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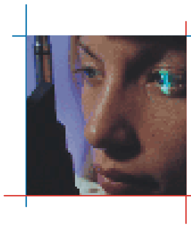

Radiometric and Photometric Concepts Based on Measurement Techniques

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Abstract

The value of the fundamental quality in radiometry, the watt, is presently realized by electrical substitution in which the temperature produced in a blackened material due to absorption of radiant energy is balanced against that produced by electrical energy whose current and voltage can accurately be measured. A new method to measure optical radiation is being explored by the National Bureau of Standards in which photons are absorbed in a semiconductor and converted with efficiency closely approaching the theoretical maximum - 100 percent.

Other radiometric concepts, such as radiance, irradiance, and radiant intensity can easily be defined through simple geometric relationships. Photometry on the other hand, while sharing these identical relationships also introduces detector response modeled after human visual traits; new measurement unit names, and reliance on source intensity made in measurement techniques will be examined from the view point of detector-based radiometry and photometry.

Introduction

Radiometry is that area of measurement science which itself with distribution of electromagnetic radiation being transferred from a source to a receiver. Original concepts in classical radiometry to describe quantities were based on two ideal entities, the point source and the perfect diffuser, with the receiver being that most readily available, the human eye of the observer. This region of radiometry, based on the receiver having the spectral response of human vision, is now called photometry. Since the basic measurement concepts are applicable to both, radiometric quantities will be discussed first followed by corresponding relationships and measurement units that have developed and are peculiar to photometry.

In traditional radiometry the emphasis was placed on sources of radiation such as the tungsten-filament lamp, and eventually the blackbody radiator so eloquently described by Plank in terms of quantity and spectral distribution of optical radiation. In 1937 the National Bureau of Standards transferred the luminous intensity produced by a platinium blackbody to a series of lamps. This original calibration has served to this date for standardization of lamps used by industry to realize the photometric scale. Recently the fundamental unit in photometry was changed from the candela, as defined by a blackbody, to the lumen, as defined by the watt, uniting the conceptual interrelationships between photometry and radiometry. [1] Changes in the photometric scale due to redefinition of its less than one percent difference in NBS lamp intensity values. [2]

Because Vλ , the mathematical representations of human visual spectral response is difficult to realize with a high degree of accuracy in a practical detector, comparison of sources with a broad spectral distribution can best be accomplished with a reference source. As the spectral distribution can best be accomplished with a reference reliance must be placed on the receiver's compliance to the Vλ function. Finally as sources approach monochromaticity, only a portion of the Vλ function is necessary and detector based photometry can achieve superior performance.

One of the earliest radiometers resembled the classical rotary vane radiometer whose silver and black surfaces rotate within a partially evacuated glass bulb, still available today in stores as a novelty. The original version by Sir William Crookes suspended the vanes and a small mirror by quartz fiber with radiation on one vane producing torque and rotating the mirror [3]

At present there are three different types of radiometers in use by the National Bureau of Standards to measure radiant power to define the radiometric scale. The first is actually a series of calorimeters, [4] encompassing a variety of means to absorb radiation, but typically equipped with internal resistive heater permitting calibration to be performed by reference to electrical power. These devices find extensive application in measurement of wide

The second category is also thermal in nature, taking the form of a radiometric balance in which one side of blackened receiver is alternately exposed to chopped radiant energy and then the other to electrical energy from a resistive heater. Temperature balance of the disc may be sensed either by a multiple series of thermocouples called a thermopile[5] or by a pyroelectric effect[6] in which temperature changes produce an electric charge. In either case the value of electrical power can be measured-with a high degree of accuracy.

Recently a different approach to radiation measurement, quantum radiometry, has been investigated and developed by the National Bureau of Standards as a means to provide an absolute measurement.[7] Photons, rather than producing heat by absorption are instead converted directly to current in a semiconductor such as silicon.

