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TECHNICAL

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SERVICES

"Luxes" & Lumens

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Introduction

Light is pretty simple. It's either bright or dim, right? Well, that may be good enough for you to keep from tripping over the piano bench on the way to answer the phone in the middle of the night, but it just does not make it as a measurement method. In video we often need to pay close attention to lighting in order to make a scene clearly visible. This carries through to many other imaging issues that we also deal with. For example, exposures for digital and SLR cameras, camera sensitivity, matching cameras to the purpose, projection of video images in demonstrations, lighting your shack and bench to prevent eyestrain, and so forth.

The first thing that most people find when they try to quantify light is a totally confusing set of measurement units which have been made even more confusing by advertising departments for photographic and video equipment. Their ad copy has been much like the power output advertisements for audio equipment in the 70's – purposely confusing in order to win the specifications war. The American National Standards Institute (ANSI) has stepped in and things are getting a little better, but the units are still a confusing mess. You will find among them the candela, foot-candle, candlepower, lux, lumen, steradian, phot, lambert, and a few more. (See the appendix "Lighting Units & Conversions") When you try to find conversions from one to the other, you will realize sometimes that, "You can't get there from here." We do not have the space to get into the details of each of the above and how and why they are applied. Whole texts have been written on the subject. The science of Photometry is even a subset of the entire subject. Therefore, we will just deal with the basic information you need to begin further study. Fortunately, only a few of the units are really needed for our purposes.

A word of warning is in order here. *Warning: If you are an illumination scientist, engineer, or specialist reading this article without an "ordinary" person to hose you down and/or comfort you — it may be hazardous.* The author will unabashedly take liberties with the absolutely correct terms and equations in order to make them approachable by "mere mortals"! There now, we can proceed without anybody getting hurt (especially me).

Measuring Light

The first point of confusion comes from the many ways that light can be measured. It can be either incident or reflected. It can be a spot measurement or an average. It can be a measure of the radiant energy or the energy available or the energy perceived. Each of these conditions, singly or in combination, results in different measurement units. The most common units you will have to deal with are the lumen, the lux, the nit, the foot-candle, and the candlepower. You will also come across f-stops, effective speed, and foot-lamberts.

These can be best described as one of three types of measurement:

- total flux,
- illuminance,
- and luminance.

For the purpose of explanation we will call total flux a measure of intensity. Also since illuminance and luminance are so similar as to be confusing we will say luminance is the same as visibility. So now we have intensity, illuminance, and visibility. Now lets explore each of these in ham radio terms as well as in their own right.

In order to do this, picture a WiFi communications system. You have a transmitter which drives a beam antenna which sends electromagnetic (EM) waves to a receive antenna and then into the receiver. Now also picture a lighting system where a source of light shines out of a fixture (luminare) and across a path to an object where it is then reflected to the viewer’s eye. Hopefully you can see the similarities. We can start with the transmitter or source and explore it.

Intensity

The intensity of the light source is, therefore, analogous to the transmitter power. There is power that goes in and power that gets converted to the type of EM wave we are interested in. The only difference is the frequency. Where the transmitter may operate at, say, 146.52 MHz, the light could be 600,000,000 MHz. Well if they are the same then they should both be measured in Watts, right? Well, sort of. Light intensity can certainly be measured in watts. For example, laser output is usually rated in milliwatts or watts. But, more commonly, you will find lumens and candlepower as measures of light source intensity. These intensity measurements are the amount of light being generated, just as transmitter power measurement is the amount of RF being generated.

This brings us to our first conversion. How do we get from watts to lumens or candlepower? Easy, one lumen is 1.47 milliwatts or 680 lumens/watt. Be careful though! When you think about transmitters you think about **Output** power. When you think about a 60 watt bulb you are thinking about **Input** power. For example, that 60 watt bulb is probably only about 2% efficient so only 1.2 watts of the total power consumed is going into useful light. So that would mean it would have a rating of about:

1.2 watts $\times$ 680 lumen/watt = 816 Lumens

This agrees pretty well with the 870 lumen rating on the box of my 60 watt bulb. However, if you listened in science class ages ago you might remember your teachers saying that the efficiency of a regular bulb was about 10%. Where did that other 8% go? Well, it turns out that there are a number of conversions from lumens to watts. Another source I had quoted the value at 179 lumens/watt. If you use the 870 lumen figure that would mean the bulb was putting our about 4.8 watts of light or 8.1% efficient. The other 2% is probably losses from the glass, bulb coating, filament supports, etc.

