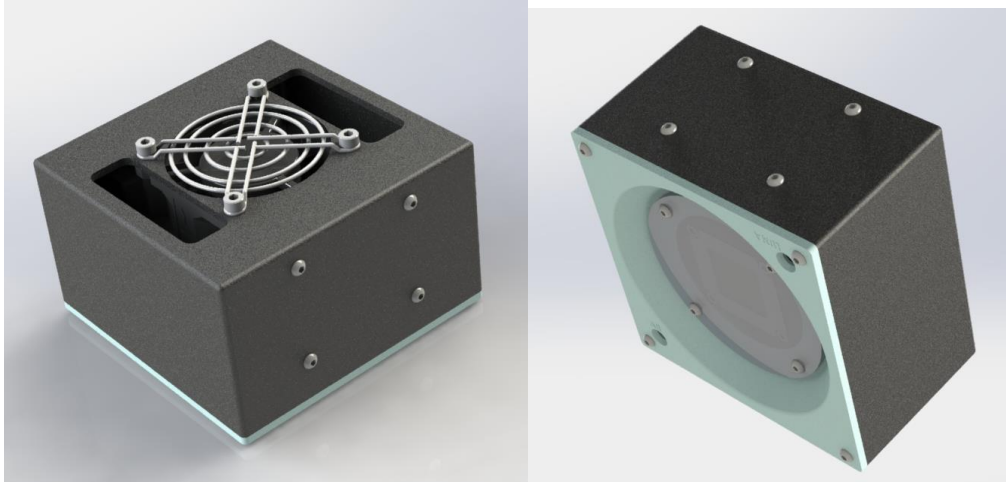


How the DLight Works (Diurnal Light)

The DLight (Diurnal-Light) is meant for reef tanks, but can be used for any simulated environment that needs to support the photosynthesis of various forms of captive life. It is intended for advanced aquarists and scientists seeking to tailor their experimental environments.



DLight consists of a Raspberry Pi platform that controls high power light-emitting diodes (LED's, > 10 watts). We use 50 W LED's with a 6300 K color temperature (approximately) for our baseline design.

Each Dlight provides PAR illumination suitable for roughly 100 Gallons¹ of reef tankage.

DLight will control the intensity of the LED based on the solar insolation curve for any latitude and longitude (which are both user GUI inputs). The user may choose a simulated time zone (say, the red sea) or local time zone (say, simulating a red sea coral, but in an aquarium in Chicago)

A single Pi platform can control multiple LED units (a single LED unit consists of one 50W LED with control PCB, cooling fan, and AC plug.

Multiple LED units can be controlled by a single platform. Therefore larger or multiple lighting installations can share the same diurnal solar insolation simulation.

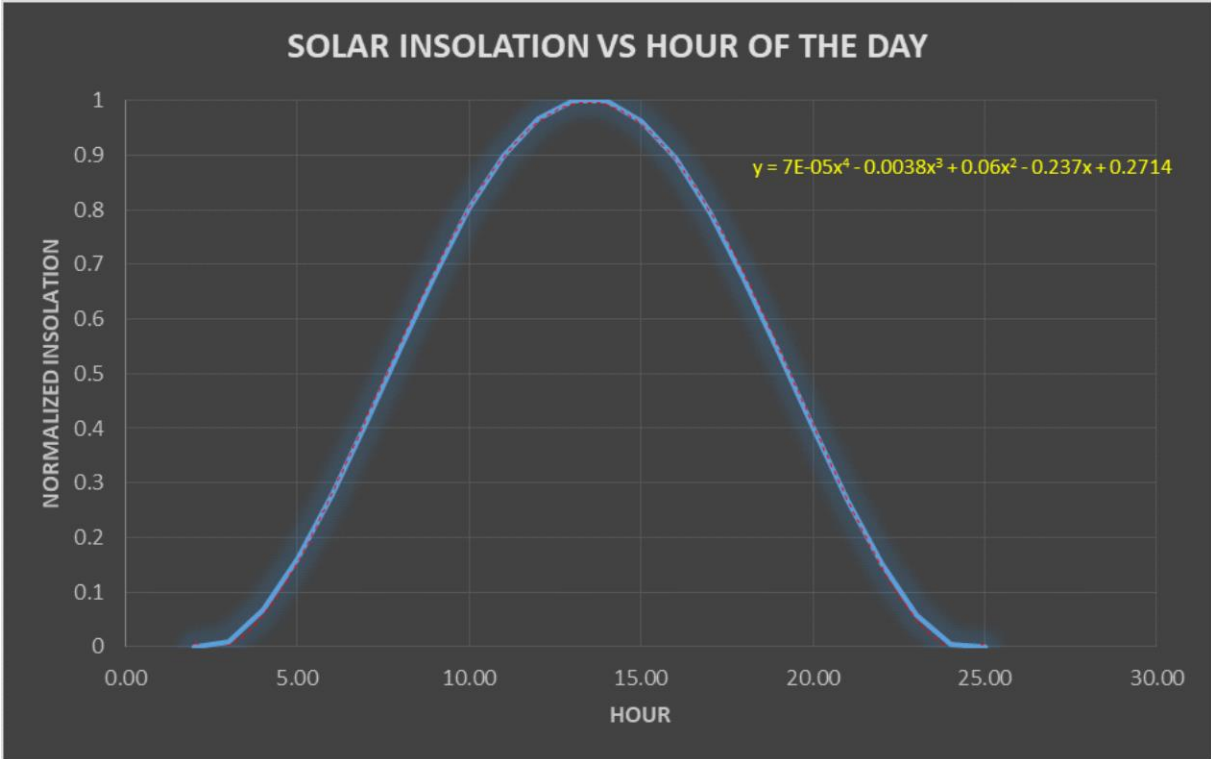
Adding a real-time clock allows the control of the led brightness to follow the curve of solar brightness during the day.

The brightness is changed by changing the control word for eight MOSFET's controlling the current going to the LED..