When light is incident on a silicon photodiode, typically twenty-five percent of the beam is reflected at the polished silicon surface and the remainder absorbed. In an inversion layer photodiode,[8] when provided with a small reverse bias voltage, essentially all absorbed photons will produce a like number of photocurrent electrons throughout the visible wavelength region. By combining four photodiodes in a retroreflective pattern [9] as shown in Figure 1, and electrically connecting them in parallel, seven surfaces are encountered for absorption of.photons prior to escape. Since each surface reflects 2 percent, seven surfaces reflect but (.25)7 or C.006 percent, neglecting the possibility of losses due to scatter.

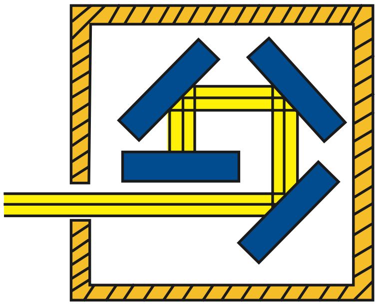

Figure 1
QED-IOO absolute radiometric detector

At 100 percent quantum efficiency photodetector responsivity, RA in amperes per watt is given by the equation:

$$R\lambda = \frac{\lambda}{hc/en} = \frac{\lambda}{1239.5}$$

where A is the incident wavelength (in air), and

h is Plank’s constant,

c is the speed of light,

e is the elementary electron charge, and

n is the average refractive index of air.

The optical path for seven reflections in the United Detector Technology Model QED-IOO is 150 millimeters, for a permissible acceptance angle of 70 milliradians (4 degrees). This necessitates the incident light be moderately collimated and of known wavelength, an ideal application for laser radiation.

Basic concepts in detector based radiometry

Since the emphasis is meant to be on concepts rather than comprehensive mathematical treatment, a bare minimum of equations will be used, referring the reader instead to the “National Bureau of Standards Self-Study Manual on Optical Radiation Measurements”, should a more in depth coverage be desired. [10]

Radiant Flux

Measurement unit: watt. The fundamental concept in detector based radiometry is the measurement of radiant flux. Flux is the power, expressed in watts, of the radiation incident on the detector. In the examples illustrated, optical power is confined by some external means to be completely within the open area of an aperture to be incident on the detector. Examples of typical flux measurements shown in Figure 2 are (a) laser beam, (b) fiber-optic, and (c) a focused beam. The aperture is shown as separate from the detector to emphasize that all detectors have an aperture, either external as shown or inherent by virtue of the finite size of the detector.

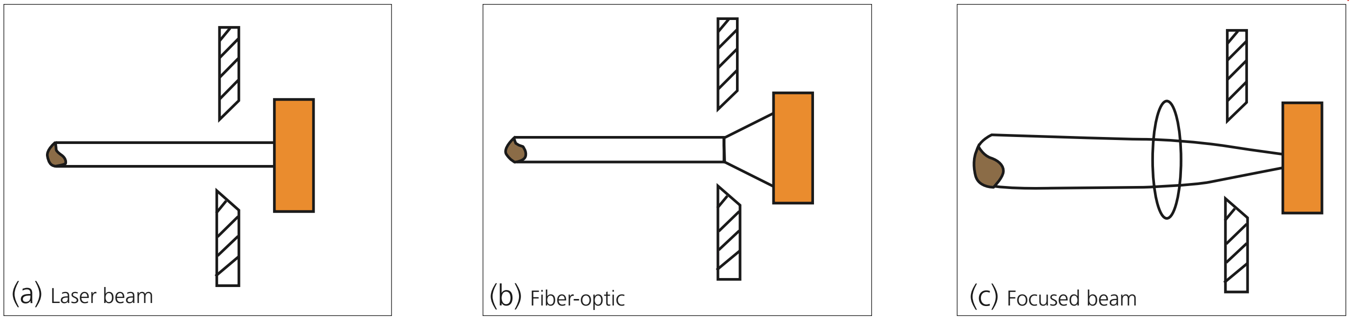

Figure 2. Typical flux measurements

In measurement of flux, beam size and uniformity are unimportant factors, but detector uniformity is essential. Otherwise detector signal output would vary as the incident beam changes shape or position instead of remaining constant.

