\lambda)\mathrm{d}\lambda}\right](\lambda_2-\lambda_1) \tag{4}$$

Next, integrate (3) between the limits λ_1 and λ_2

$$\int_{\lambda_1}^{\lambda_2} \Phi_\lambda\,\mathrm{d}\lambda = \left[A + \frac{B}{2}(\lambda_2+\lambda_1) + \frac{C}{3}\left(\lambda_2^2 + \lambda_2\lambda_1 + \lambda_1^2\right)\right](\lambda_2-\lambda_1) \tag{5}$$

Note the similarities between Eqs. (4) and (5). If the following conditions are applied,

$$\frac{\lambda_2+\lambda_1}{2} = \frac{\int_0^\infty \lambda\Re(\lambda)\mathrm{d}\lambda}{\int_0^\infty \Re(\lambda)\mathrm{d}\lambda} \qquad \frac{\lambda_2^2+\lambda_2\lambda_1+\lambda_1^2}{3} = \frac{\int_0^\infty \lambda^2\Re(\lambda\,\mathrm{d}\lambda)}{\int_0^\infty \Re(\lambda\,\mathrm{d}\lambda)} \tag{6}$$

$$\int_{\lambda_1}^{\lambda_2} \Phi_\lambda\,\mathrm{d}\lambda = \frac{I(\lambda_2-\lambda_1)}{\int_0^\infty \Re(\lambda)\mathrm{d}\lambda} \tag{7}$$

Assume that area of response curve = area of equivalent rectangle, i.e.

$$\Re_n\cdot\Delta\lambda = \int_0^\infty \Re(\lambda)\mathrm{d}\lambda \tag{8}$$

Then

$$\int_{\lambda_1}^{\lambda_2} \Phi_\lambda \mathrm{d}\lambda = \frac{I}{\Re_n} \tag{9}$$

and we have a band limited power $\Phi_{\text{in-band}}$.

Now we proceed to determine λ_1, λ_2 and $\Re_n$. Substitute:

$$M_1 = \frac{\int_0^\infty \lambda\Re(\lambda)\mathrm{d}\lambda}{\int_0^\infty \Re(\lambda)\mathrm{d}\lambda} \qquad M_2 = \frac{\int_0^\infty \lambda^2\Re(\lambda)\mathrm{d}\lambda}{\int_0^\infty \Re(\lambda)\mathrm{d}\lambda} \tag{10}$$

Then

$$M_1 = \frac{\lambda_2 + \lambda_1}{2} \qquad M_2 = \frac{\lambda_2^2 + \lambda_2\lambda_1 + \lambda_1^2}{3} \tag{11}$$

M_1 is the first moment divided by the area (zeroth moment) and is the centroid of the response curve, the effective or center wavelength λ_c.

M_2 is the second moment divided by the area, which is related to the square of the radius of gyration.

Solution of simultaneous Eqs. (11), with the substitution $M_1 = \lambda_c$, yields

$$\lambda_1 = \lambda_c - \sqrt{3(M_2 - \lambda_c^2)}\,, \qquad \lambda_2 = \lambda_c + \sqrt{3(M_2 - \lambda_c^2)} \tag{12}$$

showing the bandpass limits λ_1 and λ_2 are symmetrically disposed about the center wavelength λ_c.

The quantity $(M_2 - \lambda_c^2)$ is recognized as the variance σ^2. The bandwidth between wavelength limits λ_1 and λ_2 is:

$$\Delta\lambda = \lambda_2 - \lambda_1 = 2\sqrt{3}\,\sigma \tag{13}$$

and the short and long limit wavelengths are then:

$$\lambda_1 = \lambda_c - \sqrt{3}\,\sigma \qquad \lambda_2 = \lambda_c + \sqrt{3}\,\sigma \tag{14}$$

The bandwidth-normalized responsivity is:

$$\Re_n = \frac{1}{2\sqrt{3}\sigma}\int_0^\infty \Re(\lambda)\,\mathrm{d}\lambda \tag{15}$$

Now we have our three parameters, $\Re_n$, λ_1 and λ_2. Note that the coefficients A, B and C of the second-degree source polynomial (Eq. 3) have vanished. The implication is significant:

Any source that can be represented by a second-degree polynomial can be characterized between the wavelength limits λ_1 and λ_2 (which are determined solely by the radiometer) **without error**.

There is no ambiguity in any of the normalization parameters; they are all uniquely determined from only the spectral responsivity curve.

The errors are related to the deviation of the source function from a quadratic.

MOMENTS NORMALIZATION SUMMARY

This is the step-by-step procedure for accomplishing a moments normalization. The starting point is absolute spectral responsivity $\Re(\lambda)$.

Zeroth moment	$M_0 = \int_0^\infty \Re(\lambda)\,\mathrm{d}\lambda$
First moment	$M_1 = \int_0^\infty \lambda\,\Re(\lambda)\,\mathrm{d}\lambda$
Second moment	$M_2 = \int_0^\infty \lambda^2\,\Re(\lambda)\,\mathrm{d}\lambda$
Center wavelength (centroid)	$\lambda_c = \dfrac{M_1}{M_0}$
Variance	$\sigma^2 = \dfrac{M_2}{M_0} - \lambda_c^2$
Short wavelength limit	$\lambda_1 = \lambda_c - \sqrt{3}\sigma$
Long wavelength limit	$\lambda_2 = \lambda_c + \sqrt{3}\sigma$
Bandwidth	$\Delta\lambda = 2\sqrt{3}\sigma$
Normalized responsivity	$\Re_n = \dfrac{M_0}{2\sqrt{3}\sigma}$

JONES NSS CALIBRATION CONFIGURATION

The following pages are a replica of an obscure application note further describing the near small source method of radiometric calibration. A copy of the original document, believed to be an application note from Block Engineering, was scanned, then modern terminology was added.

****

How to calibrate a radiometer

A simple method of calibrating a radiometer using a small blackbody source close to the radiometer aperture has been described by Dr. R. Clark Jones of the Polaroid Corporation. The principles involved in this method are briefly reviewed here with special emphasis on the application to the Optitherm Radiometer Cassegrain system.

The essential point in the method is that a small radiation source close to the aperture of the Radiometer will *uniformly* irradiate an area in the focal plane of the Radiometer. The radiation on the detector (with the radiometer focussed at infinity) is then given by

ORIGINAL EQUATION	MODERN SYMBOLS	
$W = B_s A_s \omega_r$	$\Phi = L_s A_s \omega_r$	(1)

where W = radiation on detector (watts, Φ)
B_s = Source radiance (watts/steradian-cm^2, L_s)
A_s = Source area (cm^2)
ω_r = Solid angle of radiometer field of view (steradian)
$= \dfrac{\text{detector area}}{(\text{focal length})^2}$

Thus, the responsivity of a detector in a Radiometer can readily be calibrated by dividing the signal voltage output of the instrument by the radiation on the detector.

An important aspect of the method is that the radiation on the detector is independent of the Radiometer aperture and source location *providing* a uniformly irradiated area covers the detector. This restriction places limits on the source size and location as given below.

For a *point source* (see Fig. 1) the diameter of the uniformly irradiated disc D_f in tie focal plane is given by

$$D_f = \frac{f}{P} D_{P1} \tag{2}$$

where f = focal length of Radiometer
P = distance from vertex of optical system (primary mirror) to source
D_{P1} = diameter of entrance pupil of radiometer (usually diameter of primary mirror)

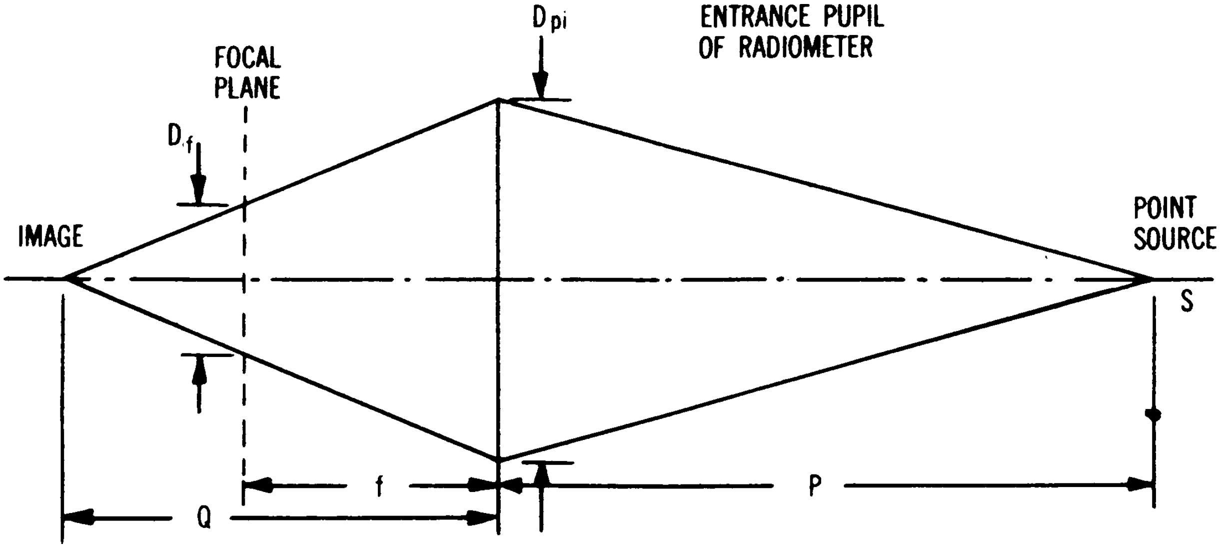

Fig. 1

If the Radiometer optical system is of the Cassegrain type, an obscured area will result and the uniformly irradiated area will then be an annular ring of width χ.and mean diameter D_m

