Measuring Light

Peter D. Hiscocks
Professor Emeritus, Ryerson University
phiscock@ee.ryerson.ca
Version 1 December 2008
Version 2 January 2011: Added Glare Calculation

Contents

1 Executive Summary

This document is in three sections: *Executive Summary*, *Introduction to Photometry* and *Measurement of Glare*.

The Executive Summary provides a brief introduction to the measurement of light levels to aid understanding of proposals in the *City of Toronto Light Pollution Abatement Guideline*. Readers will have then a better understanding of how the measurements are made, and the implication of some value of light level.

In the Executive Summary, we describe two key measures of light measurement, *luminance* and *illuminance*. We also mention the concept of *luminous efficiency*.

The second section, Introduction to Photometry, is optional reading. It provides a more complete explanation of light measurement units and their relationship.

The third section details methods of measuring *glare*.

1.1 Luminance

Light Source	**Luminance**, **candela per square metre**
Sun	1.6×10^9
Arc lamp	1.5×10^8
Maximum visual tolerance	50000
Frosted incandescent lamp	50000
Cloud (sunny day)	35000
Fluorescent lamp	12000
Surface of moon	1000
Metal-halide flood lamp	500
Convenience store sign	150
White paper under lamp	50
Neon lamp	8
Candle	7.5
Clear sky	4.0
Moon	2.5
Dark sky reserve (proposed)	0.1
Night sky	0.001
Threshold of vision	0.000003

(a) Examples

(b) Luminance Meter

Figure 1: Luminance

Luminance may be regarded as a measure of the *brightness* of a source. It is used to characterise the brightness of lamps and illuminated signs, for example. Luminance is a useful measure in identifying sources that produce glare. Luminance is measured in *candelas per square metre*. Typical luminance values are shown in figure 1(b).

A *luminance meter*, figure 1(a), is a specialized light measurement instrument that has a very small angle of acceptance. Consider a laser pointer that produces a very narrow beam and illuminates a small area on a lamp. Now consider the equivalent in a light measuring instrument: it can sample a very small area some distance away. The meter usually includes some sort of viewfinder so the operator can aim the instrument at the area to be measured.

Notice that *the luminance level does not depend on distance to the measurement point*. Luminance is a property of the light source - the surface brightness[1]. In effect, a luminance meter compensates for distance.[2]

[1] Technically speaking, *luminance* and *brightness* are not quite the same. Luminance is a measurable quantity. Brightness is the human sensation of luminance. However, as a first cut at understanding we will treat them as similar.

[2] As the table of figure 1(a) indicates, the eye can cope with an enormous range of luminance. To do so, the percieved brightness is a logarithmic function of luminance. That is, increasing the luminance by some multiplying factor causes the brightness to increase by an additive factor. In other words, increasing the luminance by a factor of ten does not increase the brightness by a factor of ten: it is some lesser amount. The human perception of loudness works in a similar fashion.

1.2 Illuminance

Illuminance is a measure of the light falling on a surface. It is measured in *lux* and is commonly used to quantify the light level in places of work, stores and homes.

Typical illuminance values are shown in figure 2(a). The measuring instrument for illuminance is shown in figure 2(b). To measure the illuminance on a surface, the white, circular sensor area is placed at the point of measurement facing upward.

Illuminance is also measured in *footcandles*, a unit which is in common useage in the United States. One footcandle is approximately the illuminance produced by a candle at 1 foot distance. A footcandle is approximately 10 lux.

For a given source, the illuminance on a surface decreases as the surface is moved away from the source, according to the *inverse square law*. That is, a doubling of distance decreases the illuminance by a factor of 4.