Besides response uniformity· another important criteria is detector linearity, for it defines the range of signal levels that can be expressed by constant calibration values and thus be accurately compared. In addition, an acceptable difference or error tolerance in percent is normally included, giving the acceptable performance criteria both length and width. Typical linear performance for selected silicon photodiodes, for instance, can span seven or eight decades within one or two percent. [11]

Finally the detector needs to be calibrated to establish the relationship between detector output signal and incident flux. This parameter is known as responsivity and is expressed in the case of silicon photodiodes, in terms of amperes per watt (although measurement levels are more typically in microamperes and microwatts). Calibration consists of direct comparison of a detector with another of known response being alternately placed in a radiant beam of known wavelength. Calibrated detectors are normally available directly from the detector manufacturer or a silicon photodiode may be leased from the National Bureau of Standards for transfer calibration. [12]

Irradiance

Measurement unit: watts per square meter.

Irradiance in detector-based concepts is the measure of flux uniformily distributed over the detector aperture urea. Although irradiance can certainly be non-uniform in its distribution measurement of irradiance requires beam uniformity to be meaningful. Consider the case in which irradiance is measured with the same calibrated uniform detector but with two different aperture sizes. If the measurements in terms of watts per aperture area differ, then one has to be in error. In reality a detector always measures average power per aperture area, but this is not necessarily irradiance. The distinction is between flux within a specific area (requiring a uniform detector) versus flux per area which implies uniformity extending beyond the area of actual measurement. Therefore, without uniformity, irradiance cannot be measured meaningfully.

Figure 3a shows an aperture creating a measurement plane in space of known area, with the flux per that aperture area being measured. Figure 3b is the identical measurement with a detector having an inherent, known aperture size. They are equivalent. In determining irradiance response from a detector calibrated for flux response, in addition to its response being uniform, the effective aperture area must be known to the same degree of accuracy. In this case the benefit of a removable aperture becomes evident since it can independently be measured. Unless placed perpendicular to the irradiance field, allowance for its change is effective area which varies as the cosine of the displacement angle must be made.

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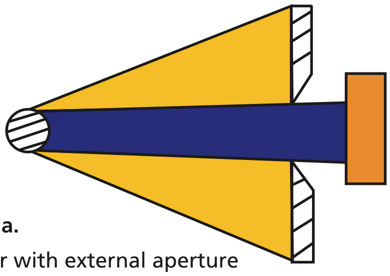


Figure 3a.
Detector with external aperture

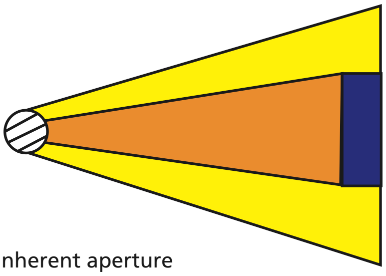


Figure 3b.
Detector with inherent aperture

An irradiance calibration may be transferred from a detector of known response to one of unknown response without knowing the effective area of either detector nor even if they have uniform spatial response. Figure 4 depicts a detector with non-uniform response. Its effective area is undefined, yet irradiance responsivitv can be determined.

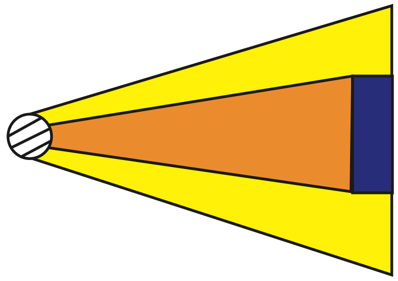


Figure 4.
Non-uniform response detector

In summary, irradiance in order to be measured meaningfully must be uniform at least over the effective area of the detector. Responsivity can be measured in separate terms of flux and effective area, or irradiance directly with the terms combined. The measurement is valid only for that area and direction can be extended only through more extensive measurement or prior knowledge of irradiance distribution.

Intensity

Measurement unit: watts per steradian.

Intensity is the other basic concept and is a property of the source. In our detector based methodology however, it might be called "irradiance-at-a-distance". To measure the intensity of an emitting source a detector with known irradiance response is placed at a known distance from the emitter. The area of the detector forms a solid angle with the source and so intercepts the flux per that solid angle, as illustrated in Figure 5. Therefore it remains only to calculate the solid angle. Solid angles are measured in steradians and are calculated from the equation:

$\Omega = A/S^2$

where Ω is the solid angle in steradians,

A is the spherical area, and
S is the separation distance in the same dimensional units as the area.