I downloaded some solar insolation curves from the NREL National Solar Radiation Data Base

¹ Based on 350 W incandescent equivalence, and 3 W / gallon

(NRSRDB), normalized them, and then curve fit them using a 4th order polynomial. Here is the normalized curve versus time of day:



The NSRDB data is the solid blue line, while the curve fit is the dashed red line.

I normalized the data so that the curve may be applied to duplicate the solar insolation curve of any locality. If one takes the peak solar insolation of the day (typically at about 13:00-14:00 hours) at some location and multiplies it by the curve-fit polynomial, they will produce a close approximation of the solar insolation curve for that locality. Just use the polynomial: replace x with the time of day (1:00 -24:00), and calculate the y (normalized insolation, or NI), then multiply the y by the peak daily insolation for your location.

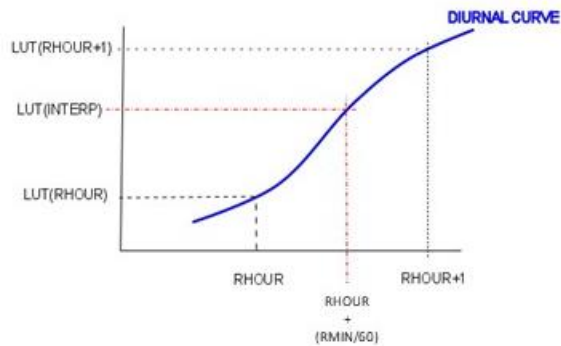
This curve is stored in the microcontroller as a look-up table of integers

hour	8-bit LUT
1	0
2.00	0

3.00	2
4.00	17
5.00	41
6.00	71
7.00	105
8.00	140
9.00	174
10.00	204
11.00	229
12.00	246
13.00	255
14.00	255
15.00	245
16.00	228
17.00	203
18.00	172
19.00	138
20.00	102
21.00	69
22.00	39
23.00	15
24.00	1

The RTC also has a register for minutes. If you read this register and divide by 256 (the 256 represents 60 minutes in an hour ... 30 minutes into the hour would be 128), you get the normalized minutes of the hour. Add that value to the hour and you get a time in decimal hours (for example, 14.5 for 2:30 P.M.). I just use linear interpolation on the LUT to find the closest integer.

Interpolation is done like this:



You read the RTC hours (RHOURL) and minutes (RMIN) elapsed since midnight. Then create a fractional hour value representing the current elapsed time of day (RHOURL+(RMIN/60)). Compute the slope between the two points:

$$\text{slope} = \frac{(LUT(RHOURL + 1) - LUT(RHOURL))}{(RHOURL + 1) - RHOURL}$$

... then, multiply the slope times the LED power setting for the LUT hour (LUT(RHOURL) in the figure above). This is a **linear** interpolation (it assumes the curve between points is actually a straight line). There are more accurate interpolations, but why bother?

$$LUT(INTERP) = RHOURL + (\text{slope} * (RHOURL + (\frac{RMIN}{60})) - RHOURL)$$

Example:

The value LUT(INTERP) is the fractional elapsed hour. The number of elapsed minutes is the right side of the decimal times 60 minutes. Say the time is 17 minutes after eleven in the morning (11:17 A.M.). The fraction hour would be 11 hours plus 17/60, or 11.283. From the LUT, we know that the LED intensity setting will be between 229 and 246.

$$\text{slope} = \frac{246 - 229}{12 - 11} = 17$$

$$\text{Interpolated LED Intensity} = 229 + (17)(11.283 - 11) = 234$$

RIPPLE:

The surface of the ocean ripples – depending on wind and tides for the magnitude of the ripples. The effect of ripples is to refract and reflect sunlight as it hits the surface. This manifests itself at the reef as a “noise” on top of the sunlight filtering through. The amplitude of this “ripple noise” is

proportional to the weather. If it's rough out, the amplitude is relatively high, if calm, it's low. DLight assumes a mild ripple (approximately 3% of the solar illuminance) randomly applied to the LUT data. This can be changed easily in the code to whatever one requires – we might even put a GUI input box for it in a future version.

Raspberry Pi3 version

I first am endeavoring to control the LED using a Raspberry Pi using Python. The 40-pin expansion header on the Pi is used to connect to the DLight. The 8-bit integer of the LED setting has its bits broken out – each bit of the integer occupying its own GPIO pin on the header

The Pi3 does not have an RTC onboard. I added one to the expansion header:

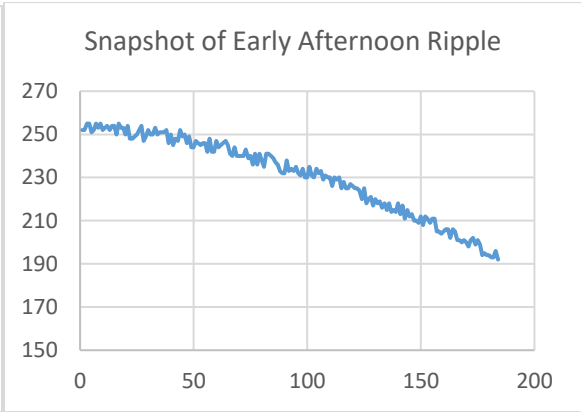
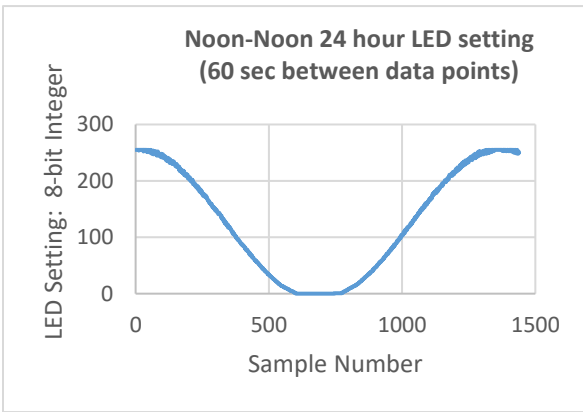
This RTC is based on the DS3231. It's \$2.90 at the [Robot Shop](#) (but can be found even cheaper on eBay). If you orient it correctly it plugs right into the Pi3 expansion header (pins 1,3,5,7,9).