$$\chi = \frac{1}{2} \frac{f}{P} (D_{P1} - D_{P2}) \tag{3}$$

where D_{P2} = Diameter of obscured disc produced by secondary mirror

$$D_m = \frac{1}{2} \frac{f}{P} (D_{P1} + D_{P2}) \tag{4}$$

If, as is always the case, the source has a finite diameter M_s, (see Fig. 2) the edges of the disc or ring will be vignetted by an amount ($f\,M_s\,/\,P$), divided equally on either side of the unblurred edge. The remaining uniformly irradiated disc or annular ring width is given by

$$D_x = \frac{f}{P}(D_{P1} - M_S) \tag{2a}$$

$$\chi = \frac{f}{P}\left[\frac{1}{2}\left(D_{P1} - D_{P2}\right) - M_S\right] \tag{3a}$$

The mean diameter of the ring remains the same as given in (4).

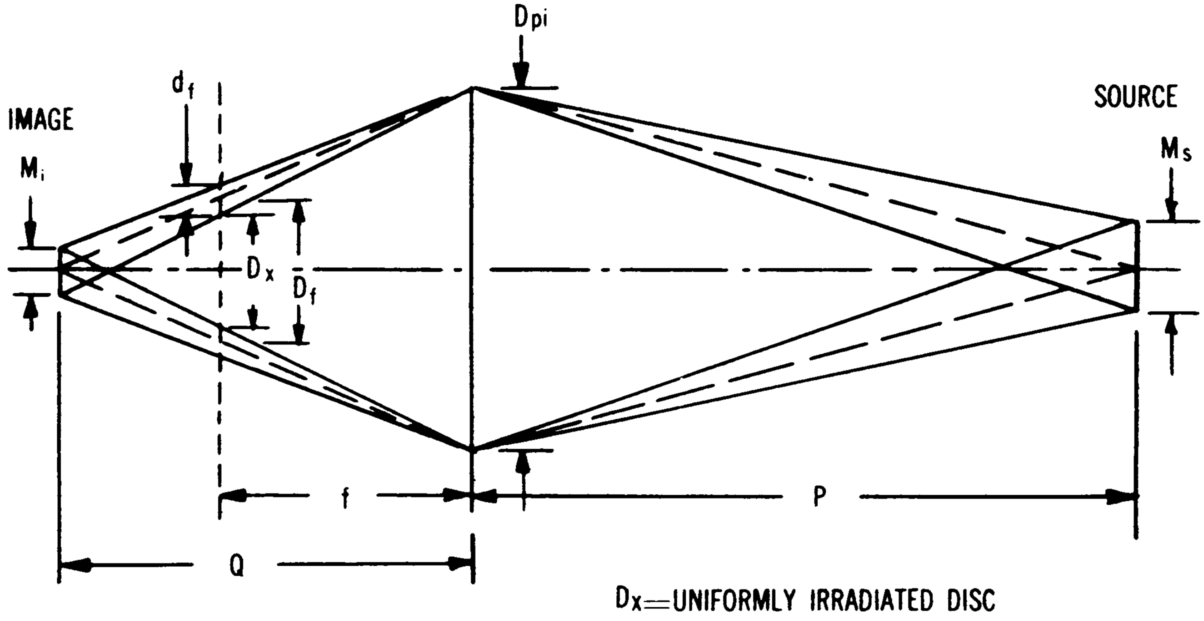

Fig. 2

In calibrating a Radiometer, a convenient source aperture and distance are first chosen. Then the size of the uniformly irradiated area must be checked to see whether it covers the detector. For example, if a Cassegrain system is used. the detector must fit in the ring of width z and mean diameter D as computed from equations (3a) and (4). The source must be placed off-axis such that the annular ring of width x falls on the detector.

Several other precautions must be observed, particularly if a thermal detector is used. Since the calibration source fills only a small part of the field of view, the detector will "see" other radiation as well. If the source is chopped, the Radiometer will respond only to it. However, in many cases the detector is chopped, and hence it responds to all radiation in its field of view. One way of separating the response to the calibration source from the background is to record the difference in response when the source aperture is opened, and when it is closed.

APPENDIX VIII

DOCUMENTARY STANDARDS FOR RADIOMETRY AND PHOTOMETRY

Numerous agencies prepare and disseminate documentary (protocol) standards for radiometry and allied fields. Those listed here are either US or international standards organizations. The European Committee for Standardization is called CEN (www.cenorm.be/); whose mission is to promote voluntary technical harmonization in Europe in conjunction with worldwide agencies and its European partners. The purposes include the lowering of trade barriers and the promotion of common technical understanding. European standards (ex, BSI from UK and DIN from Germany) may be accessed via CEN. The Japanese Standards Association (www.jsa.or.jp) also has extensive listings.

ANSI – American National Standards Institute. The US representative for ISO, the International Standards Organization. (www.ansi.org)

C78.40-1985	Specifications for Mercury lamps
C78.180-1989	Specifications for Fluorescent Lamp Starters
C78.375-1991	Guide for Electrical Measurements of Fluorescent Lamps
C78.386	Mercury Lamps - Measurement of Characteristics
C78.387	Metal-Halide Lamps - Measurement of Characteristics
C78.388	High Pressure Sodium Lamps - Measurement of Characteristics
C82.1-1985	Specifications for Fluorescent Lamp Ballasts
C82.1(a-c) 1990	Specifications for Fluorescent Lamp Ballasts (Supplement to C82.1)
C82.3-1989	Specifications for Fluorescent Lamp Reference Ballasts
C82.4-1985	Specifications for High Intensity Discharge and Low Pressure Sodium amp Ballasts
C82.5-1990	Specifications for High-Intensity-Discharge Lamp Reference Ballasts
C82.6-1985	Methods of Measurement of Discharge Lamp Ballasts
ANSI/NCSL 540-1-1994	American National Standards for Calibration - Calibration Laboratories and Measuring and Test Equipment - General Requirements

ANSI/IES RP-16, American National Standard Nomenclature and Definitions for Illuminating Engineering (1986)

ASTM The American Society for Testing and Materials (www.astm.org) maintains an extensive collection of protocol or documentary standards, including practices, specifications, guides, procedures, and test methods for a large range of materials and instrumentation for their characterization. Some 10,000 standards are published annually in a 73-volume set, of which one volume is the index alone! The ASTM Book of Standards occupies nearly 2 meters of shelf space. These documents are subject to periodic review and revision by the committees that were responsible for their generation and maintenance. Always check at www.astm.org to see if a later verions is available. A number of these standards are the result of the efforts of committee E12 on Color and Appearance, committee E20 on Temperature Measurement and committee E37 on Thermal Measurement. Special collections in specific areas are also published. For example, ASTM Standards on Color and Appearance Measurement, Sixth Edition (2000). This book contains 108 ASTM standards as well as ISO and ISO/CIE standards used in appearance analysis for a variety of materials and products, including all the standards listed above. Includes a CD/ROM with even more information. The following listing shows a selection of relevant standards to radiometry, photometry and colorimetry. Another useful guide is "Nomenclature and Definitions Applicable to Radiometric and Photometric Characteristics of Matter," ASTM Special Technical Publication 475 (1971).

