Light-Emitting-Diodes! Rev. E 20Mar08

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I am a private pilot building a Glastar/Subie, which is taking forever because everything I see I redesign. Since I bought the kit I have started a small business, Perihelion Design to sell some of my designs.

Forward:

LEDs present a global change in aircraft illumination. This article will address some general issues and techniques for correct application. Position lighting will be covered first, followed by landing lights, then anti-collision beacons. Electrical systems will not be covered since it has been covered well in this magazine and other sources.

Introduction:

The excitement with LED technology is based on a couple amazing facts—The efficiency of most light sources topped out 30 years ago, but the efficiency of LEDs is on a rocket ride to levels never before seen. Other lamps have known-degradation mechanisms, for example, tungsten filaments evaporate, but LED degradation is almost nil in comparison. And almost all other lights are filtered to produce a particular color light, but LEDs emit colors without any filters, thus saving gobs of energy.

Light sources can be characterized by the amount of visible light (lumens) per electrical power (watts). This efficiency is important because it determines the energy costs in the long run. Expected lifetime is also important because replacing lamps is expensive—and sometimes life-critical. LEDs excel in both regards.

For illustration, here are the best efficacy figures in lumens/watt for several applications.

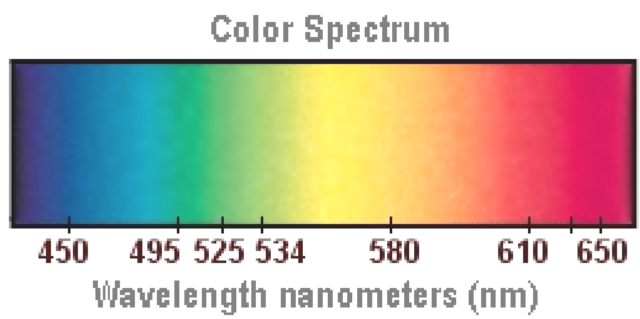
Incandescent (very small)	2	
Incandescent flashlight bulbs	6	Short lamp life
Incandescent night light (7w)	6	
Early LEDs	8	Originally only red—very long lifetime.
Incandescent (100W)	15	Short lifetimes—No further improvement
Incandescent (halogen type)	20	Long lifetime—No further improvement
2000 LEDs	25	All colors and white available
2004 White LED	25	
Xenon arc	25-40	Req. ballast—No further improvement
Compact fluorescent	48-60	

F40T12 cool white fluorescent	60-65	Require ballasts
32 watt T8 fluorescent	85-95	Require ballasts—No further improvement
2005 LEDs	45	
2006 LEDs	80	
2007 LEDs	125	Headlamps in luxury cars introduced.
2008 LEDs	140	
Metal Halide HID	50-110	Req. ballast, many gas mixes
Low Pressure Sodium	130-190	Sodium color—No further improvement
2009-2015 LEDs	150-200	Mature technology? Slowing improvements

So if these numbers mystify you, just remember that in 2010, you will be able to buy a landing light for your airplane that will be brighter than a 100W halogen, will be three times as efficient as a fluorescent lamp, will cost $35, and will last essentially forever (~100,000 hours).

So should we use them in our aircraft? Sure, but you won't even have to make the choice. LEDs will simply replace almost all the lights, in almost every place, in almost every thing. LEDs were once used only as indicators, right up to the time they became efficient enough to surpass halogen lamps in general illumination. They will chase HID metal halides in some uses for a while, but in the end almost every light, —tanning beds, street lamps, and even landing lights will be LEDs.

LED Position Lights.



Here's the situation--Now this is a bit difficult to figure since the FAA has chosen to use a lighting specification system so complicated that nobody reads it. The proof is that it has errors and typos that nobody fixes. How's this example?

> Sec. 23.1395 No position light intensity may exceed the applicable values in the following equal or exceed the applicable values in §23.1389(b)(3):

Surely nobody reads this stuff! But take heart; it all has a well-thought-out purpose. Let's take a few industrial strength No-Dozes, a triple espresso and try to do our best.

See FAR Sec. 23.1397 Color Specifications (same as MIL-C-25050A Aviation Colors).

First a couple words about the colors: Until recently all aviation colors were generated by tungsten-filament lamps behind colored glass filters, so some warmth prevails in the choice of color, but you could get almost any color you wanted. Unfortunately LEDs emit just wherever in the spectrum their strange crystalline cookie recipes demand--and no place else. So you can't get every color you might need.

