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Design and Construction of a Tunable Light Source with Light Emitting Diodes for Photosynthetic Organisms

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DESIGN AND CONSTRUCTION OF A TUNABLE LIGHT SOURCE WITH LIGHT EMITTING DIODES FOR PHOTOSYNTHETIC ORGANISMS

by

Nathan Phillipps

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Mechanical Engineering

Approved:

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ABSTRACT

Design and Construction of a Tunable Light Source with Light Emitting Diodes for Photosynthetic Organisms

by

Nathan Phillipps, Master of Science

Utah State University, 2012

Major Professor: Dr. Byard D. Wood
Department: Mechanical Engineering

This thesis describes and documents the design and construction of a light source which is tunable and has the ability to mimic the spectral output of the sun in the photosynthetic active radiation range (400 – 700 nm). To adjust the spectral output at different wavelengths different types of LEDs were chosen and combined. This thesis describes the design, construction, testing, and suggestions for further improvements to this light source. The light source is comprised of 900 LEDs with 26 different peak wavelengths within the photosynthetically active radiation range. The light source is made tunable through the use of a control system utilizing pulse width modulation. This unique light source will allow studies to be performed to understand spectral influences on microalgae and lipid production as well as other photosynthetic organisms.

(102 pages)

PUBLIC ABSTRACT

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Interest has been focused on micro algae (or algae) lately due to its potential as a renewable fuel source to help offset the petroleum diesel demand. Algae require light to grow and potentially produce lipids which are then used to make biodiesel.

Many studies have been performed to determine certain cause and effect relationships on algae lipid production. One which has not been well studied is the relationship of light spectral effects. Light has possibility to affect lipid production as well as others such as pigment adaption which would be useful to other industries. This paper is not to provide research on the effects of light on algae but rather to develop a light source to do this.

A tunable light source has been developed to perform algae experiments by illuminating photo bioreactors with different light intensities in the visible range. Such experiments will help researchers better understand light penetration. This was accomplished through a 900 LED light source with 26 different LED types.

ACKNOWLEDGMENTS

I would like to thank all those who helped in the completion of this project including family, mentors, and friends.

I would also like to thank my Father in Heaven. There were many times I struggled to find solutions to problems I encountered. Through silent prayers I was guided to the solution of these problems, which brought greater understanding and light on the subjects I was studying.

My wife, Natalie, has been both very understanding and supportive throughout this project. She has done well to understand me and gave me guidance in ways no one else could.

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Nathan Phillipps

CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

USU has spent the last decade conducting research in the biofuels and alternative energy areas. Algae have been studied as a possible solution to produce a clean renewable fuel source. As part of the research already completed, it was USU's intention to further understand the spectral effects of light on microalgae.

> **Photosynthetically active radiation** (PAR) designates the spectral range (wave band) of solar radiation from 400 to 700 nanometers that photosynthetic organisms are able to use in the process of photosynthesis. This spectral region corresponds more or less with the range of light visible to the human eye. Photons at shorter wavelengths tend to be so energetic that they can be damaging to cells and tissues, but are mostly filtered out by the ozone layer in the stratosphere. Photons at longer wavelengths do not carry enough energy to allow photosynthesis to take place [1].

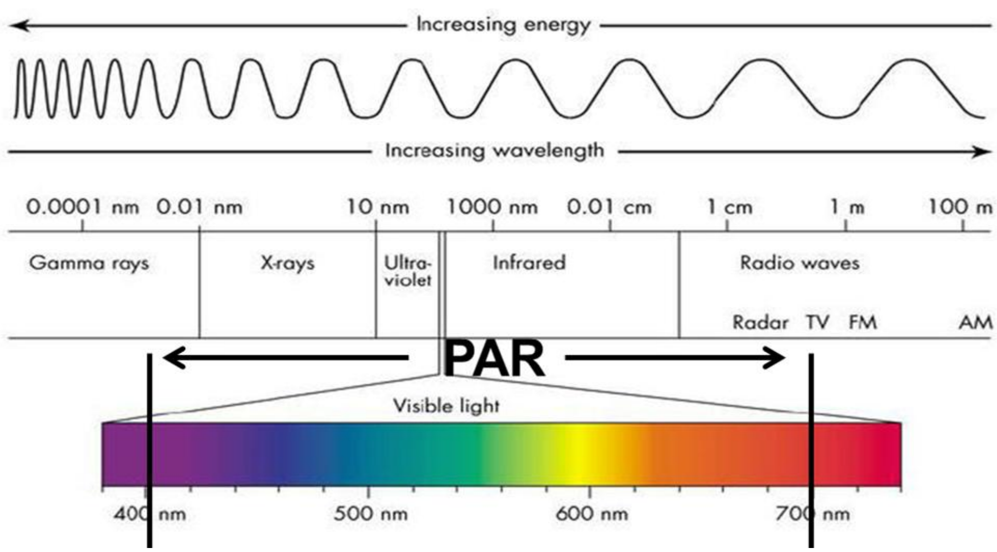

Fig. 1 Photosynthetically active radiation (PAR) range.

While it is known that light in the PAR range (Fig. 1) is required for growth, it is not well understood what effects different wavelengths of light have on algae. Some studies have indicated that providing a monochromatic light source of a particular color yielded algae pigments of the complimentary color. This pigment alteration could be significant for the cosmetic, food, and pharmaceutical industries.

USU has set forth to develop a tunable light source as a viable tool for the spectral tests on algae and other photosynthetic organisms. The primary objective of this work was to develop and characterize an LED solar simulator that could be used in the USU BioEnergy Center to study the effects of spectral light on biomass and lipid production for microalgae.

LITERATURE REVIEW

Overview

The literature review in this chapter gives a brief overview of the importance of micro algae in this research and some of the reasons why it has been a common topic as of late. This is intended to give background information to help the reader better understand the purpose in designing a tunable light source and solar simulator. A few light sources that are currently available will also be covered. The desired goals of this literature review are to perform the following:

- Give a basic understanding of why algae are being researched
- Give background information to help better understand the purpose in designing a tunable light source and solar simulator
- Provide understanding to why LEDs were chosen as the light source

Algae

Algae have surfaced again as a popular research niche. Algae have proved to provide waste water and flu gas treatment [2,3]. As of late, they are probably most well known for the extraction of lipids in a process to produce biofuels to help offset the demand for fossil fuels.

Algae are photosynthetic organisms that need light to sustain life. Whether the light source is natural or artificial, energy is released in the form of photons. Photons carry a positive charge that allows them to attract electrons in the organisms. Each photon does not carry the same amount of energy at each wavelength. More energy is associated with each photon from the ultraviolet end of the visible spectrum, and less energy from photons at the infrared end. Photons within 400-700 nm are known as the photosynthetic active radiation or PAR [4]. Algae are able to utilize the photons that are produced within this range. Many light sources claim to increase growth by simulating the sun or following the spectral absorption peaks of the pigments in the algae. According to Dr. Bruce Bugbee at Utah State University, the wavelength of the light source is of little importance for plant growth, as long as it is within the visible range. He has explained that this argument could be carried to algae being a much simpler phototrophic organism. Algae use the photons regardless of whether they come from a 400nm source or 700nm source. The amount of energy is sufficient in this range and it is the positive charge of the photon which is utilized [5].

The literature supports other possible uses and studies, which could be performed through using narrow bands of wavelengths if growth is not affected. Certain wavelengths have shown the possibility to affect lipid content as well as pigment concentrations, both of which are valuable to the military, energy, cosmetic, and pharmaceutical industries [6,7].

LED Theory

A light emitting diode, known as an LED, is a p-n junction semiconductor. LEDs have often been described as capable of generating "cold" light, referring to its low operating temperature. The 5mm LEDs usually are only 10^0 - 25^0 C warmer than the ambient temperature as opposed to an incandescent light source, which is up to several hundred degrees hotter under similar conditions.

The material used to make an LED dictates the energy of the photons leaving the diode. Each wavelength of light has a certain amount of energy associated with the photons being carried. The closer the wavelengths are to the ultraviolet range and the shorter wavelengths, the more energy the photons contain. The closer the wavelengths are to the infrared range and beyond, the less energy they contain. The greatest amount of light generated by most LEDs is around its peak wavelength [8].

Effects of Light on Algae and Uses of LEDs for Growing Algae

In speaking with Dr. Bugbee at USU, his experience has shown that the growth differences in plants are usually not from a given wavelength of light but rather from other factors, such as the light intensity, nutrition, or temperature fluctuation.

Dr. Bugbee indicated that studies have been performed with higher phototrophic organisms such as plants, where secondary compounds were produced or altered by changing such factors as light intensity, temperature, and available nutrients. There is a suggestion that perhaps a tunable light source could be used to produce more lipids or other compounds such as pigments [9]. While there is not much information in the literature about the effects of wavelengths on lipids, for better or worse, a tunable light source, if developed, could be used to study wavelength effects on lipids in microalgae strains. There is, however, more information in the literature on wavelength effecting pigments in algae. Pigments from algae benefit the food, pharmaceutical, and cosmetic industries [6].

Studies have shown that by changing the wavelengths of the light source, the algae pigments could be changed to match the complimentary color of the light source. In one journal article, algae were studied at different depths under water. Different wavelengths penetrated to different depths into the water. Hess and Tolbert showed that algae adapted to the light that was most available, taking on the complimentary color of the light available. For example, when only blue light was utilized the algae would appear yellow-brown [10].

Light intensity has also been found possibly to affect pigment concentration in algae. A paper produced by the department of Biochemistry at Michigan State University concluded that light intensity affected the rate at which the pigments changed [11].

Raceway ponds are specifically designed for growing algae. One of the difficulties in using raceway ponds however is getting enough light into the system. Algae have photoreceptors to collect photons. They are actually capable of collecting more photons than they are able to use.

This reduces the amount of photons available to other algae cells, stunting their growth. However, simply increasing the intensity to penetrate farther into the culture to provide light for more cells has a damaging effect on the photoreceptors of the algae cells and results in photo inhibition [12].

One solution that is being developed by USU is to ensure enough vertical mixing to allow proper light penetration and prevent photo inhibition. Researchers are using delta wings to create vertical currents in the raceway so that cells have the opportunity to receive light and then time to process the light [13].

Perhaps another solution for the raceway ponds would be to use varying wavelengths of light. As mentioned earlier not all light penetrates to the same depth in water. Below, Fig. 2 shows the percent of the visible spectrum for a given depth in type 5 coastal waters. The wavelength region that penetrates the deepest is within the 500-550nm range [14]. This same principle could be applied to research on raceway ponds. Transmission and absorbance tests could be performed on the algae media to determine which wavelengths penetrate the deepest. Light in this region could be increased to provide a higher photon flux deeper into the photo bioreactor or raceway pond.

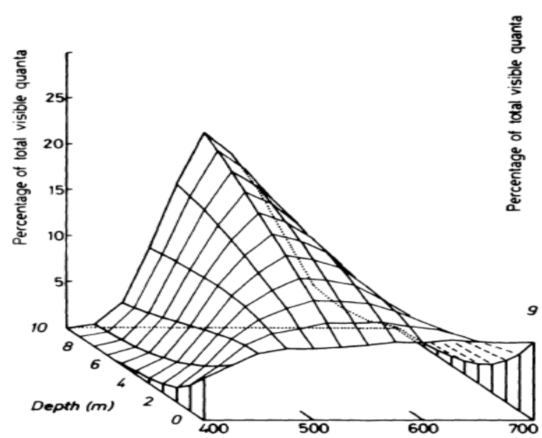

Fig. 2 Spectral distribution of light penetrating different depths (0-10m) in type 5 coastal water [14].

Pete Zemke discussed two main ways to provide the correct amount of light to the microalgae cells. They are spatially or temporally. The focus of this research uses temporal dilution that involves flashing the algae with a photon flux. The algae are exposed to light for a period. They are then exposed to the dark for a period, where they are allowed time to process the photons received. Improper timing or too many photons exposed to the algae can lead to photon inhibition. This has been previously remedied through vigorous mixing, usually performed by sparging the media with compressed air [15]. However, this can prove to be very costly on a large scale.

Often, LEDs are controlled with a pulse width modulation (PWM) which allows dimming. The PWM has the capability to change the duty cycle frequency, which simulates the temporal dilution with sparging by pulsating the LEDs. Some argue that pulsing the LEDs is more expensive and no benefit is gained from the extra cost. Others argue the contrary, that while pulsing may be more expensive, the increase in return justifies the higher cost [16]. Pulsating has the possibility of reducing the photo bioreactor sparging rate. A slower mixing rate lowers the operating cost. While some mixing is still required when using a PWM, the cost savings has direct impact on the expense of the final product [17].

LEDs were chosen for the light source experiment due to their durability, reliability, and low operating cost. Algae can only use light in the photosynthetic active range. Each LED produces wavelengths in a narrow band of light and most wavelengths can be categorized within the photosynthetic active range. Also, using LEDs as the artificial light source significantly reduces the need for the light to be filtered and for the system to be cooled [18]. Thus, LEDs are very efficient and effective light source for algae.

With such increases in light and agriculture technology, indoor farming has become a greater reality. “This use of light-emitting diodes marks great advancements over existing indoor agricultural lighting. LEDs allow the control of spectral composition and the adjustment of light intensity to simulate the changes of the sunlight intensity during the day.” [19]. The purpose of this type of farming is “With proper lighting, indoor agriculture eliminates weather-related crop failures due to droughts and floods to provide year-round crop production…" [19]. This is what scientists and engineers are trying to accomplish with algae, since one of their goals is to produce a consistent supply of fuel to help offset or replace nonrenewable fossil fuels. Many tests to grow algae indoors can be conducted with this new type of farming.

Available Light Sources

Metal halide, low-pressure sodium, and xenon lamps are all common light sources used to simulate the sun. Xenon lamps are commonly found in solar simulators because "…its spectral response closely resembles that of 5500 K sunlight especially in the visible between 400nm and 700nm" [20].

A recent solar simulator was developed and patented by Abengoa Solar that is able to mimic the sun's spectrum, or any other spectrum desired within the range of the lamps used. The devise has multiple lamps, which are used to produce a sufficient amount of intensity over a broad band of wavelengths. The light is split into wavelengths using a prism. A spatial mask is integrated into the system to act as a selective passage of certain sections of light, blocking or attenuating very specific wavelengths [21].

This patented solar simulator was designed in part to produce intensity many times greater than the sun to test photovoltaic cells. Photovoltaic cells are designed to provide electricity under a light source sometimes many times the intensity of sunlight. For the applications used at the biofuels lab however, less than full solar intensity is desired, in fact only about $1/10^{th}$ of the sun's intensity is desired [17]. A full solar simulator was not needed.

A few things not mentioned in the patent that were discussed by others include the high costs associated with operating and maintaining solar simulator lamps such as xenon. One paper discusses advantages using LEDs as a light source in solar simulators. LEDs spectrum changes very little when the intensity is dimmed. Current solar simulators do not last as long as LED lamps. Bliss et al. only utilized eight different LEDs to fill a 375-680nm range. They showed a spectrum to mimic the sun; however they did not provide a list of LEDs that would make this possible [22]. The spectrum could not be duplicated with the given information.

While such a system seems capable of producing very accurate spectrums, ultimately LEDs were chosen as a power source due to the following reasons:

- High intensity was not needed and would have been attenuated if too high
- Did not need full solar spectrum, only PAR
- Simplicity of LED circuit when compared to complexity of optical systems in the patent
- Ability to vary intensity and frequency of duty cycle already incorporated into LED circuit
- LED’s produce much less heat than conventional solar simulators
- The spectrum of the current solar simulator lamps change over time with use [23]

Some studies have been performed where frequency and duty cycle of the light source was varied while growing potatoes. Higher electrical-energy-to-growth efficiencies were achieved in this experiment/process. Studies also showed that they were able to increase growth rates over plants which used continuous lighting [24]. This supports Pete Zemke’s and Dan Dye’s findings stated in their dissertations about pulsing light and a light saturation point, respectively [15,17]. The PWM’s needed to adjust the intensity of each LED type would already be integrated into the LED circuit. The PWM’s from National Instruments would be capable of adjusting duty cycle and duty cycle frequency.

LED Testing and Verification

Once the light source was chosen, verification and testing needed to be performed to show the capabilities of the source. Two major types of measurement devices are used to measure

LEDs: photometer and spectrometer. Both instruments are designed to measure optical energy of light sources. Usually LEDs are used for a visual effect to appeal to the human eye. This is why many LEDs are classified according to dominant wavelength, which is the hue most sensed by the human eye for the given LED. However, the human eye's response is not equal throughout all wavelengths. A photometer is set up to measure the optical power as seen by the human eye. For phototrophic experiments, an absolute measurement needs to be taken to show what wavelengths, including the peak wavelength and the amounts in terms of intensity, are being made available to the biological systems.

The second device used is a spectrometer. A spectrometer has the ability to measure the intensity of light. Instead of using a broadband detector in conjunction with filtering, it takes polychromatic light and through a prism or grating separates the light into its monochromatic parts. This gives the ability to measure fully the intensity at each wavelength for a given light source. One of the difficulties in measuring LEDs occurs because not all have the same spatial distribution characteristics.

Before the light enters the spectrometer, it must be gathered. There are a few options for gathering the light. An integrating sphere is the most viable. The spectrometer is connected to the integrating sphere via fiber optic cable. Other options instead of an integrating sphere include using a goniometer or a bare optic fiber. These two devices are ideal if a radiance measurement is desired. For an irradiance measurement, which is a measurement of total flux, an integrating sphere is the easiest and quickest way to obtain the measurement [25].

To provide an accurate measurement the sphere requires a particular geometric configuration. Labsphere provides a document, "Technical Guide Integrating Sphere Radiometry and Photometry," to help users to understand the theory and proper setup and use of integrating spheres. The purpose of the integrating sphere is to diffuse the light enough so that at any point in the sphere the light appears the same. Ideally, the light flux, as well as the spectral quality, is homogenous through the sphere [25].

In order to determine a proper geometric configuration, Labsphere suggests considering these two facts when setting up equipment: the fiber optic cable that is connected to the integrating sphere should not be illuminated directly by the light source, and the fiber optic cable should not be illuminated directly by the surface on the sphere that is being directly illuminated by the source. Those suggestions are so the fiber and the spectrometer only see light that has been well diffused inside of the sphere. More detail will be given for setup and calibration of the system later in this paper.

Closing Statement

The scope of this work is not to study light effects on algae and lipid production, but rather to develop a light source for future light experiments with algae and possibly other photosynthetic organisms. From the literature review, as well as past experiments performed here at the biofuels lab, a light source was desired which could be fitted to existing reactors to perform studies comparable to those which have been previously performed. The rest of this document will discuss the objectives and requirements the light source needed to meet and how the light source was designed and verified.

OBJECTIVES

The purpose of this research was to design an LED light source that would allow further research and study on the effects of spectral light on algae. The design requirements were:

- Design and build an LED array structure to fit existing 1.5 and 3L photo bioreactors
- Design light source to be serviceable
- Utilize materials capable of dissipating heat to prevent distortion and/or damage during long periods of operation
- Select and purchase LEDs to provide light over the photosynthetically active radiation range (400-700nm)
- Produce neutral density photon flux within the 400-700nm range
    - Neutral density photon flux is defined as having equal amounts of photon flux at each wavelength over the spectrum of interest.
- Tune light source to specific wavelengths including narrow spectral bandwidths and other light source spectrums (e.g. solar spectrum) within PAR.
- Design LED array to be dimmable over its spectrum
- Verify proper function and spectral output through testing with an integrating sphere and spectrometer

Additionally, suggestions for future work will be given in the final chapter.

LED GRID

Introduction

A structure was designed and built to contain the LEDs. The purposes in designing a structure for the LEDs was more than just having an assigned location for each LED, and are as follows (not in any particular order of importance):

- Keep LEDs as close to the same distance away as possible from the photo bioreactor
- Keep the LEDs perpendicular to the surface of the photo bioreactor
- Protect them from being pushed transversely out of place
- Provide a way to dissipate heat if needed

The LED array went through a few prototypes before its current state. The final design and materials were based upon skills and capabilities of the author in order to save money and have a more intimate understanding of the project. If welding was required, steel was the preferred material, due to the difficulty in welding aluminum. Subtractive machining processes such as grinding, cutting, milling, and drilling were chosen over additive processes such as fuse deposition modeling (FDM). When machining was required, aluminum was chosen over other materials because of its light weight and ability to withstand the loads that would be applied to it. In this case, most of the load was stemming from the many 26 gauge wires coming from each of the LED leads. When the array was finished, there was over one mile of wire in the system. While most of the wire would not be supported by the LED structure, a considerable load would be transferred to it. The load was considerable, relative to the structure area, because most of the 9” x 9” area would be taken up by the LEDs, leaving a minimal amount of area for the structure after the machining processes.