It turns out that the conversion factor is highly dependent on the spectrum you integrate over. In radio terms, if your power meter ignores the harmonics and sidebands of a signal it will read a lower power than if it takes in all of the signals. My recommendation is to use the 680 lumen/watt number for sources of a single color, like a laser or LED, and go with the 179 lumen/watt number for white light sources. Just be consistent. I would not loose a lot of sleep over it, remember that the more light is “packed” into a single frequency (color) the more efficient the source will be. That is just like your radio. Later we will look at these numbers in relation to the human eye’s response.

What you should really care about is how the light sources compare among similar types. For those, just take the rated lumen output and divide it by the watts consumed. The higher the number, the more efficient the light source is. Therefore, for a given amount of needed light, the higher efficiency sources will cost less to operate. But, they will probably cost more initially. When you divide the extra initial cost by the operating cost savings per month you will get the number of months of operation it will take to pay out the extra investment. We will cover that later in “Putting it to use”, examples of how to solve real world problems.

As we discussed earlier, you can use the sidebar information to convert from lumens to candlepower. This conversion is as simple as multiplying the lumens by 0.07958 to get candlepower. Or another way, one candlepower is 12.56 lumens.

Illuminance

The second type of light measurements are those of Illuminance. This is very close to the word Luminance, but it has a very different meaning. Luminance is the energy picked up directly by your eye or camera. Illuminance is only the amount of energy striking the surface that will be lit. Think of illuminance as the amount of energy that is striking your receiver antenna while luminance is the amount of energy that actually gets converted into audio in your receiver. For illuminance we are talking about only the amount of energy striking the antenna.

The distance to the transmitter, the type of path (path loss), and the size (gain) of your antenna all effects this. Using this similar concept, you can imagine that the distance to the source, the path, and the size of the surface being illuminated would effect the illuminance from the source.

It turns out that this is exactly true. We measure illuminance in foot-candles or lux. Since one foot-candle is equal to 10.7639 lux, the conversion is simple. In fact, many lighting designs just use 10 lux to the foot-candle to simplify conversions. As you might have guessed, the candela (candle or candlepower) and the foot-candle are the older Imperial measurements. Their metric equivalents, the lumen and the lux are generally replacing them. Even so, the foot-candle is so widely used it bears a little further discussion.

As we already discussed the illuminance measure has two parts: the distance from the source and the area illuminated. The two are tightly linked and that can make things confusing. Remember that our sources are specified as ideal points of light. In other words they are isotropic radiators giving out light uniformly in all directions. That is just like the dBi measurement we use on transmitting antennas. If you put a 1 candlepower source inside a sphere then a portion of the light will fall on each piece of the inside of the sphere. From high school geometry we (might) remember that the surface area of a sphere is $4 \cdot \pi \cdot r^2$ so if our sphere were 1 foot in radius we would have an area of 12.56 square feet.

That number should sound familiar. It is the conversion from candlepower to lumens. This example is exactly how the lumen was originally derived. It is the amount of light that falls on one square foot of the one foot-candle sphere. My guess is that this is because the candle preceded the lumen as a standard and the lumen was “back engineered” to the existing standard. This is where I, and many others, begin to get confused. Much of what has been written about illuminance, intensity, and their measurements fails to separate this theory and derivation from the practical use of these measurements. So some simplification is in order.

If you imagine a sphere one foot (≈30cm) in radius that the light from the candle is striking, then the light on the sphere is said to be one foot-candle. Because the surface of the sphere gets bigger by the square of the radius, but the quantity of photons emitted by the candle are the same, the brightness of the surface goes down. You will often hear this called the “inverse square law”. It turns out that if the source length and width is less than four times the distance to the surface being lit you can simply use the square of the distance to figure the change in illuminance. Thus a light that produces 100 foot-candles at a distance of one foot will only produce about 1.5 foot-candles on the floor 8 feet below:

$(1 \div 8)^2 \times 100 = 1.5$ foot-candles [or 15 lux]

We will get into that more in the “Putting it to Use” section. So, if you know the intensity of the source and the amount of area it lights you can calculate the illuminance. One lumen shining evenly on one square foot is equal to one foot-candle. Or, in metric terms, one lumen shining evenly on one square meter is equal to one lux. That is all there is to it.