Aviation Red is orange-red to deep red, and for LEDs the CIE numbers equate to 610 nm and longer wavelengths. Although it is legal to make the red 650-680 nm or so, lot's of people are almost blind above 650 nm (including this writer). Scotopic (dark adapted) Luminous Efficacy (how well you can see it) at 610 nm is 23X what it is at 650 nm--for people who aren't red-green color-blind! Unfortunately 640 nm and 660 nm LEDs are real boomers so it's a toss up.

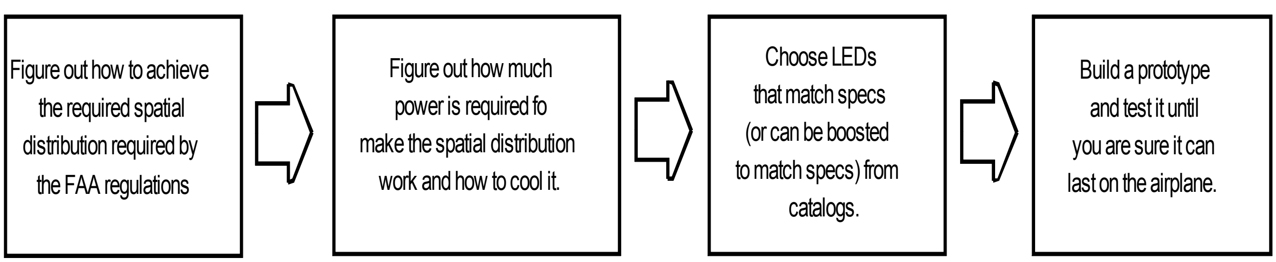
Aviation Green is 495-534 nm. LED "true green" is 525 nm and they are very efficient and a good choice. But be careful, advertising gimmickry is everywhere. There are "greens" at 555 nm, and "greens" at 565 nm, but are not FAA legal. As of this writing there is ONE single FAA-legal green led color—525 nm. What gives? Well, green leds are simply not as evolved as red leds. The selection is poor and the prices are higher. You can get the right ones but they are more expensive—often several times as much as similarly constructed red LEDs.

Aviation White is not really on any spectrum. Aviation white is based on the allowable colors provided by tungsten filament lamps that approach what are called blackbody radiators (so we refer to them in Kelvin temperatures like very hot little iron stoves). The FAA allows white from very orange 1800K to 5000K but oddly, no higher! By the rules, xenon-white and some HIDs cannot legally be used as a tail-light color, but may be used as a landing light. The ICAO and SAE are much more generous with the white specs. This writer believes that the FAA is due to revise this to reflect the reality of new light sources, and it will probably accept the ICAO colors as their own.

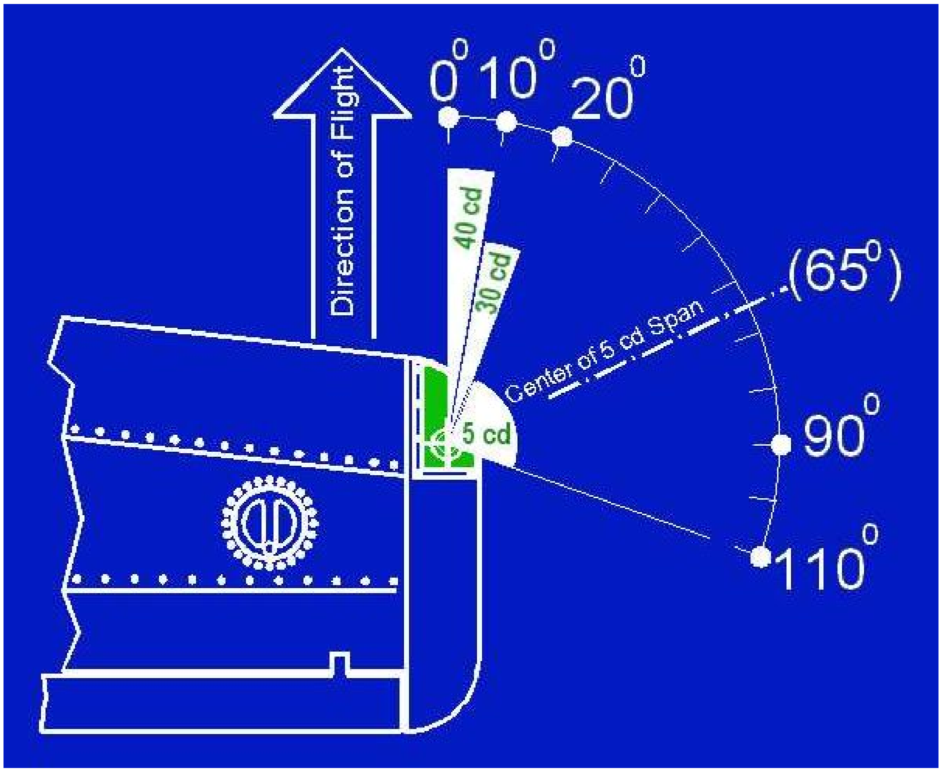
So let's dig out your book on solid geometry….and design some luminaries—