A few concerns that were considered before deciding on a design were as follows. First, while the output of the array was not known at the time, it was known that the more LEDs that could reasonably fit in the structure, the more versatile the light source could be when finished. Since it was a design requirement that the light source be dimmable, the LEDs could always be made dimmer, but the peak intensity would be dictated by how many LEDs could fit in the structure. Secondly, if it was possible to fit them in this space, was it possible to remove them for service or replacement?

Prototypes

The first prototype considered was a plate system where all LED holes would be drilled into a plate. The plate would be aluminum and all holes would be machined using a CNC. The LEDs needed to stay in place in the plate so a second plate was modeled up allowing the LEDs to be sandwiched between the two plates, Fig. 4. The small lip on the LEDs would keep them in place between the plates, Fig. 3.

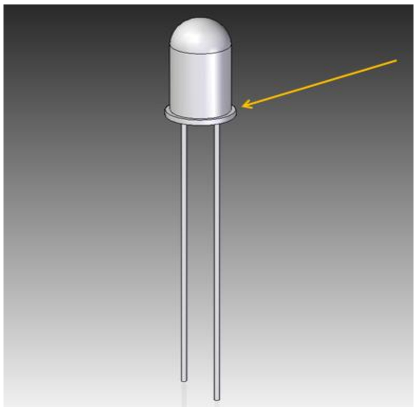

Fig. 3 Typical 5mm LED. Arrow indicates position of the lip on LED lens.

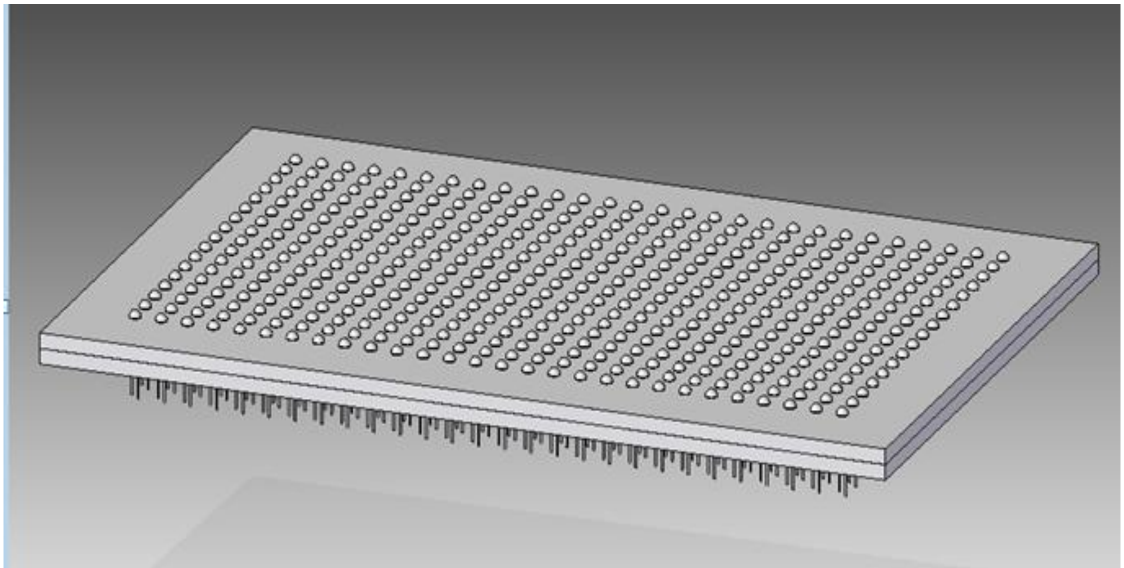

Fig. 4 First prototype utilizing two plates to sandwich LEDs in place.

Models were drawn using Solid Edge software and then converted to STL files. A rapid prototype machine converted the STL files into functional models made from ABS plastic. Before the types of LEDs were chosen, a few prototypes were made to determine approximately how many LEDs could reasonably fit in the specified space. In order to determine this, a 16-hole, LED prototype (Fig. 5) was made to check spacing and to see if the ABS plastic would provide enough structural integrity.

If the entire grid was made by the rapid prototype machine, it would have been too expensive and the model would have been too brittle to support any load. The FDM machine did not have the precision to make the holes round enough to fit the LEDs, so each hole was enlarged. However, the holes were spaced too close, which did not leave enough material to provide the required strength. To solve this problem, 900 LEDs were chosen to fill the grid. This provided enough spacing to allow sufficient material between each LED.

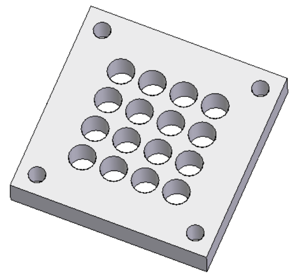

Fig. 5 16-hole LED prototype.

Then it was found that there was not enough room to insert or remove the four center LEDs when using the 16-LED grid design. This problem led to the next prototype. Instead of designing a 900-hole plate, 30 columns were fabricated, each having 30 holes (see Fig. 6), totaling 900 holes. (For complete drawing package see Fig. 33 in Appendix A) Each end of the column would bolt to an outside frame. This design would allow removal of one column at a time. Service or replacement of LEDs would be much easier with this design compared to the solid plate.

When considering which material to use, it seemed the ABS plastic would not provide enough strength. The trial was not worth making a full 9” x 9” grid out of ABS costing over $100.00 in materials. The 30- column design would use aluminum as the preferred material.

Fig. 6 Solid Edge model of 30-hole column.

An alternative design consisted of a permanent circuit that would significantly reduce the wiring in the grid. The LEDs would be soldered to the circuit. This idea was rejected, as it would not allow LEDs to be changed easily, and because of the concern of the solder breaking. Some of the same wiring problems might have arisen by using the solid plates.

Once the idea for the 30 columns was chosen, a simple steel frame was fabricated with a 9” x 9” window. Steel was chosen, as mentioned before, because it is easier to weld than aluminum.

Heat was only a minor concern for the system. Other light sources produce heat because much of the light that is released is in the form of infrared light. This is the case with incandescent light bulbs. It was not expected that the LEDs would generate significant heat, however, because they have narrow spectral bands and relatively high efficiency. Each LED is 0.25 watt. If all electricity used were converted into heat, this would result in a 225-watt heater, which would be a rather cool space heater. While this would damage LEDs and wires, the structure would not be damaged. Having an all-metal structure, especially aluminum, would also allow better heat dissipation than the ABS plastic from the FDM machine.

The small amount of heat produced would be easily controlled with a fan that was already mounted in the photo bioreactor station. Keeping the LEDs as close to room temperature as possible would allow them to maintain a constant output and extend the life of the diode.

LEDs

Research

The 5mm molded LED round lens was chosen due to its wide variety of wavelength options. It is powerful, yet small enough to fit easily into the array. Its power consumption of 0.25watt would also prevent excess heat from being generated. Higher power LEDs require some type of cooling using air fins, whether natural convection or forced air. Having the round lens also ensures that the light is semi-directional. This was desired in the design so that the majority of the light could be directed into the growth chamber.

Much time was spent seeking out information on many types of LEDs. There was not one company that manufactured all necessary LEDs for the array. This is due to the lack of materials for LED production. Most of the information available for the LEDs was only what was listed on the manufacturers' websites under the LED's specifications. This usually listed the peak wavelength, half bandwidth, and the operating conditions at which the peak wavelength was achieved. Attempts to contact companies by phone or email to gather more information, such as complete spectral data, were mostly unsuccessful. Determining the needed LEDs was an estimated guess until actual data could be acquired during testing. This was the reason 39 LEDs were tested (refer to Fig. 7), while only 25 were used in the final design. For a complete list of all LEDs acquired and their associated companies, see table 1 below.

Table 1 Complete list of all 39 LED tested with company names and product numbers included.

Company	**Product #**	**LED WV (nm)**
Riothner LaserTechnik	Not Available	350
LED Supply	L5-0-U5TH15-1	361
LED Supply	L7-0-U5TH15-1	375
Besthongkong.com	BUVC333W20UVC	380
Superbrightleds	RL5-UV0315-380	380
LED Supply	L3-0-U5TH15-1	400
Superbrightleds	RL5-UV2030	405
Digi-Key	67-2088-ND	405
Radio Shack	276-0014	405
LED Supply	L3-0-V-5TH15-1	420
Riothner LaserTechnik	LED430-06	430
LED Supply	L4-0-P5TH15-1	440

Company	**Product #**	**LED WV (nm)**
Riothner LaserTechnik	LED 450-01	450
Marubeni	L450-06	450
Riothner LaserTechnik	RLS-5B475-S	477
Superbrightleds	RL5-A9018	505
Effled	503g4sc	518
Digi-Key	754-1285	525
Superbrightleds	RL5-G8020	525
Digi-Key	C503B-GAS-CB0F0791-ND	527
Marubeni	L535-03	535
Riothner LaserTechnik	LED545-04	545
Allied Electronics	SSL-LX5093VC	550
Riothner LaserTechnik	B5B-433-014	565
Digi-Key	754-1262-ND	570
Radio Shack	276-0021	585
Superbrightleds	RL5-Y10008	588
Superbrightleds	RL5-05015	605
LED Supply	L4-0-O5TH30-1	610
Digi-Key	C503B-RAS-CY0B0AA1ND	624
Electron.com	BL-B4634	640
Superbrightleds	RL5-R2415	660
SunLED	XLZR12WF	660
Riothner LaserTechnik	ELD-670-524	670
Marubeni	L680-06AU	680
Riothner LaserTechnik	LED690-03AU	690
Riothner LaserTechnik	ELD-700-524	700
Riothner LaserTechnik	ELD-720-524	720
Marubeni	L720-06AU	720

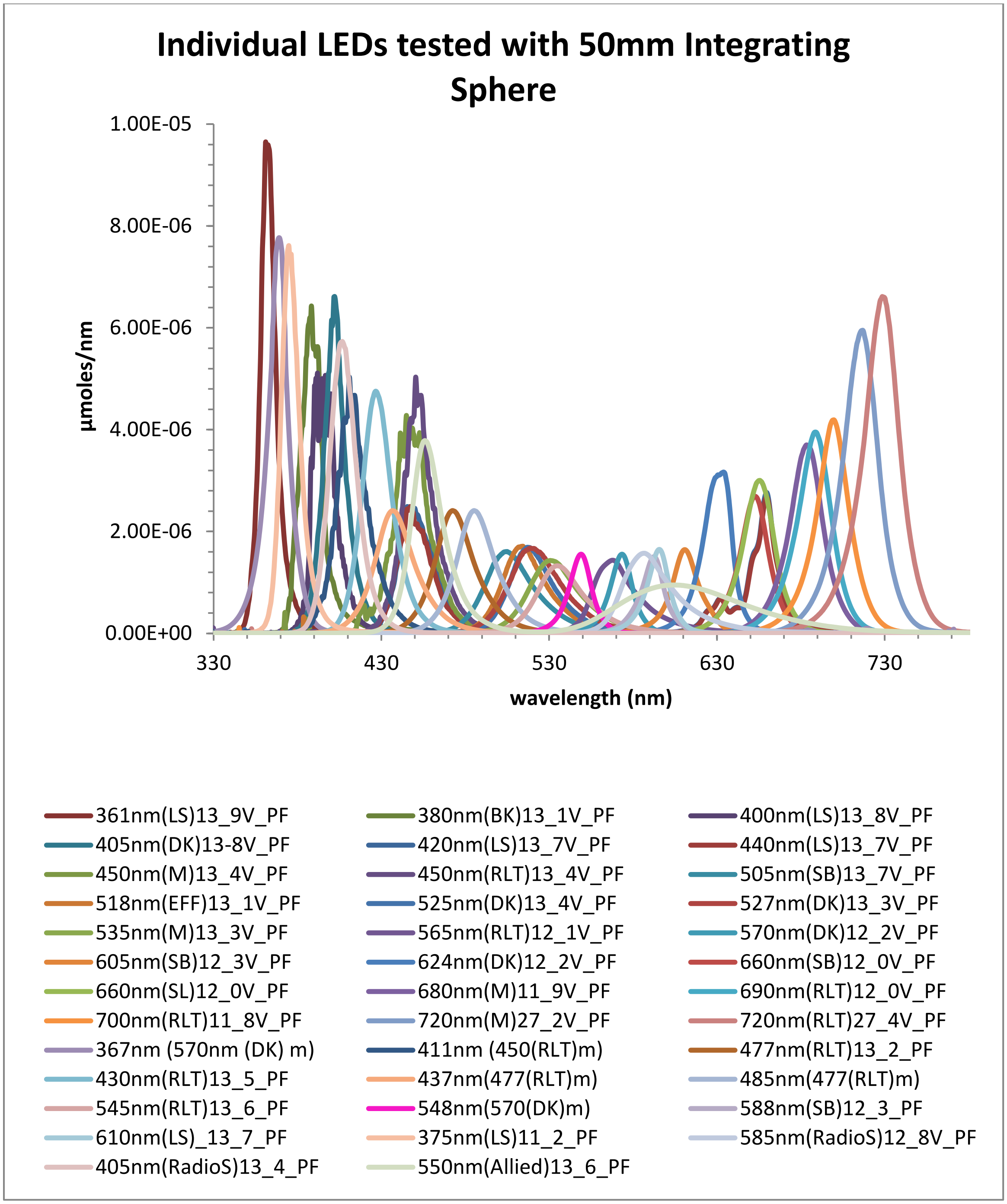

Fig. 7 All 39 LEDs tested in units of intensity (µmoles/nm) vs. wavelength (nm).

Part of the difficulty in building this spectrum is that the peak wavelengths were not quite as close as specified by the manufacturer. They were higher or lower than the nominal peak wavelength. A few voids will be noted later in this document where there was trouble in finding sufficient LEDs to fill these gaps in the spectrum.

Once a sufficient number of LEDs were tested, the results were imported into Microsoft's Excel, v.2010. The data from the tests were saved with units of (μmol/nm). Each test result was placed on the same graph to get a visual understanding of where gaps were in the spectrum.

Once all of the individual plots were made, all of the LEDs were combined using superposition. All spectral data were first cleaned up by deleting negative intensity values, since it is not possible to have a negative amount of photons leaving a light source. All LED intensities were summed up for each wavelength. This was important to do since not all LEDs have the same half-bandwidths and some LEDs have multiple peaks, such as the 420nm made by LED Supply. (It has a peak around 450nm and another one around 660nm.) The result of all combined LEDS was the experimental full spectrum; when all LEDs were on at 100% intensity this was the expected spectrum.

Each LED's specs could be slightly different from others in the same package, producing potential error. Usually only one LED was measured from each package. The results were compared with the specs given by the company (peak wavelength). If the data seemed too far off, another LED was measured to check for similar results.

<u>White Light</u>

As multiple LEDs were tested that had close but different nominal peak wavelengths it was found that, as a group they usually ended up with peak wavelengths that were very similar. This led to problems trying to fill in gaps in the spectrum. Some could not be filled, as seen in Fig. 7 with all the individual plots. Because of this, it became an iterative process to find the right LEDs and the correct amount of them to produce a neutral density of photons over the visible range. A spreadsheet was made in Excel that would allow the number of LEDs of each wavelength to be modified and would then produce the outcome of all new combined LEDs on the theoretical full spectrum.

After a number of iterations, an experimental, full-LED spectrum was developed (Fig. 8). While the line is not completely smooth, the amount of precision was respectable. If all bandwidths and intensities were more similar, the line would have had a smoother fit. This can be better understood by looking at the red and near infrared part of the spectrum. A list of LEDs and amounts used in the actual design is found in Table 2.

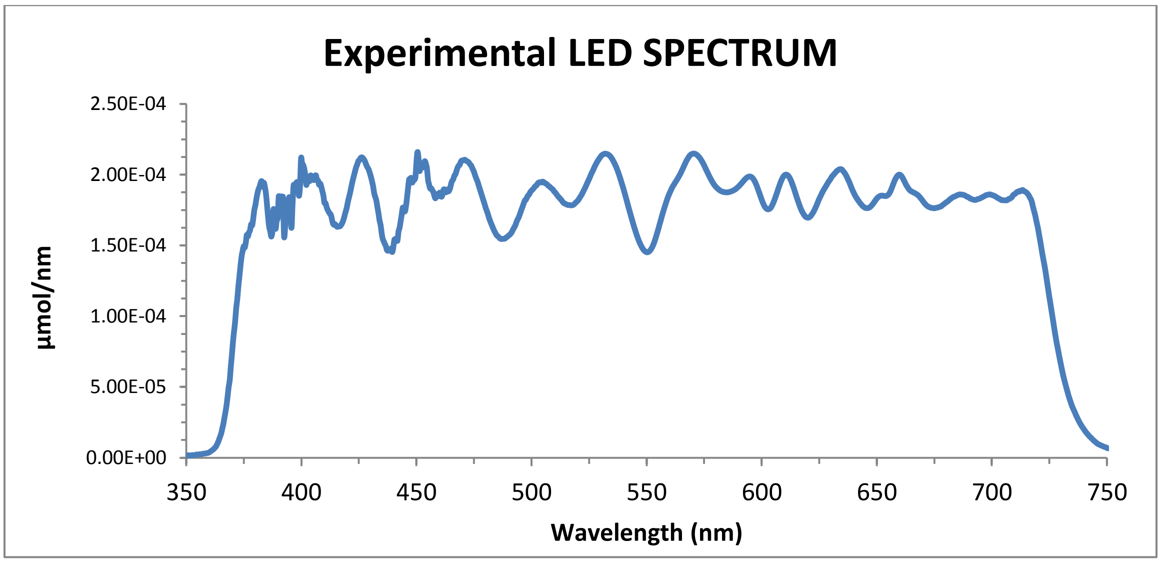

Fig. 8 Experimental Full LED Spectrum in units of intensity (µmoles/(nm)) vs. wavelength (nm).

Individual Diode Testing

To acquire the spectrums for each diode an Ocean Optics 50mm integrating sphere was used. The integrating sphere has an 8mm aperture. Small integrating spheres such as this one are advertised by Ocean Optics to measure LEDs up to 8mm in diameter. This was ideal for the 5mm LEDs used in the array.

To begin testing, one of the LEDs was pinned on a breadboard. Power was supplied to the breadboard by a variable power supply. On the LED specifications, there is usually listed a typical and maximum voltage as well as an allowable current. The typical power settings were used for the tests as found in Table 2. A few informal tests were done to see how sensitive LEDs were to their recommended maximum power setting, determining what the longevity might be if the amperage was increased passed the recommended maximum setting. Most of the LEDs seemed to be more durable than anticipated. Some LEDs were able to run five or six times the recommended amperage setting for several hours before burning out. One thing to note with LEDs is that they degrade over time, and as they wear out, they become dimmer. No tests were performed to make degradation curves for LEDs.

Table 2 LEDs used in completed array with quantity and voltage, and amperage ratings.

Company	**Product #**	**LED WV (nm)**	**Number of LEDs**	**Volt (V)**	**Amps per LED (A)**
LED Supply	L7-0-U5TH15-1	375	17	3.6	0.015
Superbrightleds	RL5-UV0315-380	380	18	3.5	0.02
LED Supply	L3-0-U5TH15-1	400	22	3.7	0.02
Radio Shack	276-0014	405	25	3.3	0.02
LED Supply	L3-0-V-5TH15-1	420	20	3.6	0.02
Riothner LaserTechnik	LED430-06	430	39	3.4	0.02
Riothner LaserTechnik	LED 450-01	450	25	3.3	0.02
Riothner LaserTechnik	RLS-5B475-S	477	70	3.1	0.02
Superbrightleds	RL5-A9018	505	96	3.6	0.02
Superbrightleds	RL5-G8020	525	5	3.6	0.02
Marubeni	L535-03	535	7	3.2	0.02
Riothner LaserTechnik	LED545-04	545	114	3.5	0.02
Riothner LaserTechnik	B5B-433-014	565	93	2	0.02
Digi-Key	754-1262-ND	570	13	2.1	0.02
Radio Shack	276-0021	585	47	2.7	0.02
Superbrightleds	RL5-05015	605	75	2.2	0.02
LED Supply	L4-0-O5TH30-1	610	43	3.6	0.02
Digi-Key	C503B-RAS-CY0B0AA1ND	624	14	2.1	0.02
Electron.com	BL-B4634	640	57	2	0.02
Superbrightleds	RL5-R2415	660	5	1.9	0.02
Riothner LaserTechnik	ELD-670-524	670	24	2.3	0.02
Marubeni	L680-06AU	680	18	1.8	0.02
Riothner LaserTechnik	LED690-03AU	690	7	1.9	0.02
Riothner LaserTechnik	ELD-700-524	700	20	1.7	0.02
Marubeni	L720-06AU	720	26	1.8	0.037

Spectrometer and Calibration Lamp

The 50mm integrating sphere was connected to an Ocean Optics HR 2000+ spectrometer via 400 micrometer 2m fiber optic cable. The spectrometer was conFig.d with Ocean Optics software, SpectraSuite.