For the prototype, I didn't want to fool with wireless (yet), so, I chose to develop a stand-alone DLight that does not require connectivity. Hence, the RTC.

So I wrote a GUI using Tkinter that allows me to input the Lat/Long of the reef I want to simulate with the DLight; the Lat/Long of where on Earth my reef tank sits; the local time (this will eventually be calculated from the tank Lat/Long); the date; and a name for the data set (like, "Palau", or "Barbados"). The name is used in my development software to create a text file that logs the LED setting vs time. The GUI saves this information to a text file so it can be recalled or reused by the control software (currently a separate program).

After some debugging, it seems to work. Here is the data from a 24-hour test (noon-noon) – complete with 3% surface ripple on top.



There is a slider switch to select Master/Slave mode. In Master mode the local microcontroller sets the brightness of the LED's according to the NI look-up table. Additionally, in Master mode, the DLight spits out its brightness data on its USB (to Slaves or a PC). In Slave mode, the local microcontroller receives brightness information from the USB (from another DLight or a PC). I2C bus activity generates an interrupt to the slave – overriding any internal calculations of LED brightness. Therefore, if the switch is in Slave mode, but the USB is not connected, the DLight functions using its internal LUT.

Another slide switch is provided that will override the microcontroller – permitting operation of the DLight in on/off mode (no control over the LED brightness... just all on, or all off). This switch is labeled “Norm/Over”.

A submersible light sensor is available to provide feedback to the DLight. Feedback is used to tailor the LED output and detect failure or errors in the brightness control.

It might be important to have a continuous light source, like the sun, rather than a variable source, like lights powered by alternating current.

Here is the oscilloscope image from a solar cell with little or no illumination:

And here is the same solar cell under illumination by a couple of mundane T8 fluorescent tubes:

Fluorescents use the phosphor coating on the inside of the tube to temporally filter the light, so that sine wave shown above is actually the “ripple” on top of a DC brightness level – that’s kind of like a “photonic capacitor”.

Even though the light LOOKS continuous to the human eye, it really just oscillates in intensity so fast that we can’t see it blinking. The phosphor coating smooths it out, like a capacitor “smooths” AC.

A PWM'd LED strobos, unless you have some mechanism for “smoothing” – even though the light

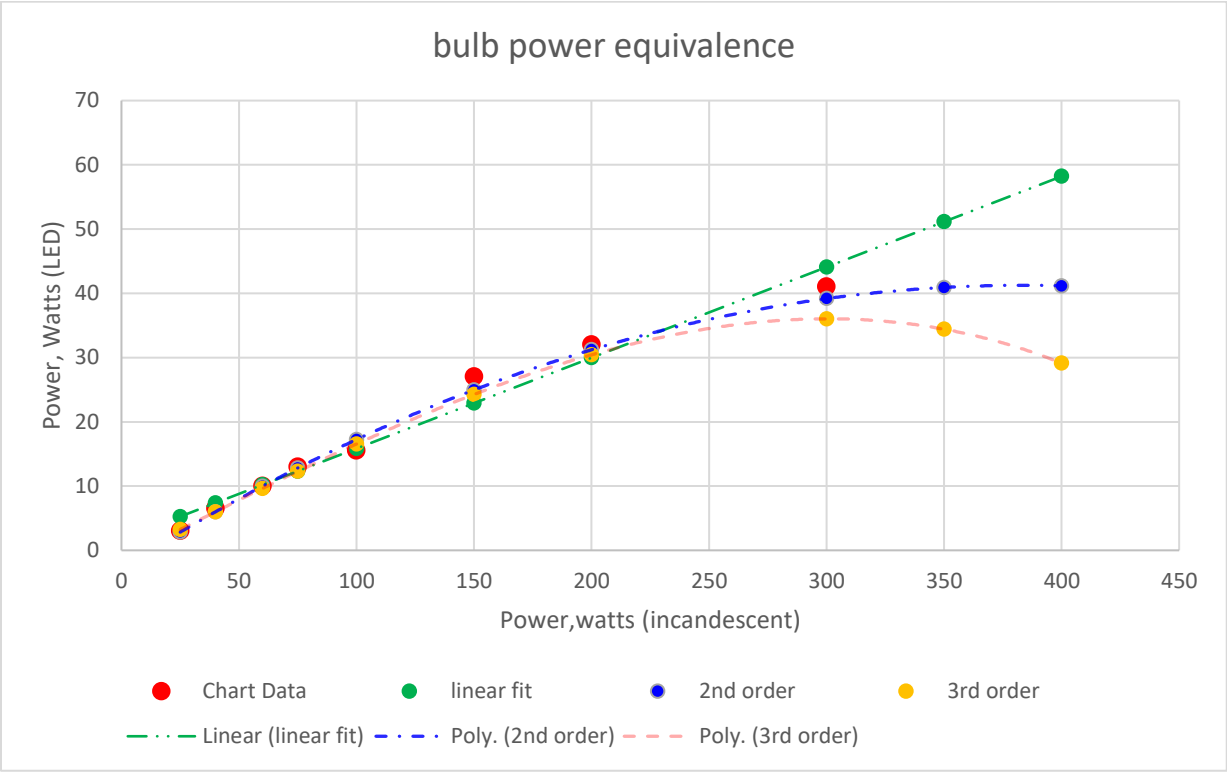
LOOKS continuous to the human eye, it really just oscillates in intensity so fast that we can't see it blinking. This is how PWM signals appear to be analog... they aren't really, they are just faster than the perception of humans (or the electronics the PWM connects to).

Different creatures live with different perceptions of their environment. I have no idea of the effect of alternating light frequencies on marine animals. What I am trying to do, in my ignorance, is to simulate their natural light environment as best I can. I know the sun is DC...it burns steadily (over the short time spans we live in), and most of the aquarium lightning available today is AC, because it is powered by an AC grid. To be a continuous source, like the sun, the light source must run off DC, or AC that has been rectified and filtered into DC.