Lighting design is difficult. It seems easy to just throw in a very bright LED and think the job is done. Not so fast! If you use a bright laser for a position light, your airplane will be invisible no matter how bright the laser is, unless it points directly at someone's pupil, and even then they won't be able to gauge the distance to your airplane.

So what about LEDs? What's the first step? It might seem that choosing a REALLY bright LED would be a good place to start. But this would be entirely backwards. Do it like this--



And be careful. You need to know that bright LEDs are usually not wide and wide LEDs are usually not bright. Don't be fooled—they use the same LED die but different optics—not magic. The FAA wants the red-green position lights to make the aircraft visible when it is approaching head-on or off the wing of other aircraft. Let's take an imaginary journey around your aircraft at night with the green position light on---



Standing in front of your aircraft, the FAA specifies that the position lights must emit 40 candelas horizontally (with respect to the flight path!) pointing directly forward (0°) parallel to the flight path, to a 10° swing away from the aircraft. This is a good time for a pause.

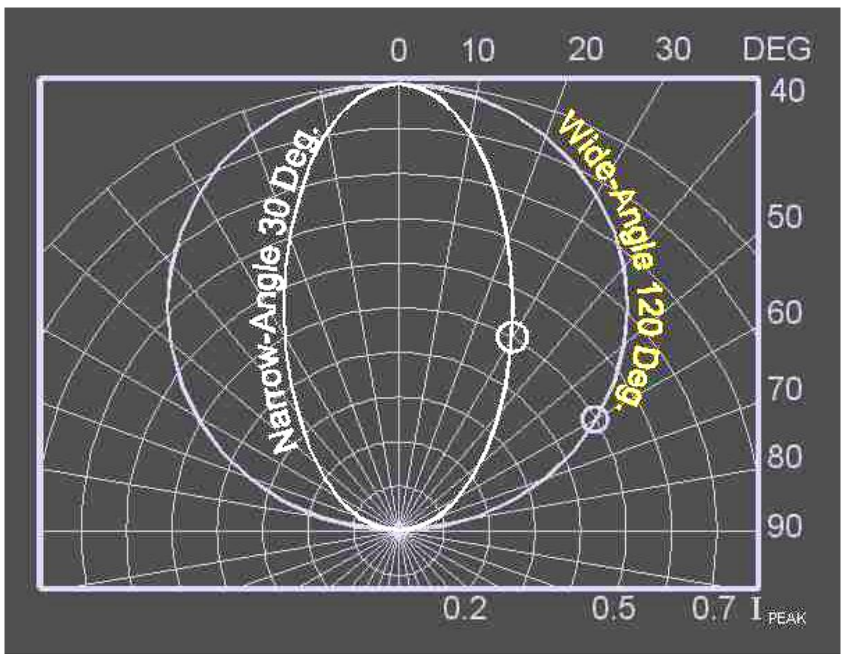
> **Here's the physics class on photometry you probably skipped: Just as you can use a voltmeter to measure current, you can use a lux meter that measures illuminance in lux (power per unit area) to measure candelas. This measurement must be done at one meter distance from the position light. A piece of string taped to the underside of the lamp will help keep this distance honest. A means of measuring the angle would be nice but you can eyeball most of it. And it should be dark. One candela causes an illuminance of one lux at a distance of 1 meter. So if you have your lux meter pointed at the position light and it reads 40 lux when it is one meter away, it means that the position light is shining 40 candelas [power per unit solid angle] in your direction. Get it? There'll be a test next Tuesday; you have all weekend to study. Lux meters are available on eBay, many old photographic meters have a lux scale, and if you are hard-up you can use a foot-candle meter and convert it to lux. Remember, 1 footcandle = 10.76 lux. For extra credit explain why.***

Now back to our imaginary trip around the green position light--The FAA wants a variety of conditions met. They want 40 minimum candelas from straight ahead to 10° outboard. From 10° to 20° they allow a fall-off to 30 candelas. This makes the aircraft easy to see when it is approaching and these areas are usually illuminated with projected light. Since another airplane is less likely to collide with the side of your airplane, only 5 candelas are required from 20° off the nose to 20° behind the wing (actually 110° away from the flight path). Only 5 candelas are required but a 90° sweep is illuminated so the power is still significant; this area was filled by light from the bare filament lamp. At 20° behind the wing, the white taillight becomes visible and takes over the job.)