Light Source	**Illuminance, Lux**,
Direct Sunlight	32,000 to 130,000
Daylight	10,000 to 25,000
Operating room	18,000
Sports field	200 to 3000
TV Studio	1000
Retail store	500
Sunrise on a clear day	400
Office	320
Overcast day	100 to 3500
Washroom	80
Gas Station	50 (IDSA recommendation)
Surface of Mars	50
Family living room	50
Candle at one foot	10
Roadway lighting	3 to 16
Civil Twilight	3.4
Sidewalk	2 to 10 (Ottawa recommendation)
Candle at one metre	1.0
Full Moon	0.27
Quarter Moon	0.01
Total starlight	0.0002

(a) Examples

(b) Illuminance Meter (LuxMeter)

Figure 2: Illuminance

1.3 Luminous Efficiency

A light source is a device for converting electrical energy into light energy. The efficiency of that process is the 'luminous efficiency', measured in *lumens per watt*. Typical values are shown in figure 3. Higher numbers are better.

Light Source	**Luminous Efficiency, Lumens per watt**
60 watt incandescent	14.5
100 watt incandescent	17.0
CFL ('60 watt')	55
Fluorescent	75
LED	90
High pressure sodium	125

Figure 3: Luminous Efficiency

In this case, the numerical values of luminous efficiency are not important except to indicate the relative efficiency of various sources. For example, a CFL (compact fluorescent lamp) is about 4 times as efficient as an incandescent lamp in converting electrical energy to light energy.

1.4 Summary

By committing a few values of luminance and illuminance to memory, it is possible to have an understanding of brightness and light levels in general. For example, if we identified a football stadium light fixture as 50,000 candela per metre squared, we can appreciate that this is an extremely bright source. If we are considering a park footpath lighting level as 0.5 lux, this is more light than cast by a full moon, but not by much.

2 Introduction to Photometry

In this section we take a more detailed and rigorous look at the measurement units relevant to light pollution. We will begin with the source of light and then see how it is propagated and illuminates a surface. To understand the source radiation, we must understand the *solid radian* or *steradian*.

2.1 Solid Angle: *Steradian* [2]

Recall from high school geometry the definition of a radian [1]: *it is the angle subtended by an arc of length equal to the radius*. Consider a circle, with some section of the circle highlighted for length r, figure 4(a). Then the angle α is one radian. This is true regardless of the radius of the circle.

The circumference c of a circle is $c = 2\pi r$ where r is the radius. Then the angle subtended by an entire circle is

$$\alpha = \frac{2\pi r}{r} = 2\pi \text{ radians}$$

This 'entire circle' angle α is also equal to 360 degrees. So we can create an equality:

$$\pi \text{ radians} = 180 \text{ degrees}$$

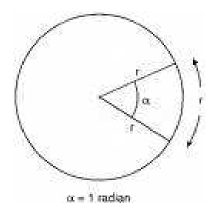
In other words, a radian is about 57 degrees.

Why is this useful? It turns out that our angle measurement of 360 degrees for a full rotation is arbitrary. Radian measurement is a much more *natural* measurement of angle, and the effect is to eliminate a factor π from many equations. Radian measurement is extensively used in electrical engineering, for example.

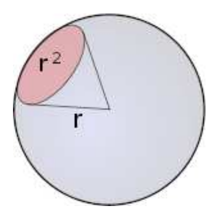
The radian is a two dimensional measurement. The *steradian* extends this to three dimensions.

The *steradian* is the solid angle subtending an area on a sphere of r^2. This area can be circular as shown in figure 4(b) or square as in figure 4(c).

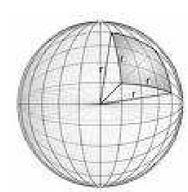
Notice that the solid angle in steradians does not depend on the size of the sphere. As the sphere gets larger, the radius increases and so does the area patch – keeping the subtended angle constant.



(a) Radian



(b) Steradian



(c) Steradian

Figure 4: Steradian [1], [2], [3]

2.2 Luminous Intensity, The *Candela* [4]

A light source is a device that converts some form of energy (eg, electricity) into light. Suppose, then, that there is a point source of light energy. The light energy radiates away from the source. *When the luminous energy flowing through a steradian is equal to* $1/683$ *watts, then the luminous intensity is one candela*. The modifier *luminous* is important, because it implies that the measurement of radiant light energy is made with a filter that weights the energy as would a human eye, giving more weight to green and less to red and purple.