In order to perform a test on a light source, calibration must first be performed. The system as a whole should be calibrated. This includes the spectrometer, integrating sphere, and fiber optic cable. To ensure that an accurate measurement can be taken, the calibration lamp spectrum should span the entire spectrum of the light source being measured. It is desirable that the calibration lamp have an intensity that is appropriate for the integrating sphere and similar to the light source being measured. If the intensity is too high, the light will saturate the spectrometer. If the intensity is too low, the integrating time will increase and noise will dominate the signal.

The spectrometer has an A/D converter, which takes a continuous signal (light) and converts it to a discrete signal in the form of counts. While the spectrometer is in “scope” mode it displays the number of counts given at each wavelength. The desired range is between 80-90% of the total available counts. Ocean Optics recommends using 85% as a good estimate to set the integration time if the user is setting the integration time manually. Using the equation below, one can find the recommended number of counts in scope mode for the given spectrometer.

$$(2^{bit} - 1) * .85 = counts \tag{1}$$

In our case, the HR 2000+ is equipped with a 14-bit converter.

$$(2^{14} - 1) * .85 = 13926\ counts \tag{2}$$

A calibration lamp and a lamp file supplied by Ocean Optics were used. The calibration lamp was a HL-2000-CAL. Twenty minutes of warm up time were allotted to the lamp to reach steady state. The calibration lamp was connected to the integrating sphere so that no external light would enter the sphere and interfere with the calibration.

Once the system was calibrated, individual LEDs were tested. LEDs were attached to a breadboard and powered as previously mentioned. The ambient lighting in the room was dimmed. An LED still attached to a breadboard was placed in the integrating sphere so that the full epoxy lens was inside of the sphere. This was in accordance with Ocean Optics' standard practice of LED measurement. Each LED was tested one time and the result was recorded in units of (μmoles/nm).

LED Superposition

During testing, a check was made to see if the LEDs could be combined using superposition. Two LEDs were used for this test. Each one was tested individually and the results recorded. Next, a test was performed where both LEDs were simultaneously measured. The integrating sphere only has an 8mm aperture, which slightly reduced accuracy, however it was sufficient for the purpose of the test. The LED light was directed into the aperture and all other light sources were turned off or covered so that no stray light would enter the sphere. The result was recorded and was compared with the two individual results that were combined through superposition. The two spectrums were very close. Differences can most likely be attributed to the simultaneous test not being inside of the integrating sphere and not capturing the light leaving all parts of the LED lens.

I/V Trace

The design for the LED circuit was to power all LEDS of the same peak wavelength. This would allow a group to be turned on or off and dimmed if needed. Controlling each individual LED was considered unnecessary for the purposes of the light system. This would be necessary for a light display but not for the intended experiments with algae.

In controlling each group of LEDs, it was unclear if one resistor would be acceptable for each group, or if resistors would be needed for each LED. Individual resistors would be needed if LEDs were not manufactured with similar enough specs. Some would have lower resistances thus taking more current from the overall group. These would appear brighter. There would also be the concern that they would burn out prematurely. Using a single resistor on each circuit would simplify the design since adjustments in current flow for the group could be made.

To find out if one resistor would work with a group, a current/voltage trace machine was used. At least three LEDs from each peak wavelength group were tested. All but two groups seemed acceptable. There was not a specific process for determining what was considered acceptable, but Dr. Don Cripps, Utah State University, suggested that one division's deviation, about 100mV, would be sufficient. Most of the data indicated that the LEDs would be fine using one resistor in series for each group. This would allow the use of a variable resistor.

Placement

After LEDs were chosen, their placement was determined so that the light would be as homogenous as possible when leaving the array. LEDs would be placed in a systematic order in the LED array to provide even amounts of a certain wavelength of light, see Fig. 9. This would also prove beneficial because the actual amount of liquid inside of the reactor was not considered when designing the light array, but rather the reactor dimensions. The reactor is not completely filled during operation since air and CO2 must pass through the algae media to enhance mixing and PH control. However, during assembly of the array it was found that it would be nearly impossible to put the LEDs in this order. It was not feasible to get the LEDs in place without tangling their wires. This would defeat the purpose of being able to maintain the LEDs. This would also make it difficult to find LEDs that were electrically shorting out their circuit.

545	565	505	477	605	640	585	430	545	610	565	505	670	405	605	545	565	505	477	605	640	585	430	545	610	565	505	670	405	605
477	545	720	400	565	505	640	450	585	545	680	605	477	565	505	477	545	720	400	565	505	640	450	585	545	680	605	477	565	505
430	610	545	380	420	700	640	565	505	477	545	605	585	624	375	430	610	545	380	420	700	640	565	505	477	545	605	585	605	375
670	565	505	545	610	605	477	640	430	505	565	545	405	720	585	670	565	505	545	610	605	477	640	430	505	565	545	405	720	585
605	477	505	565	545	400	450	680	640	610	605	477	545	565	505	605	477	505	565	545	400	450	680	640	610	605	477	545	565	505
430	375	585	380	420	545	640	565	505	477	605	670	700	545	610	430	375	585	380	420	545	640	565	505	477	605	670	700	545	610
624	565	505	405	585	640	545	477	605	430	565	505	720	400	545	624	565	505	405	585	640	545	477	605	430	565	505	720	400	545
450	570	605	477	565	505	640	545	585	610	680	535	525	565	505	450	570	605	477	565	505	640	545	585	610	720	535	525	565	505
545	477	605	430	670	380	505	565	545	640	405	585	420	477	605	545	477	605	430	670	380	505	565	545	640	405	585	420	477	605
565	545	505	610	720	400	430	605	477	545	565	505	640	450	585	565	545	505	545	720	400	430	605	477	545	565	505	640	450	585
700	624	545	690	565	505	477	605	610	670	545	430	640	565	505	700	624	545	690	565	505	477	605	610	670	545	430	640	565	505
680	405	585	545	477	605	380	565	505	375	400	545	720	640	610	680	405	585	545	477	605	380	565	505	375	400	545	720	640	610
477	565	505	605	545	585	430	450	420	570	565	505	545	477	605	477	565	505	605	545	585	430	450	420	570	565	505	545	477	605
640	670	700	505	565	545	610	624	585	405	477	605	505	545	430	640	670	700	505	565	545	610	624	585	405	477	605	505	545	430
680	640	375	570	720	400	545	380	535	690	660	610	420	700	450	680	640	375	570	720	400	545	380	535	690	660	610	420	700	450
545	565	505	477	605	640	585	430	545	610	565	505	670	405	605	545	565	505	477	605	640	585	430	545	610	565	505	670	405	605
477	545	720	400	565	505	640	450	585	545	680	605	477	565	505	477	545	720	405	565	505	640	450	585	545	680	605	477	565	505
430	610	545	380	420	700	640	565	505	477	545	605	585	624	375	430	610	545	380	420	700	640	565	505	477	545	605	585	640	375
670	565	505	545	610	605	477	640	430	505	565	545	405	720	585	670	565	505	545	610	605	477	640	430	505	565	545	405	720	585
605	477	505	565	545	400	450	680	640	610	605	477	545	565	505	605	477	505	565	545	400	450	680	640	610	605	477	545	565	505
430	375	585	545	420	545	640	565	505	477	605	670	700	545	610	430	375	585	380	420	545	640	565	505	525	605	670	700	545	610
624	565	505	405	585	640	545	477	605	430	565	505	720	400	545	624	565	505	405	585	640	545	477	605	430	565	505	720	400	545
450	570	605	477	565	505	640	545	585	610	680	535	525	565	505	450	570	605	477	565	505	640	545	585	610	680	535	525	565	505
545	477	605	430	670	380	505	565	545	640	405	585	420	477	605	545	477	605	430	670	375	505	565	545	640	405	605	420	477	605
565	545	505	610	720	400	430	605	720	545	565	505	640	450	585	565	545	505	610	720	400	430	605	477	545	565	505	640	450	585
700	624	545	690	565	505	477	605	610	670	545	430	640	565	505	700	624	545	570	565	505	477	605	610	670	545	450	640	565	505
680	405	585	545	477	605	380	565	505	375	605	545	720	640	610	660	405	585	545	477	605	380	565	505	375	400	545	720	640	610
477	565	505	605	545	585	430	450	420	570	565	505	545	477	605	477	565	505	605	545	585	430	450	420	570	565	505	545	477	605
640	670	700	505	565	545	610	624	585	405	477	605	505	545	430	640	670	700	505	565	545	610	624	585	405	477	605	505	545	430
680	640	375	570	720	400	545	380	535	690	660	610	420	700	450	680	640	375	570	720	400	545	380	565	690	660	610	420	700	450

Fig. 9 Homogenously mixed LED Grid. Each cell contains the peak wavelength of the LED.

Dye tests were previously performed by Ph. D student Dan Dye, the designer of the photo bioreactors, to ensure good mixing in the reactor tanks during algae experiments [17]. Since good mixing had been verified, the LEDs were then reordered for easier assembly. By placing all of the LEDs of the same peak wavelength together, the wires were better organized to prevent tangling.

A few of the individual LEDs ended up electrically shorting out groups of LEDs. Initially it was thought that groups of LEDs were bad. After further research, it was discovered that all of the current for a group of LEDs was shorting across leads of a single LED. This was where a printed circuit would have been ideal. If a random order of LEDs was needed, then the printed circuit would have been the better option since all LEDs would have been soldered on the board, thus excluding the wires for each LED.

The LEDs were organized into groups to try to ensure a homogenous output. The groups were organized in a pattern using one bank of lights near the ultraviolet range, then one in the middle of the visible range, and then one near the infrared (see Table 3 and Table 4). These groups were then placed in random order to achieve a homogenous light from each area of the spectrum. As demonstrated in Fig. 12 LEDs were semi-permanently fixed into the array with glue.

Table 3 Shows LEDs groups and regions.

Region	ID Number	Peak Wavelength	Group Number
Near Ultraviolet Region	1	375	1
	2	380	8
	3	400	3
	4	405	7
	5	420	6
	6	430	5
	7	450	4
	8	477	2
Middle of Visible Region	9	505	2
	10	525	4
	11	535	8
	12	545	1
	13	565	3
	14	570	7
	15	585	6
	16	605	5
	17	610	2
Near Infrared Region	18	624	9
	19	640	4
	20	660	5
	21	670	6
	22	680	7
	23	690	3
	24	700	8
	25	720	1

Table 4 Ordered LED according to group numbers.

Group	LED
1	375
	545
	720
2	477
	505
	610
3	400
	565
	690
4	450
	525
	640
5	430
	605
	660
6	420
	585
	670
7	405
	570
	680
8	380
	535
	700
9	624

Notice the orientation of the grid in Fig. 10. Groups nine and two are the top of the light source. These groups will enter the top of the photo bioreactor and will not be fully utilized by the algae.

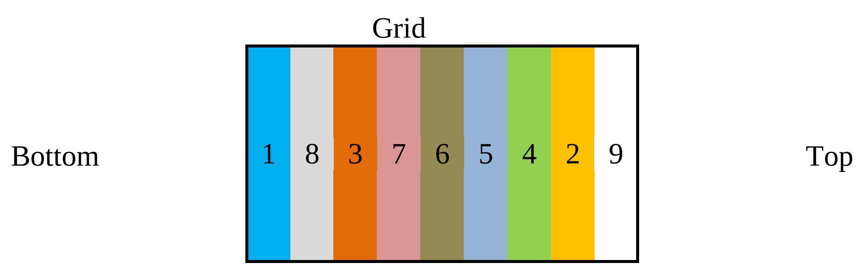

Fig. 10 Shows grid layout according to LED group numbers.

The current LED placement is found in Fig. 11 after LEDs were organized into groups.

375	545	545	545	545	720	477	477	610	505	505	505	505	565	565	565	565	450	640	640	430	605	605	660	585	585	670	570	680	700
375	545	545	545	545	720	477	477	610	505	505	505	505	565	565	565	690	450	640	640	430	605	605	660	585	585	670	570	380	700
375	545	545	545	545	720	477	477	610	505	505	505	505	565	565	565	690	450	640	640	430	605	605	660	585	585	670	570	380	700
375	545	545	545	545	720	477	477	610	505	505	505	505	565	565	565	690	525	640	640	430	605	605	660	585	585	670	570	380	700
375	545	545	545	545	720	477	477	610	505	505	505	505	565	565	565	690	525	640	640	430	605	605	420	585	585	670	570	380	700
375	545	545	545	545	720	477	477	610	505	505	505	505	565	565	565	690	525	640	430	430	605	605	420	585	585	405	570	380	700
375	545	545	545	545	720	477	477	610	505	505	505	400	565	565	565	690	525	640	430	430	605	605	420	585	585	405	570	380	700
375	545	545	545	545	477	477	477	610	505	505	505	400	565	565	565	690	525	640	430	430	605	605	420	585	585	405	570	380	700
375	545	545	545	545	477	477	477	610	505	505	505	400	565	565	565	450	640	640	430	430	605	605	420	585	585	405	570	380	700
375	545	545	545	545	477	477	477	610	505	505	505	400	565	565	565	450	640	640	430	430	605	605	420	585	585	405	570	380	700
375	545	545	545	545	477	477	477	610	505	505	505	400	565	565	565	450	640	640	430	430	605	605	420	585	585	405	570	380	700
375	545	545	545	720	477	477	477	610	505	505	505	400	565	565	565	450	640	640	430	430	605	605	420	585	670	405	570	380	700
375	545	545	545	720	477	477	477	610	505	505	505	400	565	565	565	450	640	640	430	430	605	605	420	585	670	405	570	380	700
375	545	545	545	720	477	477	477	610	505	505	505	400	565	565	565	450	640	640	430	430	605	605	420	585	670	405	680	380	700
375	545	545	545	720	477	477	477	610	505	505	505	400	565	565	565	450	640	640	430	605	605	605	420	585	670	405	680	380	700
375	545	545	545	720	477	477	477	610	505	505	505	400	565	565	565	450	640	640	430	605	605	605	420	585	670	405	680	380	700
375	545	545	545	720	477	477	477	610	505	505	505	400	565	565	565	450	640	640	430	605	605	605	420	585	670	405	680	380	624
545	545	545	545	720	477	477	610	610	505	505	505	400	565	565	565	450	640	640	430	605	605	605	420	585	670	405	680	380	624
545	545	545	545	720	477	477	610	610	505	505	505	400	565	565	565	450	640	640	430	605	605	605	420	585	670	405	680	380	624
545	545	545	545	720	477	477	610	610	505	505	505	400	565	565	565	450	640	640	430	605	605	605	420	585	670	405	680	535	624
545	545	545	545	720	477	477	610	610	505	505	505	400	565	565	565	450	640	640	430	605	605	605	420	585	670	405	680	535	624
545	545	545	545	720	477	477	610	610	505	505	505	400	565	565	565	450	640	640	430	605	605	605	420	585	670	405	680	535	624
545	545	545	545	720	477	477	610	610	505	505	505	400	565	565	565	450	640	640	430	605	605	605	420	585	670	405	680	535	624
545	545	545	545	720	477	477	610	610	505	505	505	400	565	565	565	450	640	640	430	605	605	605	420	585	670	405	680	535	624
545	545	545	545	720	477	477	610	610	505	505	505	400	565	565	565	450	640	640	430	605	605	605	585	585	670	405	680	535	624
545	545	545	545	720	477	477	610	610	505	505	505	400	565	565	565	450	640	640	430	605	605	605	585	585	670	405	680	535	624
545	545	545	545	720	477	477	610	610	505	505	505	400	565	565	565	450	640	640	430	605	605	605	585	585	670	405	680	700	624
545	545	545	545	720	477	477	610	610	505	505	505	400	565	565	565	450	640	640	430	605	605	605	585	585	670	405	680	700	624
545	545	545	545	720	477	477	610	610	505	505	505	565	565	565	565	450	640	640	430	605	605	605	585	585	670	405	680	700	624
545	545	545	545	720	477	477	610	610	505	505	505	565	565	565	565	450	640	640	430	605	605	660	585	585	670	405	680	700	624

Fig. 11 Reorganized LED array. Each cell contains the peak wavelength of the LED.

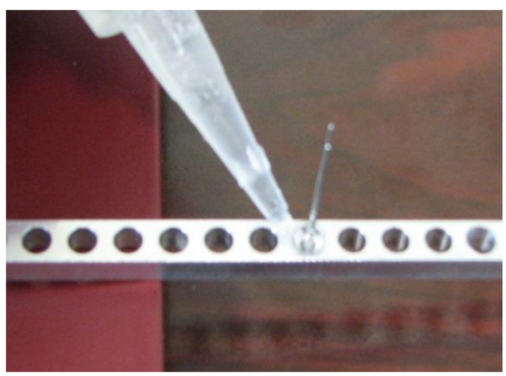

Fig. 12 Process of gluing LED in position.

Hardware

PWM

To make the LEDs tunable, pulse width modulation (PWM) was used. Essentially, a PWM is a switch that turns on and off. The PWM varies the duty cycle of the power supply. The duty cycle is the ratio of time that the power is on, to the available amount of time. At full intensity the duty cycle is 100%; power is applied continuously for the entire available time. If a duty cycle of 10% is used, the power is applied for one-tenth of the time. The frequency of the duty cycle can be high enough that the LED appears to be on continuously, even though in reality it is pulsing. Manual dimmers on the LED banks were considered. This would have provided an inexpensive solution to tune the spectrum. This solution, though initially inexpensive, would have been costly in terms of time if adjustments were needed. It would have been very difficult to reproduce the same results twice. It was decided that it would be better to control the LEDs with a computer controlled pulse width modulation device. After considering the options for which device to select, National Instruments' PWM 520 was chosen, Fig. 13.

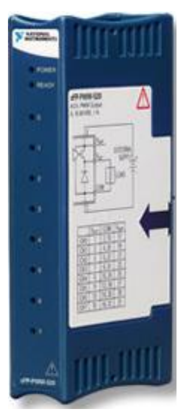

Fig. 13 National Instruments PWM 520.

National Instruments' PWM 520 has eight channels, each capable of allowing one amp per channel to be modulated. Four PWMs would be needed, which would provide 32 channels and a maximum capacity of 32 amps. Table 2 shows the nominal amounts of the amperage settings (except for Marubeni's 720nm LED which had to be lowered from 50mA to 37mA to be able to use only four PWMs instead of five) for each LED. Then by multiplying the total number for each type of LED, the total nominal amperage demand was found to be 18.4 amps. This was well within the 32 available amps.

As mentioned before, the Marubeni's 720nm LEDs could operate with 50mA. Even though the four PWMs would allow a total use of 32 amps, this presented the problem that the power from each channel could not be lent to other channels. If one channel did not use its full one amp capacity the remaining amperage could not be transferred to another channel. Therefore, the Marubeni 720nm LEDs were lowered to 37mA. Doing so would allow the most amount of current (about .962 amps in the channel) to each LED without exceeding one amp for that specific channel.

The PWM's were connected to the power supply using a cFP-180x chassis. The power supply chosen was a NI PS-15. The chassis provided a way for the PWMs to communicate to a PC using Measurement and Automation Explorer (MAX) in LabVIEW. The PWM 520 is a field point product. If the computer source is ever disconnected, the control system will continue to operate as last instructed.

Miscellaneous Hardware

To connect the LEDs with the computer, other miscellaneous hardware was needed. Panduit pressure terminal connectors (BS22-M) were used to crimp the LEDs with the wires. Twenty-six-gauge stranded wire was used to connect the LEDs to the connector blocks. The connector blocks were manufactured by Brumall Manufacturing Corporation (AS-K1-H4). Fourteen-gauge stranded wire was used to connect the connector blocks to the PWMs.

Wiring LEDs

Once all of the LEDs were chosen, they were separated into their respective peak wavelengths. The LED leads were cut to a length of 0.25 of an inch. Butt splice connecters were crimped on the cut leads of the LEDs. The wire crimps were chosen over soldering because it was thought that there might be some unintentional pulling on the wires and LEDs. Crimping would provide a more secure bond than soldering. Another benefit of using crimps over soldering is that it would expose the LEDs to less heat.