There is some naturally-occurring ripple to sunlight in the marine environment. Wave action constantly refracts and reflects the incident sunlight, so that the lighting underwater "shimmers" or "ripples". I am looking for data on this effect... suspecting it is in the band of 0.1-1.0 Hz, and causing a variance of 0-20% or less.... I can superimpose a random attenuation function atop the diurnal distribution to account for this in LED control,

Bulb Power Equivalence

Using a chart from Wikipedia ([link here](#)), I created the following chart in order to get some equivalency between bulbs and LED illumination:



The wiki chart only goes up to 300 W (incandescent), so I curve fit the data to get some idea of higher values. Since the polynomial curve fits show a round off beyond 300, I use the linear fit. According to that, a 50 Watt LED consumes the same power as a 350 Watt incandescent bulb – that should be 106 W for compact flourescent bulbs. Of course, only the linear curve fit gets to 50W

Calculating the PAR/Irradiance equivalence:

I'm going to try to calculate some sort link between PAR and solar spectral irradiance. Here is a plot from a NASA report detailing solar spectral irradiance over wavelength (through different air masses).²

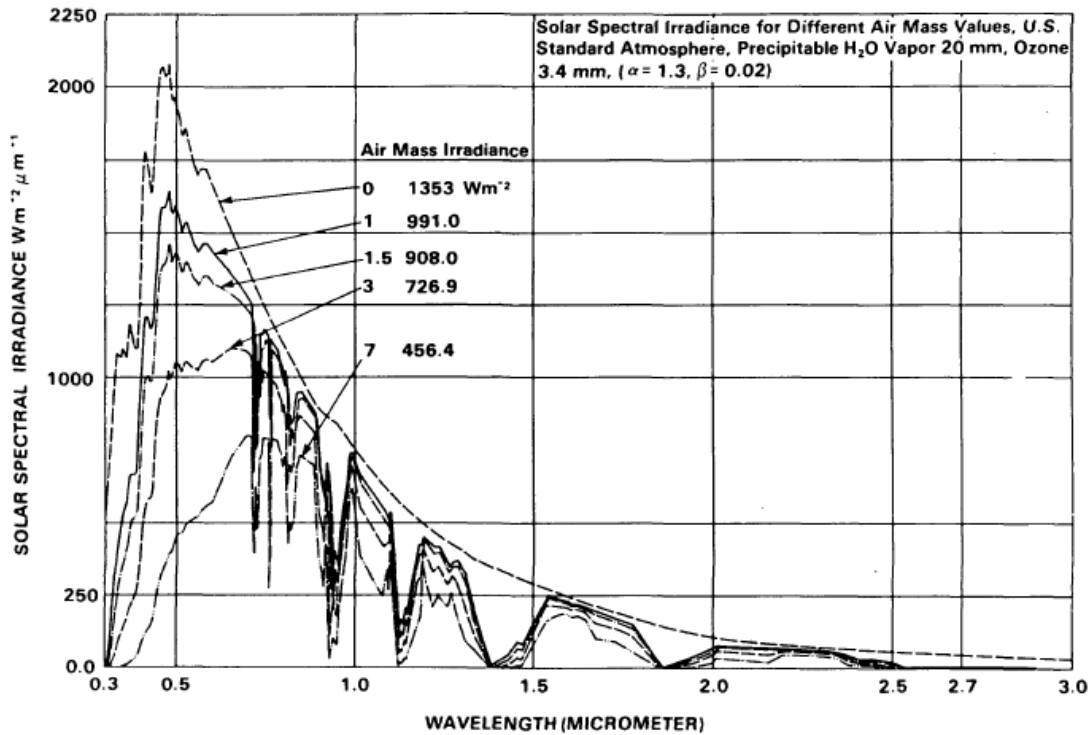
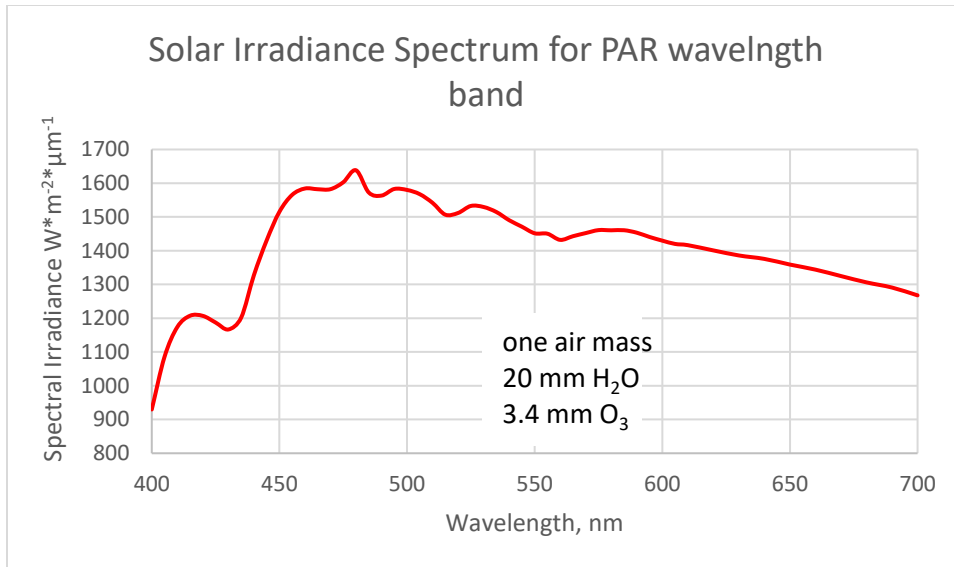


Figure 8. Solar Spectral Irradiance for Different Air Mass Values, Assuming U.S. Standard Atmosphere, Precipitable H₂O Vapor 20mm, Ozone 3.4mm, Very Clear Atmosphere ($\alpha = 1.3$, $\beta = 0.02$)

Zero air mass is the solar irradiance at the earth outside the atmosphere. The value 1353 W/m² is the average **solar constant irradiance**. This report has tabular data for these curves, so I entered the data between 400 and 700 nm (PAR definition) into Excel. There are many absorption valleys – mostly from water vapor and various gaseous atmospheric constituents.

