White Paper – Why Blue Light Can Not Be Measured in Lumens

Nearly every day, we at FireDiveGear.Com are asked how many lumens our blue light torches put out. This is a question that requires a very technical and detailed answer. The shortest answer is simply this:

A single wavelength (monochromatic) light source can't be measured in lumens.

A Short But Somewhat Clearer Answer

"Lumens" is a measure of how much light the human eye will perceive, weighted according to the specific sensitivity of the human eye to different wavelengths of light. The light of our blue light torches however is not meant to eventually reach the human eye, on the contrary, it is meant to be filtered out by the barrier mask and camera filters. Instead, it is meant to pump energy into the fluorescent pigments of the underwater organisms of interest, so the most appropriate measure for our torches is the light energy or "radiant flux" they emit. What reaches the human eye (or the camera) is the fluorescent light emitted by the fluorescent pigments, whose efficiency in doing so varies greatly depending on the organism (and the pigment) in question.

The Much More Detailed Scientific Answer

This paper will describe in *some* detail exactly why lumens don't work with monochromatic light. Entire books have been written on this topic however so this short summary may leave you wanting more (if you're a glutton for punishment). There is no way to explain this without an extensive use of technical terms so the reader is directed to sources such a Wikipedia to get more detailed information where desired. We have also tried to enlighten the reader to the concept of color and what it actually is.

What is light?

Light (a form of energy) is just one tiny portion of a broader range of the electromagnetic (EM) spectrum of waves traveling through space from radio waves to gamma rays. Figure 1, below is a graphic representation of the EM spectrum courtesy of NASA. This graph shows the various wavelengths of EM waves and their relative size to everyday objects. The measurement of light can be very challenging when deciding what to measure and how to measure it. As you can see, light is but a tiny "sliver" of the EM spectrum.

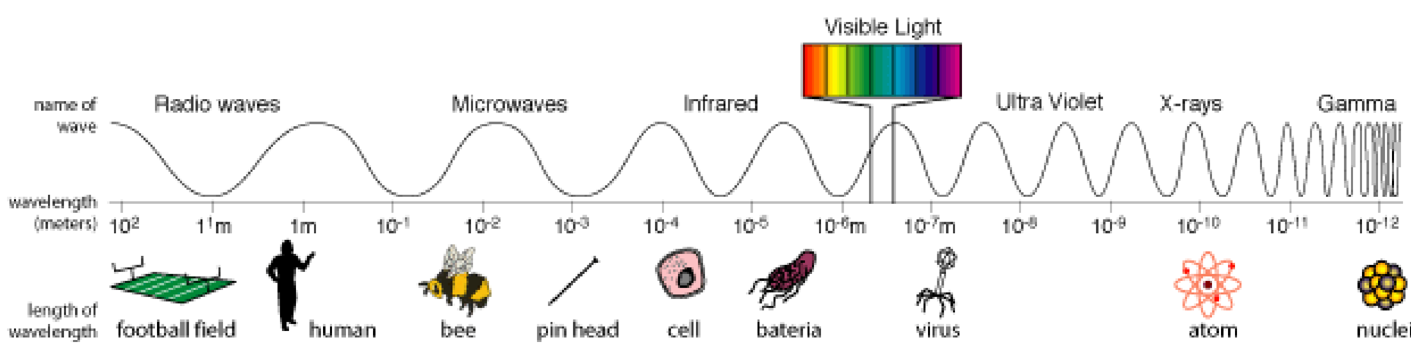


Figure 1

What is wavelength?

Wavelength (λ) is shown schematically in Figure 2 below. One wavelength is defined as the distance from one point on a wave to the same point on the next wave. For example from positive peak to positive peak, zero point to zero point, negative peak to negative peak or any other point on one wave to the same point on the next complete wave on a waveform. Wavelength (as it relates to light) is stated in nanometers (nm) of length. One nm is one billionth of a meter ($1x10^{-9}$).