The 26-gauge stranded wires were cut into four-foot sections. The wire insulation on one end was stripped 0.25 of an inch back so that it could be placed in the uncrimped end of the butt connector. White wire was designated for the anode of the LED and brown for the cathode. Color coordinating this way eliminated power connection confusion during assembly. The wire was then placed in the butt connector and crimped with the modified pliers. Shrink tube was cut into one-inch sections so it could be slipped over the crimped connector. Shrink tube was used to prevent the two LED leads from being pushed together and electrically shorting out. Once the shrink tube was slipped over each end of the connection, a heat gun was used on its low- to mid-range temperature setting to induce material shrinkage. It was important to limit the heat-affected zone of the LED by focusing as much heat as feasible toward the shrink tube.

Connector block. LEDs of the same peak wavelength were then combined in groups of 15-20. The insulation at the opposite end of the 4-foot wires was stripped back 0.5-0.75 of an inch. The group ends were twisted together and inserted into one of the holes in the connector block. The setscrew was tightened down on the connector block hole to hold the wires in place. Once all groups of wires for each peak wavelength were secured in the connector block, the connector block was clamped down to the table. Electrical tape was wrapped around each group of wires to secure them further. This was done to prevent tangling of the wires and to help dissipate the force that might be applied to one wire. This would also prevent individual wires from pulling out of the connector blocks or, more importantly, the LEDs.

Fuses and fuse blocks. Once all LED groups were wired and connected to the connector blocks (note: there were two connector blocks per PWM channel, one for the cathode side and one for the anode), 14-gauge stranded wire was used to connect the PWMs to the connector blocks. One-amp fuses were placed before the PWM to protect them from electrical surges above one amp.

Resistors. Variable resistors were chosen because it was unclear what the total impedance of the complete circuit would be. Variable resistors were placed in the circuit before the fuses. Since the resistance was not known for the rest of the circuit, rough estimates of the correct resistors were used.

Estimates of the resistors were determined for each circuit. Target set points for the allowable current in each circuit were needed. To find the target, the amount of current each individual LED in the circuit would draw was added together. Since the sensitivity to damage for each of the LED circuits was not known, the current set point was chosen conservatively. It was feared that if some LEDs drew more current than others did in the same circuit, they would burn out in a much shorter period. The target set point was 84% of the typical amperage value. There was no specific reason for choosing 84%, other than it was deemed conservative, yet still allow enough current to the LEDs to demonstrate their capability without too much dimming. The current for each circuit was then adjusted until it was as close to the set point goal as the variable resistor tolerance would allow. Some resistors would increase or decrease the current drawn in discrete steps rather than the desired continuous adjustment.

The amount of current allowed to flow through the circuit was set as a ratio to the typical current, and then turned into a percentage. The typical value was the typical current stated by the manufacture. The value was near 84%. Since all LEDs would not be at their respective typical value, it was decided they should all be set to 84% to remain similar and not skew the data by allowing some bands to have more relative power than others.

Resistors were set by measuring the amount of current flowing through each circuit. A multimeter was connected in series with the circuit, after the variable resistor, to check the amount of current flowing to the LEDs.

Power supply. One power supply was used to power all LED circuits. Made by Mean Well, the voltage regulated power supply was set for 5VDC and up to 20 amps, Fig. 14. The power supply was also equipped with a voltage adjustment screw.

Fig. 14 Mean Well 5V 20-amp voltage regulated power supply.

METHODS: CHARACTERIZATION OF LED ARRAY WITH 40-inch SPHERE

Background

The Space Dynamics Lab (SDL) near Utah State University's main campus was gracious enough to let us use their 40-inch integrating sphere made by Labsphere to perform spectral tests on the LED array.

The original purpose for the sphere when SDL purchased it was to be used as a lambertian light source. The sphere was coated on the inside with a highly reflective coating that was designed to diffuse the light inside of the sphere. It had a variety of lamps mounted inside of the sphere to produce different spectrums and intensities of light. It also had a 14-inch aperture where light would leave the sphere with nearly equal photon flux in all directions, thus becoming a lambertian light source.

Utah State University's intention for the sphere was to provide a means to take light entering the sphere and create a homogenous mixture of all the light. LEDs have strong directional light distributions, which can be neglected during measurement while using an integrating sphere. Since the light becomes diffuse, the directional properties of the LEDs are removed. This allows a fiber optic cable placed in a stationary location on the sphere to view the output of the entire LED array.

To use the sphere to take irradiance measurements required a few adjustments to the sphere that will be discussed later in this chapter. Essentially most of the sphere would have remained the same if SDL had Labsphere originally build the device, for taking irradiance measurements. The internal coating mentioned earlier was Labsphere's Spectraflect Diffuse Reflectance Coating [26]. This coating was recommended for the ultraviolet, visible, and near infrared regions of light. According to Labsphere the coating reflectance was >99% in the 400-1100nm range, with an effective spectral range of 350– 2400nm [26]. The spectrometer from

Ocean Optics was designed for the wavelength range of 350-1050nm, well suited for the range of the coating and for the desired measurement spectral range.

Labsphere indicated that the lamps and the mounting hardware inside of the sphere would create reflective disturbances on the inside surface of the sphere. The reflectance of these surfaces was not the same as that of the Spectraflect coating. This was a concern for USU, causing them to consider purchasing an Integrating Sphere. However, purchasing a large sphere with all supporting equipment far exceeded the budget of the project. For those reasons, it was decided to use SDL's integrating sphere.

Preparation in Testing

The aperture on the 40-inch sphere measured just less than 14 inches in diameter. This turned out to work very well for the spectral measurements, since the LED array was only 10.5 inches square and the entire array and calibration source fit in the aperture. Initially, Labsphere and Ocean Optics advocated that the LED array be placed inside of the sphere during measurements to capture all light leaving the array. They reasoned that if the array were butted up to the aperture of the sphere, stray light would enter and exit the sphere, skewing the results. However, it was USU's desire to keep the LED array outside of the integrating sphere for a few reasons.

Not all of the light that leaves an LED leaves out the front of the lens, some of the light exits out of the back of the LED. In an algae light experiment this light would not enter into the photo bioreactor. The data from the integrating sphere tests would be incorrect if all light leaving the LEDs were measured. Through collaboration between USU and Labsphere, it was decided that accurate spectral tests could be achieved with the LED array outside of the sphere if an adapter plate was fitted to the sphere and array.

Another issue was that if the LEDs were placed inside of the sphere, the device would still have the wires and frame attached. This would further disrupt the reflectance of the light inside of the sphere. The wiring would still have to exit the sphere, since the entire system of wiring, fuses, and PWMs would not fit inside of the sphere. The aperture where the wiring would exit would allow some of the light to escape. This was obviously very impractical.

Setup

Adaptor Plate

An adaptor plate was fabricated to minimize light leakage out of the sphere, Fig. 15. The plate was designed so that it would fit the LED array and the calibration lamp. The plate was made from 16-gauge steel sheet metal. Six holes were drilled into the plate so it could mount up to the sphere in the same position as the factory cover. As previously mentioned, the inside of the large sphere was coated with Spectraflect, so the inside surface of the adapter plate also needed to have similar reflectance characteristics to match the integrating sphere. Labsphere gave instructions to coat the plate with high temperature white paint. While this coating was not the same as Spectraflect, Labsphere assured us, based on tests they had performed using the white paint, it would be sufficient for our measurements.

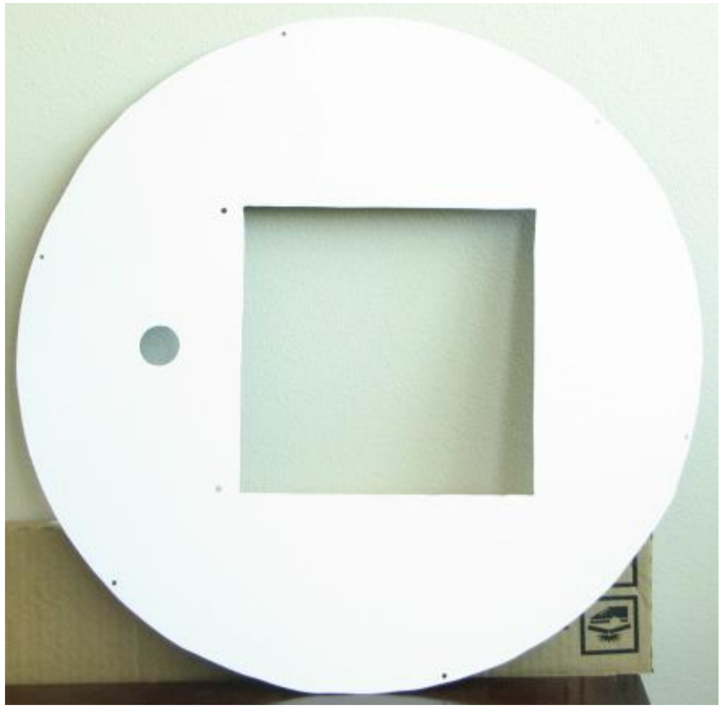

Fig. 15 Inside of adaptor plate to match integrating sphere diffuse surface.

Labsphere also instructed that the system remain unchanged during testing and calibration. Any physical changes to the system would change the way the light would be seen by the fiber optic cable and spectrometer. The calibration was performed to help reduce and factor out imperfections or differences between systems. If the system changed after the calibration was performed, it would nullify the calibration. The presence or lack of presence of an object changes the system, so if the calibration source or the LED array were not present during calibration or testing, the spectrum would not be valid.

An initial test was performed with the adaptor plate to make sure that all positions across the area of the sphere's aperture would gain equal results. Five 5mm holes were drilled into the adaptor plate. Four of the holes represented the approximate four corners of the LED array. The fifth hole was directly in the center. A test was conducted where one LED was taken and put in one of the five holes in the adaptor plate. The adaptor plate was then attached to the large sphere. The Ocean Optics spectrometer was also connected to the large sphere. The LED was turned on and a measurement was taken with the spectrometer. The LED was then moved to one of the remaining four holes and another measurement was taken. This process was repeated for all five holes. It was noted that the reading taken by the spectrometer was affected by the location of the LED. The lower right hand hole proved to be the most intense reading. This was because there was a direct line of sight from the LED just under the baffle.

A baffle was located inside of the sphere above where the fiber optic cable was connected. This was to prevent the fiber from seeing the light source directly. However, the lower corner of the LED array was low enough that light could enter underneath the baffle and its light, not fully diffused, could be seen by the fiber optic cable. An addition to the baffle was made as discussed below.

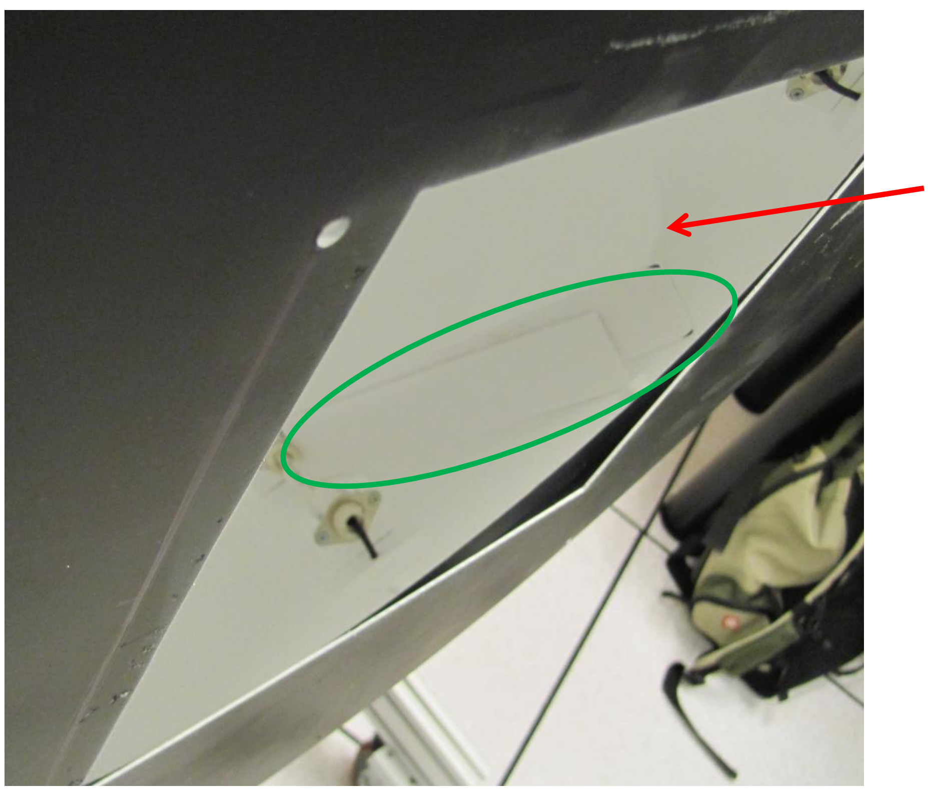

Fig. 16 Looking into 40-inch integrating sphere through adaptor plate. The red arrow indicates position of Labsphere’s installed baffle. Green oval indicates position of the two rectangular pieces over one side of the baffle.

Baffle addition

Labsphere recommended that the fiber should never be exposed to the source or the first reflection of light, for the light is not yet properly diffused at this point. To remedy this, two rectangular pieces of foam were laid against the baffle (Fig. 16). The adaptor plate test was repeated for all five holes, which verified that the solution worked.

6.25-inch Integrating Sphere

To perform the calibration of the system, a light source of known output was needed. SDL provided us with a small integrating sphere, which was used as the calibration lamp for the integrating sphere system (refer to Fig. 17 for integrating sphere schematic).

The 6.25-inch integrating sphere was coated with Spectralon and had a 75W tungsten halogen lamp inside of the sphere for the light source. It produced a high intensity lambertian light source out of the one-inch exit port, which provided a sufficient calibration light source, as far as the intensity was needed, for the sphere and spectrometer combination.

It was not ideal to use an integrating sphere as a calibration source. During operation, light would enter the 40-inch integrating sphere from the calibration source or the LED array. Some of the light would be transferred back into the 6.25-inch integrating sphere, and a fraction of that light would then return to the larger sphere. This problem was deemed minimal because of the one-inch aperture of the 6.25-inch sphere relative to the 40-inch sphere. Calibration of the system also helped to render the influence of the two spheres on one another as insignificant as well.

The 6.25-inch integrating sphere was calibrated in July 2011 by Labsphere. For fear of unknown degradation of the lamp, SDL attached a detector with a filter wheel to the sphere. After the sphere was first calibrated by Labsphere, the detector and filter wheel assembly were attached to the sphere and spectral measurements were taken. These values were stored and every time the integrating sphere was turned on, the spectrum was monitored by the detector and filter wheel. The detector and filter wheel system had to be removed while the sphere was attached to the adaptor plate, but values were checked before and after the LED tests were completed and the lamp was still well within acceptable range according to SDL.

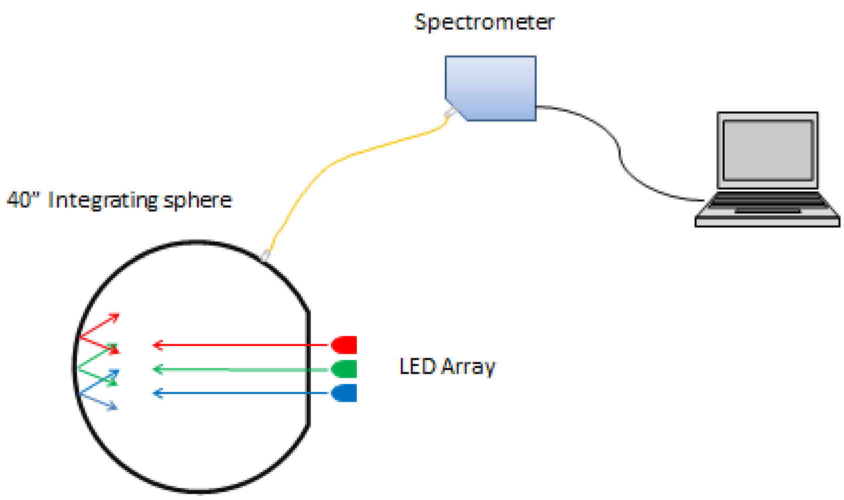

Fig. 17 Schematic of spectrometer and 40-inch integrating sphere system.

<u>Excel file modification</u>

The 6.25-inch sphere was calibrated in July 2011 by Labsphere, which also included a file of the calibration data. The calibration was measured as a spectral radiance with units of:

$$\frac{mW}{cm^2 * sr * um} \tag{3}$$

To be able to use the sphere as a calibration source, a lamp file had to be made. Following the directions from Ocean Optics a notepad file was created. The units of measurement had to be changed to be acceptable to the spectrometer software from Ocean Optics, SpectraSuite

[27]. Ocean Optics and Lapsphere were also contacted to help with the unit conversion, from spectral irradiance to:

$$\frac{uW}{cm^2 * nm} \tag{4}$$

The difficultly came when trying to convert the steradians. Through communicating with Labpshere, and Ocean Optics, it was determined that the solid angle that was leaving the sphere was π steradians. However, in talking with SDL, this was incorrect. The solid angle is calculated when the light source is treated as a point source. Instead, the projected solid angle was calculated. This was calculated since it was actually the throughput of the sphere that was desired; the cross sectional area of the aperture multiplied by the projected solid angle. The cross sectional area had already been included in the conversion thus far and it was the projected solid angle that was necessary to convert the steradian value as seen in Eq. (5).

$$\Omega = \int \cos\theta \, d\omega = \pi \sin \Theta^2 \tag{5}$$

Below, in Fig. 18, a top view of the 6.25-inch integrating sphere is shown with the 1-inch exit port or aperture. To convert the Excel file from SDL, the available angle coming from the sphere's aperture needed to be determined (see Fig. 18 and Fig. 19), and this angle plugged into Eq. (5) to find the projected solid angle.

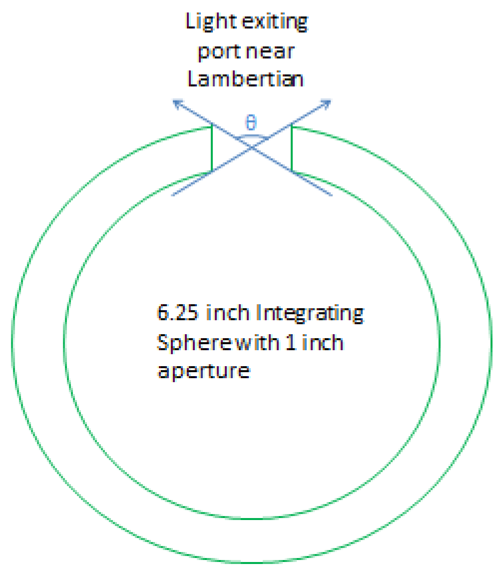

Fig. 18 Top view of 6.25-inch integrating sphere.

To calculate the angle leaving the aperture Eq. (6) was used.

$$\Theta = 180 - 2 * \alpha \tag{6}$$

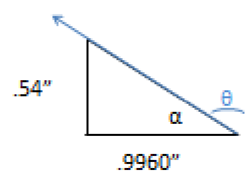

Fig. 19 Right triangle used to calculate angle of light leaving 1-inch aperture.

The aperture was measured with a pair of digital calipers. The diameter and depth of the aperture was also measured. A simple right triangle was drawn to calculate alpha. The opposite leg of the triangle was the depth of the aperture while the tangent leg was the full diameter of the aperture. Alpha and theta were found to be respectively 28.465^{O} and 123.07^{O}. The theta used in Eq. (5) is at most a quarter-sphere or 90^{O}, which means the angle used is half of 123.07^{O} or 61.535^{O}. The projected solid angle was then calculated and found to be 2.428 steradians. The

Excel file that SDL sent was modified and then saved in Notepad as an .lmp file. The .lmp (lamp) extension was necessary to help the software recognize the file as the calibration lamp file.

Once the system was set up for calibration and measuring, it was not disassembled or further altered. Although there was not continuous surveillance of the system, the recording of the system was believed to remain undisturbed for the duration of the tests over a several week period. The system was stable in its position.

Calibration and Testing

Preparation

The 6.25-inch integrating sphere was equipped with a 75W tungsten halogen lamp. The lamp was allowed 30 minutes to reach steady state to ensure that the calibration was performed the same way each time.

While the lamp was warming up, the spectrometer was connected to the computer, and the fiber optic cable was attached to both the spectrometer and the 40-inch integrating sphere. The Field Point DAQ was connected to the computer through an Ethernet connection. All other power supplies were plugged in and turned on. Ocean Optics' SpectraSuite and LabVIEW's Measurement and Automation Explorer were opened up to allow all devices to be recognized.