Over the PAR band, the irradiance curve through one air mass looks like this:

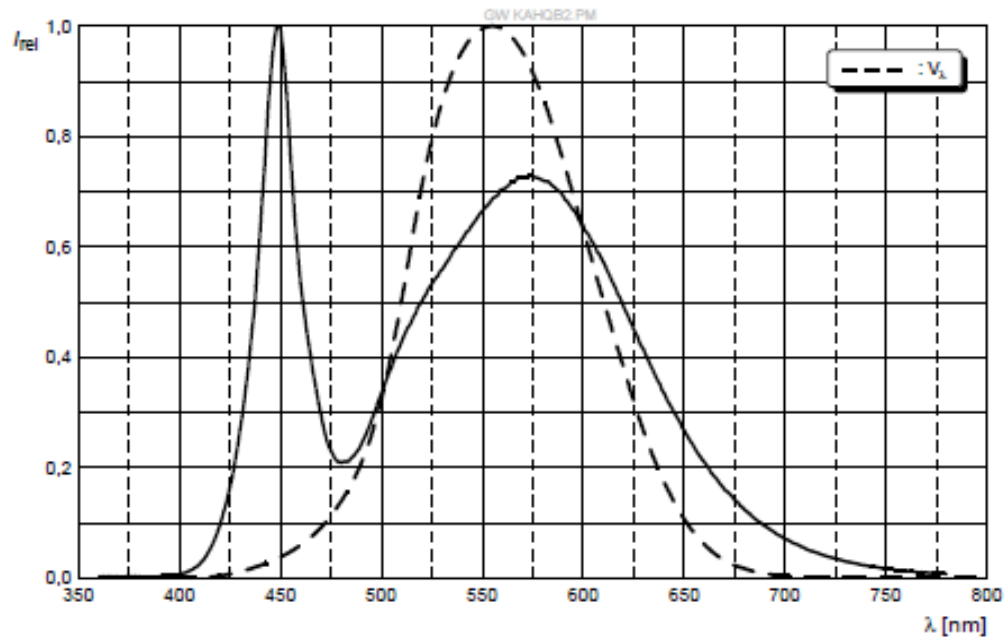
² A. T. Mecherikunnel, J. C. Richmond; "Spectral Distribution of Solar Radiation"; NASA Technical Memorandum 8202, Sept. 1980.



By numerically integrating this curve, I get approximately 425 W/m² for the PAR band.

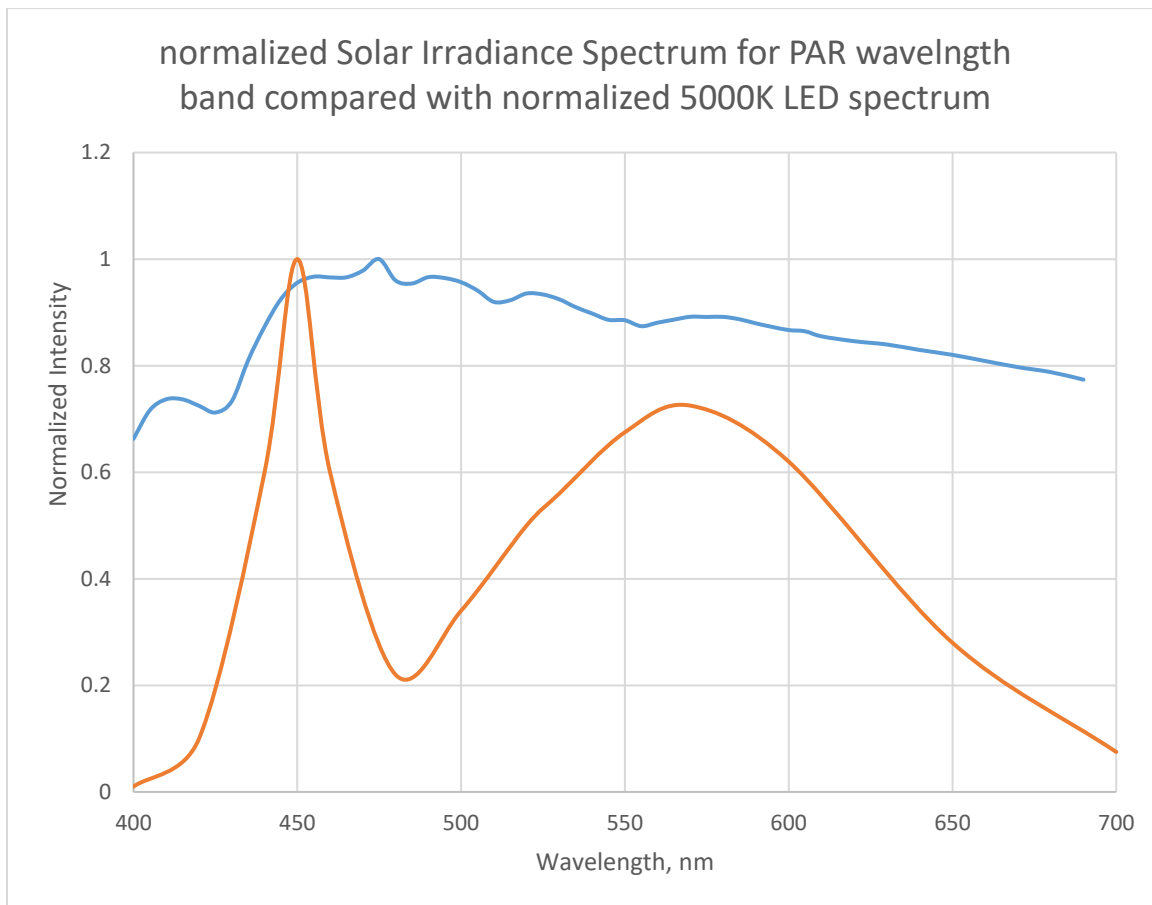
Here is the PAR band spectrum from an OSRAM 5000K 50W LED I pulled from a datasheet:

Relative Spectral Emission - $V(\lambda)$ = Standard eye response curve ^{3) page 17}
Relative spektrale Emission - $V(\lambda)$ = spektrale Augenempfindlichkeit ^{3) Seite 17}
 $\Phi_{rel} = f(\lambda)$; $T_S = 85 \text{ }^\circ\text{C}$; $I_F = 1500 \text{ mA}$



I plotted this curve (normalized) with the solar spectrum (normalized) curve for comparisons

purposes:



*Be careful about interpreting these curves It is only a **spectral** comparison ... nothing more.*

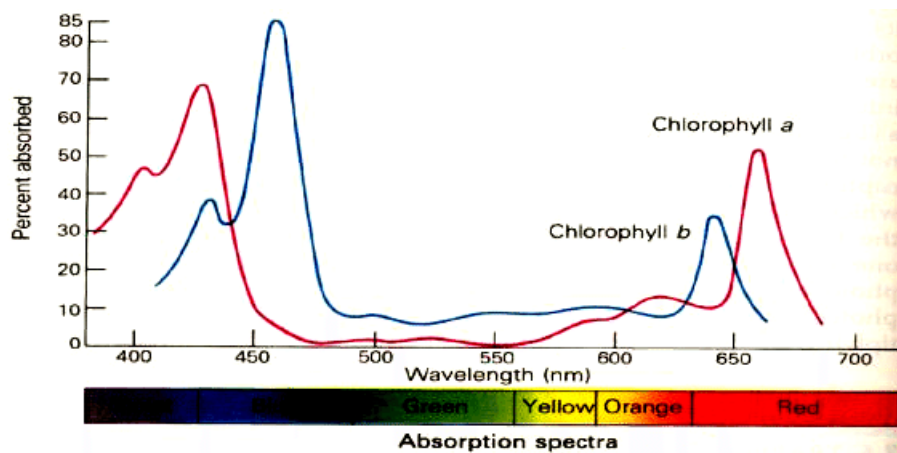
450-490 nanometers (the valley for the LED spectrum is around 480) is blue - leaning towards cyan. However, there is a strong peak at 450 nm ... right at the border between blue and violet.

Corals, Dinoflagellates, PCP, and Light

*Corals and anemones do not utilize light directly. They rely on symbiotic chlorophyll-containing plankton in their tissues to absorb light and CO₂ for the production of proteins. Those symbiots are generally dinoflagellants of the genus *Symbiodinium*.*

**Symbiodinium* contain PCP³ (Peridinin-Chlorophyll a-Protein). Peridinin is a carotenoid that absorbs light in the 470–550 nanometers band. It then fluoresces light around 670 nanometers (give or take ... depending upon the specific species of *Symbiodinium*).*

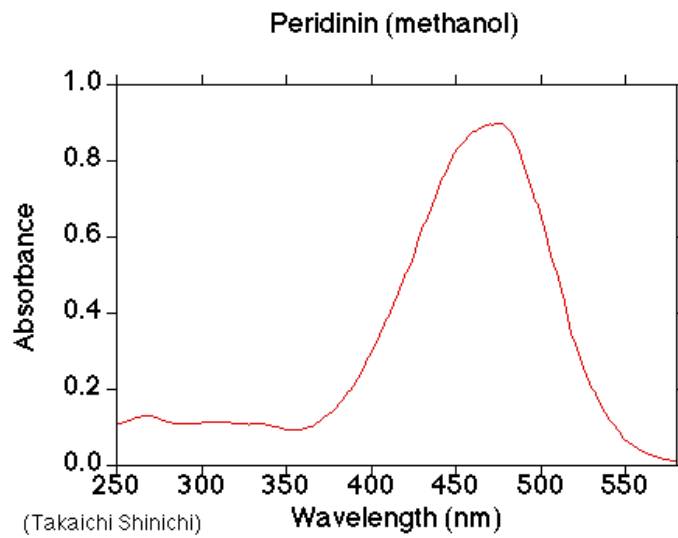
You may recall that Chlorophyll a has two absorption peaks: around 440 nm (blue) and 670 nm (red) This is illustrated on the graph below:



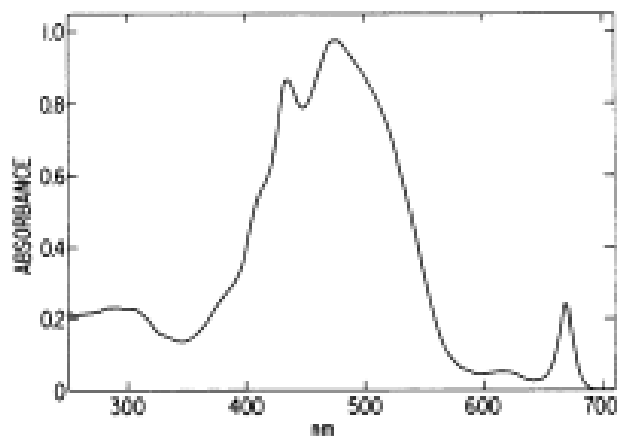
Therefore, the Peridinin makes more light energy available for the Chlorophyll a by gathering more blue-green light (not used by Chlorophyll a) and down-converting it (through fluorescence) into a wavelength the Chlorophyll a can use.

Here is what the absorption spectrum of Peridinin looks like:

³ This PCP is NOT the drug Phencyclidine (angel dust).