The steradian is the basis for the inverse-square law of radiation which states that irradiance varies as the square of the distance from the source. However, it should be noted that the spherical area is not the same as the planar area we have defined as the detector active area. In most cases the difference is small enough to be ignored and has given rise to the radiometric rule-of-thumb that the detector should be at least ten diameters away from source to measure intensity within one percent.

To estimate the actual error one can use the following formula: [1 3]

$$\text{correction factor} = \frac{S^2 + R^2}{S^2}$$

where S is the detector source separation distance, and R is the detector radius in the same dimensional units.

Thus it is readily evident that the original rule was ten times the radius since $\{10^2 + 1^2)/10^2 = 1.01$ or one percent error. The source size makes an equal and additive contribution to the error and can be calculated from the same equation. So even when both the source and detector diameters are equal but separated by a distance ten times either, the error is but one half-percent, an acceptable limit and reason to retain the rule for general use.

Now since irradiance was required to be uniform, it follows that intensity within the measurement solid angle must also be uniform. Otherwise another measurement along the same measurement axis using a smaller aperture could give a different intensity reading. This indeed has been a problem in the past in measurement of light-emitting diode intensity, when, even with correctly calibrated detectors and instrumentation, two measurements performed at two different locations have disagreed by up to 50 percent. The problem was that although each observer believed he had measured intensity, he had instead measured flux per aperture area and because the flux distribution was far from uniform and the two observers had used different aperture areas, their results did not agree. The solution would seem to be at least report the intensity measured, direction, and measurement angle (in either millisteradians or cross-section degrees) whenever there is any element of doubt that the irradiance may not be uniform over the dector aperture at the distance chosen for measurement.

In summary, intensity requires that the radiation be uniformily distributed within the solid angle of measurement and is only valid for that particular solid angle. Again extension of the intensity characteristics of a source requires more extensive measurements or knowledge of the source's distribution characteristics.

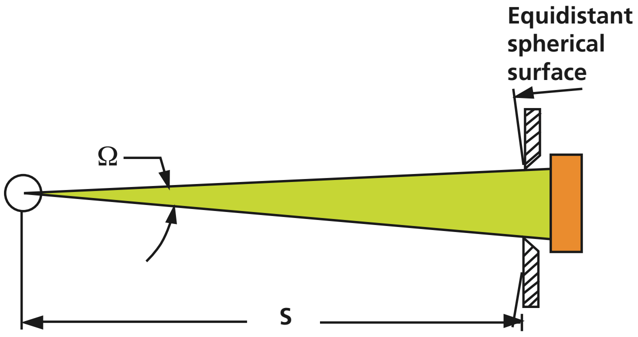


Figure 5. Intensity measurement

Radiance

Measurement unit: (watts/steradian) per square meter. Radiance is but a uniform distribution of intensity over an area, analogous to irradiance as a uniform distribution of flux over an area.

One distinctive characteristic of radiance, diagrammed in Figure 6, is that two apertures are always present, one determining source area and the other solid angle received. Futhermore, it is the separation distance between these two apertures which determines radiance. Notice too the symmetry present in radiation transfer between source and receiver, each with an effective aperture.

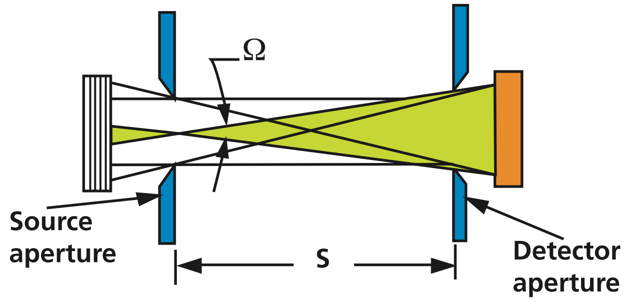


Figure 6. Radiance measurement

Detector responsivity can be expressed in separate terms of flux and effective aperture are aorirradiance with the terms combined. As an example, it is not appropriate to refer to the radiance of a coiled filament because the intensity distribution is far from uniform and the effective filament area is variable. A central portion of a flat filament lamp on the other hand, may be uniform in intensity distribution and measured by imaging a known area of the filament onto a detector for measurement. More will be described concerning measurement techniques applicable to radiance in the section on luminance. In summary, radiance requires a uniform distribution of intensity over the measurement area, and, as with intensity, is valid only in the direction of measurement and within the solid angle of measurement.