Ocean Optics

After 30 minutes, the calibration source had reached steady state conditions. The spectrometer was connected to both the 40-inch integrating sphere and the computer. The integrating sphere connected to the spectrometer via 400-μm fiber optic cable and the computer via USB. SpectraSuite was opened, the integrating time was acquired, and the light and dark spectrums were obtained. The calibration file was loaded and saved. See Appendix B for print screens and a more detailed setup of the software.

Each LED light bank was then measured independently so that the correct integration time was used for each light source. Three different PWM settings were measured for each light bank: 100%, 75%, and 50%. Measurements with duty cycles below 50% were not taken because the signal for many of the banks was too dim and the integration time was high enough that noise became an issue. The different PWM settings were measured to determine if there was a linear relationship between the duty cycle and the output of the LEDs. If this were true, new spectrums in Excel could be devised to see how versatile the array was without having to perform all of the tests. Triplicates of all measurements were taken.

It should also be noted that the sample frequency of the spectrometer was not considered. The frequencies of the LEDs did not need to be reproduced. Only the mean output was needed, and to determine a standard deviation. Therefore, the frequency of the sampling rate was not important, other than the integrating time, which needed to be fast enough to take a measurement without saturating the spectrometer, yet slow enough to capture the full signal of the light source. As mentioned before, that was performed by the software to obtain the 85% of available counts.

File modifications

Once measurements were taken with the integrating sphere system, results were saved as text files and later imported into Excel. Then, superposition was used to combine all LED files tested for a specified duty cycle test. Measurements in units of power (μW/nm) and photon (μmol/nm) were saved for each test. Power files were saved as a way to compare data with the photon files in case of glitches. For biological experiments, photons are what matter most as a way of quantifying sufficient light supplied. The desired units were in photon flux (μmol of photons/(nm*m^2*s)), or more commonly used (μmol/(nm*m^2*s)). Initial tests and LED choices were based upon the units of (μmol/(nm)). Later, units of (μmol/(nm*m^2*s)) were used during testing to be comparable and understood for biological experiments.

When the software saved data for the photon files it saved the total number of photons measured at a given wavelength over the total integration time, so two banks of LED circuits might appear to give the same results. One circuit may be putting out less photon flux but have a higher integration time, while another circuit might a higher flux with less integration time. The two saved files would give similar results. To give an accurate comparison the integration time was divided out. The photon spectrum files were also divided by the area of the array to give the same units as many other light sources.

The sun's spectrum, as well as other quantified light sources used in biological experiments, has units reported in (μmol/(nm*m^2*s)). The functioning part of the LED array measures 0.05226m^2. This included the area of the LED field where the actual lamps were visible, which was the 9"x 9" window mentioned previously. It did not include the steel frame (painted black in Fig. 20) around the functioning part of the array.

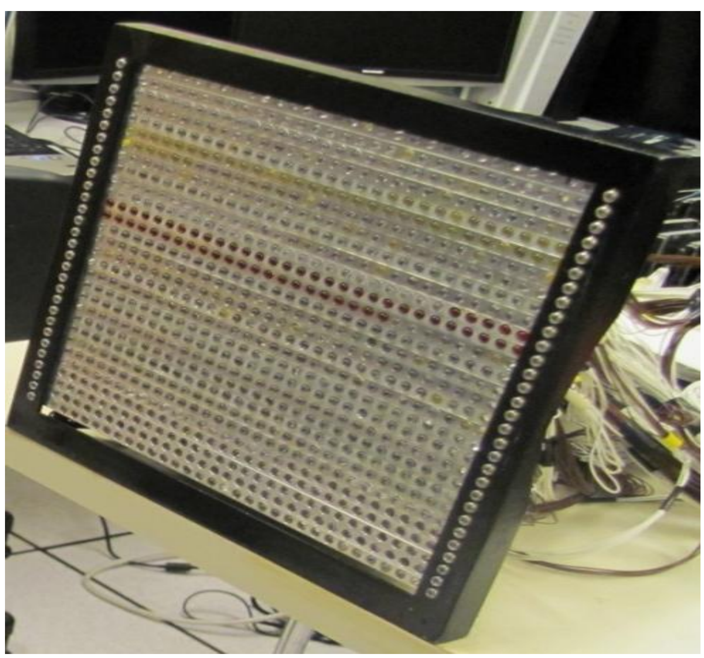

Fig. 20 Front of LED array with all 900 LEDs visible.

LabVIEW's Measurement & Automation Explorer

LabVIEW's Measurement and Automation was the software required to run the Field Point DAQ, which controlled the LED array. Once the software initialized, the DAQ was accessed through the "remote systems" tab. Devices were found and the duty cycle was written for the specified channel. See Appendix B for print screens and a more detailed setup of the software.

METHODS: CHARACTERIZATION OF LED ARRAY WITH 50mm SPHERE

Background

After tests were completed with the 40-inch sphere, it was necessary to ensure that the tests were indeed correct and comparable to those first completed with the 50mm sphere. When initial tests were performed with the 50mm sphere, individual LEDs were placed inside of the sphere. While this provided the total output of the LED, this was not the measurement needed. As mentioned before and performed with the 40-inch integrating sphere tests, only the forward flux of the LED was to be measured since this is what would enter a photo bioreactor. Those tests resulted in lower total output but were more accurate in terms of light entering the photo bioreactor.

Setup

<u>Aperture distance</u>

One concern with using the smaller sphere was that a significant amount of the signal would not enter the aperture, being only 8mm in diameter. A simple calculation was performed to verify the amount by taking the widest half angle of 20^{O}. A right triangle with a 20^{O} angle was drawn, with the adjacent leg of the triangle measuring 4mm and the opposite leg being the unknown length, representing the maximum allowable distance between the LED lens and the back of the integrating sphere aperture. (The aperture had a thickness, which needed to be taken into account, of 2.58mm.) It was determined that the maximum distance away from the LED that the aperture could be was 8.41mm (see Fig. 21 and Fig. 22).

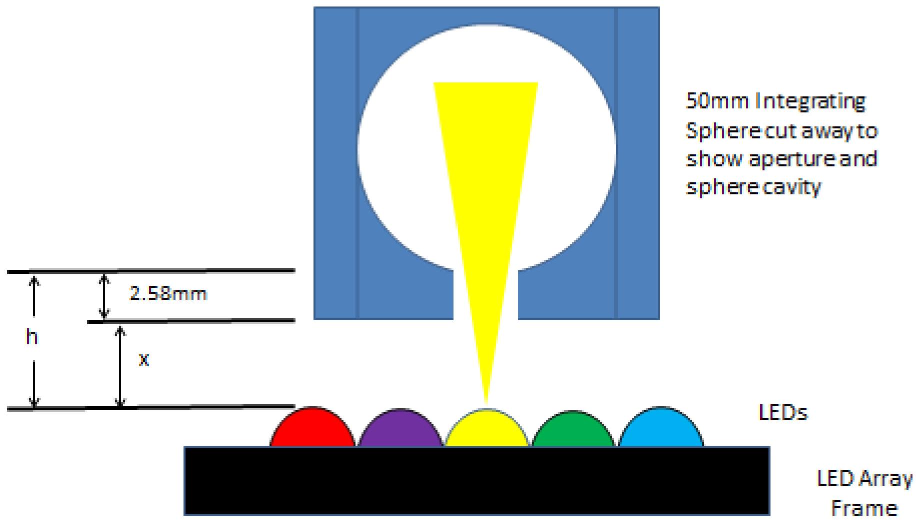

Fig. 21 Schematic of 50mm integrating sphere and LED array to determine maximum allowable distance between integrating sphere and LEDs.

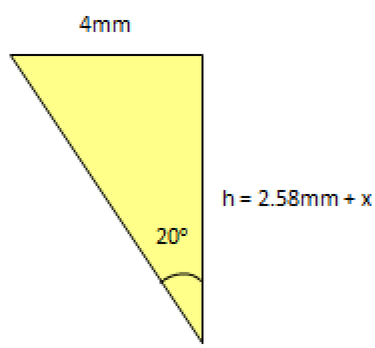

Fig. 22 Right triangle representing half of light leaving LED found in Fig. 21 to determine maximum distance allowable between integrating sphere and LEDs.

Card

Since the LEDs were controlled one bank at a time rather than individual LEDs, a method was devised so that the spectrometer would see only one LED at a time. The method was also used to prevent stray light from other LEDs, which reflected off other surfaces, from entering the sphere.

A simple manila folder was cut approximately four inches square. The backside of the square was covered in thick duct tape to prevent light penetration. A hole was cut using a standard single-hole punch to a diameter of 6.5mm. Once finished, the backside of the card had loops of electrical tape stuck to it. This provided an adhesive surface so the hole in the card would remain directly over the LED being tested. The integrating sphere could then be placed on the card.

Warmup

A few other trial tests were made and it was found that some of the LEDs being tested were not reaching a steady state condition after a few minutes of operation. A test was conducted to see when one of the more unstable banks of LEDs (375nm) was reaching their steady state. It was found that after 25 minutes, the LEDs had finally reached steady state conditions. The assumption was made that all LEDs behaved similarly and reached steady state at or before 25 minutes. After conducting tests for each of the banks, the assumption proved to be correct.

During this same time, the calibration source was also tested to see when steady state was achieved. The USU protocol for the calibration source indicated a 20-minute warmup time for the lamp. However, it was found that its steady state was not achieved until 55 minutes had passed.

After this , both the calibration source and the LED lamps were allowed a minimum of 55 minutes and 25 minutes, respectively, before measurements were taken.

Testing

Calibration and Preparation

Calibration was similar to the procedure followed with the 40-inch integrating sphere. The calibration source used was the HL-2000-CAL and SpectraSuites software. Refer to Appendix B for a detailed outline of steps taken in running SpectraSuite software. As mentioned before, the calibration lamp needed a minimum of 55 minutes of warm up time as opposed to the recommended 20 minutes.

Note: The temperature in the room was recorded over a few days. The temperature was approximately in the range of 70-73^{O} F.

Testing

During testing similar steps were followed as in the calibration. The light bank being tested was allowed a minimum of 25 minutes to warm up. Only one light bank at a time was on during testing. The power supply for the array was a voltage-regulated source; however, the power supply would drop voltage when more than one light source was on, to the point that the LED output was noticeable in the software. Any characterization of how the power supply affects LED output was not made. The reported output of the LED array spectrum in this document assumed the power supply used would not vary depending on electrical load applied, given the load is within the range of the power supply.

To begin the test, five LEDs were chosen out of each bank. One was usually chosen away from the structural frame of the array. This way the integrating sphere could sit perpendicular to the LED. This was not always feasible but a conscious effort was made to do this whenever possible. LEDs were usually chosen near the beginning or end of the bank of lights to make them easier to find if tests were repeated on other days. Once the first LED was chosen, four more were chosen, usually the next four in consecutive order. This provided more ease in taking the measurement. They were considered randomly chosen because the LEDs were positioned and assembled at random in the array.

Once the LEDs were chosen, the manila card was placed over the first LED, with the hole centered on the LED. The integrating sphere was placed with the aperture over the LED, while the SpectraSuite window was open in scope mode. The integrating sphere was positioned so that the highest count reading was obtained. The integration time in scope mode was adjusted to fit the output of the LED being measured.

A new absolute irradiance measurement was then taken as outlined in Appendix B. Scans to average were set to ten instead of five because the integration time was much faster using the smaller integrating sphere. Power and photon files were saved as tab delimited text documents. All graphs were closed in SpectraSuite except for the graph in scope mode. The integrating sphere and the manila card were then removed from the LED array and then repositioned. This was done to reduce the error from the position of the card and integrating sphere when placed on the LED and to account for the position error inside of the precision uncertainty analysis, since at least three measurements would need to be taken for an uncertainty analysis.

After the card and sphere were again reposition over the LED, the measurement process was repeated. Five total measurements were taken of each LED. After the five measurements were taken, the other four LEDs on the same bank were also tested in the same manner for a total of 25 measurements per LED bank. A minimum of three LEDs would have needed to be tested, each three times, to include an uncertainty analysis. However, five LEDs were chosen and each measured five times to give a better idea of the actual output. Five LEDs from each bank were chosen, in part because this was the largest number that could be tested within the given time. Five measurements of each LED were chosen because the integrating sphere was positioned manually over the LED, and it was beneficial to have a fair distribution of the data tested. Over 850 measurements were taken to quantify the output of the array, which took a little over 1.5 months. For this reason, only five LEDs were tested from each bank.

RESULTS

Overview

After testing was complete it was found that Labsphere's warning was correct, that much of the signal was being absorbed in the 40-inch sphere rather than reflected. The large sphere, as mentioned, diffused the light more uniformly when compared to a small integrating sphere, making the signal entering the fiber optic cable much lower than when using a smaller sphere. The signal was further attenuated through disruptions in the 40-inch sphere from other objects being present, such as the lamps and baffles. The data collected from the tests using the 40-inch sphere were still considered valuable, in that it showed the system had a linear response of power input to light output. For this reason, the setup of the 40-inch integrating sphere was still included and will be discussed here after. The results from the 50mm integrating sphere will also be included.

40-inch Integrating Sphere Tests

The first tests performed were the 100% tests. PWM duty cycles were set to 100% to show the full photon flux for each LED circuit. Tests at duty cycles of 75% and 50% were also performed. At first glance, the three spectrums seemed to show a linear relationship between PWM duty cycle and LED output, Fig 23. A linearity test was performed to verify this, which is discussed in the next section.

An advantage of using LEDs as a tunable light source was seen in the actual tests performed, and mentioned previously in the literature. The spectrum changed very little with intensity [22]. The duty cycle was altered to 75% and 50% to test the output. Tests for the overall LED array were not performed below 50% because some of the LEDs' signals were very weak below 50% duty cycle. It was feared that such large integration times would introduce too much noise in the signal.

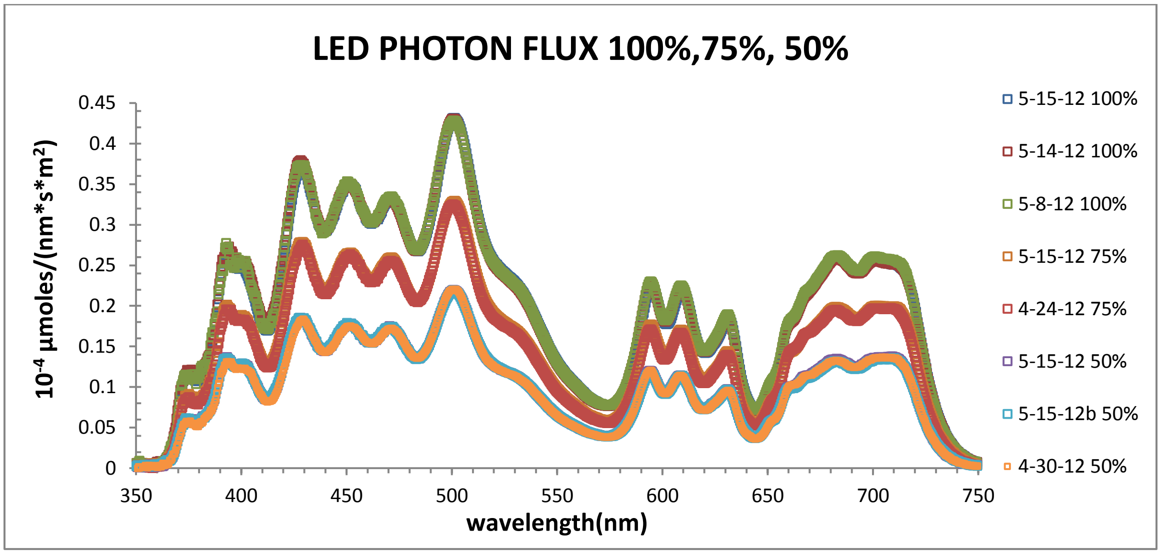

Fig. 23 LED output at 100%, 75%, and 50% duty cycles.

Data from the May 8 and 14, 2012 tests were copied and modified. The values from these 100% tests were multiplied by .75 and .5 and saved as a “calculated or expected spectrum.” These files were compared to the 75% and 50% tests, respectively. When compared to the actual measured values of 75% and 50%, this gave a rough idea of how much the spectrum varied as the intensity changed.

A linearity test was performed to see if varying the duty cycle behaved linearly with the LED output. The motive behind this was, if a linear relationship was established, spectrums could be made in Excel based on data from the 100% tests. Due to the integrating sphere size, which needed to fit the entire LED array, some of the LED circuits did not have enough light to properly fill the sphere down at lower duty cycle levels of the PWMs. USU was also on a time constraint with using the sphere and would not always have access to it since it was needed by SDL for other projects. A method needed to be developed to provide ways in the future to set up spectrums for light tests without always having access to an integrating sphere.

The mean values for both the 75% and 50% tests were calculated. The mean for the 100% tests were also calculated and were multiplied by .75 or .5 and were compared to the means of the 75% and 50% tests, respectively. The calculated values were graphed in comparison to the measured values (see Fig. 24and Fig. 25). A linear fit of the data was generated by Excel and the y-intercept forced to zero. By forcing the y-intercept to zero, the difference of the slope compared to one would give the approximate error overall for the data at that duty cycle, Table 5.

50mm Integrating Sphere Tests

Once testing was completed using the 40-inch and 50mm integrating spheres, data of each was compared. After the data were analyzed, it was noticed that the output of the array, as indicated by the 40-inch sphere, was approximately six times lower than the predicted output. Differences in test procedures could have been the cause of this. (The first set of tests referred to were the ones done with the 50mm sphere to acquire the experimental, full LED spectrum.) Some differences included:

- Approximately 85% of the typical current value was used in later tests when 100% was used in the first set of tests
- LEDs were organized in parallel circuits with a single resistor in the final design, thus some may have been getting more current than others were. LEDs which were tested in the first set of tests were in a circuit by themselves
- The impedance of the circuit and extra hardware was ignored in the final design, thus the overall resistance may have been higher in the final design and the overall current may have been lower

  The configuration of the integrating sphere and light source were different as well.

The problems Labsphere had talked about with modifying SDL's 40-inch sphere indeed seemed to be a problem even with carefully executed measurements.

Table 5 Associated error of output with respect to duty cycle.

LED Intensity	Error (Measured - Ideal)
100%	0
75%	0.0035
50%	0.0135

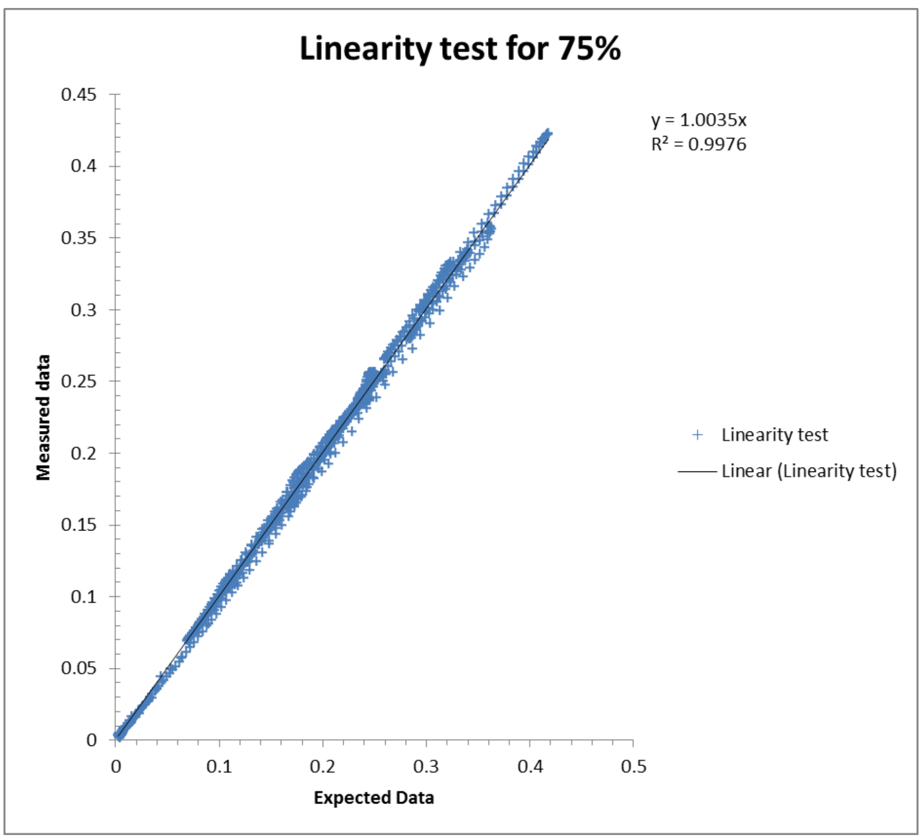

Fig. 24 Linearity test performed for the measured values and expected values for 75% duty cycle. R value of 0.9976. A line was fit to the data in Excel as well as the equation of the line. The error of the data (0.35%) is the difference of the slope and one. One being a perfectly linear relationship.