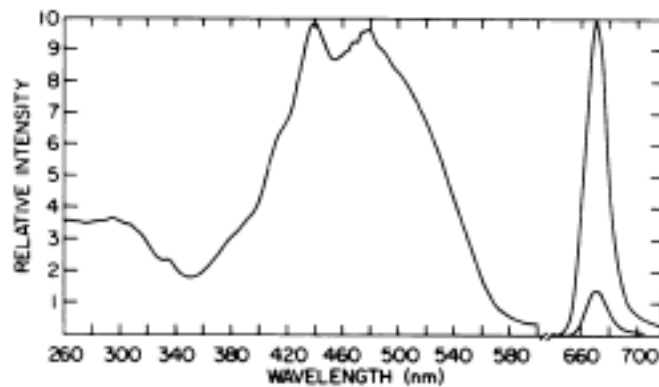


Combining chlorophyll a absorption with that of peridinin give us something like this:



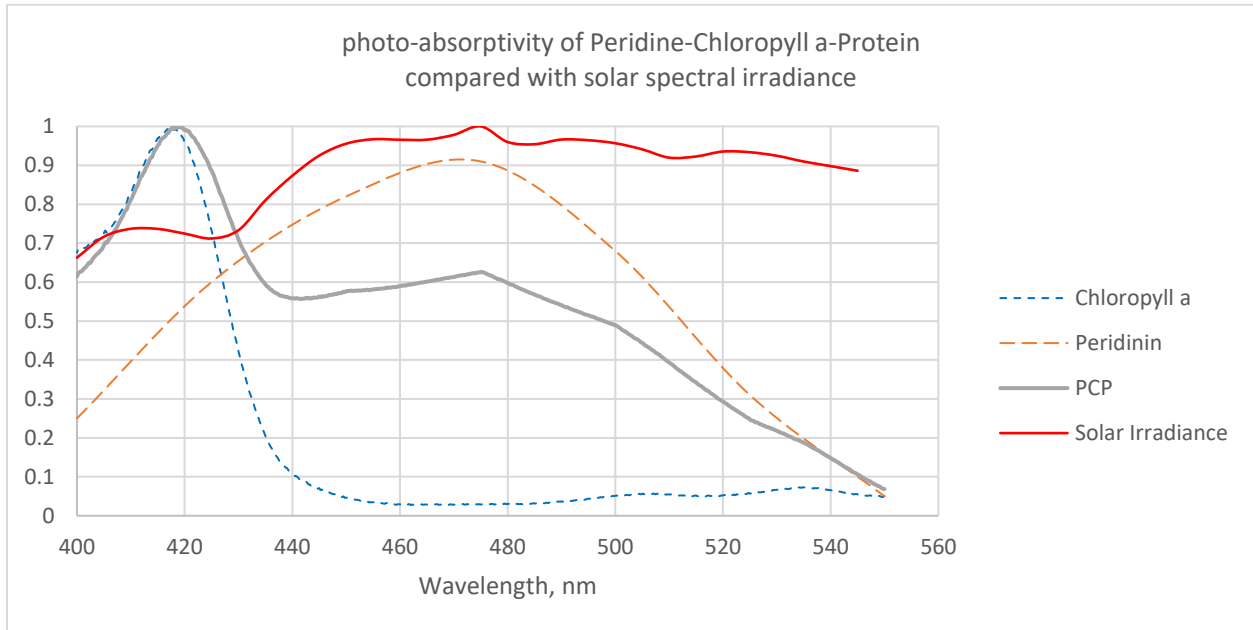
Notice the little peak around 670 ... that's Chlorophyll a, because peridinin fluoresces at about the same wavelength.

Here is a plot of Chlorophyll a and peridinin with the light emitted by the peridinin:



The big emission peak is at 675 nm ... and totally encompasses the chlorophyll a absorption peak at about 670 nm.

For comparison's sake, I normalized all these curves and put them on one plot – overlaying a normalized solar spectral irradiance curve so one can compare the effects of the peridinin/chlorophyll combination:



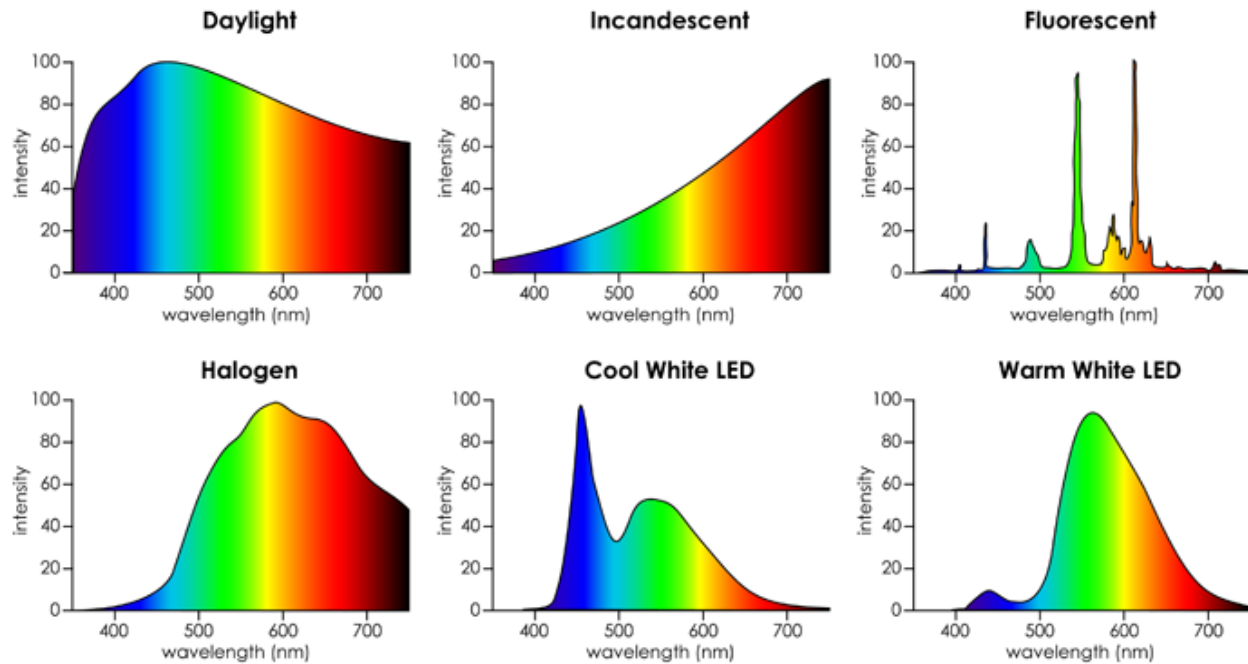
This graph essentially tells one that PCP allows the coral/anemone dinoflagellate to better utilize the sunlight so that it encompasses the peak emission wavelength of sunlight

The PCP content should allow one to use illumination weak in the red, as the peridinin provides (through its fluorescence) the red used by Chlorophyll a.