So what did the FAA have in mind? Well, they obviously were measuring a bare tungsten lamp with a reflector behind it, but with LEDs you'll find it more practical to use different sets of LEDs to do the job cost effectively.

Are we done? This is the FAA remember? It turns out that the FAA wants your aircraft to be seen at other angles than head-on and to the side. They also want your aircraft to be visible from below and above and other "dihedral angles".

(Back to class for more terminology—Filament lamps usually put out the same amount of light in almost all directions, called "isotropic" which is Latin for "*the same in all directions*" and the FAA designed the position-light standard for this characteristic plus a reflector for the forward lighting. LEDs have to be made to do this type of distribution. How the light is distributed around the light source is called the "spatial distribution" a phrase that real optical physicists throw around a lot, so be sure to use it when the FAA asks.)



But let's look at a diagram of one narrow and one wide LED. The LED is at the center of the chart pointed toward the top of the page. The radial distance indicates how bright it is AT THAT ANGLE. The small circles indicate where the LED is 50% as bright as it's maximum I_{peak}. This is important because this is how the LEDs "viewing angle" is defined (that is—the LED spread angle is where the beam brightness is 50% of maximum). The numbers on the bottom are just to indicate which circle indicates what. The 0.5 distance circle is 50%.

Now-- there is a problem if a specification requires a certain illuminance over a certain angle because the light is only 50% brightness at the margins of its beam by definition. So be careful.

So the FAA wants a minimum of 5% of the peak illuminance (that the FAA confusingly calls "**I**" in one place and "**L**" in another-- but worse yet this is the "minimum peak" so to speak.) to show straight down and straight up with FAA-defined progressively greater amounts of light as the angle approaches the horizontal, where we started this thing. Notice also that the FAA requires 100% of I_{peak} horizontally *but* only 80% from 0° to 5°. This is a logical problem, but we'll comply with the harder interpretation. This is not too hard, but we have to add a few more LEDs and bend some others—

That pesky 5% of $\mathbf{I}_{peak}$ must be directed up and down. You might believe that we can ignore a mere tiny little 5%, but since the eye has a dynamic ratio of a billion-to-one, 5% is a whole dump truck full of visibility. It's very easy to notice and must be complied with!

~~But try this. Starting with the white tail.~~

~~We know the FAA wants 20 candlepower (same thing as 20 Candelas) in a truncated hemispherical dome pointing rearward (it's a bit more complicated, but this will do fine for this estimate). Now, given the numbers published by the LED manufacturers, one would think we would start with the LED's luminous intensity, but this is *completely backwards*. It is necessary to realize that we need to cover a solid hemisphere with LEDs that usually emit less than a full hemispherical angle.~~

~~Imagine a dozen kids at the center of a dome tent with a bunch of LED flashlights. We want an outside observer to see a smooth light distribution (isotropic) instead of the beams of the individual flashlights. Overlapping is good too, but dark areas are not.~~

~~So...If the tent is one meter in radius, the surface area of the dome is 2XPi or 6.28 square meters (or feet or whatever) in area. You can skip all length units since they cancel out. I am skipping the steradians and some of the math, etc.; just trust me on this.~~

~~So how many flashlights or cones of LED light are needed to fill the area of the domed tent? We have to select an LED and find out how much area it will cover on the dome. A little trigonometry says we take the half-angle of the LED beam, set hypotenuse=1 meter (or whatever) and the opposite side is the sine of the angle. For example if the LED cone of light is 20 degrees, then the sine of 10 degrees is 0.17. (This then is the radius R of the spot on the tent wall. (Geometers will note this is not *quite* correct but ignore them...they should get a life….). And the area of the LED lighted spot on the domed tent surface is then Area=Pi X R X R = 0.09 square "Whatevers".~~

~~Now from this we gather that since 6.28/0.09=66.29...LEDs, 6.28 Square "Whatevers" require 67 evenly distributed LEDs of 20 degrees cone angle to cover the surface. Now what luminous Intensity must each LED be? The FAA requires 20 Candelas so 20/67= 0.300 candelas or 300 mcd (millicandelas) each.~~

~~Note that, in this example, you cannot get away with fewer than 67 LEDs (and a few more might be better). But if we get wider angle LEDs, say 30 degree LEDs, then we can get away with 30 LEDs. And then we need 20 candelas/30 or 667 mcd each.~~

~~But if we get the widest high power LEDs that fulfill the spatial distribution requirements, we can just stack up a few LED parallel and get the required light intensity by simple addition. We can now do this in some cases with one single white LED.~~

Okay, the FAA wants 20 cd in spherical wedge 70 degrees on each side of the airplane's tail.

