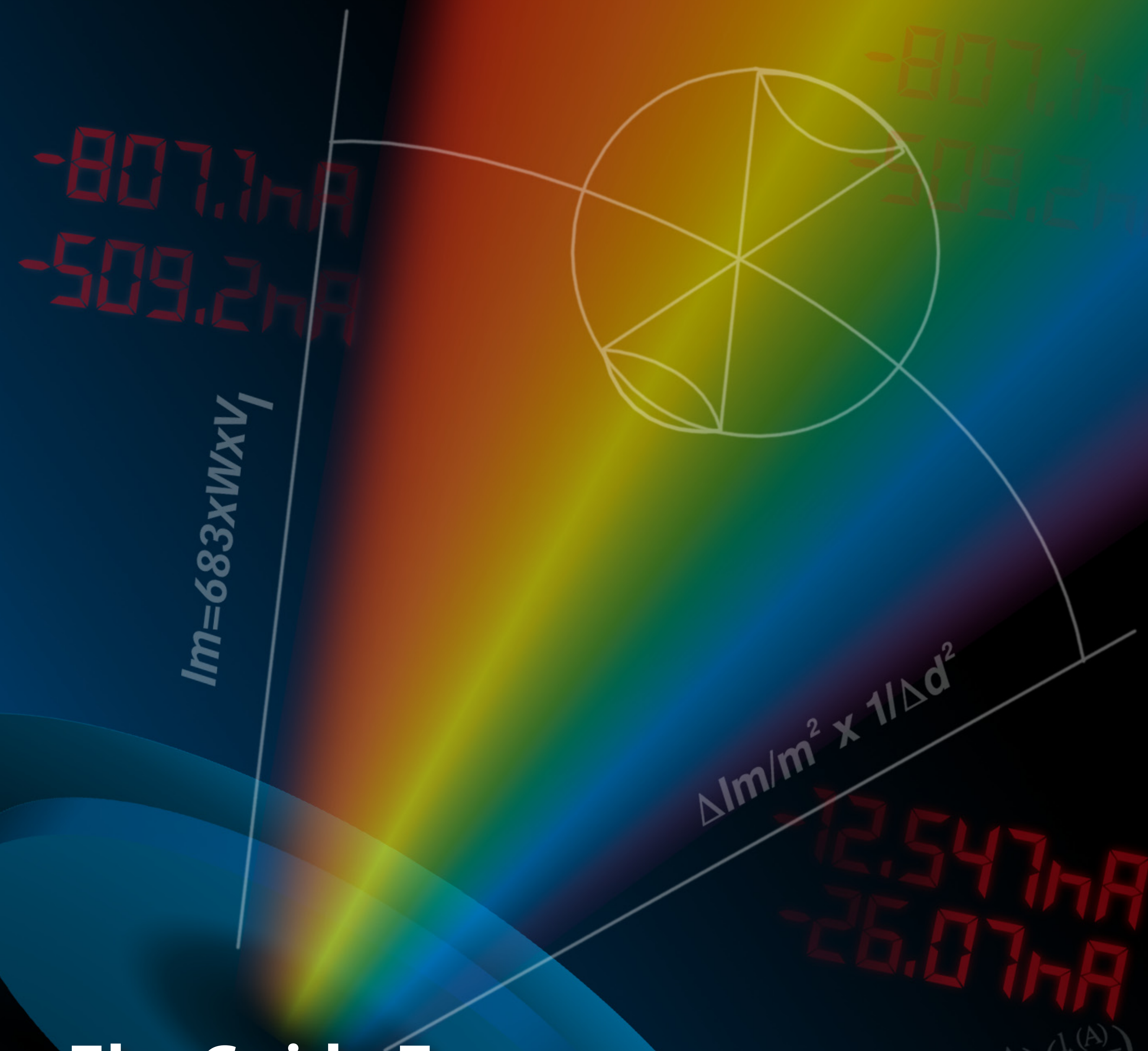
UDT INSTRUMENTS

MAKING LIGHT WORK OF LIGHT MEASUREMENT



The Guide To PHOTOMETRY

Photometry Guide Contents

About UDT Instruments

Application Information

Additional References from UDT Instruments:

Photomety & Radiometry:

Guide to Photometer & Radiometer System Configuration
(PDF; including a catalog of UDTi components)

Application Pages (on the UDTi website):

Display Measurement
LED Test & Measurement
Laser Test
Fiber-Optic Test
General Photometry
General Radiometry

About UDT Instruments

HISTORY

The early beginnings of UDT Instruments can be traced to 1967 when a small group of inventors at United Detector Technology (UDT) began manufacturing the first commercially available transimpedance amplifiers for planar-diffused and Schottky barrier silicon photosensors. Over the next several years, this same group of people went on to pioneer leading-edge technological innovations for photometers, radiometers, fiber-optic power meters and optical position-sensing instruments. By the early 1980's, this highly skilled and successful group grew into an autonomous entity known as UDT Instruments.