There are a number of recommended standards for illumination for various work tasks. These are published in various places, but all are rooted in the work done by the Illumination Engineering Society (IES). Some of these can be found on their site http://www.iesna.org .

You will find that a good “ball park” for lighting to maneuver around in, like a parking lot, needs to be about 2-5 foot-candles (25 lux). For general work you will probably need 25-50 foot-candles (250-500 lux). Television and video studios are often 60-100 foot-candles (600-1,000 lux). And, for close detailed work you will want 125-150 foot-candles (1,250-1,500 lux).

For comparison full sunlight is typically 3,200-10,000 foot-candles (32,000-100,000 lux). From this you can estimate the foot-candles or lux required.

One word of caution though, many new cameras are rated (confusingly) in lux. What they are talking about is the amount of light required by the camera to show a usable picture, not necessarily a good picture. That means that the surface being viewed must give the camera this minimum amount of lux in the darkest area of interest. This is not the same as the amount of light in the scene as measured by illuminance. The third measure of light will explain why these are not the same thing.

Visibility (illuminance)

As mentioned above, the terms luminance and illuminance are just too similar to avoid confusion. So we will use the term visibility to mean luminance. The explanation for visibility is pretty simple. It is the amount of light received from a source or object. The actual measurement and calculation of visibility (luminance) is not so straightforward, however. This is where our simple radio system analogy begins to break down in all but one way – complexity.

A receive system has to consider antenna polarization, antenna position, multipath, feedline losses, receiver sensitivity, IF bandwidth and selectivity, gain, noise, and a host of other items. Calculating the visibility of an object has just as many factors. For example there is the angle of the object, its reflectance, its surface shape, reflected light from the source, its distance from the

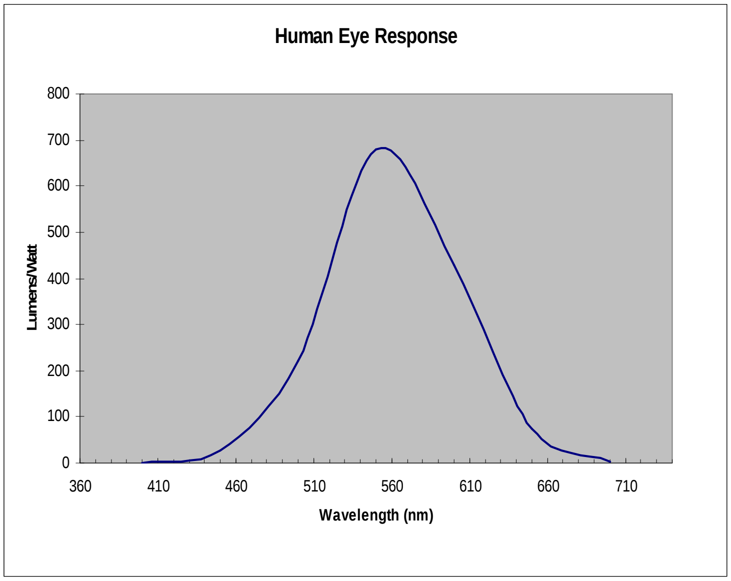

Fig. 1 - What a human eye sees

observer, the color of the light, the color of the object, and the sensitivity curve of the observer (human, still or video camera, electronic sensor, etc.).

The common measurement of visibility is the Lambert. This was in honor of Lambert's law which says the luminance of a perfectly diffuse object will be the cosine of the its angle to the observer. Interestingly there is no physics involved in this law; actually it is used most often in the reverse — to define a perfectly diffuse surface.

A particularly handy item, especially if you have a photographic light meter, is what used to be called a 50% gray card. More recently it is called an 18% gray card. If you have Red, Green, and Blue (RGB) values of 50%, you get what is called 18% gray. This can be purchased very reasonably from any good photo supply house or your favorite online source.

It, theoretically, gives you a perfectly diffuse surface with 50% reflectance. This is what all photographic meters are calibrated to. If you put the gray card at the subject and measure it with your meter, the exposure you read will be as close to accurate as possible. It is also an excellent item to use for setting up your video cameras.