"Guide for Recommended Uses of Photoluminescent Safety Markings," ASTM E2030 (1999)

"Specification for Photoluminescent Safety Markings," ASTM Z6474Z

"Standard Practice for Preparation of Pressed Powder White Reflectance Factor Transfer Standards for Hemispherical Geometry and Bi-Directional Geometries," ASTM E259 (1998)

"Recommended Practice for Goniophotometry of Objects and Materials," ASTM E167 (1996)

"Specification for Daytime Pedestrian Visibility Enhancement," ASTM E1896 (1997)

“Standard Guide for Describing and Specifying the Spectrometer of an Optical Emission Direct-Reading Instrument,” ASTM E1507 (1998)

"Standard Guide for Designing and Conducting Visual Experiments," ASTM E1808 (1996)

“Standard Guide for Establishing Spectrophotometer Performance Tests,” ASTM E1866 (1997)

“Standard Guide to Evaluation of Optical Properties of Powder Coatings,” ASTM D5382 (1995)

“Standard Guide for Examining Electrical and Mechanical Equipment with Infrared Thermography,” ASTM E1934 (1999)

"Standard Guide for Modeling the Colorimetric Properties of a Visual Display Unit," ASTM E1682 (2001)

“Standard Guide for Preparation, Maintenance, and Distribution of Physical Product Standards for Color and Geometric Appearance of Coatings,” ASTM D5531 (1999)

“Standard Guide for Quality Assurance of Laboratories Using Molecular Spectroscopy," ASTM E924 (1994)

"Standard Guide for Quantitative Analysis by Energy-Dispersive Spectroscopy," ASTM E1508 (1998)

"Standard Guide for Raman Shift," ASTM E1840 (1996)

“Standard Guide for Selection of Geometric Conditions for Measurement of Reflection and Transmission Properties of Materials,” ASTM E179 (1996)

“Standard Guide for Use of Lighting in Laboratory Testing," ASTM E1733 (1995)

“Standard Guide to Evaluation of Optical Properties of Powder Coatings,” ASTM D5382 (1995)

"Standard Guide to Properties of High Visibility Materials Used to Improve Individual Safety," ASTM F923 (2000)

“Standard Method for Calibration of Reference Pyranometers With Axis Vertical by the Shading Method,” ASTM E913 (1999)

"Standard Practice for Angle Resolved Optical Scatter Measurements on Specular or Diffuse Surfaces," ASTM E1392 (1996)

"Standard Practice for Calculating Solar Reflectance Index of Horizontal and Low-Sloped Opaque Surfaces ," ASTM E1980 (2001)

"Standard Practice for Calculating Yellowness and Whiteness Indices from Instrumentally Measured Color Coordinates ," ASTM E313 (2000)

"Standard Practice for Calculation of Photometric Transmittance and Reflectance of Materials to Solar Radiation," ASTM E971 (1996)

"Standard Practice for Calculation of Weighting Factors for Tristimulus Integration," ASTM E2022 (2001)

"Standard Practice for Calibrating Thin Heat Flux Transducers," ASTM C1130 (2001)

"Standard Practice for Calibration of Ozone Monitors and Certification of Ozone Transfer Standards Using Ultraviolet Photometry," ASTM D5110 (1998)

"Standard Practice for Calibration of the Heat Flow Meter Apparatus," ASTM C1132 (1995)

"Standard Practice for Calibration of Transmission Densitometers," ASTM E1079 (2000)

"Standard Practice for Calculating Yellowness and Whiteness Indices from Instrumentally Measured Color Coordinates," ASTM E313 (2000)

“Standard Practice for Color Measurement of Fluorescent Specimens," ASTM E991 (1998)

"Standard Practice for Computing the Colors of Fluorescent Objects from Bispectral Photometric Data," ASTM E2152 (2001)

"Standard Practice for Computing the Colors of Objects by Using the CIE System," ASTM E308 (1999)

"Standard Practice for Describing and Measuring Performance of Dispersive Infrared Spectrometers," ASTM E932 (1997)

"Standard Practice for Describing and Measuring Performance of Fourier Transform Mid-Infrared (FT-MIR) Spectrometers Level Zero and Level One Tests," ASTM E1421 (1999)

"Standard Practice for Describing and Measuring Performance of Laboratory Fourier Transform Near-Infrared (FT-NIR) Spectrometers: Level Zero and Level One Tests," ASTM E1944 (1998)

“Standard Practice for Describing and Measuring Performance of Ultraviolet, Visible, and Near-Infrared Spectrophotometers," ASTM E275 (2001)

“Standard Practice for Describing and Specifying Inductively-Coupled Plasma Atomic Emission Spectrometers," ASTM E1479 (1999)

"Standard Practice for Describing Photomultiplier Detectors in Emission and Absorption Spectrometry," ASTM E520 (1998)

“Standard Practice for Describing Retroreflection," ASTM E808 (1999)

"Standard Practice for Determining the Steady State Thermal Transmittance of Fenestration Systems," ASTM E1423 (1999)

"Standard Practice for Electronic Interchange of Color and Appearance Data," ASTM E1708 (2001)

"Standard Practice for Establishing Color and Gloss Tolerances," ASTM D3134 (1997)

"Standard Practice for Evaluating Solar Absorptive Materials for Thermal Applications," ASTM E744 (1996)

"Standard Practices for General Techniques of Ultraviolet-Visible Quantitative Analysis," ASTM E169 (1999)

"Standard Practice for Goniophotometry of Objects and Materials," ASTM E167 (1996)

"Standard Practice for Identification of Instrumental Methods of Color or Color-Difference Measurement of Materials," ASTM E805 (2001)

"Standard Practice for Measuring Colorimetric Characteristics of Retroreflectors Under Nighttime Conditions," ASTM E811 (2001)

"Standard Practice for Measuring Photometric Characteristics of Retroreflectors," ASTM E809 (2000)

"Standard Practice for Measuring Practical Spectral Bandwidth of Ultraviolet-Visible Spectrophotometers," ASTM E958 (1999)

"Standard Practice for Near Infrared Qualitative Analysis," ASTM E1790 (2000)

"Standard Practice for Obtaining Bispectral Photometric Data for Evaluation of Fluorescent Color ," ASTM E2153 (2001)

"Standard Practice for Obtaining Colorimetric Data from a Visual Display Unit Using Tristimulus Colorimeters," ASTM E1455 (1997)

"Standard Practice for Obtaining Spectrophotometric Data for Object-Color Evaluation," ASTM E1164 (1994)

"Standard Practice for Obtaining Spectroradiometric Data from Radiant Sources for Colorimetry," ASTM E1341 (2001)

"Standard Practice for Preparation of Pressed Powder White Reflectance Factor Transfer Standards for Hemispherical Geometry and Bi-Directional Geometries," ASTM E259 (1998)

"Standard Practice for Preparation of Textiles Prior to Ultraviolet (UV) Transmission Testing," ASTM D6544 (2000)

"Standard Practice for Qualifying Spectrometers and Spectrophotometers for Use in Multivariate Analyses, Calibrated Using Surrogate Mixtures," ASTM E2056 (2000)

"Standard Practice for Reducing the Effect of Variability of Color Measurement by Use of Multiple Measurements," ASTM E1345 (1998)

"Standard Practice for Selecting and Calibrating Sources for the Visual Assessment of Object Colors," ASTM Z6606Z

"Standard Practice for Selection and Use of Portable Retroreflectomers for the Measurement of Pavement Marking Materials," ASTM E1743 (1996)

"Standard Practice for Solar Simulation for Thermal Balance Testing of Spacecraft," ASTM E491 (1999)

"Standard Practice for Specifying and Matching Color Using the Colorcurve System," ASTM E1541 (1998)

"Standard Practice for Specifying and Verifying the Performance of Colorimeters, Spectrocolorimeters and Goniospectrocolorimeters," ASTM Z6899Z

"Standard Practice for Specifying Color by the Munsell System," ASTM D1535 (2001)

"Standard Practice for Specifying Color by Using the Optical Society of America Uniform Color Scales System," ASTM E1360 (2000)

"Standard Practice for Specifying the Geometry of Observations and Measurements to Characterize the Appearance of Materials," ASTM E1767 (1995)

"Standard Practice for the Periodic Calibration of Narrow Band-Pass Spectrophotometers," ASTM E925 (1994)

"Standard Practice for Testing Fixed-Wavelength Photometric Detectors Used in Liquid Chromatography," ASTM E685 (2000)

"Standard Practice for Testing Variable-Wavelength Photometric Detectors Used in Liquid Chromatography," ASTM E1657 (2001)

"Standard Practice for Transfer Standards for Reflectance Factor for Near-Infrared Instruments Using Hemispherical Geometry ," ASTM E1791 (2000)

"Standard Practice for Validation of Multivariate Process Infrared Spectrophotometers ," ASTM D6122 (1999)

"Standard Practice for Visual Appraisal of Colors and Color Differences of Diffusely-Illuminated Opaque Materials," ASTM D1729 (1996)

"Standard Practice for Visual Color Evaluation of Transparent Sheet Materials ," ASTM E1478 (1997)

"Standard Practice for Visual Evaluation of Metamerism ," ASTM D4086 (1997)

"Standard Practices for General Techniques of Ultraviolet-Visible Quantitative Analysis," ASTM E169 (1999)

"Standard Practices for Infrared Multivariate Quantitative Analysis ," ASTM E1655 (2000)

"Standard Practices for Internal Reflection Spectroscopy ," ASTM E573 (2001)

"Standard Solar Constant and Zero Air Mass Solar Spectral Irradiance Tables," ASTM E490 (2000)

"Standard Specification for Infrared Thermometers for Intermittent Determination of Patient Temperature," ASTM E1965 (1998)

"Standard Specification for Nighttime Photometric Performance of Retroreflective Pedestrian Markings for Visibility Enhancement," ASTM E1501 (1999)

"Standard Specification for Photoluminescent (Phosphorescent) Safety Markings," ASTM E2072 (2000)

"Standard Specification for Physical Characteristics of Nonconcentrator Terrestrial Photovoltaic Reference Cells," ASTM E1040 (1998)

"Standard Specification for Retroreflective Sheeting for Traffic Control," ASTM D4956 (2001)

"Standard Specification for Silvered Flat Glass Mirror," ASTM C1503 (2001)