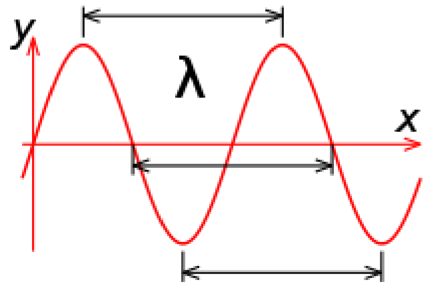


Figure 2

What is photometry?

Photometry is concerned with the measurement of optical radiation as it is perceived by the human eye. Photometry became a modern science in 1942, when the Commission Internationale de l'Eclairage (CIE) met to define the response of the "average" human eye. CIE measured the light adapted eyes of a sizeable sample group of people from all walks of life and compiled the data into the CIE Standard Luminosity Function.

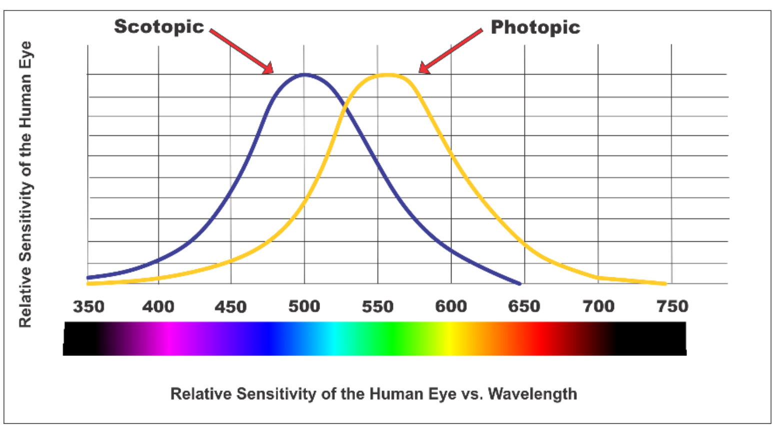


Figure 3

Photopic light (bright light – yellow curve) and scotopic light (dim light – blue curve) luminosity functions relate to the light sensitivity of the human eye (more detail below). The horizontal axis is wavelength in nm and the vertical axis is the eye's relative sensitivity. The photopic includes the familiar CIE 1931 standard color chart shown in Figure 4.

The CIE 1931 Standard Observer established a standard based on the *average* human eye response under normal illumination with a two degree field of view. The tristimulus values represent an attempt to describe human color recognition using the three sensitivity curves (ρ, γ, and β). Using tristimulus measurements, any color can be described as shown in Figure 4. Also shown is the familiar Kelvin color temperature scale for reference, Figure 5.

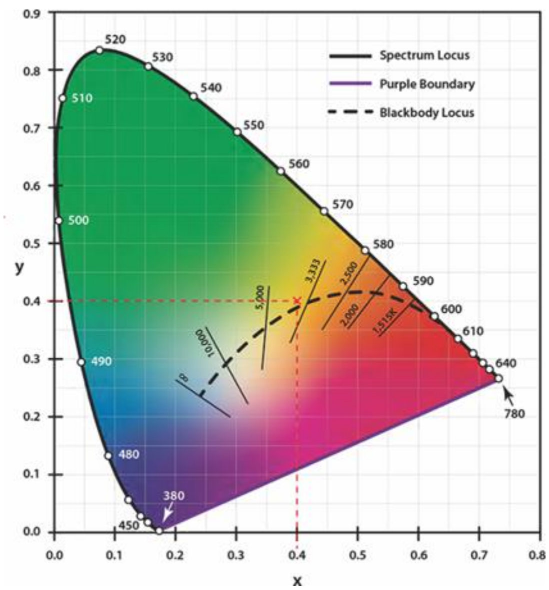


Figure 4

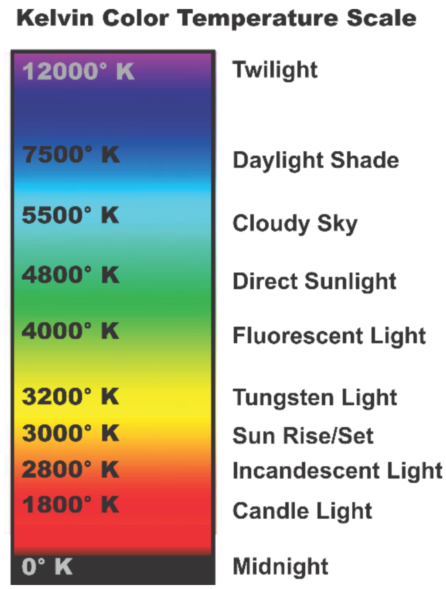


Figure 5

The term “color temperature” arises from the apparent color changes of an object when it is heated to various temperatures and is designated in degrees Kelvin (^{O}K). For reference: the freezing point of water is 0^{O}C, 32^{O}F and 273^{O}K.