One last bit of theory and we will be ready to put all this information to some practical use. You will find a number of references to the color response of the human eye. The correct name for this is the tristimulus curves. They reflect the relative response of each of the three color receptors to wavelength. Often it is summed together into a single, more useful curve. This is shown in Fig. 1. Similar curves can be found for CMOS cameras and other devices.

Putting it to use

If you have made it to this point, you have enough theory and understanding to do some calculations on "real world" examples. Lets work through a few examples of light source calculations first. We can then give some attention to various cameras (including the human eye).

Lasers

First we will tackle some laser calculations. A laser is a unique light source because it is coherent. In radio terms that means that all the phase fronts are aligned and that the frequency is like a pure carrier. Because of this and the way that laser light is generated, a typical laser beam has a very "tight" beam (small divergence). The most common laser specifications will indicate the power, the frequency, and the beam divergence. One common question is, "How does my laser compare to other light sources?"

Well, lets try out some of our new conversions and see if we can find the answer. First, calculate the equivalent brightness of our laser. My homebrew HeNe laser is fairly typical of many low cost lasers. It is rated at 1.5 mW. That is the only specification found on it. If we look up the "normal" frequency of HeNe we find that 633 nM is the most common. From Fig. 1 we can read a value of about 200 Lumens/Watt. So our laser would have a brightness of only 0.3 Lumens! The calculation is:

0.0015 Watt × 200 Lumens/Watt = 0.3 Lumens = 0.02 candlepower

But, the real secret to the laser is its narrow beam. That 0.3 Lumens is all concentrated in a spot about 1 mm in size.

When I measured the beam on my laser at 60 feet (18 m) it had a diameter of about 1.89” (48 mm). So lets see what that would work out to be based on the distance. The area of the spot is $\pi \cdot r^2$ so that works out to be:

$3.1416 \times (1.89 \times 2 \times 12)^2 = 0.0195\ ft^2$

Then dividing our 0.3 lumens by this we find the illumination to be a respectable 15.4 foot-candles (154 lux).

Hmmm. What brightness bulb would we need to give that illumination if the bulb were shining in all directions like a regular light bulb? Well, lets calculate it from our illumination equations. If we had a sphere 60 ft in radius it would have an area of:

$(4\times \pi \times (60\ ft)^2) = 45238\ ft^2$

So if we had 45238 lumens on this 45238 ft^2 it would be 1 lumen/ft^2, which we know is one foot-candle. That means to get the same 15.4 foot-candles as the laser we would need:

15.4 foot-candles × 45,238 ft2 = 696,680 lumens

Wow, that is about 800 times brighter than my 60 watt bulb! Putting all that light in a tight little beam really makes a difference.

Lets look at one more laser specification. Remember that on my laser the beam started at about 1 mm that means that it grew by a factor of 48 over 60 feet (18 m). The formula for calculating the length of the opposite side of a triangle is to multiply the sin of the angle by the length of the adjacent side. So in my case the 60 feet becomes 720 inches and since the spot was 1.89 inches we can write:

1.89 × 720 = sin(beam divergence)

so beam divergence = 0.150°

On some laser specifications you will be lucky enough to find a beam divergence number. 1.2 mr is fairly common on commercial lasers. That means that the beam spreads in an angle of 1.2 milliradians. Since there are $2\cdot\pi$ radians in a 360° circle we can calculate that a milliradian is 1000th of 57.296° or 0.0573°. So multiplying that means my laser had a divergence of 2.6 mr. That is probably pretty reasonable for an inexpensive laser.

LED’s

The candlepower has gone the way of the megacycle and is being replaced by its new name, the candela. About the only place you will commonly encounter the candela or candlepower is in light output specifications for LED’s, a few small bulbs (particularly automotive), and headlights/searchlights from about a decade ago.

Recently there has been another “specification war” and most are now in lumens. Keep in mind that from what we just calculated, the beam width is critical in the calculations so “lumens” listed on the box without wavelength or beamwidth is quite ambiguous and probably not very useful.

The candela is a very old unit that was derived originally from the amount of light actually produced by a standard candle. (Yes there was such a thing.) Our modern equivalent must be the LED since the LED measurements in catalogs will show the LED outputs in millicandela (mcd). Technically these are usually “spherical candlepower” instead of candelas, but for our purposes you can treat them as the same measurement.