"Standard Specification for Solar Simulation for Terrestrial Photovoltaic Testing." ASTM E927 (1997)

"Standard Tables for References Solar Spectral Irradiance at Air Mass 1.5: Direct Normal and Hemispherical for a 37° Tilted Surface," ASTM G159 (1998)

"Standard Terminology of Appearance," ASTM E284 (2001)

"Standard Terminology Relating to Molecular Spectroscopy," ASTM E131 (2000)

"Standard Terminology Relating to Photovoltaic Solar Energy Conversion," ASTM E1328 (1999)

"Standard Terminology Relating to Solar Energy Conversion," ASTM E772 (1993)

Standard Test Method for 20-deg Specular Gloss of Waxed Paper," ASTM D1834 (2000)

Standard Test Method for 45-deg Specular Gloss of Ceramic Materials," ASTM C346 (1998)

Standard Test Method for 60-deg Specular Gloss of Emulsion Floor Polish," ASTM D1455 (1997)

“Standard Test Method for Assessing the Quality of Sources for the Visual Assessment of Object Colors ," ASTM Z6607Z

“Standard Test Method for Calibration of a Spectroradiometer using a Standard Source of Irradiance," ASTM G138 (1996)

“Standard Test Method for Calibration of Heat Transfer Rate Calorimeters using a Narrow-Angle Blackbody Radiation Facility," ASTM E638 (1992)

“Standard Test Method for Calibration of Narrow- and Broad-band Ultraviolet Radiometers using a Spectroradiometer," ASTM G130 (1995)

"Standard Test Method for Calibration of a Pyranometer Using a Pyrheliometer,” ASTM G151 (2000)

“Standard Test Method for Color and Color-Difference Measurement by Tristimulus (Filter) Colorimetry," ASTM E1347 (1997) (formerly E97).

“Standard Test Method for Determining the Linearity of a Photovoltaic Device Parameter with respect to a Test Parameter," ASTM E1143 (1994)

“Standard Test Method for Estimating Stray Radiant Power Ratio of Spectrophotometers by the Opaque Filter Method," ASTM E387 (1995)

"Standard Test Method for Field Measurement of Raised Retroreflective Pavement Markers Using a Portable Retroreflectometer," ASTM E1696 (2001)

"Standard Test Method for Haze and Luminous Transmittance of Transparent Plastics," ASTM D1003 (2000)

"Standard Test Method for Identifying Fluorescence in Object-Color Specimens by Spectrophotometry," ASTM E1247 (2000)

"Standard Test Method for Luminous Reflectance Factor of Acoustical Materials by Use of Integrating-Sphere Reflectometers," ASTM E1477 (1998)

“Standard Test Method for Measuring and Calculating Emittance of Architectural Flat Glass Products Using Spectrometric Measurements,” ASTM E1585 (1993)

“Standard Test Method for Minimum Detectable Temperature Difference for Thermal Imaging Systems,” ASTM E1311 (1999)

"Standard Test Method for Noise Equivalent Temperature Difference of Thermal Imaging Systems," ASTM E1543 (2000)

"Standard Test Method for Obtaining Colorimetric Data From a Visual Display Unit by Spectroradiometry," ASTM E1336 (1996)

“Standard Test Method for Obtaining Colorimetric Data from a Visual Display Unit Using Tristimulus Colorimeters," ASTM E1455 (1997)

“Standard Test Method for Obtaining Spectroradiometric Data From Radiant Sources for Colorimetry," ASTM E1341 (1996)

"Standard Test Method for Photopic Luminance of Photoluminescent (Phosphorescent) Markings," ASTM E2073 (2000)

“Standard Test Method for Radiation Thermometer (Single Waveband Type)," ASTM E1256 (1988)

“Standard Test Method for Reflection Haze of High-Gloss Surfaces," ASTM D4039 (1999)

“Standard Test Method for Reflectance Factor and Color by Spectrophotometry Using Bidirectional Geometry," ASTM E1349 (1998)

"Standard Test Method for Solar Absorptance, Reflectance and Transmittance of Materials Using Spectrophotometers with Integrating Spheres," ASTM E903 (1988)

“Standard Test Methods for Solar Energy Transmittance and Reflectance (Terrestrial) of Sheet Materials," ASTM E424 (1993)

“Standard Test Method for Solar Absorptance, Reflectance, and Transmittance ofMaterials Using Integrating Spheres," ASTM E903 (1996)

“Standard Test Method for Spectral Bandwidth and Wavelength Accuracy of Fluorescence Spectrometers," ASTM E388 (1998)

"Standard Test Method for Specular Gloss," ASTM D523 (1999)

"Standard Test Method for Specular Gloss of Paper and Paperboard at 75°," ASTM D1223 (1998)

"Standard Test Method for Total Luminous Reflectance Factor by Use of 30/T Integrating-Sphere Geometry," ASTM E1651 (1999)

"Standard Test Method for Transfer of Calibration From Reference to Field Radiometers," ASTM E824 (1994)

"Standard Test Method for Transmittance and Color by Spectrophotometry Using Hemispherical Geometry," ASTM E1348 (1996)

"Standard Test Method for Transparency of Plastic Sheeting," ASTM D1746 (1997)

"Standard Test Method for Visual Evaluation of Gloss Differences Between Surfaces of Similar Appearance," ASTM D4449 (1999)

“Standard Test Method for Total Hemispherical Emittance of Surfaces From 20 to 1400°C,” ASTM C835 (2000)

"Standard Test Method for Brightness of Pulp, Paper, and Paperboard (Directional Reflectance at 457 nm)," ASTM D985 (1997)

"Standard Test Method for Calculation of Color Differences From Instrumentally Measured Color Coordinates," ASTM D2244 (2000)

“Standard Test Method for Calibration of Pyrheliometers by Comparison to Reference Pyrheliometers,” ASTM E816 (1995)

"Standard Test Method for Calibration of a Pyranometer Using a Pyrheliometer," ASTM G167 (2000)

"Standard Test Method for Calibration of a Spectroradiometer Using a Standard Source of Irradiance," ASTM G138 (1996)

"Standard Test Method for Calibration of Narrow- and Broad-Band Ultraviolet Radiometers Using a Spectroradiometer," ASTM G130 (1995)

"Standard Test Method for Calibration of Primary Non-Concentrator Terrestrial Photovoltaic Reference Cells Using a Tabular Spectrum," ASTM E1125 (1999)

"Standard Test Method for Calibration of Reference Pyranometers With Axis Tilted by the Shading Method," ASTM E941 (1999)

"Standard Test Method for Calibration of Silicon Non-Concentrator Photovoltaic Primary Reference Cells Under Global Irradiation," ASTM E1039 (1999)

"Standard Test Method for Calorimetric Determination of Hemispherical Emittance and the Ratio of Solar Absorptance to Hemispherical Emittance Using Solar Simulation," ASTM E434 (1996)

"Standard Test Method for Coefficient of Retroreflection of Retroreflective Sheeting Utilizing the Coplanar Geometry," ASTM E810 (2001)

"Standard Test Method for Color and Color-Difference Measurement by Tristimulus (Filter) Colorimetry," ASTM E1347 (1997)

"Standard Test Method for Color of Liquids Using Tristimulus Colorimetry," ASTM D5386 (2000)

"Standard Test Method for Conducting Aqueous Direct Photolysis Tests," ASTM E896 (1997)

"Standard Test Method for Detecting Delaminations in Bridge Decks Using Infrared Thermography," ASTM D4788 (1997)

"Standard Test Method for Determining Solar or Photopic Reflectance, Transmittance, and Absorptance of Materials Using a Large Diameter Integrating Sphere," ASTM E1175 (1996)

"Standard Test Method for Determining the Linearity of a Photovoltaic Device Parameter with Respect To a Test Parameter," ASTM E1143 (1999)

"Standard Test Method for Diffuse Light Transmission Factor of Reinforced Plastics Panels," ASTM D1494 (1997)

"Standard Test Method for Electrical Performance of Photovoltaic Cells Using Reference Cells Under Simulated Sunlight," ASTM E948 (1995)

"Standard Test Method for Evaluating Color Image Output from Color Printers and Copiers," ASTM F1206 (2000)

"Standard Test Method for Evaluation of Color for Thermoplastic Traffic Marking Materials," ASTM D4960 (1998)

"Standard Test Method for Evaluation of Visual Color Difference With a Gray Scale," ASTM D2616 (1996)

"Standard Test Method for Haze and Luminous Transmittance of Transparent Plastics," ASTM D1003 (2000)

"Standard Test Method for Hiding Power of Paints by Reflectometry," ASTM D2805 (1996)

"Standard Test Method for Identifying Fluorescence in Object-Color Specimens by Spectrophotometry," ASTM E1247 (2000)

"Standard Test Method for Linearity of Fluorescence Measuring Systems," ASTM E578 (2001)

"Standard Test Method for Luminous Reflectance Factor of Acoustical Materials by Use of Integrating-Sphere Reflectometers," ASTM E1477 (1998)

"Standard Test Method for Measuring Total-Radiance Temperature of Heated Surfaces Using a Radiation Pyrometer," ASTM E639 (1996)