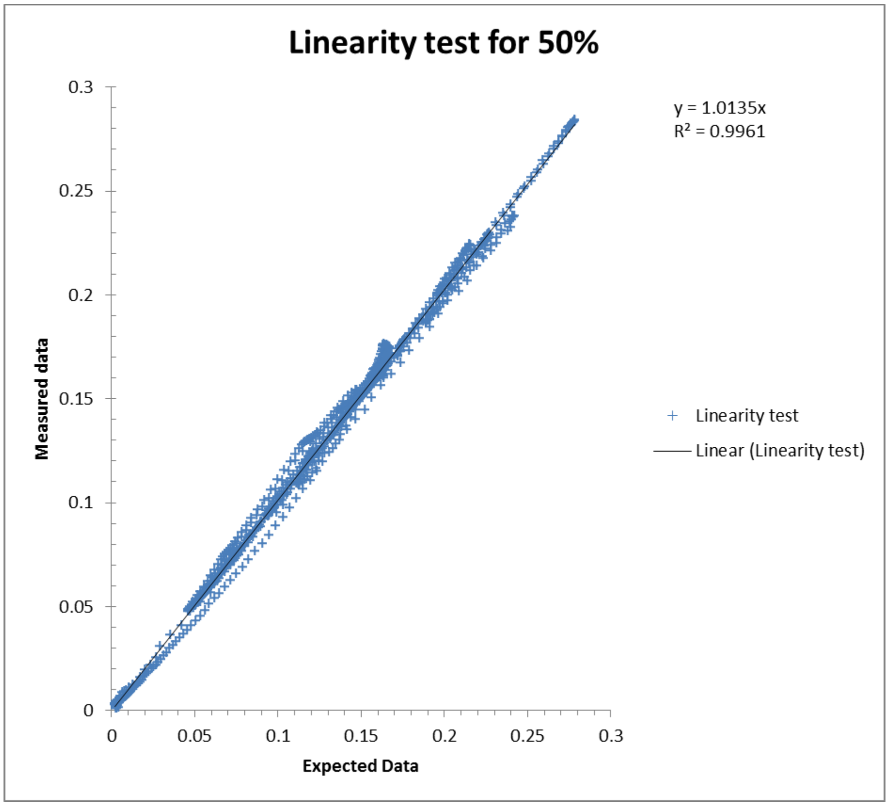

Fig. 25 Linearity test performed for the measured values and expected values for 50% duty cycle. R value of 0.9961. A line was fit to the data in Excel as well as the equation of the line. The error of the data (1.35%) is the difference of the slope and one. One being a perfectly linear relationship.

Before testing with the 40-inch integrating sphere, Labsphere had indicated that it was easy to acquire accurately the shape of a measured spectrum, but the intensity was more difficult to measure. It was found that the 40-inch sphere was absorbing much of the signal due to physical disruptions and imperfections inside of the sphere. It was often assumed that there was a linear relationship of the PWM duty cycle and voltage output. It was mentioned previously that the LED spectrums change very little when dimmed [22]. This agrees with findings from the 40-inch sphere tests in that the change in voltage from the PWM was not altering the LED spectrums, causing them to shift horizontally or change shape all together. To further solidify our findings, and be able to assume that the duty cycle and LED output was indeed linear, a simple test was also conducted with the 50mm sphere and one LED bank. It was found that the peak wavelength’s amplitude did vary vertically in a linear fashion with the PWM duty cycle. This agreed with our findings and data of the 40-inch sphere. It was concluded that testing of multiple duty cycles for each LED bank with the 50mm sphere was not needed.

Since the data for the larger sphere was kept to understand the linear response, only 100% duty cycle tests were done with the 50mm integrating sphere. The full output of the spectrum is shown in Fig. 27 with the uncertainty analysis. Only 170 LEDs were tested out of the 900 due to time constraints on the project. Five LEDs from each bank were tested. Each LED was tested five times, giving 25 measurements per LED bank. It was found during testing that many of the LEDs varied relative to one another more than anticipated. It should be noted that while testing the three banks of 545nm LEDs that there was also a different LED mixed in with the banks. It was not known where this other type of LED came from. It was thought that it was possibly sent in the 545nm packing by mistake from the manufacturer. These LEDs were not recognized as one of the other 39 originally tested. This meant the LED array was comprised of 26 different LED types (see Fig. 26).

The differences between LEDs are accounted for in the larger error bars on some areas of the spectrum, see Fig. 27. The very large error bars found on the lower part of the spectrum comes from the noise associated in the signal from all LEDs. This varied so much in part due to the calibration source. The source was very steady in the 300-400nm region. The intensity of the calibration source was also very low in this region and could have contributed to the larger error.

The tests of the individual LEDs were very close in value. When comparing data of individual LEDs it was noticed that the repeats of the tests were consistent. However, when comparing LEDs of the same type with each other, the spectrums were noticeably different. It appeared that most of the error was coming from the differences in LEDs of the same type and the calibration source. The bias error was ignored in the uncertainty analysis because it was much smaller than the precision error and contributed very little to the overall uncertainty. A two-sided, 95% confidence interval was established for each data point over the spectrum. For more details on the uncertainty analysis, see Appendix C.

375	545	545	YG	YG	720	477	477	610	505	505	505	565	565	565	565	690	690	640	640	605	605	660	660	585	585	405	570	380	380
375	YG	YG	YG	YG	720	477	477	610	505	505	505	565	565	565	565	690	690	640	640	605	605	605	660	585	585	405	570	380	380
375	YG	YG	YG	545	720	477	477	610	505	505	505	400	565	565	565	690	690	640	640	605	605	605	660	585	585	405	570	535	380
375	YG	545	YG	545	720	477	477	610	505	505	505	400	565	565	565	690	525	640	640	605	605	605	660	585	585	405	570	535	380
375	YG	545	545	YG	720	477	477	610	505	505	505	400	565	565	565	450	525	640	640	605	605	605	420	585	585	405	570	535	380
375	YG	545	YG	545	720	477	477	610	505	505	505	400	565	565	565	450	525	640	430	605	605	605	420	585	585	405	570	535	380
375	YG	YG	YG	545	720	477	477	610	505	505	505	400	565	565	565	450	525	640	430	605	605	605	420	585	585	405	570	535	380
375	545	545	YG	545	477	477	477	610	505	505	505	400	565	565	565	450	525	640	430	605	605	605	420	585	585	405	570	535	380
375	545	YG	YG	YG	477	477	477	610	505	505	505	400	565	565	565	450	640	640	430	605	605	605	420	585	585	405	570	535	380
375	YG	545	545	545	477	477	477	610	505	505	505	400	565	565	565	450	640	640	430	605	605	605	420	585	585	405	570	700	380
375	YG	YG	YG	545	477	477	477	610	505	505	505	400	565	565	565	450	640	640	430	605	605	605	420	585	585	405	570	700	380
375	545	YG	545	720	477	477	477	610	505	505	505	400	565	565	565	450	640	640	430	605	605	605	420	585	670	405	570	700	380
375	545	YG	YG	720	477	477	477	610	505	505	505	400	565	565	565	450	640	640	430	605	605	605	420	585	670	405	570	700	380
375	YG	YG	YG	720	477	477	477	610	505	505	505	400	565	565	565	450	640	640	430	605	605	605	420	585	670	405	680	700	380
375	YG	545	YG	720	477	477	477	610	505	505	505	400	565	565	565	450	640	640	430	605	605	605	420	585	670	405	680	700	380
375	YG	545	YG	720	477	477	477	610	505	505	505	400	565	565	565	450	640	640	430	605	605	605	420	585	670	405	680	700	380
375	545	YG	545	720	477	477	477	610	505	505	505	400	565	565	565	450	640	640	430	430	605	605	420	585	670	405	680	700	624
YG	YG	545	YG	720	477	477	610	610	505	505	505	400	565	565	565	450	640	640	430	430	605	605	420	585	670	405	680	700	624
545	YG	YG	YG	720	477	477	610	610	505	505	505	400	565	565	565	450	640	640	430	430	605	605	420	585	670	405	680	700	624
YG	545	YG	545	720	477	477	610	610	505	505	505	400	565	565	565	450	640	640	430	430	605	605	420	585	670	405	680	700	624
YG	YG	YG	YG	720	477	477	610	610	505	505	505	400	565	565	565	450	640	640	430	430	605	605	420	585	670	405	680	700	624
545	YG	545	545	720	477	477	610	610	505	505	505	400	565	565	565	450	640	640	430	430	605	605	420	585	670	405	680	700	624
YG	YG	YG	YG	720	477	477	610	610	505	505	505	400	565	565	565	450	640	640	430	430	605	605	420	585	670	405	680	700	624
YG	YG	545	545	720	477	477	610	610	505	505	505	400	565	565	565	450	640	640	430	430	605	605	420	585	670	405	680	700	624
YG	YG	YG	YG	720	477	477	610	610	505	505	505	505	565	565	565	450	640	640	430	430	605	605	585	585	670	405	680	700	624
545	545	YG	545	720	477	477	610	610	505	505	505	505	565	565	565	450	640	640	430	430	605	605	585	585	670	670	680	700	624
545	YG	YG	YG	720	477	477	610	610	505	505	505	505	565	565	565	450	640	640	430	430	605	605	585	585	670	670	680	700	624
545	YG	YG	YG	720	477	477	610	610	505	505	505	505	565	565	565	450	640	640	430	430	605	605	585	585	670	670	680	700	624
YG	YG	YG	545	720	477	477	610	610	505	505	505	505	565	565	565	450	640	640	430	430	605	605	585	585	670	670	680	700	624
YG	YG	YG	YG	720	477	477	610	610	505	505	505	505	565	565	565	565	640	640	430	430	605	605	585	585	670	670	680	680	624

Fig. 26 Current LED array with yellow green LEDs (YG) mixed in with 545nm. Compare with Fig. 11.

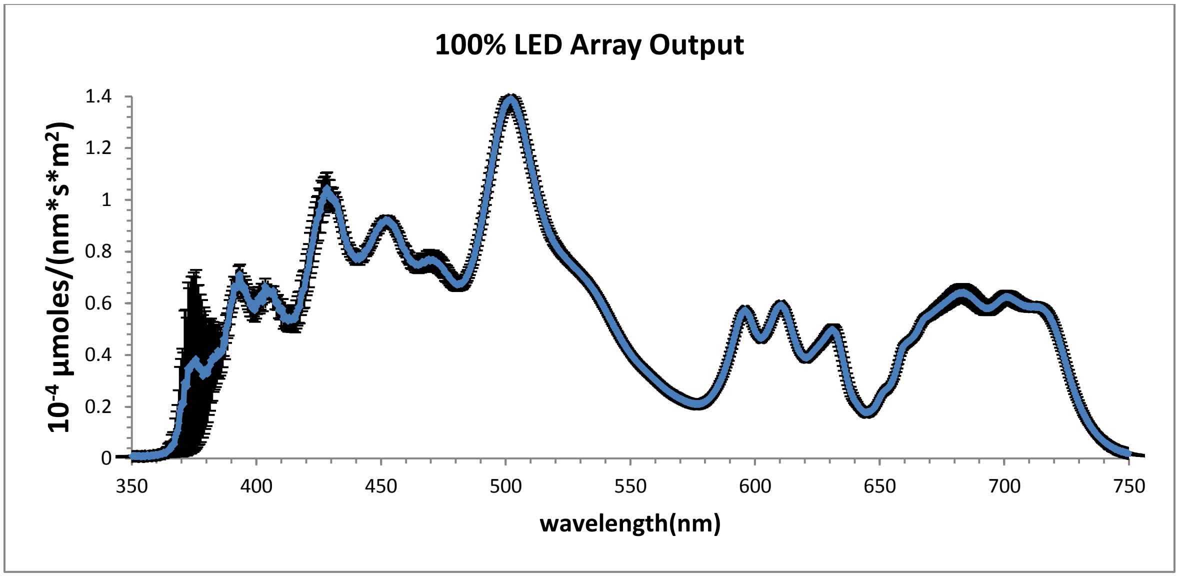

Fig. 27 Full LED array output at 100% duty cycle. Uncertainty error bars included.

Current White Light

Since the response of the duty cycle and output was linear, data from the 100% duty cycle tests with the 50mm integrating sphere was used to calculate the white light, or neutral photon flux density capability, of the array as part of the verification of the LED array. The data was taken from each of the LED circuits' tests and a value of 0.0-1.0 was assigned as a multiplier to all of the values for that specific LED bank. This was done for each of the 31 different LED banks. This was to simulate the duty cycle of the PWM from 0-100%. The multipliers were adjusted to achieve the white light spectrum (see Table 6) found in Fig. 28. This spectrum was not optimized, but used to show the capability of the array.

It was thought that this spectrum would possibly provide a baseline in algae and other photosynthetic experiments. Using that information, other spectral experiments could be performed and then compared to this baseline test, where most of the spectrum was centered on a certain target photon flux. As mentioned earlier, light in the PAR range is required for growth. Being able to test narrow bandwidths of light would help researchers understand possible spectral effects on algae, such as pigment adaptation.

Table 6 Duty cycles of the LED banks to obtain the Neutral Density Photon flux (White Light).

DUTY CYCLE WHITE LIGHT	
375	100%
380	100%
400	50%
405	65%
420	80%
430	37%
450	35%
477	60%
477b	60%
505	25%
505b	25%
525	40%
535	50%
545	80%
545 yg	100%
545b	80%
545byg	100%
545c	80%
545c yg	100%
565	100%
565b	100%
570	100%
585	100%
605	65%
605b	65%
610	70%
624	85%
640	100%
640b	100%
660	100%
670	70%
680	45%
690	60%
700	60%
720	60%

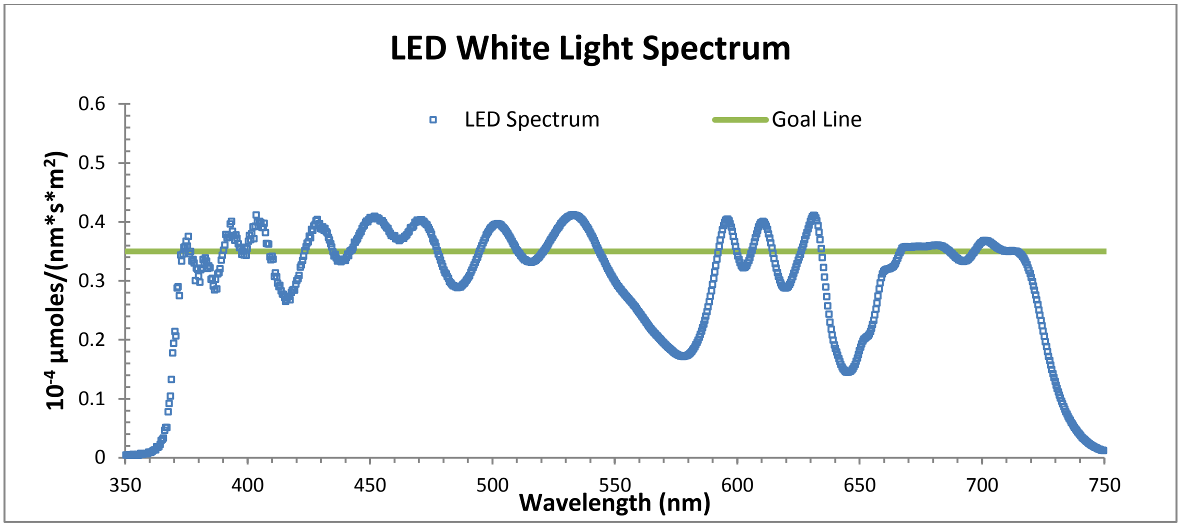

Fig. 28 Neutral Density Photon flux (White Light) capablity of LED array. The green line represents the goal spectrum.

Solar Spectrum vs. LED Spectrum

One of the main reasons for developing this tunable light source was to be able to mimic the sun's spectrum. While the original goal was to achieve 1/10th of the sun's full intensity, the current array achieved approximately 1/20th intensity. At solar noon on the summer solstice the total photosynthetic photon flux (400nm-700nm) is approximately 2100 µmoles of photons/m^2/sec. 1/20th of this is about 105 (µmoles of photons/ (m^2*s)). The plot for the LED spectrum simulating the solar spectrum was tuned in the same manner as the white light spectrum, Fig. 29, by modifying the multipliers representing the duty cycle of that channel refer to Table 7. Once again, the spectrum was not optimized.

Table 7 Duty cycles of the LED banks to obtain the solar spectrum.

DUTY CYCLE SUN vs. LED	
375	40%
380	40%
400	16%
405	42%
420	35%
430	25%
450	37%
477	55%
477b	55%
505	25%
505b	24%
525	100%
535	100%
545	65%
545 yg	100%
545b	65%
545byg	100%
545c	65%
545c yg	100%
565	100%
565b	100%
570	100%
585	100%
605	70%
605b	72%
610	76%
624	95%
640	100%
640b	100%
660	100%
670	90%
680	43%
690	65%
700	60%
720	70%

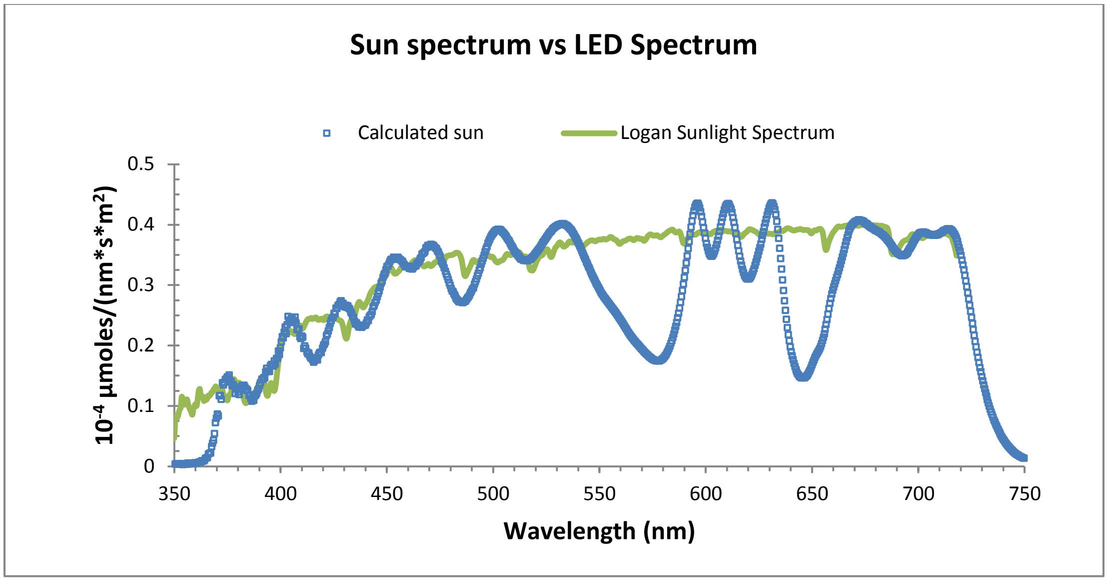

Fig. 29 Solar spectrum capability of LED array. Green line is the solar spectrum at solar noon on the summer solstice provided by Dr. Bugbee.

CONCLUSIONS

Introduction

After testing the LED array with two integrating spheres and multiple duty cycle settings, the capabilities of the array are better understood. A few conclusions can be made following these tests. The first and possibly most important is that the array duty cycle and output behave linearly. This is an important step for setting up the light source. This will save time if future testing of specific spectrums is initiated. Since it is understood that the array behaves linearly, a spectrum can be developed in Excel before it is tested with an integrating sphere. This will save many hours of time so that the correct spectrum can be chosen and then tested rather than iteratively finding the spectrum during testing.

A few other conclusions will be made about the sphere's target outputs, the neutral density photon flux, also known as white light spectrum, and the simulated solar output.

White Light Spectrum

The spectrum proved to be desirable. Using LEDs makes the spectrum impossible to be completely flat, which was expected because there are only discrete peak wavelengths available; however, the LED spectrum was still able to produce a neutral density photon flux as required in the design. The strong points of the spectrum were near the infrared wavelengths. A near flat line was achieved in the 670-720nm range. Most of the rest of the spectrum produced an output whose mean was centered on the goal line. A few trouble areas occurred around the 550-590nm and 640-670nm ranges. This was due to the lack of LEDs available in those wavelengths. If there were LEDs available in these wavelengths, they were very dim and required many more LEDs to make up the difference.