As you might expect the mcd is one one-thousandth of a candela. Going back to our original concept of bright and dim, you can say that one of the ultra-bright 10,000 mcd LED's is about 1/3 as bright as an automotive tail light. And a 10,000 microcandela (µcd) blue LED is pretty dim since it is only about 1/1000th as bright. Watch the units closely, especially on blue LED's, because they are sometimes specified in the smaller µcd. It is easy to misread this and end up with a brightness mismatch on the front panel of your new homebrew widget.

As we saw in the laser calculations, the beam width is critical when comparing LED's or doing calculations of illumination. For example, lets look at the Digikey 67-2027-ND white LED. If we want to make it into a mini-flashlight we want to see how bright it might be when held 2 feet away from a page in our note book. Well, the specifications show it to be 11,000 mcd with a beam angle of 20°. At a distance of one foot the beam would be about:

2 ft × 12 in/ft × sin(20°) = 8.2 inches in diameter

That would work out to be about 0.368 ft^2 for our 11,000 mcd to cover. So lets convert the mcd to lumens and find the lumens/ft2 which will give us foot-candles:

(11,000 mcd × 0.001 cd/mcd × 12.57 lumen/cd) × 0.368 ft^2 = 50.5 foot-candles (550 lux)

As it works out, that is about an ordinary 40 watt bulb would put out, but only in the 8 inch spot. But, for about 1/600th the power and 1/3 the price.

"Regular" Lighting

Now that we have explored candlepower, lumens, and beam divergence lets try some of the same techniques on conventional tungsten lighting. You are probably beginning to see the importance of beam width and illuminated area in our determination of how bright something really is. This can be useful in checking out efficiencies. Remember that we converted candles to lumens by multiplying by 12.57. That means the super-mega-whopper 1.5 million candlepower handheld searchlight I use to peer into the woods behind my house would be rated at 18 million lumens. If the manufacturer thought, for even a second, that people would believe that they would jump on it for their ad copy.

This may confuse you. If the thing puts out 18 million lumens of white light, then using the 179 lumens/watt conversion would say that the light source would be consuming 105 KW at even 100% efficiency! That would go up to nearly 1 MW for a 10% efficiency. That seems pretty impossible for even a big handheld light. Think back to our analog of the transmitter. What do we use besides output power to measure the effective power of our transmitted signal? Right, we use EIRP – Effective Isotropic Radiated Power, the power that an isotropic source would have to be to create the same field strength (intensity). An isotropic source is one that radiates uniformly in all directions, like a spherical pattern.

The way to increase the EIRP is by antenna gain. Now it begins to make sense, the spotlight has a gain "antenna" built in. It is the parabolic dish of the reflector. The equations are all the same as microwave dish equations. It is just that in this case the wavelength is 400-600 nm. Since the dish is about 5 inches (12.7 cm) across, that means it is about 254,000 wavelengths in diameter! No doubt that it has some real gain.

Let's use an old engineer's trick to figure out an approximation of the gain. If the bulb is a 50 watt halogen we can guess that it is about 10% efficient. That means that it puts out about 5 watts of white light which converts (using 179 lumens/watt) to about 900 lumens. Since we just converted the manufacturer's specification to 18 million lumens we can "back into" the gain. By dividing 18 million by 900 we get a gain of

20,000. If you remember the equation for converting to dB of gain you can calculate this to be a gain of 43 dB. That number seems pretty reasonable given the 250,000 wavelength diameter.

Let’s tackle another example. Suppose we go to the store to buy the right brightness bulbs for our shack to properly light the video area. Well, all the lights are rated in lumens. If we know the area to be lighted and the lumens we can calculate the number of lux or foot-candles. Basically, you calculate the area illuminated by the bulb and the distance to the bulb from the surface. This will allow you to calculate the equivalent sphere being illuminated as we have done in the previous examples. When that spherical space is divided into the lumens you get the lux (metric) or foot-candles (english) on the surface.

Since we will be doing close, surface mount work on dark PC boards the target should be about 125 foot-candles (1,250 lux). If our bench area is 3 ft by 2 ft that is 5 ft^2. That means that the total lumens divided by 5 ft^2 will be equal to our desired value of 125 foot-candles. So the total lumens at the surface must be 625. If the work lights are mounted 5 feet above the bench then light at the source would be 5 squared or 25 times the 625. That is equal to 3,125 lumens at the source if they only had the proper beam width.