Drawing on the momentum generated by UDT's precision photometric instruments,the company developed an inventive handheld colorimeter for the growing television and computer peripherals markets. The development of UDT's SLS9400 colorimeter promises to strengthen our company's position as a leader in precision electro-optics instrumentation, while meeting the stringent demands of a multitude of CRT calibration requirements. UDT is poised and ready to excel to greater technological excellence with only one goal in mind: to meet and exceed the ever-changing needs of its customers worldwide.

SERVICE

We at UDT Instruments stand behind our products and the companies who use them. For this reason, we continue to service those same light-measuring instruments that we built twenty years ago. By offering these services to our customers, both new and established, we stay involved with our products and extend a personal touch to our business relationships. We know of no other company in our industry that hires more qualified sales engineers, people who really understand light measurement principles and practices. By hiring such knowledgeable engineers, we ensure you that you will get the best electro-optic instruments to fit your application and budget.

QUALITY

The instrument you receive is certain to be reliable and accurate. We maintain a Quality program that affects every indicator module, sensor head, and optical accessory we sell. And when it comes time for re-calibration, upgrades, or repairs, you'll discover that our service and metrology departments reflect this same commitment to quality and personalized service.

About UDT Instruments

TECHNOLOGY

UDT Instruments has always been and continues to be at the forefront of light measurement technology. We hold U.S. and worldwide patents on our QED products, which are absolute radiometric reference standards in the visible and near IR spectrum. Our QED-200 product won a prestigious IR-100 award as one of the 100 most significant U.S. inventions in 1986. These products were developed in conjunction with the National Institute of Standards & Technology (NIST) and the National Physical Laboratory (NPL). UDT Instruments continues to work with the NIST under Cooperative Research And Development Agreements (CRADA) in order to develop even more state-of-the-art products into the 21st Century.

PUBLICATIONS

In addition to our comprehensive "Guide To" tutorial series, UDT regularly publishes articles in trade journals and other scientific literature which we've made available as application notes to explain subtle details and applications of our technology.

PROFESSIONAL SOCIETIES

UDT is committed to supporting the industry through its professional society affiliates. We are proud to be sustaining members of:

- Society of Photo Optical Instrumentation Engineers (SPIE)
- Optical Society of America (OSA)
- National Association of Broadcasters (NAB)
- Laser Institute of America (LIA)
- Illuminating Engineering Society of America (IES)
- Society For Information Display (SID)

UDT also actively participates in the Council for Optical Radiation Measurement (CORM) and the Commission Internationale l'Eclairage (CIE).

WARRANTY

UDT Instruments warrants that its products are free from defects in material and workmanship under normal use and service for a period of one year from the date of shipment from our factory. UDT Instruments's obligation under this warranty is limited to the replacement or repair of any product determined to be defective during the warranty period, provided the product is returned to the factory prepaid. This warranty does not apply to any equipment that has been repaired or altered, except by UDT Instruments, or which has been subject to misuse, negligence, or accidents. It is expressly agreed that this warranty will be in lieu of all warranty of merchantability. No other warranty is expressed or implied. UDT Instruments is not liable for consequential damages.