Solar Spectrum vs. LED Spectrum

The solar spectrum produced by the LED array also proved to be desirable. As with the white light spectrum, a specified spectrum was not required since it was unknown what the capabilities were. As mentioned before, the LED array was not intended to be a full intensity, full solar simulator ranging over the UV, visible, and infrared regions, but to be able to simulate the spectrum with lesser intensity in the PAR range. When comparing the output of the LED array simulating the solar spectrum and a Metal Halide lamp (Fig. 30) the precision of the LED array can be better appreciated. From what has been seen in the literature, no LED light source has been able to mimic the solar spectrum as close.

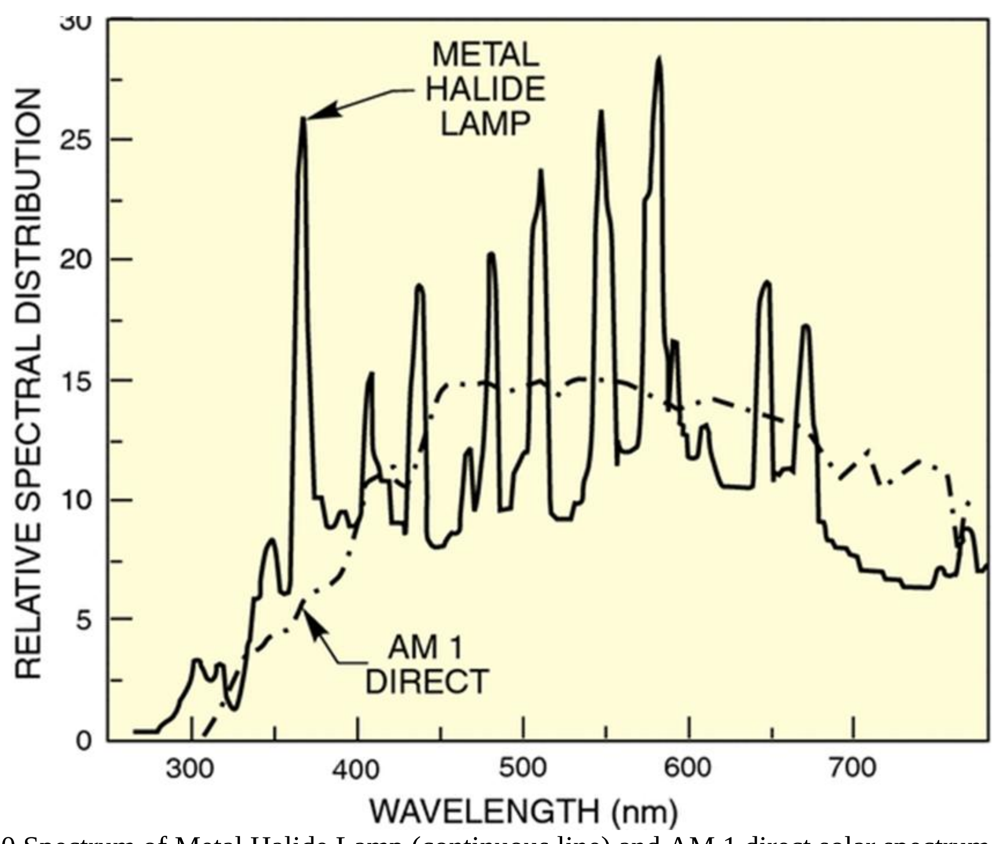

Fig. 30 Spectrum of Metal Halide Lamp (continuous line) and AM 1 direct solar spectrum (dash-dot line) [28].

FUTURE WORK

The designing, building, and testing of the LED array has provided enough information to see that LEDs can be used as a tunable light source, and within that category can be included solar simulator. Suggestions in this section will help make improvements to possible future editions of the light source.

The current LED array had more variability in the spectrum during the 100% duty cycle than desired. This was due mostly to the change in units of measurement. Initially units of (μmol/nm) were used, which were fine to classify LEDs. For biological experiments, units of (μmol/(nm*m^2*s)) were desired. Choices and quantities of LEDs used in the LED array were based on the first set of units. This is partly the reason why the intensity of the spectrum was not as neutral as desired during the 100% duty cycle tests.

As seen before, modifications were made in Excel to the data files. Then, instead of varying the duty cycle, the actual amounts of LEDs were changed (see Table 8) until the spectrum in Fig. 31 was obtained. While the spectrum is much more desirable in terms of being smoother, the intensity remains unchanged when compared to the previous white light spectrum. This is because to fill in the gaps seen on the current spectrums, many more LEDs in the problematic areas had to be used. This is because those wavelengths usually had very weak LEDs.

The power supply for the LED banks system was adequate for testing one circuit at a time. However, if multiple circuits were on simultaneously the intensity of the circuits would decrease a noticeable amount. To ensure that the spectrum remains unchanged regardless of which LED circuits are on or off, a higher-grade power supply should be purchased.

The ability of the array to produce different spectrums makes it good all-around to produce a variety of spectrums, but is not optimized for just one spectrum. The white light spectrum can be improved, as shown in the future work section.

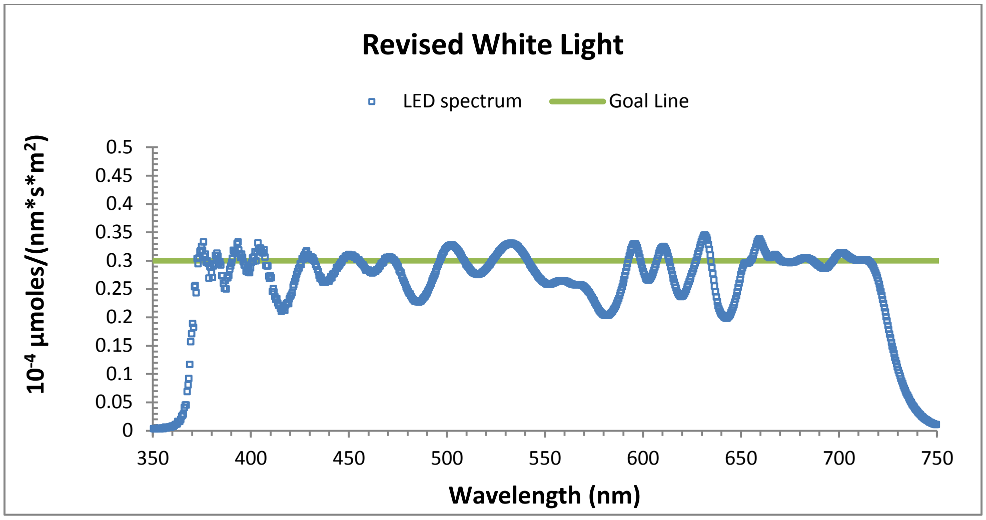

Fig. 31 Revised Neutral Density Photon flux (White Light) capablity of LED array. The green line represents the goal spectrum.

It should be noted however that not a great deal of increase in intensity can be achieved if a white light source is desired, even after the recommended changes are made, at least for the LEDs currently used in the grid. This is because not all of the LEDs produce the same flux. Some of the larger problematic areas are in the 550-590nm and 650nm range. These areas have some LEDs available but they are very weak and require many more LEDs to make up the difference in intensity. Gaps with an LED light source are inherent due to the nature of LEDs. LED peak wavelengths are limited by materials available that can provide the correct amount of energy released when electrically excited to match a certain wavelength. This is why there are discrete peak wavelengths available. One of the difficulties in building a spectrum with LEDs is that there are a limited number of available peak wavelengths.

Table 8 Quantities of the LED groups to obtain the revised white light spectrum.

REVISED WHITE LIGHT	
LED Bank	Quantity
375	15
380	18
400	9
405	13
420	14
430	11
450	6
477	16
477b	16
505	10
505b	10
525	2
535	2
545	7
545 yg	23
545b	10
545byg	20
545c	7
545c yg	23
565	141
565b	138
570	39
585	141
605	19
605b	19
610	22
624	9
640	29
640b	28
660	30
670	12
680	7
690	4
700	10
720	13
Total	893

A similar revision was also completed for the LED solar spectrum; refer to Fig. 32 and Table 9. The LED array in the revised spectrum is approximately 1/30th of the solar intensity, roughly 75 (µmoles of photons/ (m^2*s)).

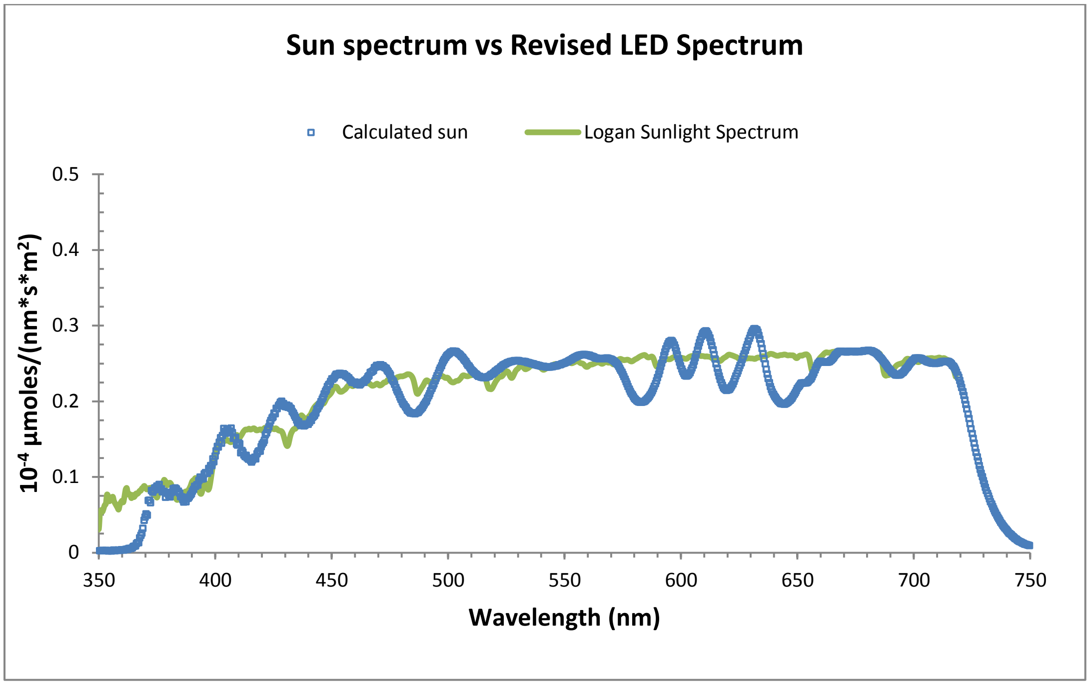

Fig. 32 Revised Solar spectrum capability of LED array. Green line is the Solar spectrum at Solar noon on the summer solstice provided by Dr. Bugbee.

Table 9 Quantities of the LED groups to obtain the revised solar spectrum.

REVISED SUN vs. LED	
LED Bank	Quantity
375	4
380	5
400	2
405	7
420	6
430	7
450	6
477	13
477b	13
505	8
505b	8
525	0
535	6
545	2
545 yg	39
545b	2
545byg	33
545c	3
545c yg	39
565	71
565b	69
570	52
585	188
605	17
605b	17
610	17
624	6
640	102
640b	98
660	10
670	10
680	7
690	2
700	8
720	11
Total	888

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APPENDICES

APPENDIX A.

Drawing Package

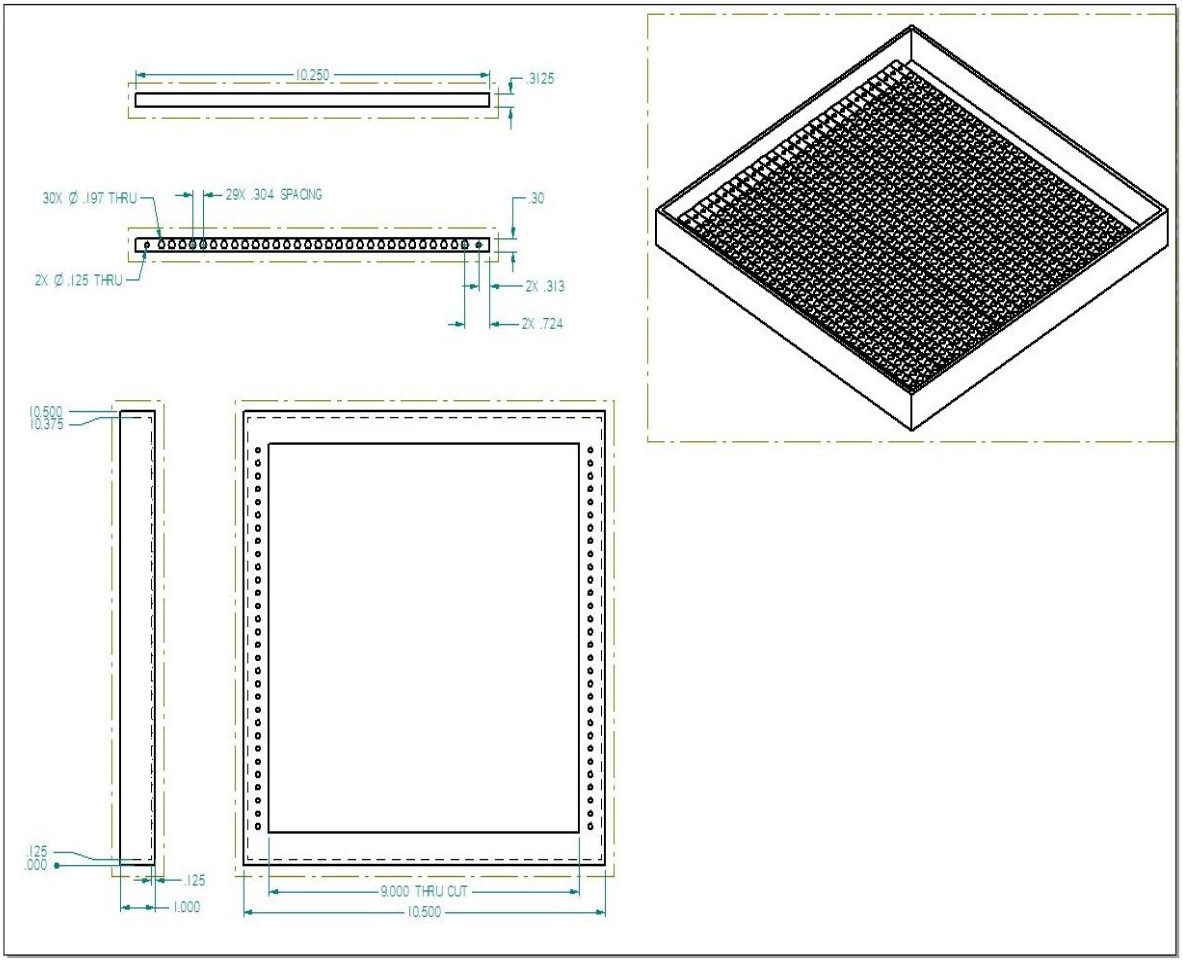

Fig. 33 Drawing package for LED array structure.

APPENDIX B.

Visual Setup of Ocean Optics

Once SpectraSuite was opened, a “New Absolute Irradiance Measurement” was chosen for the test. This was found under “File,New, New Absolute Irradiance Measurement”, Fig. 34.

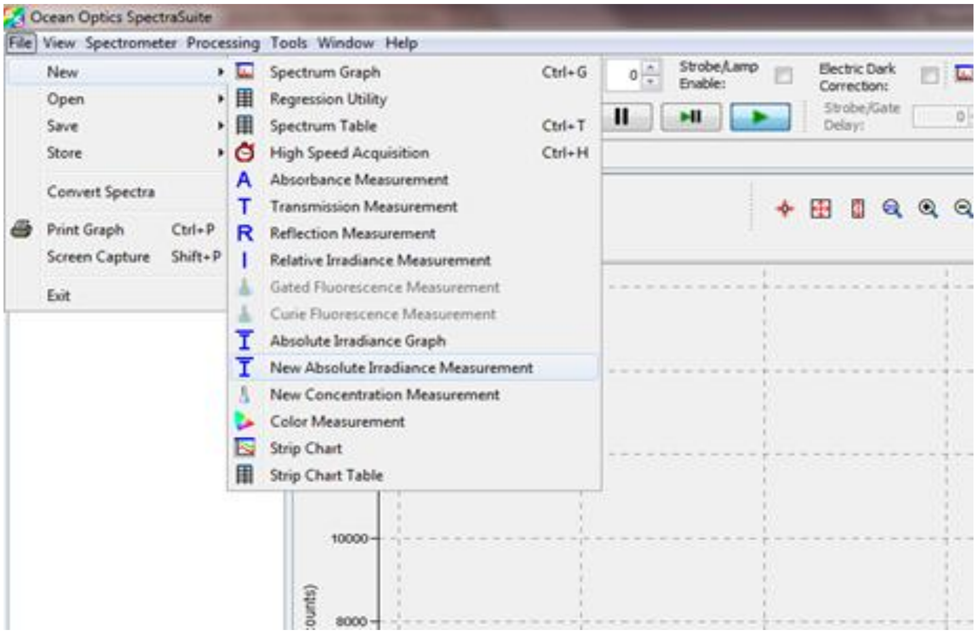

Fig. 34 Instructions to open a “New Absolute Irradiance Measurment.”

Then the software asked the user to select the spectrometer being used. In this case, it was the HR 2000+, Fig. 35.

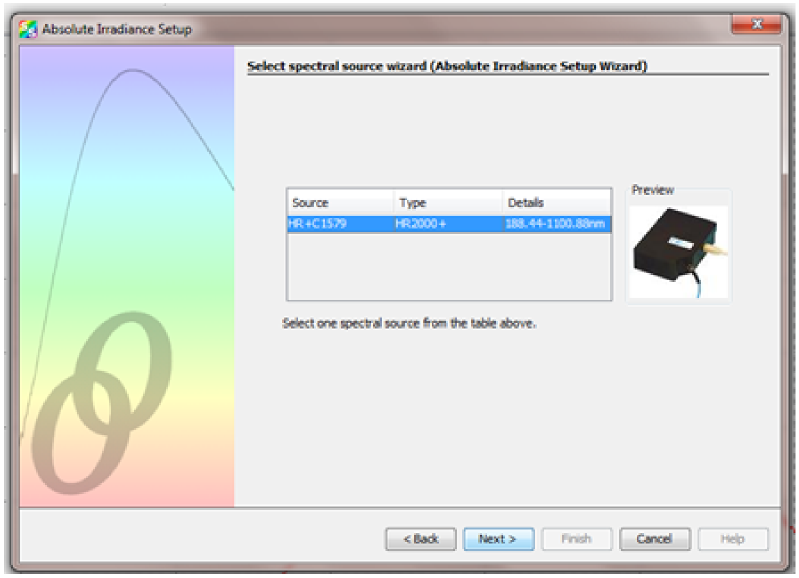

Fig. 35 Setup Wizard window to select spectrometer.

By clicking “next”, the software then prompted the user to select the type of calibration to be performed. The radio button “New Calibration” was chosen, Fig. 36. At the beginning of each test day, a new calibration was performed to ensure accurate results. After the calibration was taken, Ocean Optics stated in their tutorial video that if the system remained intact and undisturbed a new calibration would not need to be performed for each measurement.

Note: After the calibration was taken for that test day, a new calibration was not taken for each irradiance measurement but the calibration was loaded by clicking the “Get Irradiance Calibration from File” radio button would suffice.

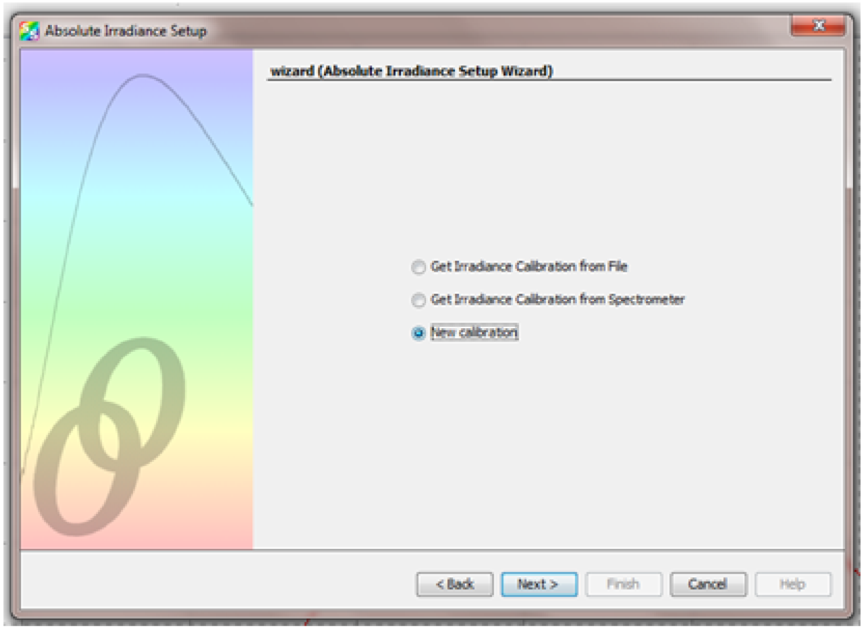

Fig. 36 Setup Wizard window to select proper calibration.