"Standard Test Method for Measurement and Calculation of Reflecting Characteristics of Metallic Surfaces Using Integrating Sphere Instruments," ASTM E429

"Standard Test Method for Measurement of High-Visibility Retroreflective-Clothing Marking Material Using a Portable Retrorelectometer," ASTM E1809 (1996)

"Standard Test Method for Measurement of Retroreflective Pavement Marking Materials with CEN-Prescribed Geometry Using a Portable Retroreflectometer," ASTM E1710 (1997)

"Standard Test Method for Measurement of Retroreflective Signs Using a Portable Retroreflectometer," ASTM E1709 (2000)

"Standard Test Method for Minimum Detectable Temperature Difference for Thermal Imaging Systems," ASTM E1311 (1999)

"Standard Test Method for Minimum Resolvable Temperature Difference for Thermal Imaging Systems," ASTM E1213 (1997)

"Standard Test Method for Noise Equivalent Temperature Difference of Thermal Imaging Systems," ASTM E1543 (2000)

"Standard Test Method for Normal Spectral Emittance at Elevated Temperatures," ASTM E307 (1996)

"Standard Test Method for Normal Spectral Emittance at Elevated Temperatures of Nonconducting Specimens," ASTM E423 (1996)

"Standard Test Method for Obtaining Colorimetric Data From a Visual Display Unit by Spectroradiometry," ASTM E1336 (1996)

"Standard Test Method for Opacity of Paper (15°/Diffuse Illuminant A, 89% Reflectance Backing and Paper Backing)," ASTM D589 (1997)

"Standard Test Method for Photoelastic Measurements of Birefringence and Residual Strains in Transparent or Translucent Plastic Materials," ASTM D4093 (1995)

"Standard Test Method for Reflectance Factor and Color by Spectrophotometry Using Hemispherical Geometry," ASTM E1331 (1996)

"Standard Test Method for Reflectance Factor and Color by Spectrophotometry Using Bidirectional Geometry," ASTM E1349 (1998)

"Standard Test Method for Reflection Haze of High-Gloss Surfaces," ASTM D4039 (1999)

"Standard Test Method for Relative Tinting Strength of Aqueous Ink Systems by Instrumental Measurement," ASTM D6531 (2000)

"Standard Test Method for Relative Tinting Strength of White Pigments by Reflectance Measurements," ASTM D2745 (2000)

"Standard Test Method for Retroreflectance of Horizontal Coatings," ASTM D4061 (2000)

"Standard Test Method for Solar Absorptance, Reflectance, and Transmittance of Materials Using Integrating Spheres," ASTM E903 (1996)

"Standard Test Method for Solar Photometric Transmittance of Sheet Materials Using Sunlight," ASTM E972 (1996)

"Standard Test Method for Solar Transmittance (Terrestrial) of Sheet Materials Using Sunlight," ASTM E1084 (1996)

"Standard Test Method for Spectral Bandwidth and Wavelength Accuracy of Fluorescence Spectrometers," ASTM E388 (1998)

"Standard Test Method for Specular Gloss," ASTM D523 (1999)

"Standard Test Method for Specular Gloss of Glazed Ceramic Whitewares and Related Products," ASTM C584 (1999)

"Standard Test Method for Total Luminous Reflectance Factor by Use of 30/t Integrating-Sphere Geometry," ASTM E1651 (1999)

"Standard Test Method for Transmittance and Color by Spectrophotometry Using Hemispherical Geometry," ASTM E1348 (1996)

"Standard Test Method for Transparency of Plastic Sheeting," ASTM D1746 (1997)

"Standard Test Methods for Continuous Measurement of Ozone in Ambient, Workplace, and Indoor Atmospheres (Ultraviolet Absorption) ," ASTM D5156 (1995)

"Standard Test Methods for Measurement of Gloss of High-Gloss Surfaces by Goniophotometry ASTM E430 (1997)

"Standard Test Methods for Measuring and Compensating for Emissivity Using Infrared Imaging Radiometers," ASTM E1933 (1999)

"Standard Test Methods for Measuring and Compensating for Reflected Temperature Using Infrared Imaging Radiometers," ASTM E1862 (1997)

“Standard Test Methods for Measuring and Compensating for Transmittance of an Attenuating Medium Using Infrared Imaging Radiometers," ASTM E1897 (1997)

“Standard Test Methods for Measuring Optical Reflectivity of Transparent Materials," ASTM E1682 (1996)

"Standard Test Methods for Measuring Spectral Response of Photovoltaic Cells ASTM E1021 (1995)

“Standard Test Methods for Measuring Total-Radiance Temperature of Heated Surfaces using a Radiation Pyrometer" ASTM E639 (1990)

"Standard Test Methods for Measurement of Gloss of High-Gloss Surfaces by Goniophotometry," ASTM E430 (1997)

“Standard Test Methods for Minimum Detectable Temperature Difference for Thermal Imaging Systems" ASTM E1311 (1993)

“Standard Test Methods for Minimum Resolvable Temperature Difference for Thermal Imaging Systems" ASTM E1213 (1992)

“Standard Test Methods for Noise Equivalent Temperature Difference of Thermal Imaging Systems" ASTM E1543 (1994)

“Standard Test Methods for Radiation Thermometers (Single Waveband Type),” ASTM E1256 (1995)

"Standard Test Methods for Solar Energy Transmittance and Reflectance (Terrestrial) of Sheet Materials ASTM E424 (1993)

“Standard Test Methods for Total Normal Emittance of Surfaces Using Inspection-Meter Techniques,” ASTM E408 (1996)

BIPM The BIPM (Bureau International des Poids et Mesures) (www.bipm.fr) is an international institute, operating under the supervision of the Comite International des Poids et Mesures (CIPM). It is charged with the establishment and maintenance of reference standards, the organization of international comparisons and carrying out of calibrations, and fundamental investigations that may result in better reference standards or measurement techniques. The prototype kilogram is located here. Some of their publications include:

Principles Governing Photometry (1983)

The International System of Units (SI), BIPM, 7th Edition, 1998

Supplementary Information for the International Temperature Scale of 1990, BIPM, 1990 Chapter 6: Radiation Thermometry

International Vocabulary of Basic and General Terms in Metrology, joint BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML Standard, 1993

Guide to the Expression of Uncertainty in Measurement, joint BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML Standard, 1993

CIE -- The Commission Internationale de L'Eclairage (www.cie.co.at/cie/) has numerous Technical Committee Reports that are relevant. Write to Thomas Lemons, TLA- Lighting Consultants Inc., 7 Pond St., Salem, MA 01970 or call (508) 745-6870, FAX (508) 741-4420 for a listing of current publications and pricing. Check into their web page for more information. Division 1 at http://nml.csir.co.za/~cie1/ is involved with Vision and Colour while Division 2 at http://cie2.nist.gov/ deals with the Measurement of Light and Radiation. The US National Committee of the CIE is at http://www.cie-usnc.org. Some pertinent reports, primarily from Division 2, are:

13.3 Method of measuring and specifying colour rendering of light sources (1995)

15.2 Colorimetry, 2nd ed. (1986)

17.4 International lighting vocabulary, 4th ed. (Joint publication IEC/CIE) (1987)

18.2 The basis of physical photometry, 2nd ed. (1983)

38 Radiometric and photometric characteristics of materials and their measurement (1977)

41 Light as a true visual quantity: Principles of measurement (1978)

44 Absolute methods for reflection measurements (1979)

46 A review of publications on properties and reflection values of material reflection standards (1979)

53 Methods of characterizing the performance of radiometers and photometers (1982)

54 Retroreflection: Definition and measurement (2001)

59 Polarization: Definitions and nomenclature, instrument polarization (1984)

63 The spectroradiometric measurement of light sources (1984)

64 Determination of the spectral responsivity of optical radiation detectors (1984)

65 Electrically calibrated thermal detectors of optical radiation (absolute radiometers) (1985)

69 Methods of characterizing illuminance meters and luminance meters: Performance, characteristics and specifications (1987)

70 The measurement of absolute luminous intensity distributions (1987)

75 Spectral luminous efficiency functions based upon brightness matching for monochromatic point sources, 20 and 100 fields (1988)

76 Intercomparison on measurement of (total) spectral radiance factor of luminescent specimens (1988)

78 Brightness-luminance relations: Classified bibliography (1988)

81 Mesopic photometry: History, special problems and practical solutions (1989)

84 Measurement of luminous flux (1989)

85 Solar spectral irradiance (1989)

86 CIE 1988 2 spectral luminous efficiency function for photopic vision (1990)

87 Colorimetry of self-luminous displays - A bibliography (1990)

96 Electric light sources - State of the art - 1991 (1992)

105 Spectroradiometry of pulsed optical radiation sources (1993)

114 CIE Collection in Photometry and Radiometry (1994)

121 The Photometry and Goniophotometry of Luminaires (1996)

125 Standard Erythema Dose, a Review (1997)

127	Measurement of LEDs (1997)
130	Practical Methods for the Measurement of Reflectance and Transmittance (1998)
141	Testing of Supplementary Systemsof Photometry (2001)

IES The Illuminating Engineering Society of North America (IESNA) (www.iesna.org) has an extensive list of publications dealing with illumination. Their "IESNA Lighting Handbook – Ninth Edition" is the definitive reference. The following are procedures dealing with photometric measurements of varoius lamps and luminaires.