We do not have the space to go through the area of a sphere calculation again to find out what size of bare bulbs would be needed. But, that is really not important because you will probably use some type of focusing fixture or light anyway.

It turns out that a 150 watt PAR spotlight has about the right beam width for these dimensions and puts out a rated 1740 lumens. So a pair of them would be just about right for the desired illumination.

As a matter of fact, I tried exactly that configuration and measured almost exactly 120 foot-candles (1,200 lux) at the bench top. There was a problem though, using only two narrow beam lights caused bad shadows and resulted in poor visibility.

I found that by converting to my favorite LED, the Hyperikon BR40 15W dimmable flood mounted 3 feet above the bench I got a more uniform light, better shadowing, and similar illumination. The bulb also gives a CRI (color rendering index) of 90+ and a natural color temperature of 4000K.

Moving Further

Now that you understand lighting and how to calculate intensity and illumination from common sources, we can build on this knowledge and in another article tackle visibility examples. This would allow us to calculate how much light would be needed to light a scene for proper response from your video camera or photographic camera. We could also see how color effects the camera and your eye. That would include filters and different types of lights like High Pressure Sodium and Fluorescent. Reflectance and density are also important to look at. Finally, we could look at room lighting calculations and methods.

Sadly, though I am out of space. That means that you will have to pursue these things on your own, but now you have the foundation necessary to do it successfully. I would like to thank both Ed Manuel and CQ magazine for allowing me to write this guest column.

Lighting Units and Conversions					
Total Flux (intensity)					
1	Watt	±	680.3		Lumen (monochromatic 550nM)
1	Watt	±	179		Lumen (white)
1	Watt	±	100		Lumen (real candle)
1	Lumen	=	0.079577472		Candle
1	Candle	=	1		Candela
1	Candle	=	1		Candlepower
1	Candle	=	1		Candlepower (Spherical)
1	Candle	=	12.56637061		Lumen
1	Candle	=	0.96		Candle (English)
1	Candle	=	0.95		Candle (German)
1	Candle	=	0.1		10-cp Pentanes
1	Candle	=	0.104		Carcel
1	Candle	=	1.11		Hefner
Illuminance					
1	Lux	=	0.09290304		Foot-Candle
1	Foot-Candle	=	10.76391042		Lux
1	Foot-Candle	=	0.001286		btu
1	Foot-Candle	=	1.3566		watt-seconds
1	Lux	=	1		Lumen/m^2
1	Lux	=	0.1		milliPhot
1	Lux	=	0.0001		Phot
1	Lumen/ft^2	=	1		Foot-Candle
1	Lumen/ft^2	=	1		Light Flux Density Unit
1	Lumen/m^2	=	1		Lux
Luminance (visibility)					
1	Lambert	=	1		Brightness Unit
1	Lambert	=	0.318309886		Candle/cm^2
1	Lambert	=	2.053608062		Candle/in^2
1	Lambert	=	3183.098862		Candle/m^2
1	Lambert	=	929.0304		Foot-Lambert
1	Ft^2 of perfectly diffuse surface lit by 1 Foot-candle	=	1		Foot-Lambert
1	Lumen/ft^2	=	1.076391042		milliLambert
1	Lumen/cm^2	=	1		Lambert
1	Lumen/cm^2	=	1		Phot
1	Candle/cm^2	=	1		Stlib
1	Candle/M^2	=	1		Nit
1	Lumen/cm^2/Steradian	=	1		Candle/cm^2
1	Lumen/cm^2/Steradian	=	6.283185307		Candle/in^2
1	Lumen/cm^2/Steradian	=	3.141592654		Lambert
1	Lumen/cm2/Steradian	=	3141.592654		milliLambert

Other Useful Measures					
1	hemisphere	=	2		Steradians
1	sphere	=	4		Steradians
	Light Adapted Human Eye	±	1		milliLambert
	Dark Adapted Human Eye	±	0.00001		milliLambert
	Human Peak Blue Response	±	445		nM
	Human Peak Green Response	±	555		nM
	Human Peak Red Response	±	600		nM
	HeNe Laser Frequency (most common)	=	632.8		nM
1	milliRadian	=	0.05729578		degrees