The area of the curved surface of this wedge at 1 meter radius is 4.9 m sq.

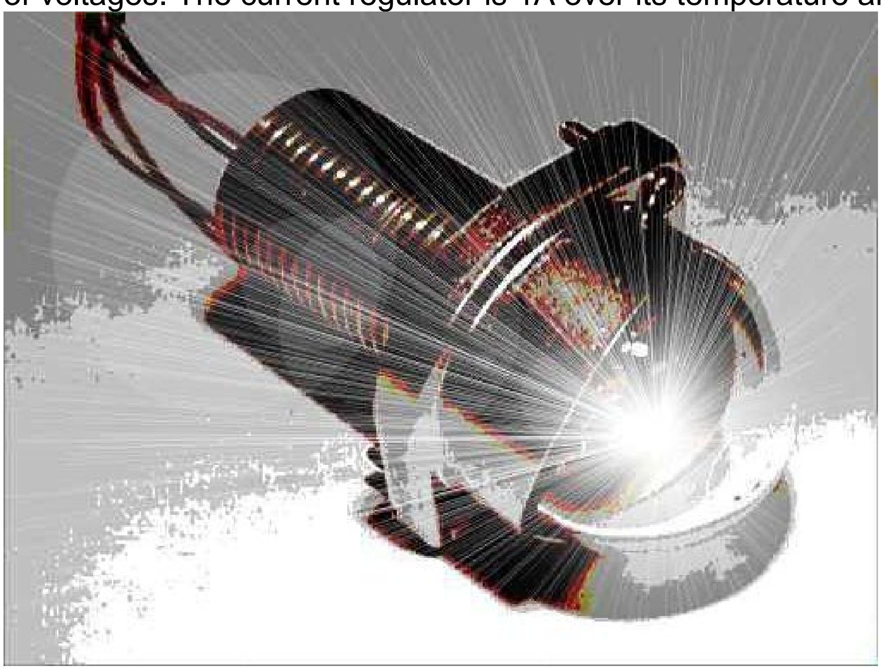
If the light source is 20 cd, then we expect 20 lux on this surface (you can measure it with an incidence [lux] photometer).

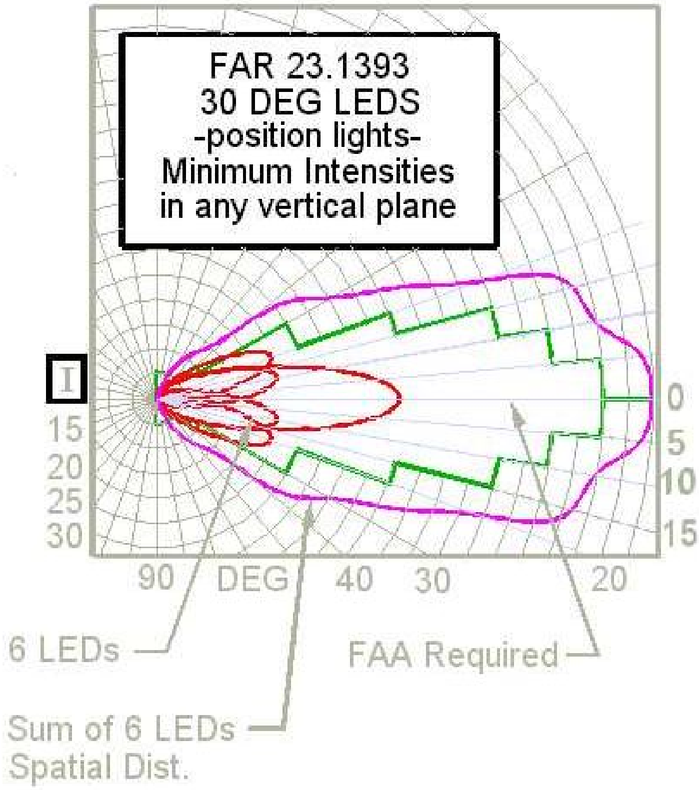
So we need "X" lumens / 4.9 meters=20 cd. Solve for "X" lumens and we get about 100 lumens. This is the <u>minimum</u> flux produced by the LED needed to do the job.