LM-9	Electrical & Photometric Measurements of Fluorescent Lamps
LM-10	Photometric Testing of Outdoor Fluorescent Luminaires
LM-11	Photometric Testing of Searchlights
LM-20	Photometric Testing of Reflector-Type Lamps
LM-31	Photometric Testing of Roadway Luminaires
LM-35	Photometric Testing of Floodlights Using High-Intensity Discharge Lamps or Incandescent Filament Lamps
LM-41	Photometric Testing of Indoor Fluorescent Luminaires
LM-44	Method for Total and Diffuse Reflectometry (1985)
LM-45	Electrical and Photometric Measurements of General Service Incandescent Filament Lamps
LM-46	Photometric Testing of Indoor Luminaires Using HID Discharge or Incandescent Filament Lamps
LM-50	Photometric Measurement of Roadway Lighting Installations
LM-51	Electrical and Photometric Measurements of High-Intensity Discharge Lamps
LM-52	Photometric Measurement of Roadway Sign Installations
LM-54	Lamp Seasoning
LM-55	Measurement of Ultraviolet Radiation from Light Sources
LM-58	Spectroradiometric Measurements
LM-59	Electrical and Photometric Measurements of Low-Pressure Sodium Lamps
LM-63	Standard File Format for Electronic Transfer of Photometric Data
LM-64	Photometric Measurements of Parking Areas
LM-66	Electrical and Photometric Measurements of Compact Fluorescent Lamps
LM-68	Photometric Evaluation of Vehicle Traffic Control Signal Heads
LM-70	Near-Field Photometry
LM-72	Directional Positioning of Photometric Data
RP-16	Nomenclature and Definitions for Illuminating Engineering (ANSI Approved)

ISO The International Standards Organization (www.iso.ch)

ISO 2470: Brightness for Fluorescent Materials 1999

ISO/CIE 10526: CIE standard illuminants for colorimetry (CIE S005/E-1998) 1999

ISO/CIE 10527:CIE standard colorimetric observers (CIE S002, 1986) 1991

ISO/CIE 15469: Spatial distribution of daylight -- CIE standard overcast sky and clear sky (CIE S003, 1996) 1997

ISO/CIE 16508: Road traffic lights - Photometric properties of 200mm round signals (CIE S006) 1999

ISO17166: Erythema reference action spectrum and standard erythema dose (CIE S007) 1999

ISO 11475: Paper and board -- Determination of CIE whiteness, D65/10 degrees (outdoor daylight) 1999

ISO 11476: Paper and board -- Determination of CIE-whiteness, C/2 degrees (indoor illumination conditions) 2000

ISO 8599: Optics and optical instruments -- Contact lenses -- Determination of the spectral and luminous transmittance1994

ISO 9845-1: Solar energy -- Reference solar spectral irradiance at the ground at different receiving conditions -- Part 1: Direct normal and hemispherical solar irradiance for air mass 1,5 1992

ISO 9022-9: Optics and optical instruments -- Environmental test methods -- Part 9: Solar radiation 1994

ISO 9022-17: Optics and optical instruments -- Environmental test methods -- Part 17: Combined contamination, solar radiation 1994

ISO 9050: Glass in building -- Determination of light transmittance, solar direct transmittance, total solar energy transmittance and ultraviolet transmittance, and related glazing factors 1990

ISO 9059: Solar energy -- Calibration of field pyrheliometers by comparison to a reference pyrheliometer 1990

ISO 9060: Solar energy -- Specification and classification of instruments for measuring hemispherical solar and direct solar radiation 1990

ISO 9488: Solar energy -- Vocabulary 1999

ISO 9845-1: Solar energy -- Reference solar spectral irradiance at the ground at different receiving conditions –Part 1: Direct normal and hemispherical solar irradiance for air mass 1,5 1992

ISO 9846: Solar energy -- Calibration of a pyranometer using a pyrheliometer 1993

ISO 9847: Solar energy -- Calibration of field pyranometers by comparison to a reference pyranometer 1992

ISO/TR 9901: Solar energy -- Field pyranometers -- Recommended practice for use 1990

ISO 6: Photography -- Black-and-white pictorial still camera negative film/process systems -- Determination of ISO speed 1993

ISO 2240: Photography -- Colour reversal camera films -- Determination of ISO speed 1994

ISO 8478: Photography -- Camera lenses -- Measurement of ISO spectral transmittance 1996

ISO 12232: Photography -- Electronic still-picture cameras -- Determination of ISO speed 1998

IEC (International Electrotechnical Commission)

Founded in 1906, the International Electrotechnical Commission (IEC) is the world organization that prepares and publishes international standards for all electrical, electronic and related technologies. The IEC was founded as a result of a resolution passed at the International Electrical Congress held in St. Louis (USA) in 1904. The membership consists of more than 50 participating countries, including all the world's major trading nations and a growing number of industrializing countries.

IEC 61966-2-1 Ed. l: 1999	Multimedia systems and equipment - Colour measurement and management Part 2-1: Colour management - Default RGB colour space - sRGB
IEC 61966-3 Ed. l: 2000	Multimedia systems and equipment - Colour measurement and management Part 3: Equipment using cathode ray tubes
IEC 61966-4 Ed. 1: 2000	Multimedia systems and equipment - Colour measurement and management Part 4: Equipment using liquid crystal display panels
IEC 61966-5 Ed. 1: 2000	Multimedia systems and equipment - Colour measurement and management Part 5: Equipment using plasma display panels
IEC 61966-8 Ed. 1: 2001	Multimedia systems and equipment - Colour measurement and management Part 8: Multimedia colour scanners
IEC 61966-9 Ed. l: 2000	Multimedia systems and equipment - Colour measurement and management Part 9: Digital cameras

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NVLAP (National Voluntary Laboratory Accreditation Program)

Established in 1976 and administered by the National Institute of Standards and Technology (NIST), NVLAP is an unbiased, government-based, third party system for accrediting calibration laboratories and testing laboratories found competent to perform specific tests or calibrations. Criteria for NVLAP accreditation are published in the Code Federal Regulations (Title 15, Part 285) and encompass the requirements of ISO/IES Guide 25 and the relevant requirements of ISO 9002. NVLAP accreditation is available to commercial laboratories; manufacturers' in-house laboratories; university laboratories, federal, state, and local government laboratories; and foreign-based laboratories.

NIST Handbook 150, National Voluntary Laboratory Accreditation Program (NVLAP), Procedures and General Requirements, J. L. Cigler and V. R. White (March 1994)

NIST Handbook 150-1, National Voluntary Laboratory Accreditation Program (NVLAP), Energy Efficient Lighting Products, L. S. Galowin, W. Hall, and W. J. Rossiter, Jr. (July 1994)

NIST Handbook 150-2 DRAFT, National Voluntary Laboratory Accreditation Program (NVLAP), Calibration Laboratories Technical Guide, J. M. Crickenberger, ed. (reprinted Dec. 1997)

* Handbook 150 and 150-1 are available on the NVLAP website at http://www.ts.nist.gov/nvlap

NVLAP identifies its accredited laboratories in a published directory, NIST Special Publication 810, and on their web site.

National Institute of Standards and Technology
National Voluntary Laboratory Accreditation Program
100 Bureau Drive, MS 2140
Gaithersburg, Maryland 20899-2140
Telephone: 301-975-4016
Fax: 301-926-2884
E-Mail: NVLAP@nist.gov
Website: http://www.ts.nist.gov/nvlap

SAE (Society of Automotive Engineers) (www.sae.org) is a non-profit educational and scientific organization dedicated to advancing mobility technology to better serve humanity. Nearly 70,000 engineers and scientists, who are SAE members, develop technical information on all forms of self-propelled vehicles including automobiles, trucks and buses, off-highway equipment, aircraft, aerospace vehicles, marine, rail, and transit systems. SAE disseminates this information through meetings, books, technical papers, magazines, standards, reports, professional development programs, and electronic databases. Here is a selection of their relevant standards, mostly dealing with lighting and its measurement.