Below is a graph of the human eye’s sensitivity to light showing the tristimulus sensitivity function, Figure 6.

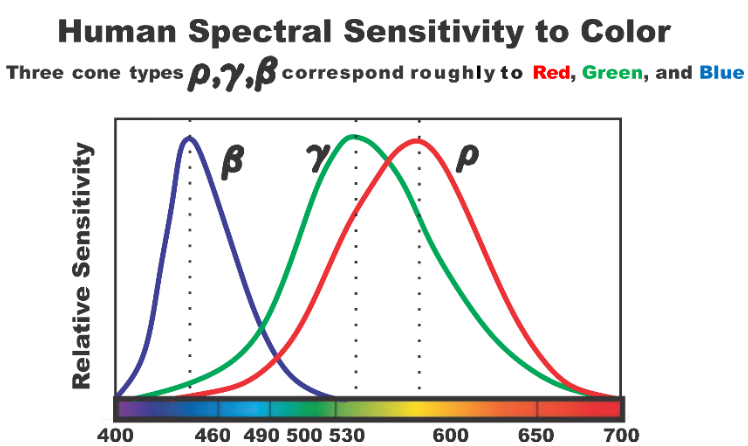
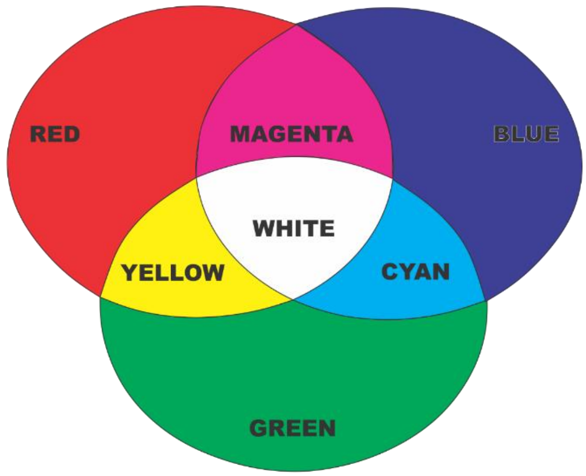


Figure 6

The Greek symbols ρ, γ, and β are the three different cones in the human eye (tristimulus) that each respond to a particular peak wavelength of light. Each of these cones is responsible for being able to see in low light conditions (β– scotopic) to bright light conditions (γ and ρ - photopic). All three combined provide you with the ability to "see" in varying conditions. Again, when combined, these curves correspond to the solar output spectrum ***and*** a luminosity curve of white light. The combination of all the wavelengths (colors) from the sun creates white light (see Figure 7 below).



Additive Color Mixing

Figure 7

What *IS* color?

Most models of perceived color contain three parts: lightness, hue and saturation. In the CIE color space, color is demonstrated as a sphere, with lightness making a linear transform from black to white and hues modeled as opposing pairs. Saturation is the distance from the lightness axis.