The factor $1/683$ aligns this definition with an earlier definition, which was based on a standard candle[3]. So, a candle radiates approximately 1/683 luminous watts through each steradian solid angle. Or, put another way, it would take 683 candles[4] to radiate one luminous watt through a steradian.

As in the definition of steradian, it does not matter where this measurement takes place. The amount of light energy flowing through each steradian is a constant.

2.3 Luminous Power: *Lumens* [5]

The total luminous power in lumens flowing out of a source is equal to the product of the luminous intensity in candela times the radiating angle in steradians.

Example: One candela radiating through 1 steradian emits one lumen. Running this backward through the definition of *candela*, this is a luminous power of $1/683$ watts. One candela radiating in all directions emits 4π lumens.

It's useful to picture that the number of lumens flowing out of a source is a measurement of the total luminous power in watts of the source. [5]

2.4 Luminance: *Candela per Square Metre*, (*Nit) [6]*

Consider that the luminous energy from the previous point source intersects with some surface such as the envellope of a bulb or the frosted plexiglass surface of a sign. This surface then becomes an extended (area) source of light. The brightness of this surface is proportional to the luminous intensity of the source, in candela, and inversely proportional to the area. The measure of this brightness is the *luminance* in *candela per square metre*[6].

2.4.1 Luminance and Brightness

We have used the terms *luminance* and *brightness* interchangeably. There is a difference. Luminance is a quantity that can be measured objectively by an instrument. Brightness is the subjective impression of luminance. For those familiar with sound measurement, this is analogous to the relationship between sound level (an objective measurement) and loudness (a subjective perception).

[3]The standard candle was made of pure spermaceti (a wax present in the head cavities of the sperm whale), weighing one sixth of a pound, and burning at the rate of 120 grains per hour [4]. Not the sort of thing one buys at Home Hardware

[4]Picture a very, very large birthday cake.

[5]The output in lumens can be measured in the lab using an 'integrating sphere', a large spherical container painted white on the inside. The light source is placed inside. All the light from the source, regardless of its direction, reflects repeatedly from the interior surface of the sphere. The light level inside is sampled by a measuring device. This, it turns out, is proportional to the total light output of the source. The integrating sphere method of measuring light output is not a practical technique for field measurements, where the source could be located at the top of a pole.

[6]The candela per square metre is also called the *nit* in the USA, from latin "nitere" = "to shine". This nit should not be confused with the larva of the head louse, of *nitpicking* infamy.The illumination nit is frequently used in the specification of brightness of electronic displays, such as plasma panels. The cgs unit of luminance (candela per square centimeter) is the now-depreciated *stilb*.

2.4.2 Measurement Angle

Many sources, such as the frosted plexiglass panel of an illuminated sign, are *diffuse*, that is, they scatter light. It may be shown [7] that the luminance of a diffuse surface is independent of the viewing angle. This is *not* the case for sources with lenses, such as certain street lamps, which are highly directional.

2.5 Illuminance: *Lux* [8]

When lighting a room or the pavement under a street lamp, we are concerned with the light level on that surface, or the *illuminance*. Light level is measured in *lux*.

The technical definition of one Lux is one Lumen per square meter. Lumens are a measure of the available lighting energy, and Lux is the brightness after that energy is spread over a surface.

For an analogy, conside painting a surface: The total light energy in lumens corresponds to the amount of paint in the can. The illuminance in lux corresponds to the amount of paint per unit of surface area, the thickness of the paint.

For example, lighting a living room with one sixty-watt bulb gives a low level of brightness on the room surfaces. Lighting a closet with one sixty watt bulb gives a higher level of brightness on the room surfaces because the available light energy is spread over a smaller area. The *luminance* of both these sources is exactly the same, the light output in lumens is exactly the same, but the *illuminance* is different.

A *lux meter* takes a photometric measurement of illuminance, that is, one that compensates for the colour sensitivity of the eye and corresponds to the human perception the amount of light falling on a surface.

For a given fixed source, the illuminance decreases with distance according to the inverse square law. As the distance doubles, the illuminance decreases by a factor of 2 squared, or 4.