Now lumens (lm) are the standard unit of photometric "Flux

This 100 lumens is easy to get in an LED like the Cree. This LED is 3 Watts and 220 lumens of white light and is the LED in my white LED tail light. I have measure this and it satisfies the FAA requirements— with a reasonable margin. And this LED dissipates 3 watts of heat. Keeping the temperature down is critical to enjoying the LED's long life.

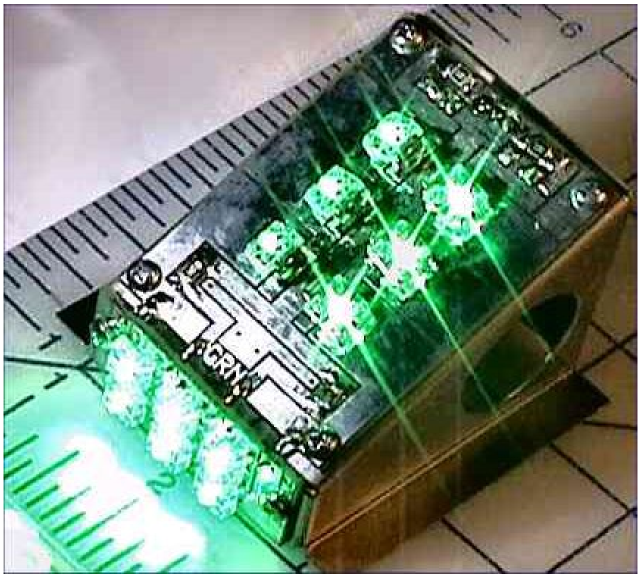
Our white LED tail light is designed to be used with a current regulator since there is a temperature coefficient involved in the LED and the ageing characteristics might change the current in way not entirely predictable—and aircraft electrical systems can be a range of voltages. The current regulator is 1A over its temperature and voltage range.