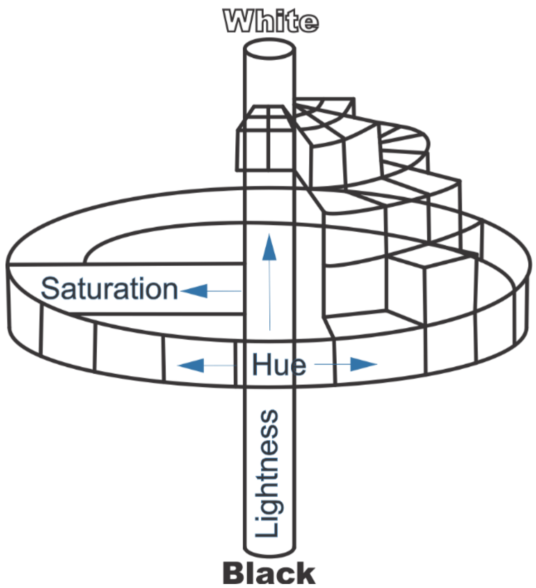


Figure 8

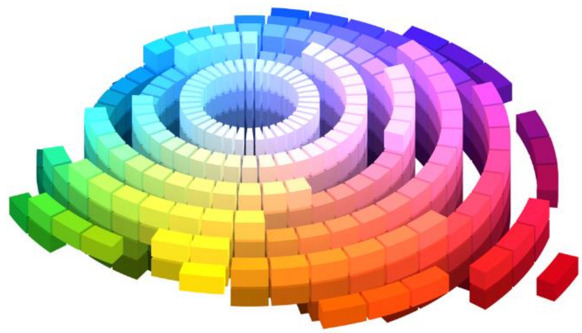


Figure 9

What is the solar spectrum?

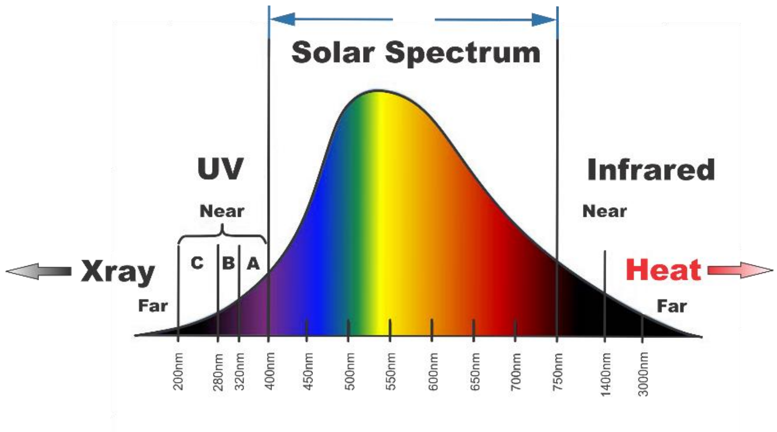


Figure 10

Figure 10 represents the portion of the EM spectrum emitted by the sun known as the solar spectrum of light also referred to as solar irradiance. In the above figure, to the left of the visible spectrum is the UV (ultraviolet). This is the light (invisible) that causes sun burn and skin cancer. To the right, we transition into the IR (infrared) which we feel as heat. A more precise chart of solar irradiance is shown if figure 11.

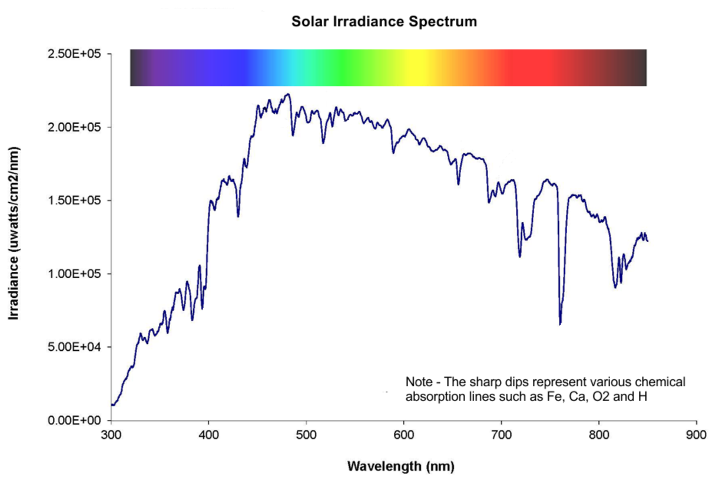


Figure 11

The solar spectrum is simply the small portion of the EM spectrum that represents the continuant colors we see. Each color has a different level of intensity or irradiance (vertical axis) as shown in Figure 11. The vast majority of the light we receive from the sun is blue/green in color.

What is a lumen?