Photometry

Within the purview of radiometry there are many areas of special interest due to the interaction of radiation of specific spectral content with matter. Thus we have biological effects (germicidal, sunburn, suntan, eye damage, plant growth), detector spectral sensitivities (vision, photographic films, photoelectric sensors), and media spectral transparency (ocean water, atmosphere, fiberoptic materials) each describing a spectral weighting factor to describe effectiveness. Of these it is human vision that predominates in attention, with measurement quantities in photometry named and defined on the basis of detector spectral response to that region of the electromagnetic spectrum we call light, approximately 400 to 700 nanometers in wavelength.

In relation to measurement, the preceding radiometric conceptual relationships are still completely valid in their entirety for photometry. Modifications due to the special nature of the detector or typical measurement situations will be considered in this section.

Luminous flux

Measurement unit: lumen. The unit for luminous flux is the lumen, related to the watt by the following equation:

$$\text{Lumen} = 683 * \text{watt} * V\lambda \qquad (4)$$

where Vλ is the relative luminosity, a mathematically defined function which approximates human visual response and its unity at the peak, 555 nanometers.

In order to measure lumens at any specific wavelength it is only necessary to measure watts and make the conversion according to equation (4). Although this is applicable to monochromatic sources, many sources of interest emit radiation throughout the visible spectrum making calculation almost impossible except in cases where the source spectrum can be accurately defined. As a consequence, detector response is often modified by the addition of a spectral filter, colored glass in most cases, which is chosen to produce a constant detector response at all wavelengths in terms of luminous flux, the lumen.

For broad spectrum sources such as incandescent or fluorescent lamps, visual response the green and yellow radiation predominates with conformance of the filter in the blue and red regions being less critical, and plus and minus deviations can be balanced somewhat against each other. For quasi-monochromatic sources, however, such as the green, yellow and red LED's a more precise match at each wavelength is important and is usually accompanied by specifically formulating the filter design to fit this limited portion of the spectrum. Because matching purposely ignores wavelengths below 550 nanometers, this filter is not suitable for measurement of broadband sources.

Illuminance

Measurement unit: lux. Illuminance could be determined by measurement of luminous flux using a detector having a photometric spectral response together with an aperture of known area. The fact that this is rarely done except for perhaps isolated monochromatic sources is undoubtedly due to the predominance of broad wavelength sources, extended in distribution through reflection or scattering, and the availability of incandescent lamp[3] for standardization. For these reasons the cosine diffuser is commonly used.

The purpose of the cosine diffuser, shown in cross-section in Figure 7, is to present an effective area to an emitting source which varies as the cosine of the angle formed with the perpendicular detector axis. A simple aperture would qualify for this task were it possible to have a detector collecting all luminous flux uniformly from all angles. Instead a practical method is to employ a diffuser whose light scattering properties are as close to cosine and spectrally neutral as possible. Because cosine response in useful materials tends to decrease at low angles, the diffuser is bevelled at the edges to present an auxillary surface that increases in effective area to a maximum at the bevel angle to compensate for diffusion loss. [14] Finally, when important to eliminate light below its horizontal plane, an extended guard ring can be incorporated as illustrated.