After clicking "next", the setup wizard would then need an integration time, Fig. 37. Under the "Advanced Settings", the "Nonlinear" function was selected, and then "OK". Next, the "Set automatically" button was selected so that the software would find the best integration time for the particular spectrometer. The "scans to average" was set to 30, which was recommended by Ocean Optics. This produced a much smoother curve than if no scans were averaged, since it would be displaying more of a mean of the source output rather than an instantaneous one.

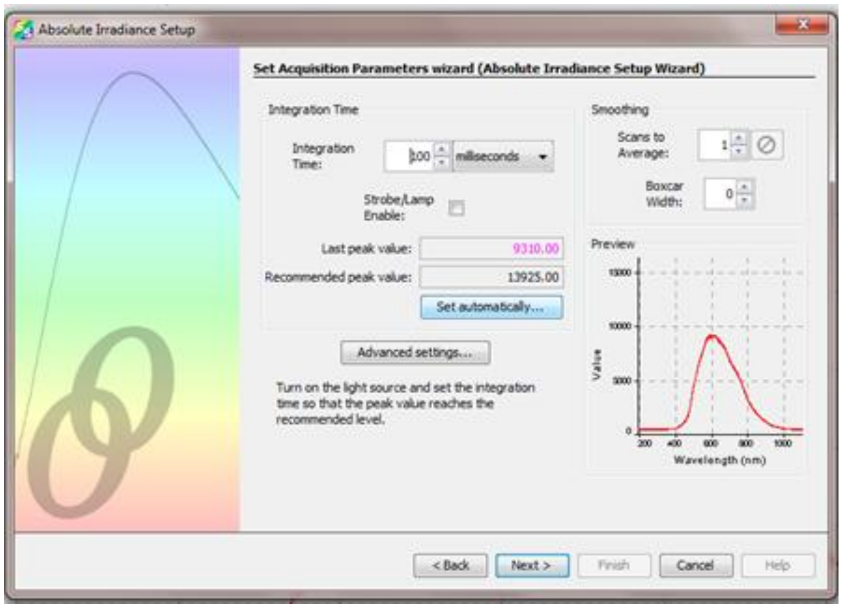

Fig. 37 Setup Wizard window to have software automatically select integration time.

After light and dark spectrums were stored, the calibration file loaded, and the calibration saved, the spectrometer was ready for testing.

To perform an irradiance measurement such as for an LED circuit as opposed to an irradiance calibration most of the same steps were followed. A “New Absolute Irradiance Measurement” was chosen. The proper spectrometer was chosen. Once the calibration window opened in wizard the “Get Irradiance Calibration from File” radio button was selected (the file being the same that had been saved for that day’s calibration). An integration time with the nonlinear function selected, and dark spectrums were again saved for the new test. Scans to average were also lowered from 30 to 5, or 10 depending on spectrometer used. Five was used for the 40-inch sphere and ten for the 50mm sphere. This was done for time constraints.

It was not necessary to open a “new absolute irradiance measurement” for each test. The proper changes such as integration time and generating a new dark spectrum could have been performed in irradiance mode, which is the window which displays the spectrum vs. wavelength. However to change the integration time one would need to be perform it manually in scope mode (displays spectrum in counts vs. wavelength). It was easier and thought to be more accurate and have higher precision using the software to pick the integration time. This is why a new irradiance measurement was opened for each new test.

Once the software was back in irradiance mode, the spectrum was displayed in units of power (µw/nm). This file was saved as a tab delimited text file specifying the LED circuit, which was the peak wavelength of the LEDs for that circuit. The file of power flux was saved as a way to check the work if need be since the units of µw could be converted into µmole of photons. However, since photon flux was required and the software converted the units this was used rather than performing all conversion manually. As a side note, units were converted manually at times from µw to µmoles of photons to check that they agreed. In the software under the "Processing" tab units were converted into photon flux (µmole of photon/nm). This file was then also saved as a tab delimited text file.

Visual Setup of LabVIEW's Measurement & Automation Explorer (MAX)

Plug in power supplies for both the DAQ and LED array. Open LabVIEW's MAX. Once MAX was opened, the left hand side of the page provided a tree to access the field point system, Fig. 38 . In this case, the data acquisition system was connected via Ethernet connection directly to an HP laptop. For this connection, the system was obtained under "remote systems".

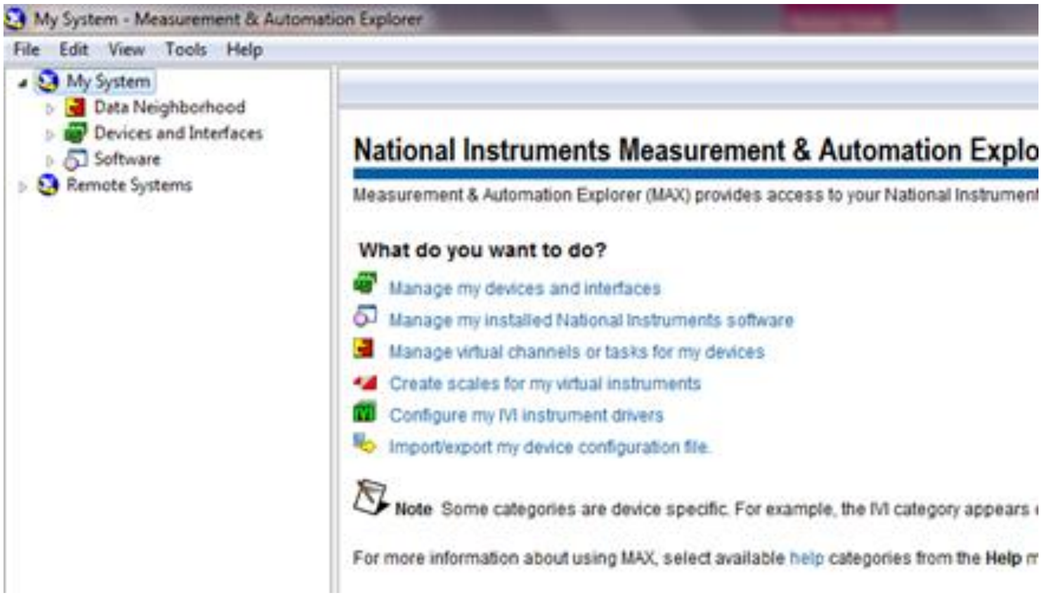

Fig. 38 First window once MAX was opened.

Once “Remote Systems” was selected, the IP address of the DAQ appeared for access, Fig. 39. When the IP address was highlighted, “Find Devices” became accessible in the top of the screen, Fig. 40. This would allow MAX to recognize the DAQ and PWMs.

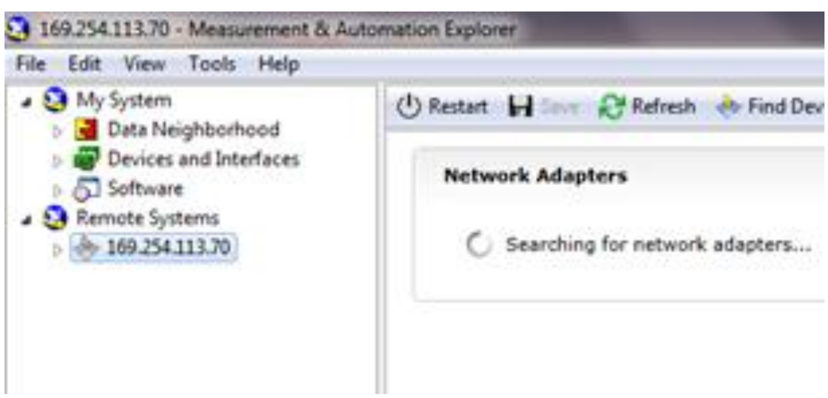

Fig. 39 Selecting the IP address of the DAQ.

The software would start a new source for the given IP address.

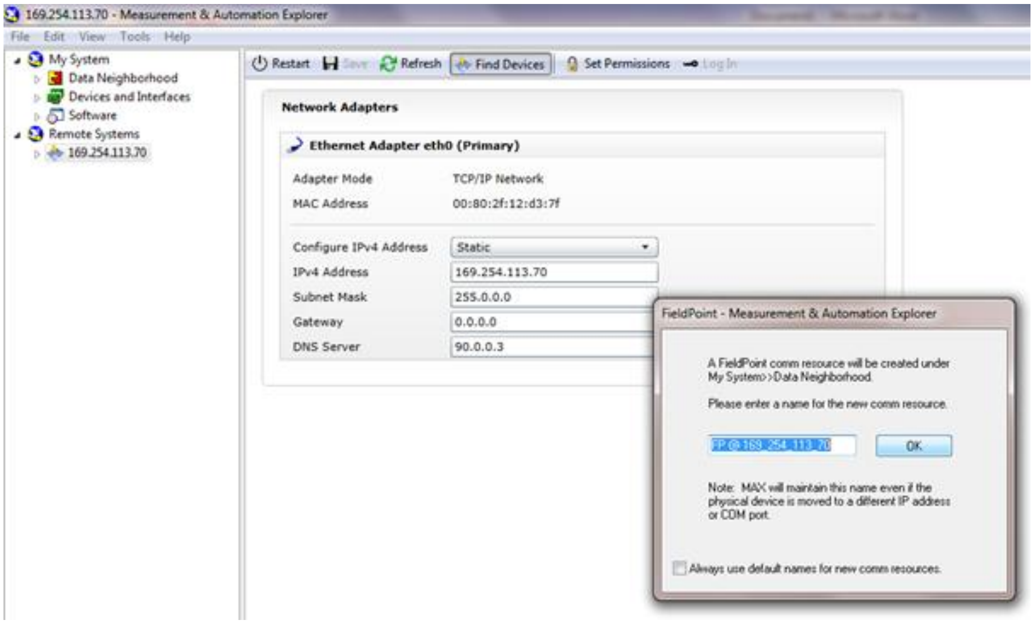

Fig. 40 Selecting the button "Find Devices" in the main window and then "OK" button in the Measurement & Automation Explorer.

Once the "OK" button was clicked on MAX's Explorer, the devices were automatically found. All four PWMs were accessible with each of their respective eight channels (0-7), Fig. 41.

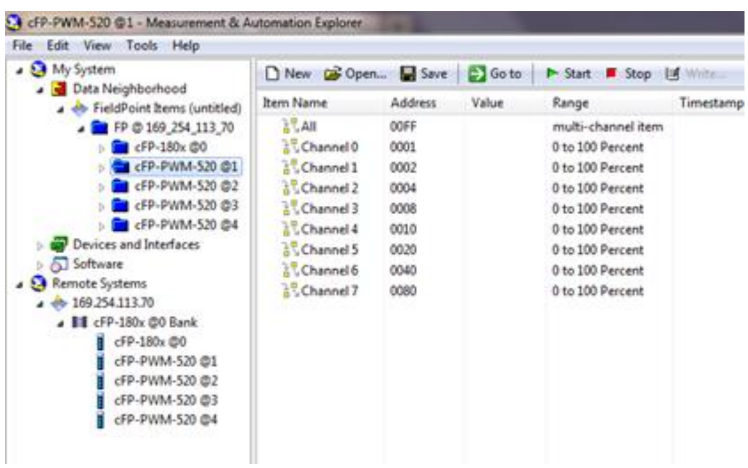

Fig. 41 Print Screen after all PWM's were found.

Once all of the channels were visible, the next step was to set the duty cycle for the LED circuit being tested. A channel was then selected, Fig. 42.

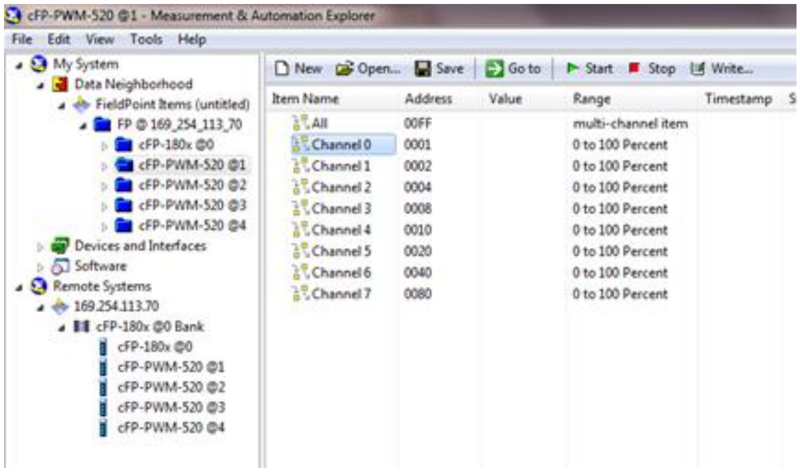

Fig. 42 Selecting PWM #1 Channel 0 as an example.

Once the channel was selected, the “Write” box at the top of the screen became accessible, Fig. 43. Once this box was clicked, a box would pop up and a real number in the range of 0.000000-100.000000 could be entered into the field. Once “Write” was clicked, the LEDs would turn on with the specified duty cycle.

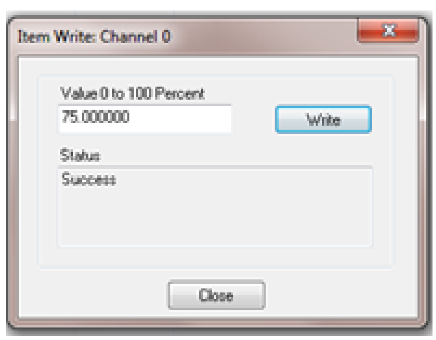

Fig. 43 Setting the percent duty cycle for PWM #1 Channel 0.

APPENDIX C.

Uncertainty Analysis

An uncertainty analysis was performed for the data measured with the integrating sphere system. This consisted of two parts. First, finding the uncertainty of each LED bank, and secondly, the total uncertainty of the banks together. Part of taking measurements is determining the error involved. It is not enough just to compare results to a theoretical value to determine if the measurement taken was acceptable or not. Error is the difference between what was actually measured and what the true value is. However in many cases the true value is not known, this is the reason why a measurement was taken, and therefore true error is not known either. To answer this statics are used to estimate the error's range [29].

$$Error = \varepsilon \equiv x_m - x_{true} \tag{7}$$

Estimating the error with a certain range of uncertainty (u) having some level of confidence is required. In this paper a, 95% two-sided confidence interval is used.

$$x_m - u \leq x_{true} \leq x_m + u \tag{8}$$

The variables x_m and x_{true} are the measured and true values respectively.

The next step in accessing the error is to find the sources where error may have occurred. Most experimental errors can be placed in one of two groups, random or systematic errors. Random errors, or precision errors, consist of the random or differences in the measurements taken. They can be caused by small changes in the way the user measured the data or even vibration of equipment, both having the ability to cause variability in measurements. While the errors are different for each measurement, the mean of the error is zero. With enough measurements taken the error can be appropriately estimated. At least three independent samples are needed to determine a precision error. For small samples (less than 30), a Student t-distribution is assumed. A t-distribution was assumed in this paper, number of samples (n) = 25.

Systematic or bias errors are errors that occur the same way each time. This means they have a fixed value. Because the value is fixed, the mean is not equal to zero and there is not distribution of the error. Statistics cannot be used to estimate the bias error since there is no distribution. Rather, the error must be found by taking a measurement of a known source. This is the reason calibrations are performed on equipment before measurements are taken.

Since the integrating sphere was calibrated, with each use a known bias error was established. The calibration file sent from Ocean Optics (not the file that was saved each day) was used as the known value and what the spectrometer reported to the computer was the measured value (the file that was saved each day). Two times the standard deviation of the mean error gave the bias uncertainty. However, if the bias error is less than .25 of the precision error it can be ignored, since it will contribute very little to the overall uncertainty.

To calculate the precision error, the sample mean, and standard deviation of the sample, mean must be calculated.

The mean of the samples measured is:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad (9)$$

The standard deviation of the sample mean:

$$S_x = \frac{1}{n}\sqrt{\sum_{i=1}^{n}\left(\bar{x} - x_i\right)^2} \qquad (10)$$

The precision uncertainty for the mean of the data measured with 95% confidence interval:

$$P = t_{\alpha/2,\upsilon} * \frac{S_x}{\sqrt{n}} \text{ (95\%)} \tag{11}$$

The total uncertainty one of the banks measured, U_x, is found through the root-mean-square of the precision and bias errors.

$$U_x = \sqrt{B_x^2 + P_x^2} \tag{12}$$

However since the bias error was smaller than .25 of the precision error it can be ignored. The precision error becomes the total uncertainty.

$$U_x = P_x \tag{13}$$

Since there were 26 different types of LEDs that were tested, a precision error was found for each type and then propagated through a data reduction equation to find a total uncertainty for the spectrum [30]. To begin, the equation for the total array output is given per wavelength (nm). The total output ($Output_{Total}$) is the sum of all the outputs for the individual types ($Output_{Type}$) multiplied by the number of the quantity of that type (M_{Type}). The types are the 26 different LEDs.

$$Output_{Total} = \sum_{Type=1}^{26} M_{Type} * Output_{Type} \tag{14}$$

Since the equation above is solved for the experimental result, the uncertainty equation is found in part by taking the partial derivative of the total output with respect to each measured variable. In this case, it is the output of each LED type. The partial derivative in each case is the number of LEDs of that type [30]. FigureFig. 44 plots the mean output at 100% duty cycle with error bars included.

$$Uncertainty_{Total} = \sqrt{\sum_{Type=1}^{26} \left(\frac{\partial Output_{Total}}{\partial Output_{Type}}\right)^2 * Uncertainty_{Type}{}^2} \tag{15}$$

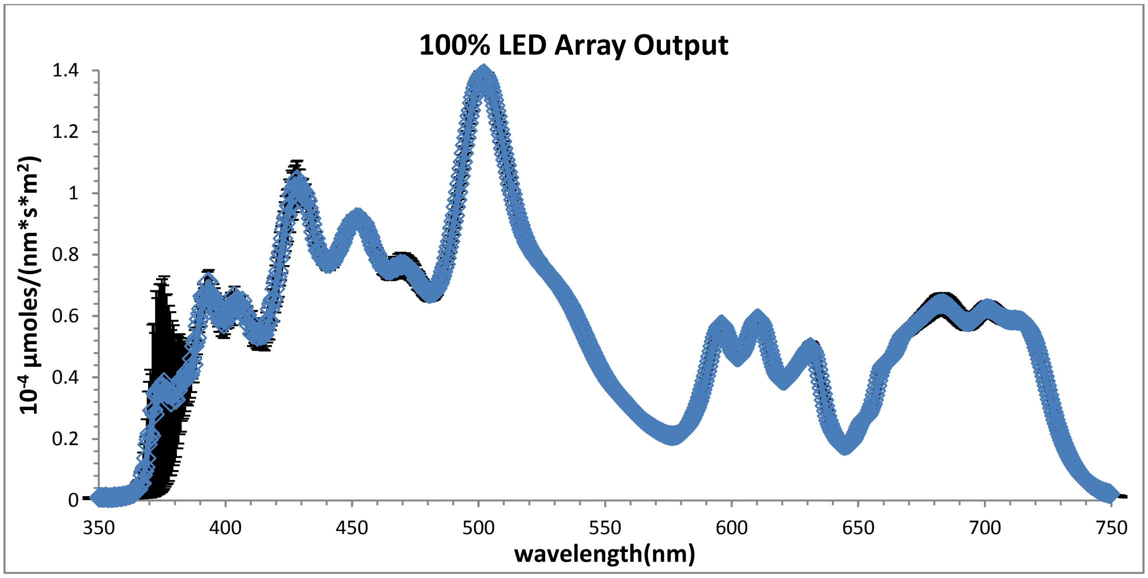

Fig. 44 Full LED array output at 100% duty cycle. Uncertainty error bars included.