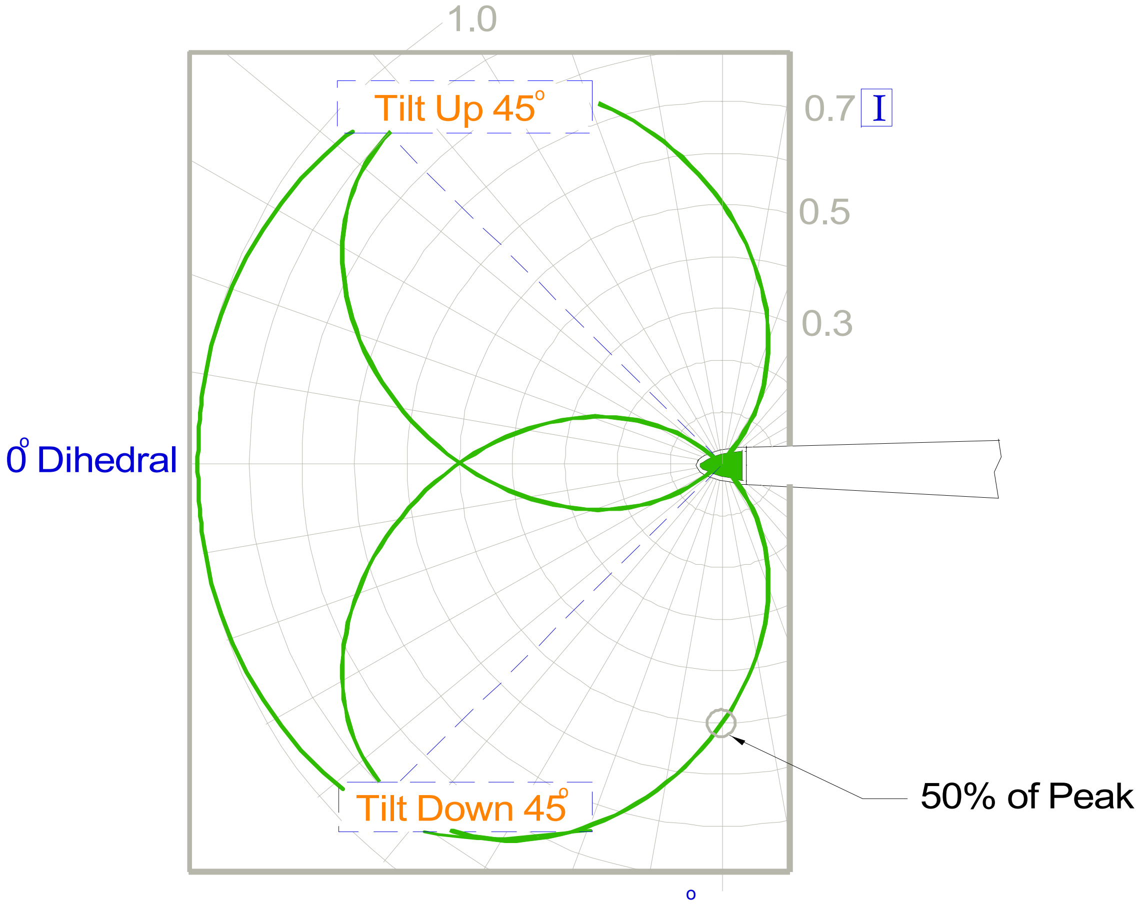




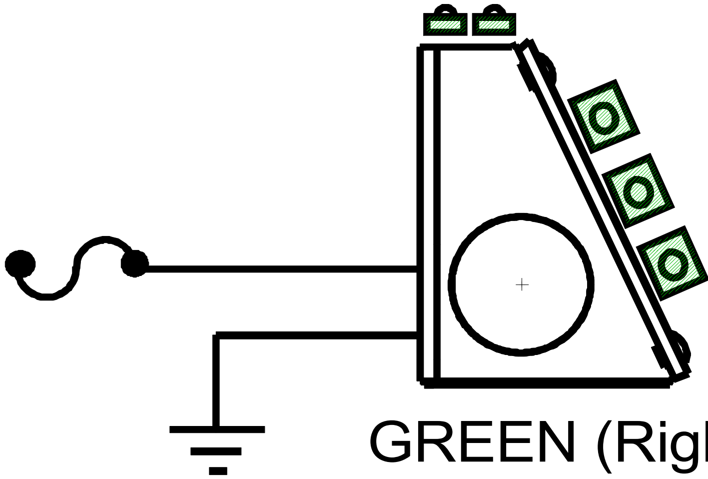
Here is a graph of the FAA requirement for vertical plane minimum intensity, showing how it is achieved with 6, 30°, 10000 mcd LEDs splayed 2 at 0°, 2 at + and – 10°, and 2 at + and – 20°.

And here is the final graph of how the pesky 5% is covered with the 10-up and 10-down LEDs:





1.0
0.7
I
0.5
0.3
Tilt Up 45°
0° Dihedral
Tilt Down 45°
50% of Peak I



GREEN (Right)

So are we done with the FAA? Not quite….

Let's review the FAA Regulations on Aircraft lighting—
23.1381 Instrument lights. You need them, but not applicable here.
23.1383 Taxi and landing lights. You need them, but not applicable here
23.1385 Position light system installation. DONE
23.1387 Position light system dihedral angles. DONE.
23.1389 Position light distribution and intensities. DONE.
23.1391 Minimum intensities in the horiz. plane of position lights. DONE.
23.1393 Minimum intensities in any vertical plane of position lights. DONE
23.1395 Maximum intensities in overlapping beams of position lights. This is important but it is a function of the aircraft shape and light-housing construction, etc. Basically the FAA does not want the various position lights to visually interfere with one another. Specific limits are called out. The builder should review this.
23.1397 Color specifications. DONE.
23.1399 Riding light -- For Floatplanes. Easy to do with a few LEDs
23.1401 Anticollision light system—Hey--We could make an Anticollision lighting system with LEDs!

- *—Because one square-meter equals 10.76 square-feet. Easy, huh?

But let's look at some practical matters involved in building these new lights. Most filament lights operate at extremely high temperatures. In fact, halogen lamps have quartz envelopes so they can be operated at very high temperatures since the halogen cycle they depend on for their long life requires very high temperatures. Cooling halogen lamps leads to light-intensity fall-off and early failures. But LEDs are semiconductor devices and work best at lower temperatures. Recently one company built a retrofit replacement for the common filament position lamps without taking sufficient care to remove the heat from the design. Very short lifetimes and disappointed customers resulted.

Here's the path to proper heat sinking of LEDs: First, realize that "watts is watts" (A phrase that entered thermodynamic-engineering advice from the 1980's "Parts is Parts" Wendy's Hamburger commercial, now on U-Tube…)—the rated power of the LED does not turn into light—it almost all turns into heat. Even an LED of futuristic-efficiency, might be awfully bright, but would still dissipate its watts as heat. What turns into light is specified in "lumens per watt", but regardless of the lumens, watts is watts. The heat must be removed to keep the LED temperatures within limits.