2.6 An Illuminated Surface as a Source

An illuminated surface can be treated as a source. The light falling on the surface would be measured by an *illuminance photometer* or *luxmeter*, shown in figure 2(b) on page 3, yeilding a result in lux or lumens per square meter.

The light radiating from the source would be measured by a *luminance photometer*, figure 1(b) on page 2, yeilding a result in candela per square meter.

By carefully taking into account the measurement units, the ratio of these two measurements would indicate the degree to which the surface re-radiates the incident light.

3 Measurement of Glare

It is a complicated matter to measure the effect of glare on human vision. There are several metrics, including *disability glare* and *discomfort glare*, and different formulae for calculating them. For example, the effect of glare depends on the size of the source, the contrast between the background light and glare source, and even the age of the viewer. For field measurements that are taken by non-specialists, this is dauntingly complex. However, it is clear that glare is a problem in many lighting installations, so there is a need for a practical system of measuring it.

Glare may be measured from luminance (candelas per square metre) as described in sections 3.1 and 3.2 below. Lewin [19] argues against luminance and supports measuring glare from intensity (candelas), which is the method described in CIE standard 150:2003 (section 3.3 below).

3.1 Glare from Luminance: Luminance Meter

It is clear that the effect of glare is proportional to surface brightness. The perceived surface brightness is in turn proportional to the *luminance*, measured in candela/metre^2. Although there are measuring instruments that can provide a direct measurement of luminance (see figure 1(a)), they are expensive.

3.2 Glare from Luminance: Digital Camera

A calibrated digital camera provides a straightforward, low-cost method for measuring luminance. The value of each pixel in the image[7] is proportional to the intensity of the source, in candelas per square metre. This technique may hold the greatest promise in the long run because it simultaneously documents the scene and the luminance of light sources in the scene.

- The camera must be calibrated against a known luminance.
- Camera images are usually compressed into the JPEG format. Although it is theoretically possible to use JPEG compressed images for luminance measurement, this complicates the process considerably because each pixel value is a non-linear function of the luminance. Accurate calibration is easier to obtain from a RAW image, that is, one that has not been compressed. Then each pixel value is directly proportional to the luminance in the image. RAW image format available on DSLR (Digital Single Lens Reflex) cameras and some point-and-shoot digital cameras.
- Care must be taken to ensure that the image pixels are not overloaded by the light source. Most camera light meters cannot be counted on to provide the correct automatic exposure and the exposure must be set on *manual*.

At the time of this writing, the author is establishing a method of digital camera calibration and measurement that is relatively simple to use.

3.3 Glare from Intensity: CIE Standard Method

CIE Standard 150:2003 [17] sets a method of measuring the glare produced by a distant light source. The method measures the *intensity* of a luminous source in candela. The visibility of a distant light source is proportional to it's intensity [19]. As a result, it's reasonable to use intensity as a measure of glare. The measurement of intensity has the advantage that it is simple to do and uses readily available equipment: an illuminance meter (luxmeter) and distance measuring device (tape measure or laser rangefinder). The method trades off simplicity for a number of assumptions:

- The glare of a source is proportional to the luminous intensity (in candela) of a light source.
- The source is concentrated into a small radiating area.
- In a glare measurement, contrast is important. This technique assumes that the glare measurement is with reference to a dark-sky background (night-time measurement).
- Each light source can be measured independently. Where there are several light sources that cannot be operated independently (eg, sports lighting at the top of a pole), we need a method of assigning the total brightness to the individual sources. (See below).
- There are no other interfering sources of light (such as nearby street lamps).

[7] Image pixel values may be determined using an image analysis program such as *ImageJ* [16] .

Theoretical Basis

Lewin [19] points out that the visibility of a distant source is governed by *Allard's Law* [18], which says that the visibility of the source is determined by its intensity[8].

Suppose that a light source produces a luminous intensity of I candela. One candela radiates one lumen through one steradian. If the source is omnidirectional, then the total radiation angle is 4π steradians, Then the total light energy (luminous flux) flowing out of the source is $4\pi I$ lumens.