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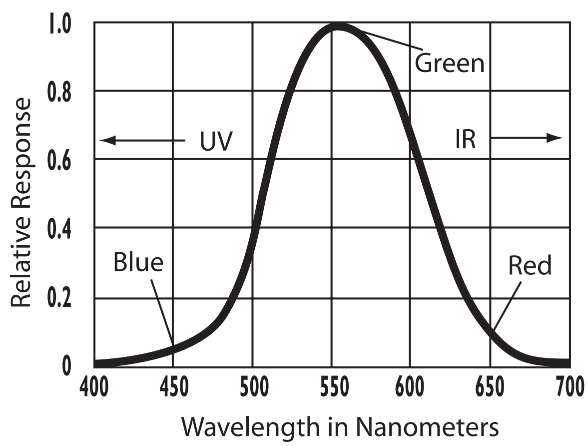
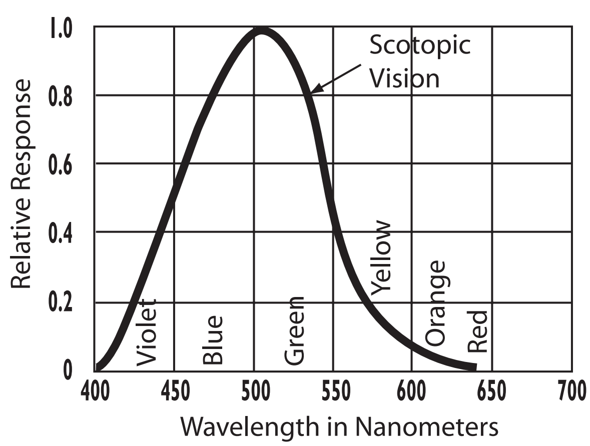
INTRODUCTION



CIE phototopic response curve.



CIE scotopic response curve.

Photometry is the science concerned with measuring human visual response to light.

Because the eye is a highly complex organ, this is by no means a simple task. It involves the meeting of many disciplines: psychology, physiology, and physics among them.

Photometry can be said to have become a modern science in 1924, when the Commission Internationale de l'Eclairage (CIE) met to define the response of the average human eye. The Commission measured the light-adapted eyes of a sizable sample group, and compiled the data into the photopic curve. Simply stated, the curve reveals that people respond strongest to the color green, and are less sensitive to the spectral extremes, red and violet.

The eye has an altogether different response in the dark-adapted state, wherein it also has difficulty determining color. This gave rise to a second set of measurements, and the scotopic curve.

Having defined the eye's spectral response, CIE sought a standard light source to serve as a yardstick for luminous intensity. The first source was a specific type of candle, giving rise to the terms footcandle and candlepower. In an effort to improve repeatability, the standard was redefined in 1948 as the amount of light emitted from a given quantity of melting platinum.

BASIC CONCEPTS

The basic unit of photometry is the lumen, which is related to its radiometric analog, the Watt, by:

$lm = 683 \times W \times V\lambda$

Where $V\lambda$ is the relative luminosity, a coefficient scaled to visual response. Unity occurs at the eye's peak response wavelength, 555 nanometers.

Two useful laws in photometry recur: the inverse square law and the cosine law. The first defines the relationship between illumination from a constant-intensity light source and its distance from a surface. It states that the intensity per unit-area on the surface, varies in inverse proportion to the square of the distance between the source and surface, or:

$\Delta lm/M^2 \propto 1/\Delta d^2$

Accordingly, successive illuminance measurements are only as accurate as the control of source to surface distance. Further, if illuminance is known at one distance, it can, barring interference, be calculated for any distance.

The cosine law indicates the intensity of light on a surface of fixed area, varies with incident angle. In fact, the intensity falls off as the cosine of the angle. This results because the projected surface area, in the plane perpendicular to incidence, is proportionally reduced.

Thus in measurements of environmental lighting, sensors require cosine correction to account for off-axis light. Without it, considerable errors will occur, especially with bright sources at low incident angles (e.g., windows). This often accounts for the difference in readings between two photometers.

The cardinal challenge in photometry is to recreate the spectral response of the human eye. But electronic sensors have distinct response characteristics which bear no resemblance to the CIE standard observer. Therefore, these sensors must be spectrally corrected. Two techniques are conventionally used to accomplish this: wavelength scanning, and detector/filter matching.

Scanning can be accomplished with discrete-wavelength, scanning monochromators, or multi-channel detectors. In either case, the intensity of a light source is measured wavelength-by-wavelength, and then the results are mathematically fitted to the photopic curve. For this reason, such techniques do not occur in real time, and require microprocessor control. Scanning approaches offer high accuracy, but tend to be costly, and complex to operate.

Optical filtering offers a simple and cost-effective solution. With only one photo-current signal to process, single-channel electronics can be used. Also, recent advances in filter design, and improvements in solid-state detectors, allow this method to rival scanning systems for photometric accuracy.

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BASIC CONCEPTS

Photometric to radiometric conversion factors.