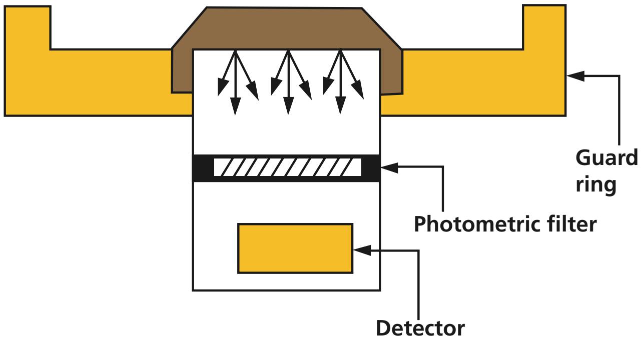


Figure 7. Cosine diffuser

When using a cosine diffuser its surface defines the measurement plane, in essence becoming the detector. Although spatial response is symmetrical about its axis, it is seldom uniform across its surface. Calibration, therefore necessitates establishing a uniform illuminance whose value can be established by another detector or derived from source intensity and distance.

Common measurement units for illuminance are expressed in the uniform distribution of alumen per unit areas. Thus we have:

Lumen per square meter: lux

Lumen per square foot: footcandle

The lux is the international unit, and as can be seen in the definitions, the conversion factor is the ratio of the two areas.

Luminous intensity

Measurement unit: candela. Luminous intensity is a source property, defined by the quantity of luminous flux uniformly distributed within a given angle in a particular direction. A lumen per steradian is called a candela. For nearly monochromatic sources, such as light emitting diodes, measurement of luminous flux can readily be performed by using a detector with constant luminous responsivity with a fixed aperture, calculating the solid angle from separation distance between aperture and source. For broad wavelength sources, however, lack of a detector with constant luminous response over the entire range of wavelengths makes lamp standards more practical.

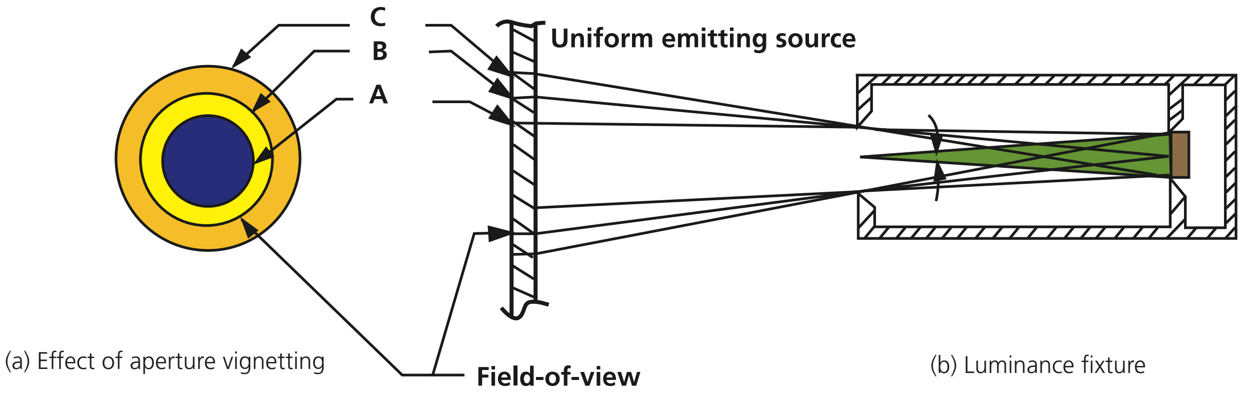
In 1937 the National Bureau of Standards intercompared a bank of incandescent lamps with platinium freezing point blackbody to establish standards of luminous intensity. Lamps based on these measurements are presently available from NBS as well as certain commercial laboratories, specifying lamp current, direction of measurement axis, and intensity at a specific color temperature, 2856 kelvins. Lamps standards have frosted envelopes even though this increases their effective emitting area, but produces better irradiance uniformity by an order of magnitude over comparable clear envelope quartz halogen types. [15]

Luminance

Measurement unit: candelas per square meter. Luminance is the uniform distribution of luminous intensity per a specific area, also called "photometric brightness", the qualifying term necessary to distinguish it from the physiological concept "brightness" which is influenced by how luminance is perceived under a variety of circumstances. One method of measurement suitable for emitting sources such as fluorescent lamps or cathode ray tubes is to mask off a certain uniform portion and measure its intensity. Masking not only isolates a uniform sample but also limits source size, and, in turn, separation distance necessary to comply with the inverse square law rule-of-thumb.