HS-34	SAE Ground Vehicle Lighting Standards Manual (1999)
J387	Terminology - Motor Vehicle Lighting (1995)
J1330	Photometry Laboratory Accuracy Guidelines (1994)
J575	Test Methods and Equipment for Lighting Devices and Components for Use on Vehicles Less than 2032 mm in Overall Width (1992)
J 1383	Performance Requirements for Motor Vehicle Headlamps (1996)
J2217	Photometric Guidelines for Instrument Panel Displays that Accommodate Older Drivers (1991)

TAPPI

TAPPI is the leading technical association for the worldwide pulp, paper, and converting industry. TAPPI provides its members rapid access to: (1) the largest international group of technically experienced people in the industry, (2) the most comprehensive collection of reliable technical information and knowledge in the industry , and (3) the highest quality products and services created to meet the needs of people who solve technical problems in the industry. Among their documentary standards are the following:

T-425	Opacity of Paper (15/d geometry, Illuminant A/2°, 89% Reflectance
T-452	Brightness of Pulp, Paper and Paperboard (Directional Reflectance at 457 nm)
T-480	Specular Gloss of Paper and Paperboard at 75,° (1999)
T-560	CIE Whiteness and Tint of Paper and Paperboard (Using d/0°, Diffuse Illumination and Normal Viewing)
T-562	CIE Whiteness and Tint of Paper and Paperboard (Using 45°/0° Directional Illumination and Normal Viewing)
T-1209	Identification of Instrumental Methods of Color or Color Difference Measurement
T-1212	Light Sources for Evaluating Papers, Including Those Containing Fluorescent Whitening Agents
T-1213	Optical Measurements Terminology (Related to Appearance Evaluation of Paper)
T-1214	Interrelation of Reflectance, R_o; TAPPI Opacity, $C_{0.89}$; Scattering, s; and Absorption, k
T-1215	The Determination of Instrumental Color Differences
T-1216	Indices for Whiteness, Yellowness, Brightness and Luminous Reflectance Factor
T-1217	Photometric Linearity of Optical Properties Instruments
T-1218	Calibration of Reflectance Standards for Hemispherical Geometry

(http://www.tappi.org)

APPENDIX IX

RADIOMETRY AND PHOTOMETRY ON THE INTERNET

Hop on the Internet and start surfing! The World Wide Web (WWW or W^3) gets larger and hopefully more educational every day. The following list includes some of the sites that I have found useful and informative.

OPTICS, RADIOMETRY, PHOTOMETRY STUFF

OSA OpticsNet	www.osa.org/
SPIE HOME PAGE	www.spie.org/
RADIOMETRY by JMP (my page)	www.optics.Arizona.edu/Palmer/
NIST Optical Physics	www.physics.nist.gov/
NIST Boulder	www.boulder.nist.gov/div815/
NPL	www.npl.co.uk/
CSIRO (Australia)	www.dap.csiro.au/
NRC (Canada)	www.corpserv.nrc.ca/corpserv/
PTB (Germany)	www/ptb/de/english/welcome.html
CORM	www/corm.org/
International Commission on Illumination (CIE)	www.cie.co.at/cie/
Infrared Information Analysis Center (IRIA)	www.erim.org/IRIA/iria.html"
IEEE Home Page	www.ieee.org/
University of Arizona Remote Sensing	www. optics.Arizona.edu/rsg/
Remote Sensing Data and Information	www.rsd.gsfc.nasa.gov/rsd/RemoteSensing.html
USU Space Dynamics Laboratory	www.cal.sdl.usu.edu/
AIP American Institute of Physics	www.aip.org
ANSI American Nat'l ,Standards Institute	www.ansi.org/
ASTM	www.astm.org
BIPM International Bureau of Weights and Measures	www.bipm.fr/
Color Vision Lab at UCSD	cvision.uscd.edu/
IESNA Illuminating Engineering Society of North America	www.iesna.org/
ISO International Standards Organization	www.iso.ch/
IUPAP International Union of Pure and Applied Physics	www.physics.umanitoba.ca/iupap/

SEARCH ENGINES - Here are several good search engines that will also lead you to many interesting sites. Surf by entering the keyword *radiometry*, and see how much comes up!

All The Web	www.alltheweb.com/
Alta Vista	www.altavista.com/
Excite	www.excite.com/
Google	www.google.com/
HotBot	www.hotbot.com/
Lycos	www.lycos.com/
Northern Lights	www.northernlight.com/
OpenText Index	www.opentext.com/
Yahoo	www.yahoo.com/
DejaNews NewsGroup Archives	www.dejanews.com/

APPENDIX X

RADIOMETRY & PHOTOMETRY BIBLIOGRAPHY

In 1969 Fred Nicodemus authored a paper “Optical Resource Letter on Radiometry” (JOSA **59**,243). It was reprinted in an AIP “Radiometry” reprint collection in 1981. This bibliography is intended to update and supplement the 1969 version. The topic breakdown is more in line with the order of topics in this book than the original. Individual papers are for the most part bypassed in favor of books, significant book chapters, monographs or reprint collections.

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MISCELLANEOUS

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Poynton, C.A., A Technical Introduction to Digital Video, Wiley (1996)

TECHNICAL ORGANIZATIONS IN RADIOMETRY & PHOTOMETRY

CIE

The Commission Internationale de L'Eclairage (CIE) has numerous Technical Committee Reports that are relevant. Write to Thomas Lemons, TLA- Lighting Consultants Inc., 7 Pond St., Salem, MA 01970 or call (508) 745-6870, FAX (508) 741-4420 for a listing of current publications and pricing. Check into their web page for more information. Some pertinent reports, primarily from Division 2, are listed in Appendix VIII

CORM

The Council for Optical Radiation Measurements (CORM) was founded over twenty years ago to promote optical radiation measurement science and engineering and foster cooperation among the many government agencies, industrial firms and universities, and to formulate and transmit national needs to NIST. They meet annually in May and publish *Optical Radiation News Optical* bi-annually. Contact: CORM Treasurer, 1043 Grand Ave. #312, St. Paul, MN 55105. (www.corm.org) CORM documents are listed in Appendix VIII.

NEWRAD

The NEWRAD conference series is an outgrowth of a meeting organized by Peter Foukal and held in Cambridge MA in 1985. The proceedings of the first meeting were a private publication. The second meeting took place at NPL in London in 1988, and the proceedings were published as New Developments and Applications in Radiometry, N. Fox and D. Nettleton, eds, by IOP Publishing, London (1989). The proceedings of the next four meetings, held in Davos (1990), Baltimore (1992), Berlin (1995) and Tucson (1997). The proceedings of these meetings were published as special issues of *Metrologia* (Elsevier), Volumes **28**(3), **30**(4), **32**(6) and **35**(4), respectively. The seventh conference was held October 25-27, 1999 in Madrid. Check out http://newrad.metrologia.csic.es.

NIST

The U.S. National Institute of Science and Technology (NIST, formerly National Bureau of Standards, NBS) has a number of valuable special publications that describe their calibration services and procedures. Appropriate ones include the following. They may be purchased from NTIS.

NBS Measurement Services: Spectral Radiance Calibrations, J. H. Walker, R. D. Saunders, and A. T. Hattenburg, Natl. Bur. Stand. (U.S.), Spec. Publ. 250-1 (1987).

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NBS Measurement Services: Radiometric Standards in the Vacuum Ultraviolet, J. Z. Klose, J. M. Bridges, and W. R. Ott, Natl. Bur. Stand. (U.S.), Spec. Publ. 250-3 (1987).

NBS Measurement Services: Regular Spectral Transmittance, K. L. Eckerle, J. J. Hsia, K. D. Mielenz, and V. R. Weidner, Natl. Bur. Stand. (U.S.), Spec. Publ. 250-6 (1987).

NIST Measurement Services: Spectral Reflectance, P. Y. Barnes, E. A. Early, and A. C. Parr, Natl. Inst. Stand. Technol. Spec. Publ. 250-8 (1987, revised 1997).

The NBS Photodetector Spectral Response Calibration Transfer Program, E.F. Zalewski, Natl. Bur. Stand. (U.S.), Spec. Publ. 250-17, 45 (1988).

NIST Measurement Services: Photometric Calibrations, Y. Ohno, Natl. Inst. Stand. Technol. Spec. Publ. 250-37 (1997).

NIST Measurement Services: Radiance Temperature Calibrations, Natl. Inst. Stand. Technol. Spec. Publ. 250-43 (1997).

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NIST Measurement Services: Spectroradiometric Detector Measurements: Parts I and II -- *Ultraviolet and Visible to Near Infrared Detectors*, T. C. Larason, S. S. Bruce, and A. C. Parr, Natl. Inst. Stand. Technol. (U.S.), Spec. Publ. 250-41, (1998).

NIST Measurement Services: Spectroradiometric Detector Measurements: Part III -- *Infrared Detectors*, A. L. Migdall and G. Eppeldauer, Natl. Inst. Stand. Technol. (U.S.), Spec. Publ. 250-42, (1998).

SPIE

Proceedings of the S.P.I.E. are published unrefereed papers as presented at conferences of SPIE - The International Society for Optical Engineering. Several conferences and resulting proceedings have been devoted to radiometry and photometry. They are:

196	Measurements of Optical Radiations (1979)
499	Optical Radiation Measurements I (1984)
888	Laser Beam Radiometry (1988)
1109	Optical Radiation Measurements II (1989)
2161	Photometry (1993)
2815	Optical Radiation Measurements III (1996)

OPEN LITERATURE

Numerous archival and trade journals also offer significant papers on radiometry and detection of optical radiation. They include:

Applied Optics (OSA)

IEEE Transactions on Electron Devices

Infrared Physics and Technology (Elsevier)

Journal of the Optical Society of America A (OSA)

Journal of Scientific Instruments

Laser Focus World (free)

Lightwave Technology (IEEE)

Optical Engineering (SPIE)

Photonics Spectra (free)

Review of Scientific Instruments

PUBLICATIONS AVAILABLE ON THE WORLD WIDE WEB

All you ever wanted to know about the SI is contained at BIPM (www.bipm.fr) and at NIST (physics.nist.gov/cuu). Available publications (highly recommended) include:

"The International System of Units (SI)" 7th edition (1998), direct from BIPM. The official document is in French; the English translation is available in PDF format.