The **lumen** (symbol: **lm**) is the SI derived unit[1] of luminous flux, a measure of the total "amount" of visible light (~400-700nm) emitted by a source. Luminous flux differs from power (*radiant flux – detailed below*) in that luminous flux measurements reflect *the varying sensitivity of the human eye* to different wavelengths of light, while radiant flux measurements indicate the total power of all electromagnetic waves emitted, *independent of the eye's ability to perceive it.* ***The lumen assumes a white light source (spectrum) like that of the sun.***

A lumen relates the intensity of light perceived by the human eye relative to the entire solar spectrum of light. Hence, the intensity of white light torches is stated in lumens.

Lumens are related to lux in that one lux is one lumen per square meter. The lumen (lm) is defined in relation to the candela (cd, a SI unit) [1] as: 1 lm = 1 cd·sr, where sr is steradian.

A full sphere has a solid angle of 4π steradians, so a light source that uniformly radiates one candela in all directions has a total luminous flux of 1 cd × 4π sr = 4π cd·sr ≈ 12.57 lumens. Figure 12 is a graphic representation of a steradian:

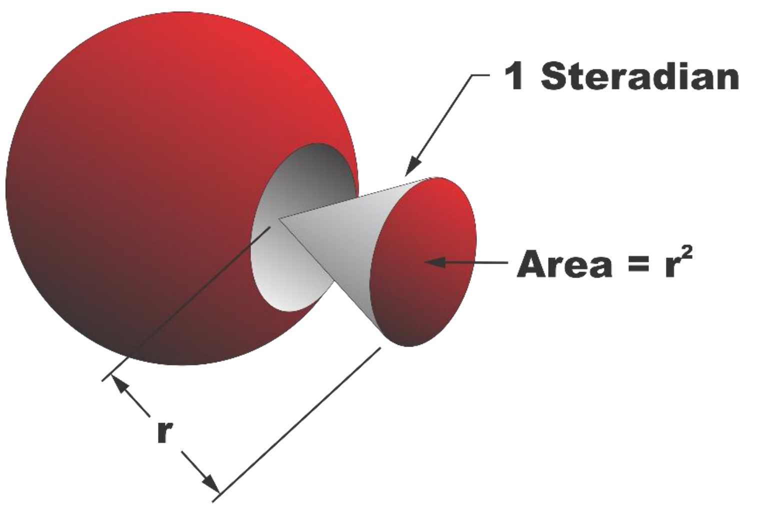


Figure 12

Ain't physics fun? – Still with me? – It gets worse!

In photometry, luminous flux or luminous power is the measure of the perceived power of light as described in detail above. The lumen is the photometric equivalent of the watt, weighted to match the eye response of the "standard observer". It differs from radiant flux (described below), the measure of the total power of electromagnetic radiation (including infrared, ultraviolet, and visible light), in that luminous flux is adjusted to reflect the varying sensitivity of the human eye to different wavelengths of light.

The lumen can be thought of casually as a measure of the total "amount" of visible light in some defined beam or angle, or emitted from some source. The number of candelas or lumens from a source depends on its spectrum, via the nominal response of the human eye as represented in the luminosity function described earlier.

Since blue light torches are not white light, lumens are consequently a meaningless term.

OK! So we can't measure a blue light torch in lumens. How do you quantify the light intensity of a blue light torch? We must use radiometry to get the answer.

What is radiometry?

In radiometry, radiant flux or radiant power (irradiance) is the radiant energy emitted, reflected, transmitted or received, per unit time, and spectral flux or spectral power is the radiant flux per unit frequency or wavelength, depending on whether the spectrum is taken as a function of frequency or of wavelength. The SI unit of radiant flux is the watt (W), that is the joule per second (J/s) in SI base units, while that of spectral flux in frequency is the watt per hertz (W/Hz) and that of spectral flux in wavelength is the watt per meter (W/m)—commonly the watt per nanometer (W/nm).