Laboratory measurement of luminance often is performed with a fixture shown in Figure 8b.[16] A detector with a photometric filter (not shown for clarity) calibrated for response in lumens per square centimeter is placed at one end of a tube, blackened and baffled to avoid stray light. At the other end is a source aperture whose area is known, at a known distance from the detector. Calculation of luminous flux per the solid collection angle (formed by the detector area of source aperture center) gives intensity in candelas.

This fixture is also suitable for reflective, rather than self-emitting sources, and is independent of fixture-to-source distance so long as the acceptance angle is uniformily illuminated. Figure 8a shows the manner in which radiation from a surface is incident on the detector. Within the central area defined by diameter 'A', radiation is incident on the entire detector, linearly decreasing outside of this region. Along perimeter 'P-', radiation falls on only half of the detector area, and beyond 'C', none is received. The angle defined by ring 'c' is the detector acceptance angle, the maximum angle in which radiation is received, and ring 'B' the detector field-of-view. Were detector size progressively decreased, rings 'A' and tc' would approach ring 'B', showing field-of-view is independent of detector size, while acceptance angle is not.



(a) Effect of aperture vignetting

(b) Luminance fixture

Figure 8. Luminance Measurement

A more common method to measure luminance incorporates a positive lens, Figure 9, to image a distant surface onto the detector plane. In focus, acceptance angle and field-of-view are identical. Curiously there is a role reversal in effect. Detector effective area is determined by the size of the lens aperture, and establishes the measurement plane. On the other hand, detector aperture-size determines the field-of-view and is shown projected in object space by the lens.[17] In either design, lens or aperture, the importance of baffles to eliminate stray light cannot be overemphasized [18] but have been eliminated from the diagrams for clarity.

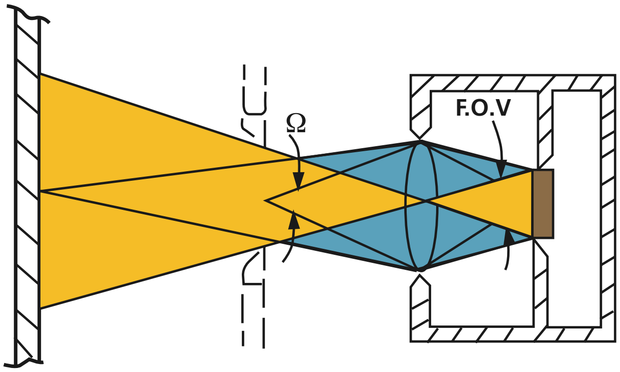


Figure 9. Positive lens luminance fixture

Finally we turn to measurement units for luminance, a venerable contributor to error and confusion, often finding its way even into texts that otherwise contain reasonably accurate information. Most of the problem, it seems, can be traced to when the point source, in order to create an emitting area, was surrounded by the perfect diffuser. This led not only to twice as many measurement units than otherwise likely, but also confusion in concepts based on spatial distribution of intensity that are correct only for an ideal diffuser, and invalid when applied to real physical diffusers.

A unformily illuminated spherical diffuser has a hemispherical surface area equal to $2\pi R^2$ but appears to an observer as a circular disc of uniform luminance with an area equal to πR^2 . Unity areas are then available in both square and circular versions, the latter exactly π times as large as its couterpart. Luminance units were based on both, but footlamberts, prevalent in the U.S., is gradually yielding to the international unit, candelas per square meter.

Unit Name	**Value**
stilb	candela/square centimeter
cd/m^2	candela/square meter
cd/ft^2	canaela/square foot
Lambert	candela/π square centimeters
apostilb	candela/π square meters
footlambert	candela/π square feet

Conclusion

Fundamental measurement quantities describing energy transfer between an emitter and receiver are based on the unit of power, the watt, and derived from geometrical area relationships, and the concept of uniformity. Flux can be measured absolutely and is independent of size and distribution. Irradiance measures flux uniformily distributed over an aperture of known size. Intensity is measured as irradiance with direction and distance specified, defining flux within the solid angle formed, and radiance is intensity uniformly distributed over a sample aperture of known size. Photometric equivalents are luminous flux, illuminance, luminous intensity, and luminance respectively.

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