Wavelength (nm)	Vλ CIEPhotopic Luminous Efficiency Coefficient	Photopic Lumen/Watt Conversion Factor
380	0.0000	.05
390	0.0001	0.13
400	0.0004	0.27
410	0.0012	0.82
420	0.0040	2.73
430	0.0116	7.91
440	0.0230	15.7
450	0.0380	25.9
460	0.0600	40.9
470	0.0910	62.1
480	0.1390	94.8
490	0.2080	142.0
500	0.3230	220.0
510	0.5030	343.0
520	0.7100	484.0
530	0.8620	588.0
540	0.9540	650.0
550	0.9950	679.0
555	1.0000	683.0
560	0.9950	679.0

Wavelength (nm)	Vλ CIEPhotopic Luminous Efficiency Coefficient	Photopic Lumen/Watt Conversion Factor
570	0.9520	649.0
580	0.8700	593.0
590	0.7570	516.0
600	0.6310	430.0
610	0.5030	343.0
620	0.3810	260.0
630	0.2650	181.0
640	0.1750	119.0
650	0.1070	73.0
660	0.0610	41.4
670	0.0320	21.8
680	0.0170	11.6
690	0.0082	5.59
700	0.0041	2.78
710	0.0021	1.43
720	0.0010	0.716
730	0.0005	0.355
740	0.0003	0.170
750	0.0001	0.820
760	0.0001	0.041

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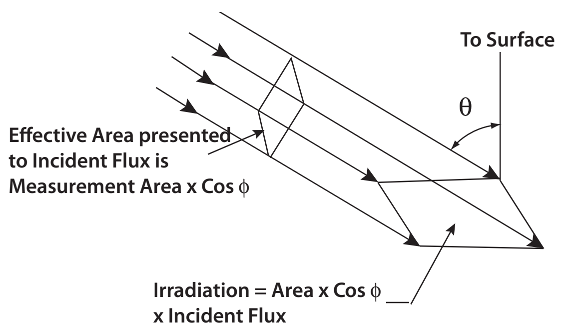
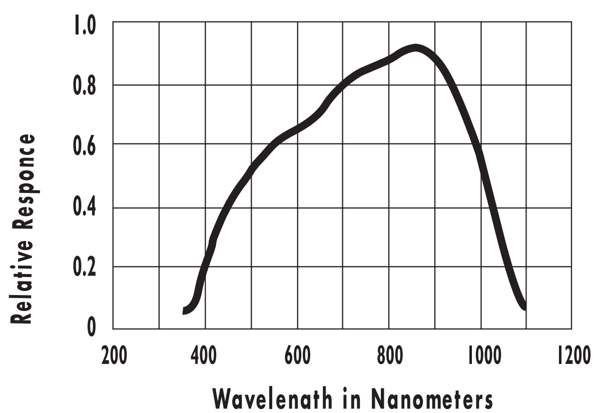
BASIC CONCEPTS



The intensity of off-axis light decreases relative to the cosine of incident light.



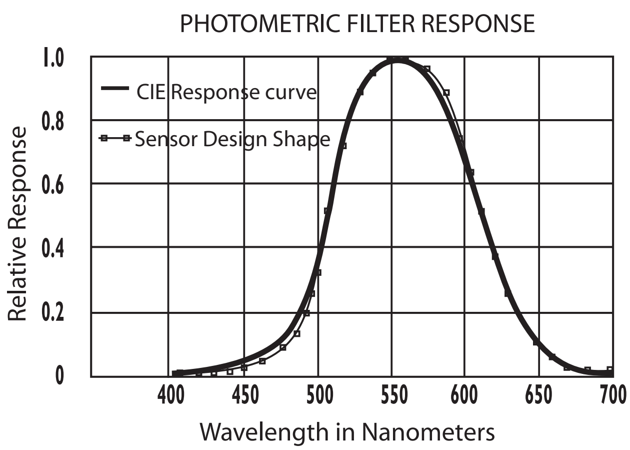
The typical spectral response of silicon photodetectors.

This filter-matching technique involves the layering of colored-glass filters over an optical detector. Each element functions to attenuate selective wavelengths until the detector's response simulates the CIE curve. Planar diffused silicon photodiodes offer the best photosensor characteristics, since they afford high sensitivity and linearity throughout the visible spectrum. Using silicon photodetectors, and advanced filter designs, UDT Instruments matches the CIE human eye response curve within 1% total area error. This is the best match achievable, according to CIE.