Figure 13

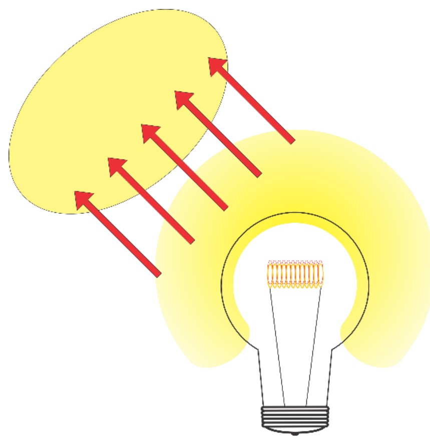


Figure 13 is a graphic showing the output of a light source and its irradiance on a unit area.

Sadly, radiometry measurements are not all created equal; therein lies yet another series of problems in specifying a torch's brightness.

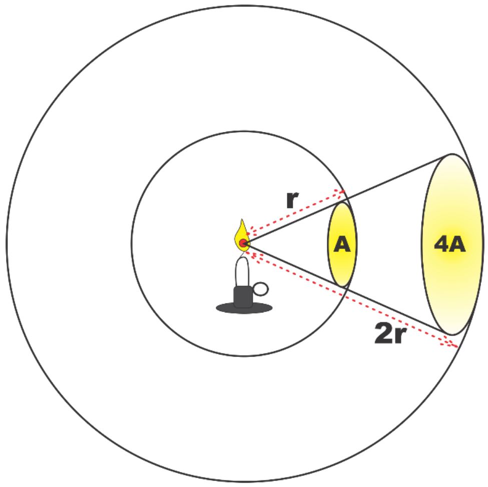
We have discussed in excruciating detail why lumens can't be used for a monochromatic (single wavelength light source). Now we shall delve into the methods to measure radiant flux/power (the only accurate way to measure monochromatic blue light).

The simplest method is to use a radiometer which is a laboratory instrument that uses a sensor that is illuminated at some pre-defined distance by the torch under test. This method uses the inverse square law to yield a number in watts/cm^2/nm.

This is a good time to point out that inexpensive hand held lux meters are not functional for this type of measurement because once again they are calibrated on the assumption that they will be exposed to white light. They CAN be used to measure the "relative" brightness from one blue torch to another (assuming the wavelength is exactly the same and any dichroic filters used are identical) but the number(s) they display are meaningless other than to say torch "A" is brighter than torch "B" all other parameters being equal.

Figure 14 demonstrates the inverse square law.

Figure 14



In the center we have our light source, in this case a candle. "A" is the unit beam area at a distance of radius "1r". At 2r, the beam area increases by a factor of 4 ***BUT*** *the intensity is subsequently reduced by a factor of 4*!

Here is the first problem: Manufacturer "X" measures the radiant power at 1 meter while manufacturer "Y" measures it at 0.5 meter. Manufacturer Y, will claim 4 times as much power as manufacturer X for the same torch.

This leads to the second problem: Neither manufacturer specifies the measurement distance (or even the methodology for that matter). Sometimes this is just an oversight, other times it's meant to claim an amazing output for a not so amazing torch from Y to compete with a truly amazing unit from X.

There are other issues in the measurement also such as the use of an integrating sphere to "contain the parameter space".

Now let's throw in problem three. Manufacturer "Z" doesn't make *any* actual radiometric measurements. They simply use Ohm's law to calculate output in watts (P = I x E), where P is power in watts, I is system current and E is the system voltage. This is fine except is doesn't account for the efficiency of the LED, the transmissivity of the front lens or if there is a dichroic filter on the front of the torch. A dichroic filter can attenuate the light output by as much as 80%.

The point is that without knowing the methodology, you are comparing apples to oranges rather than apples to apples and hence, *absolutely nothing* can be gleaned from the claimed specifications. Some manufacturers ("Y") use nefarious methods while others ("X") simply don't make any claims because of the risk of having "puny" numbers compared to ("Y") when in fact torch ("X") dramatically outperforms "Y" if measured in equal terms.

Summary

So there it is. Stating a brightness in lumens for a monochromatic light is not possible and output power measurements are unreliable unless the manufacturer explains in detail their measurement methodology. Our recommendation is to buy from a well-respected source that doesn't try to deceive you with numbers that mean nothing.

[1] - A system of physical units (SI Units) based on the meter, kilogram, second, ampere, kelvin, candela, and mole, together with a set of prefixes to indicate multiplication or division by a power of ten.