If you build an LED lighting device, figure out the total watts that need to be removed. Simply calculate the optimal thermal dispersion coefficients…just kidding… *I am so easily amused*—Here's the plan:

There's a tiny junction where the LED die meets the case. It is a hotspot with an impossible to observe temperature, the junction temperature T_J 145 ºC maximum—as hot as a two-dollar pistol. But you can't do anything about it. So leave it for later.

Heat is conducted to the outside of the LED-mounting package through a material that has a thermal resistance of 8 ºC/Watt. This too is unavoidable, so forget it (Eric's school of engineering wisdom again).

The next hurdle is the attachment of the LED-mounting package to the heatsink. You need to do the very best job you can, but most people know how to do it because transistors and most hot electronic parts are mounted this way. Apply a thin layer of thermal goop or thermal tape to the LED assembly and bolt the assembly firmly to the flat heatsink. Light up the LED, let it come up to operating temperature—let it cool off and re-tighten it.

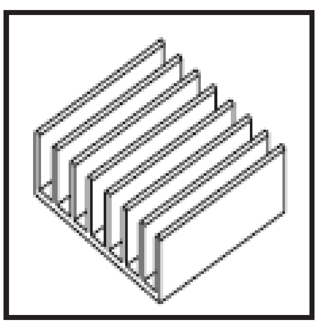
Heatsinks are rated by their temperature-rise versus power dissipation, ºC/Watt. This means, if everything is as good as it was in the test lab, a properly attached 5W LED would raise the temperature of the 1 ºC/Watt heatsink by 5 ºC. But no, it's not that easy. Let's look at some real technical-thermal stuff.

Maximum Operating Temperature	85 °C
Thermal Resistance, die junction to mounting	8 °C/W
LED Junction Temperature	145 °C

There are only three pieces of data here, and BIG problems occur when you don't design for them. The first is the Maximum Operating Temperature. But we can make life easier by looking at this last. You will know soon enough if you exceed it.

Let's start at the beginning—Ambient temperature can be figured at 30 ºC. The LED package maximum temperature is 85 ºC. So we have only 85-30=55 ºC temperature rise possible. We want to dissipate 5 watts. So we need a heatsink better than 55ºC/5 watts, or 11 ºC/watt. Such a heatsink can be looked up in catalogs, although many catalogs have the watts and dimensions only. A visit to the manufacturer's data is often required

Here's a Wakefield solution:



Wakefield Series 517, 518, 527,528

Material: Aluminum, Black Anodized

P/N	W in. H in. Tall in	Orientation	60°C Rise
517-95AB	2.28 x 2.40 x 0.95	Horizontal	11W
527-45AB	2.28 x 2.40 x.0.45	Horizontal	7W
527-24AB	2.28 x 2.40 x.0.24	Horizontal	5W
518-95AB	2.40 x 2.28 x.0.95	Vertical	11W
528-45AB	2.40 x 2.28 x.0.45	Vertical	7W
528-24AB	2.40 x 2.28 x.0.24	Vertical	5W

We want a maximum temperature rise of 55ºC and 5W dissipation, so we can estimate that 517-45AB or 528-45AB, which have a 60ºC rise at 7W, might work well. For high altitudes or restricted airflow 11W heatsinks would be a better choice. Analyzing this more thoroughly is probably not justified for homebuilders. However any thermocouple is worth its weight in gold for what it can tell you about your design..

It turns out that theoretical calculations are very hard to do compared to building and measuring the temperature a particular design. Vane re-radiation and airflow is impossible to calculate. And temperature calculations are always hard.

Any aluminum airplane part can be a great heatsink. You could just bolt about anything to the centerline of an aluminum spar without fear of overheating. What can save more heatsink weight than NO heatsink? Just smear the back of the LED with thermal grease and bolt it to some thermally conductive structure.

One additional point that needs to be made—Power supplies.

Pulse Width Modulation: A fancy name for rectangular waves; useful because you can vary (modulate) their width. Many people believe that LEDs must be run by PWM for dimming or whatever. This notion evolved from microprocessors that ran early LEDs on a time-sharing basis.

Additionally PWM power adds the possibility of visual strobe effects when the LEDs are dimmed, as well as EMI interference.

Usually, there is every reason to run LEDs on straight DC, and stack a few up to take advantage of the small forward voltage needed to run them. Example—From 12 volts DC you can light four series LEDs (each 2 Vf) at 30 mA through a 133 Ohm resistor.

So in summary, Do the engineering before believing that the job is done….Those shining lights do look convincing----but are they right?

This is a safety issue. If your best friend uses some cheapo LEDs—remember *his aircraft's visibility is a big problem <u>for you</u>*. Lot's of people will die because someone neglects to say, "This is wrong bubela!"

End