There is another more important specification of the quality of a photometric detector and that is the f_1' value. This is defined by the CIE and is a numerical value assigned to the average deviation of the photometric detector's response from the CIE curve. An $f_1' < 1.5\%$ is the best possible laboratory grade detector while an $f_1' < 3\%$ is considered suitable for most applications.

However, the relationship between a given detector and filter is delicate. Once the two have been matched, they should not be interchanged with other photometric detector/filter pairs. Each detector exhibits unique response characteristics that require a specific combination of filter layers and thicknesses.

BASIC CONCEPTS



UDT Instruments photometric filters match the CIE curve to within 1% total area error.

Once the detector's response is fixed, it is calibrated using the transfer of standards technique. This requires a detector of known response, which can be obtained from the National Institute of Science and Technology (NIST). A detector/filter pair is positioned before an optical source with constant wavelength and intensity characteristics (usually a tungsten halogen lamp). The electrical output of the detector under test is then compared to the standard detector's output.

Once the sensor's luminous response is determined, it can be matched to a precision gain-controlled electronic amplifier and readout system.

Calibration by Transfer of Standards

R_t = Responsivity of the test detector (A/lm)

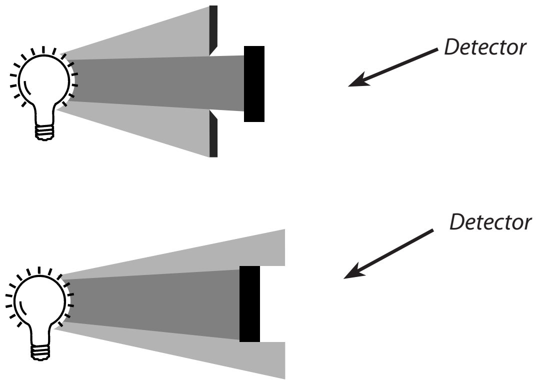
R_r = Responsivity of the reference detector (A/lm)

I_t = Measurement of the test detector (A)

I_r = Measurement of the reference detector (A)

$$R_t\left(\frac{A}{lm}\right) = R_r\left(\frac{A}{lm}\right)\left(\frac{I_t(A)}{I_r(A)}\right)$$

IMPORTANT TERMS



In illuminance measurements, area is determined by the detector unless there is an external aperture.

Luminous Flux

Luminous flux is expressed in lumens, the fundamental unit of photometry. It is a measure of the total optical output of a visible light source.

The measurement requires all of a source's power to be concentrated on a detector. This can be a problem with divergent sources like LEDs, and lamps. In these cases, integrating spheres are often used.

Illuminance

Illuminance is a measure of the amount of visible light incident upon a prescribed surface area. In English units, one lumen of flux falling on one square foot is termed a footcandle. The metric equivalent, one lumen per square meter, is called a lux (10.76 lux = 1 footcandle).

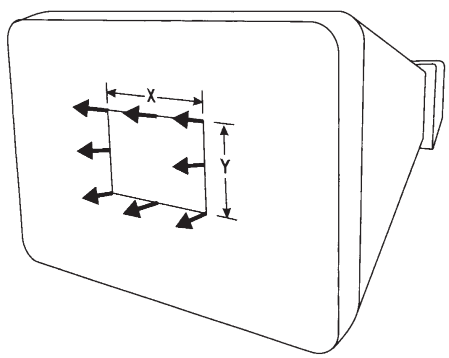
Of course, detectors don't have such large areas. So the area of the detector is multiplied proportionally. Special attention is due when the detector is under-filled or used behind corrective optics, since the sensor's area no longer defines the surface being illuminated.

For example, illuminance measurements are particularly susceptible to errors introduced by off-axis light. So cosine-correcting diffusers are used with the detector head. Since the cosine diffuser is essentially imaged onto the sensor, the diffuser's area, not the sensor's, represents the measurement surface.