NIST Special Publication SP330 "The International System of Units (SI)." The US edition of the above BIPM publication. Available in PDF format.

NIST Special Publication SP811 "Guide for the Use of the International System of Units (SI)." Available in PDF format.

Papers published in NIST Journal of Research since 1995 are also available on the web in PDF format.

APPENDIX XI

SELECTED VENDORS OF RADIOMETRIC EQUIPMENT

NOTICE

Items of commercial equipment identified in this section are part of a survey of the field of available equipment. This identification does not imply endorsement by the author or the University of Arizona nor does it imply that the identified equipment is the best available for the purpose. This list is by its very nature both incomplete and at the same time obsolete. See buyers' guides from *Lasers and Optronics*, *Laser Focus World*, *Photonics Spectra, Physics Today,* and *Spectroscopy* for more up-to-date listings.

BLACKBODY RADIATION SOURCES

CI Systems
Electro-Optical Industries
Eppley Laboratory
Graesby Infrared
Mikron Instrument
Santa Barbara Infrared

OTHER CALIBRATION SOURCES

Eppley Laboratory
Gamma Scientific
Hoffman Engineering Corp
Labsphere
LI-COR
Optronic Laboratories
Oriel Instruments

LIGHT SOURCES, LUMINESCENT

American Ultraviolet
Cathodeon - deuterium
Hamamatsu
Hanovia
ILC Technology
ORC Lighting Products
Oriel Instruments
Osram-Sylvania
Xenon Corp

LIGHT SOURCES, THERMAL

Buck Scientific
DBA Systems
Gilway Technical Lamp
Oriel Instruments
Welsh-Allen

DETECTORS - PHOTOCONDUCTIVE

EG&G Vactec - CdS, CdSe
Fermionics - HgCdTe
OptoElectronics - PbS, PbSe

DETECTORS - PHOTODIODE

Advanced Photonix
Centronic
Cincinnati Electronics - InSb
EG&G Judson - Ge, InSb
EG&G Optoelectronics
EG&G Vactec
Epitaxx - InGaAs
Fermionics - InGaAs, HgCdTe
Hamamatsu
International Radiation Detectors
Silicon Sensors
UDT Sensors - Si

DETECTORS - PHOTOMULTIPLIER

Burle
EMR Photoelectric
Hamamatsu
Philips
Thorn EMI

DETECTORS - THERMAL

Amber - bolometers
Cal-Sensors - pyroelectric, thermopiles
Dexter Research Center - thermopiles
EDO Barnes - bolometers, pyroelectric, thermopiles
EG&G Heimann - pyroelectric, thermopiles
Eltec Instruments - pyroelectric
Eppley Laboratories - thermopiles
Infrared Laboratories - bolometers
Laser Probe - pyroelectric
Meggett Avionics - thin film thermopiles
Midwest Research Technologies - bolometers
Molectron Detector - pyroelectric
Sensor Physics - thermopiles
Spiricon - pyroelectric

DETECTOR ARRAYS

Amber
CID Technologies
Cincinnatti Electronics
Dalsa
Eastman Kodak
EEV Ltd
EG&G Reticon
Hamamatsu
Loral Fairchild
Mitsubishi
Philips Photonics
Rockwell Electro-Optical Center
Scientific Imaging Technologies (SITe)
Texas Instruments
Thompson Components & Tubes
Toshiba

GENERAL PURPOSE RADIOMETERS

- EG&G Gamma Scientific
- Electro-Optical Industries - infrared
- Graesby Optronics - general purpose and absolute QED
- International Light
- Labsphere
- Laser Probe - pyroelectric and ECR
- Optronic Laboratories - wide range

LASER POWER AND ENERGY METERS

- Coherent Instruments
- DigiRad
- ILX Lightwave
- Laser Probe - pyroelectric
- Molectron - pyroelectric
- Newport Corp.Ophir Optronics
- Scientech - calorimetric
- Spawr Optical Research - high power
- Spiricon - pyroelectric arrays

FIBER OPTIC RADIOMETERS

- Anritsu
- EXFO
- Fotec
- ILX Lightwave
- Photodyne
- Thorlabs

PHOTOMETERS

- Gamma Scientific
- Hoffman Engineering
- International Light
- LMT Lichtmesstechnik
- Photo Research

SPECIALIZED METERS AND INSTRUMENTS

- Biospherical Instruments - underwater
- Cambridge Research & Instrumentation - cryogenic absolute ECR
- Eppley Laboratories - solar radiation instrumentation
- Exotech - portable, environmental studies
- LI-COR - quantum, underwater, solar
- Oxford Instruments - cryogenic absolute ECR
- Spectronics - ultraviolet
- Stanford Research Systems - photon counter, LIA

MISCELLANEOUS RADIOMETRIC ACCESSORIES

- Eastman Kodak - IR detection cards, $BaSO_4$ reflectance Standard
- Hoffman Engineering - integrating spheres
- Labsphere - transmission and reflection diffusers, integrating spheres

MEASUREMENT AND CALIBRATION LABORATORIES

National Institute of Standards and Technology (USA)
National ResearchCouncil (Canada)
Optical Test & Calibration, Ltd.
Opto-Cal

MONOCHROMATORS

Acton Research
Bentham Instruments
CVI Laser
Instruments SA
McPherson
Optronic Laboratories
Oriel Corp
Photon Technology International
Research Support Instruments
Scientific Measurement Systems
Spectral Energy
SPEX Industries

SPECTROPHOTOMETERS

Acton Research
Beckman Instruments
Bomem Hartmann & Braun (FTIR)
Bruker Instruments
Buck Scientific
Edinburgh Instruments
Hitachi Instruments
Mattson Instruments (FTIR)
Milton Roy
Nicolet Instruments (FTIR)
Perkin-Elmer
Shimadzu Corporation
Spectral Instruments
Thermo Jarrell-Ash
Varian Associates (Cary)

SPECTRORADIOMETERS

Analytical Spectral Devices
Bentham Instruments
Biospherical Instruments - underwater
Control Development
EDO Barnes Engineering - multispectral filter
Gamma Scientific - general purpose
Geophysical & Environmental Research
Li-Cor - portable, underwater
Ocean Optics - miniature fiber optic
Optronic Laboratories - wide-band, high precision
Oriel Instruments
Spectron - diode array, portable

SPECTROREFLECTOMETERS

AZ Technology
Labsphere
Optronic Laboratories

RADIATION THERMOMETERS

- Anritsu
- Capintec
- Everest Interscience
- Ircon
- Land Instruments
- Linear Laboratories
- Mikron Instrument
- Omega Engineering
- Pyrometer Instrument Co.
- Raytek
- Wahl Instruments
- Williamson Corp

THERMAL IMAGING SYSTEMS

- AGEMA Infrared Systems
- Amber
- FLIR Systems
- Inframetrics
- Mitsubishi

COLOR AND APPEARANCE INSTRUMENTS

- HunterLab
- Macbeth
- Minolta
- Photo Research
- X-Rite

last update 1/3/2000 jmp

APPENDIX XII

RADIOMETRY PROGRAMS AND DATA ON THE CD

1. **Introduction to radiometry** ***(SUN)***

2. **Propagation of optical radiation**
several configuration factors
Foote's law including $\cos^4$

3. **Radiometric properties of materials**
Transmission, reflection, absorption
Relationship between transmission, reflection and absorption
Specular materials
Diffusing materials

4. **Generation of optical radiation**
BB1992C.EXE and spreadsheet, watts & photons
tungsten emissivity, along with other materials
directional emittance from specular surfaces
fluorescent lamp spectra
reflectances, artificial & natural
sunlight, AM0,1,2,3,5
LOWTRAN curves (2 meter lab, 1 km, several condx horiz, vertical
phosphors
globar, xenon & mercury arcs
curve fitting for tungsten lamps

5. **Detection of optical radiation**
photopic and scotopic curves
spectral response of film
spectral response & D* of detectors
absorption coeff of Si

6. Radiometric Instruments

mirror reflectances
select filter transmissions, absorption & interference, vs angle
transmission & reflection diffusers, spectral & angular, whites, blacks
op-amp characteristics
noise bandwidth
chopping factors
cold stop improvement
snr vs low-pass
sig avg demo, LIA demo

7. Radiometric Measurements

measurement equations
Range equations
normalization, bw & fov
photometry
colorimetry, tristimulus curves
action spectra UVA, UVB, UVC, PhAR, etc.
Correlated color temp
Distribution temp
Diffraction calculation

8. Radiometric Calibration

Standard calibration wavelengths
representative FEL curve
transmittance & didymium transmission curves
Halon & $BaSO_4$ reflectance
Au and Al standard spectral reflectances
Kodak gray card reflectance