I found this interesting image⁴ on the internet. It compares the spectra of various lighting sources: Warm White LEDs; Cool White LEDs; Halogen bulbs; fluorescents; incandescent lights; and daylight.

I know, there are lots of variations – especially for fluorescent, incandescent, and halogen, or mixtures thereof – but this illustration will do, generally.

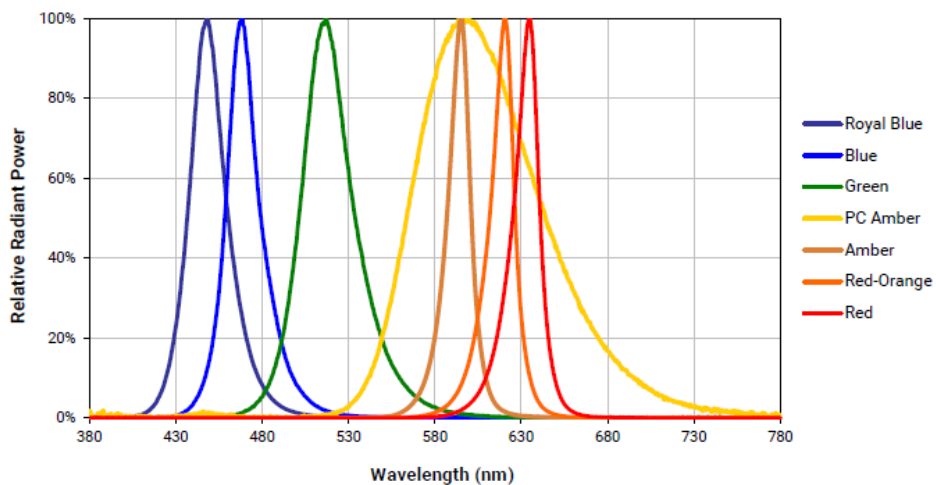
⁴ https://www.powersscientific.com/wp-content/uploads/2016/12/spectral_responses2.png



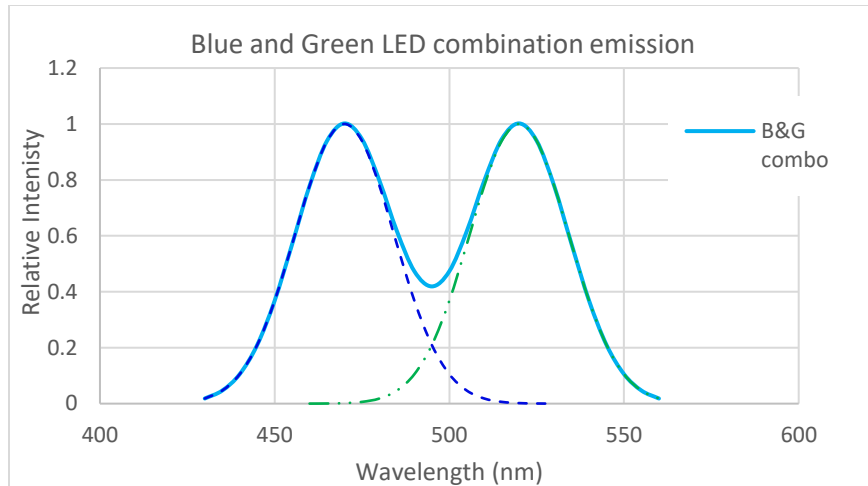
The cool white LED comes closest to providing the blue/green (actually blue/cyan) band utilized by the PCP used by most/some dinoflagellates for photosynthesis. If we fill in the 480 nm valley in the emission curve, we may get a light source more tailored to the needs of corals.

Unfortunately, a 480 nm LED turns out to be rather rare.

One solution might be to use a blue and a green led whose feet overlap. Consider this graph of Cree's XBD LED's:



One may partially fill the 480 nm valley by utilizing two overlapping LEDs (Blue and Green in the above spectral graph). However, the resulting spectrum is somewhat unsatisfactory due to the separation of their emission peaks. Here is a plot of the result of combining one blue and one green of these leds:



Another solution might be to create an LED to fill this gap by using a UVLED and coating it with a tri-calcium phosphate (TCP) phosphor to down-shift the emittance to 480 nm. An erbium-doping of TCP

Whatever means used to fill the 480nm valley can also be used (eventually) for lunar irradiance – as the general color of lunar irradiance is near cyan, as well. This necessitates a separate lunar irradiance control mechanism to be integrated with the solar illuminator. Lunar irradiance cycle and control is discussed in detail elsewhere.

The importance of circadian rhythms for corals and other marine critters

There is growing evidence that the diurnal solar cycle is a zeitgeber⁵ for various marine lifeforms. We know that phytoplankton⁶ (and probably cnidarians) sense pre-dawn and prepare themselves for photosynthesis of the coming sunlight. Accordingly, twilight cues them for switching gears into assimilating their photo-synthetically-produced nutrients and turning them to cell growth.

They cannot prepare as well if we just suddenly flip the lights on or off. Therefore, we must be inducing stress with traditional lighting – and stress is an inhibitor to growth and general well-being.

⁵ I love this word ... zeitgeber Here it is: a rhythmically occurring natural phenomenon which acts as a cue in the regulation of the body's circadian rhythms.

⁶ Anderson, R.A., "Algal Culturing Techniques", Elsevier Academic Press, 2005, pp.347-364.