Photometric Quantities and Units

Quantity	*Symbol*	*Units*	*Abbreviations*
Luminous energy	*Q*	*lumen•second…talbot*	*lm•s…talbot*
Luminous Density	*U*	*lumen•second/m^3*	*lm•s/m^3*
Luminous Flux	*F*	*lumen*	*lm*
Illuminance	*E*	*lumen/m^2…lux*	*lm/m^2…lx*
		lumen/cm^2…phot	*lm/cm^2…ph*
		lumen/ft^2…footcandle	*lm/ft^2…fc*
Luminous Exitance	*M*	*same units as illuminance*	
Luminance (brightness)	*L*	*candela/m^2…nit*	*cd/m^2…nt*
		candela/cm^2…stilb	*cd/cm^2…sb*
		candela/π ft^2…footlambert	*cd/π ft^2…fl*
		candela/π m^2…apostilb	*cd/π m^2…asb*
		candela/π cm^2…lambert	*cd/π cm^2…L*
Luminance intensity	I_u	*lumen/steradian…candela*	*lm/st…cd*

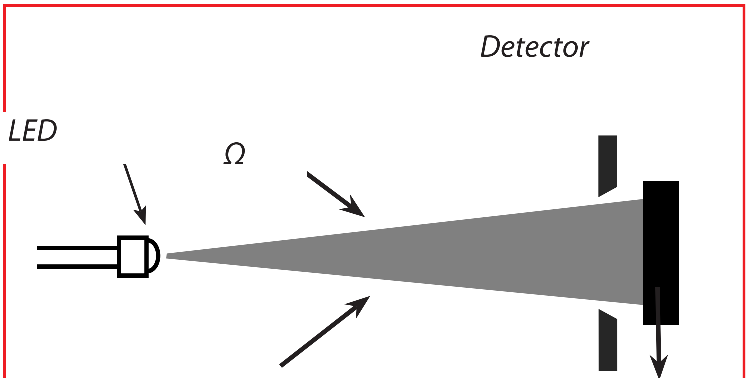
IMPORTANT TERMS



Luminous exitance is calculated by measuring luminous flux and dividing by the source's area.

Luminous Exitance

Luminous exitance is an intrinsic property of a light source. It is calculated by measuring luminous flux (lumens), and dividing by the surface area of the source. This measurement is also expressed in lumens per square meter, but is not to be confused with illuminance measurements or lux. The area referred to in luminous exitance is that of the light source, not the illuminated surface. This measurement is most applicable to emitters with flat surfaces.



Luminous intensity is a measure of the flux emitted into a solid angle.

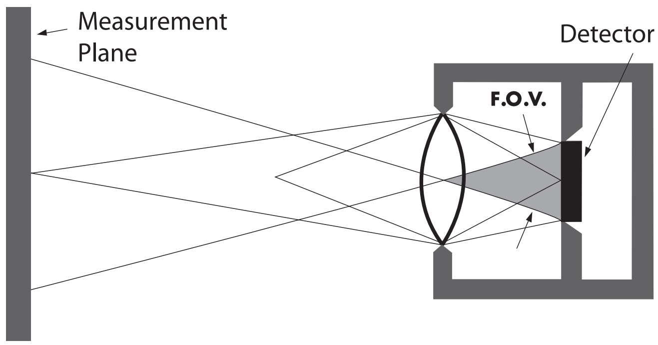
Luminous Intensity

Luminous intensity is also a source property, but one where the source's direction and divergence come into play. Defined as the quantity of luminous flux emitted uniformly into a solid angle, the basic unit of luminous intensity is the candela, equal to one lumen per steradian.

Several things are suggested by this definition. One, this measurement is not applicable to collimated light sources. Two, it is inaccurate for non-uniform emitters.

To calculate luminous intensity, the detector's area (or the area prescribed by the aperture in front of it), and its distance from the light source must be known. From these, the solid angle can be calculated, and then divided into the flux reading.

IMPORTANT TERMS



One luminous measurement technique involves fixing the detector's field-of-view through the use of a lens.

Luminance

Also known as photometric brightness, luminance is a measure of the flux reflected by, or emitted from, a relatively flat and uniform surface. The technique takes into account the area of the surface measured, and the angle subtended by an observer looking at it.

Luminance may be thought of as luminous intensity per unit area, and so in metric terms is expressed as
candelas per square meter. But a host of other terms are used for this measurement, some to describe a
circular measurement area rather than a square one (see Photometric Quantities and Units chart).

To measure luminance, the detector field-of-view must be restricted, and its angle calculated. Usually, a lens or baffle is used to achieve this. In fact, the human eye, with its lens and aperture, functions as a luminance meter.