At some distance d from the source, this energy flows through a surface equal to the surface area A of a sphere with a radius of d metres. Then the illuminance E_d in lumens per square metre (lux) at distance d is:

$$E_d = \frac{4\pi I}{A} = \frac{4\pi I}{4\pi d^2} = \frac{I}{d^2} \tag{1}$$

Rearranging equation 1 to solve for I, the luminous intensity, we have:

$$I = E_d d^2 \text{ candela} \tag{2}$$

That is, an some distance d the luminous intensity I of the source in candela is equal to the illuminance E_d in lux at distance d, multiplied by the distance d in metres, squared.

Notice that the distance of the measurement is not critical. It can be taken where physically convenient. Ideally, one could take several measurents illuminance (in lux) at several distances (in metres). Equation 2 should give the same results for each measurement.

In practice, that is not quite the case because the output of the light fixture will vary somewhat with angle. Different measurement positions result in different viewing angles back to the source.

Resolving Multiple Sources

When there are multiple sources of light, there are three possible ways to determine the luminous intensity of each individual source:

- Direct the luxmeter measurement so that it 'sees' the individual sources, possibly by restricting the field of view of the meter with a hollow tube.
- Assume that all the sources are equal in luminous intensity, then divide the total luminous intensity by the number of sources.
- Photograph the sources with a digital camera that produces images in the RAW format. Ensure that the image is not saturated (over-exposed). Then the pixel values of the individual sources can be determined using an image analysis program, and the total luminous intensity assigned proportionally.

References

[1] Radian: `http://content.answers.com/main/content/img/oxford/Oxford_Sports/0199210896.radian.1.jpg`

[2] Steradian: `http://en.wikipedia.org/wiki/Steradian`

[8] For completeness, we state Allard's Law: $E_v = P_o x^{-2} e^{-\sigma x}$ where E_v is the *threshold illuminance* in lux, P_o is the luminous power of the source in watts and σ is the *extinction coefficient* The intensity of a source I in candela is directly proportional to its luminous power in watts, so this states that the illuminance is proportional to the intensity. The x^{-2} term arises from the inverse square law of illuminance vs distance.

[3] Steradian: http://www.lichtconsult.nl/p/19/118/mo8-cg22%7Ccoi=S*

[4] Candela: http://en.wikipedia.org/wiki/Candela

[5] Lumen: http://en.wikipedia.org/wiki/Lumen_(unit)

[6] Luminance: http://en.wikipedia.org/wiki/Luminance

[7] Lambert's Cosine Law: http://en.wikipedia.org/wiki/Lambert%27s_cosine_law

[8] Lux: http://en.wikipedia.org/wiki/Lux

[9] Radiometry and photometry FAQ
James Palmer
http://www.optics.arizona.edu/Palmer/rpfaq/rpfaq.pdf

[10] Luminance: http://www.schorsch.com/kbase/glossary/luminance.html

[11] Luminance: http://www.ledshift.com/Lichtstaerke%20English.html

[12] Four basic physical units of light
http://www.nvc-lighting.com/showuseInfo.Aspx?typeID=42&ID=94

[13] Brightness, Luminance and Confusion,
Charles P. Halstead
http://www.crompton.com/wa3dsp/light/lumin.html

[14] Illumination,
J. B. Calvert, 14 August 2003
http://mysite.du.edu/~jcalvert/optics/lumens.htm

[15] The unit of luminous intensity: the candela (cd)
http://www.natmus.dk/cons/tp/lightcd/light_cd.htm

[16] ImageJ, an Image Analysis Program
http://rsbweb.nih.gov/ij/

[17] CIE Technical Report
Guide on the Limitation of the Effects of Obtrusive Light from Outdoor Lighting Installations
CIE Standard 150:2003
ISBN 978 3 901906 19 0

[18] Allard's Law
http://amsglossary.allenpress.com/glossary/search?id=allard-s-law1

[19] Further Consideration of Obtrusive Light
Ian Lewin, Lighting Sciences Inc.
http://dmdeng.com/pdf/learning/Further_Consideration_of_Obtrusive_Light.pdf