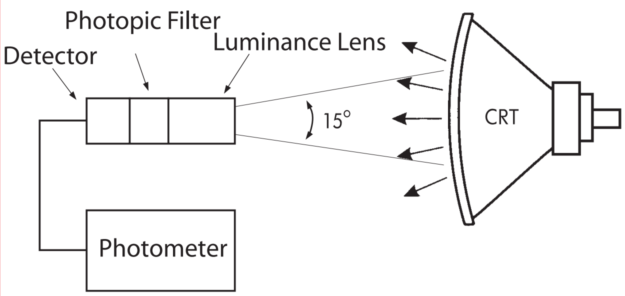
Note that so long as the detector's field-of-view is filled, this measurement is independent of the distance between the detector and measurement planes. That's because field size and source intensity vary in direct proportion to one another as a function of distance.

Luminous Energy

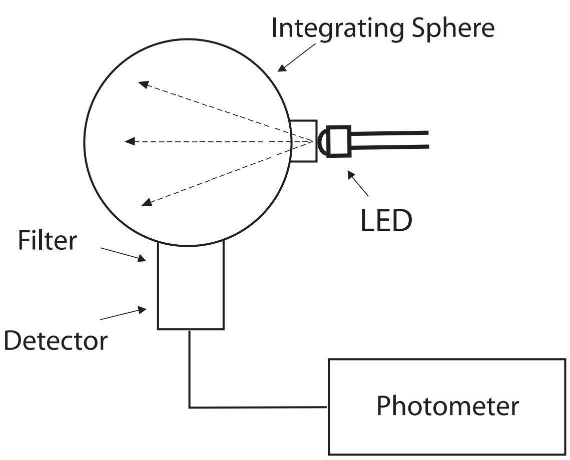
Luminous energy is a measure of the rate of flow of flux, and so is expressed in lumen-seconds. Generally, it is applied to flashed or pulsed sources.

It is also possible to measure any photometric quantity on a time-dependent basis. For instance, the illuminance of a rotating beacon in one direction could be integrated over time to yield foot-candle-seconds.

HOW TO SPECIFY A PHOTOMETER SYSTEM



CRTs and other displays are typically measured in terms of luminance.



Integrating spheres are the most accurate means of measuring small, divergent sources like LEDs.

Specifying a photometer system is best approached in three steps. First, evaluate the source to determine which measurement technique best applies. Then, select a detector and optical system (detector head) that suit the measurement. And finally, match the detector head to the particular electronics which provide the most effective user interface for the application.

Consider the Source

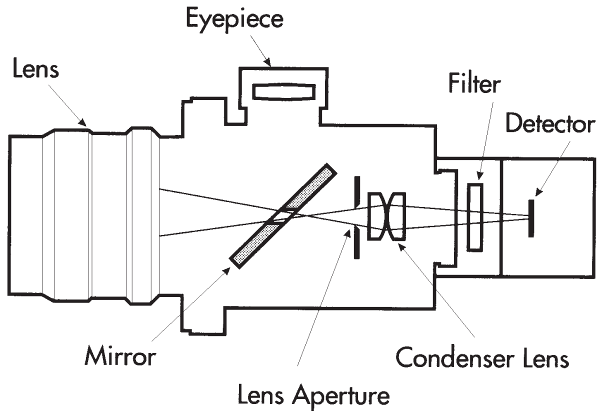
Common sense goes a long way in determining the right measurement for an application. After all, photometry is concerned with the relation of light to the human eye. So, the first question is: how will people be affected by the source to be measured?

For instance, measurements of ambient or environmental lighting are concerned with people's ability to read print or safely see objects in an area. It is not the power of a particular source that is of concern, but rather how well the source lights the area of interest. For this reason, lighting for the outdoors, offices, factories, and photography are measured in terms of illuminance.

However, if in the same room or space one wished to determine the brightness of walls, fabric, or painted surfaces, the measurement changes altogether. Because now the amount of reflected light received by the eye is of concern. Since all of these surfaces are diffuse and relatively uniform, a luminance measurement would best apply.

SEE ALSO: The *Guide to Photometer & Radiometer System Configuration*, available as a free PDF download at **www.udtinstruments.com**

HOW TO SPECIFY A PHOTOMETER SYSTEM



For luminance measurements requiring small fields-of-view, a lens system with view-through optics is essential.

Electronic displays such as CRTs, avionics, and automotive panels are incident directly upon the eye too. But alpha-numeric characters and line detail are generally small. So the measurement system's field-of-view must be limited or focused in order to measure only the lighted portions of the display. This is, by definition, a luminance measurement. So display brightness is usually specified in footlamberts.

Lamps are used in so many applications that it is impossible to define just one way to measure them. As previously mentioned, lamps and lamp systems for area lighting (rooms, streets, stadiums) call for illuminance measurements. But in automotive exterior lighting, headlights are usually measured for illuminance, taillights for luminance. There are a number of miniature, lensed lamps on the market, and since their divergence is of concern, they would be measured for luminous intensity. Incandescent and fluorescent lamp manufacturers specify products in terms of luminous flux (or the radiometric equivalent, watts) since these will be placed in fixtures meant to diffuse and measure their total output.

Lasers and LEDs also require a careful approach. They are measured in radiometric terms for scientific applications. But when their potential damage to the eye is of concern, they would probably be measured for luminous flux. A lensed LED, however, is a divergent, though directional, source. Luminous intensity would best characterize it. But with surface or edge emitting LEDs, emission as a function of surface area is significant. This describes a luminous exitance measurement.

Luminous energy measurements apply to any periodic source. Pulsed LEDs, photographic flash units, strobe lights, arc lamp systems, and rotating or scanning lights are several examples of sources whose flux is time dependent.

Selecting the right detector head

The measurement type dictates your choice of detector head assemblies.

UDT Instruments offers a modular photometric sensor-head design approach. In all cases, a silicon photodetector, detector housing, and photometric filter assembly are provided. And for those luminous flux measurements where all incident light is collimated or focused onto the detector, this simple head will suffice.

However, if flux levels exceed 70 lumens per square centimeter, the detector may become saturated, and its output nonlinear. In such instances, attenuation is recommended. Neutral-density filters, apertures, or integrating spheres achieve the desired effect. The correct selection depends upon the amount of attenuation desired: it should be enough to avoid detector saturation, but not so much as to lose sensitivity and dynamic range.

SEE ALSO: The *Guide to Photometer & Radiometer System Configuration*, available as a free PDF download at **www.udtinstruments.com**

HOW TO SPECIFY A PHOTOMETER SYSTEM

The simple detector/filter arrangement is also effective for ambient measurements if all light is at normal incidence. But when off-axis light, such as from windows and peripheral sources, contributes to the total flux, a cosine diffuser is needed.

In addition to being widely applied by lamp manufacturers, integrating spheres are useful for measurements of small divergent sources like lensed LEDs or miniature lamps. These can be inserted right into the sphere's entrance port to ensure that all light is collected.

Luminance measurements require a prescribed sensor-head field-of-view. The size of the source in the measurement-field plane, and the sensor-to-subject distance determine the angle. With large, but close fields, a simple baffle (steradian shade or aperture) will do. But small images, such are those on CRTs or avionics, call for a lens system, as do measurements at a distance. A variety of lens assemblies and optical accessories are available from UDT Instruments, to accommodate most any luminance measurement, whether microscopic or telescopic.

UDT Instruments offers a wide range of optical accessories for out-of-the-ordinary measurements. These include: fiber optic probes, for convenience in measuring sources hidden in hard-to-reach places; LED measurement systems specific to either segmented or discrete LEDs; low-profile sensors for slipping into tight spaces, such as in photolithography exposure systems; and a variety of sensor heads customized for Display luminance measurements.

SEE ALSO: The *Guide to Photometer & Radiometer System Configuration*, available as a free PDF download at **www.udtinstruments.com**

UDT Model 1120 Telephotometer

HOW TO SPECIFY A PHOTOMETER SYSTEM

Choosing electronics matched to the application

The light sensor in each UDT Instruments photometric head is a silicon photodiode. Though sensor size may vary, the output will in all cases be a low amplitude current signal. This signal will be converted into a
voltage by a transimpedance amplifier circuit, and then used according to the requirements of the particular application.

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Your choice of electronics depends upon the answers to a few basic questions:

1. Is field portability needed?
2. Will the instrument be interfaced with a computer?
3. Is a visual display desired, or will an analog output suffice?
4. Will more than one measurement be conducted concurrently?

UDT Instruments offers photometer controllers and electronic amplifiers that satisfy any combination of answers to these questions. The instruments range from simple analog amplifiers and hand held photometers, to multichannel computer-controllable laboratory instruments. Versions are available which suit most any budget.