Design of an LED Based Solar Simulator

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Abstract

A solar simulator is a device with the capability of producing a small area of high-intensity light to mimic the sun. The purpose of a solar simulator is to provide for research and testing of photosensitive materials such as sunscreen, plastics, solar cells, and solar fuels. This product is a fully light-emitting diode (LED) based solar simulator. Using a collection of variable LEDs, the device is able to emulate several varying environmental settings in a manner that one would expect of natural sunlight on any given day. Rather than using a single concentrated light source, such as a lightbulb, this device is able to create and replicate realistic conditions that the sun and weather patterns are capable of producing. In order to achieve this replicability, the solar simulator relies on its three key aspects: an adjustable spectrum, an adjustable intensity, and spatial uniformity. Most commercial solar simulators on the market use high arc Xenon lamps to produce a full spectrum ray of light, however, this is power intensive and not easily configurable. This product is a relatively low-power solar simulator compared to the typical Xenon arc lamps.

Chapter 1. Introduction

Society has found itself in a position where there's a push for entirely renewable energy. With such a push, there also comes a demand for the testing of photosensitive materials like solar arrays and solar panels. A solar simulator solves the issue of testing devices such as solar arrays on such a large scale in varying environmental conditions. Essentially, a solar simulator can be thought of as a very bright, uniform light that produces a full spectrum of wavelengths. Because actual weather conditions can be unpredictable, the actual sun may not always be the best resource that is readily available for testing solar panels and other renewable energy technologies. As a result, relying solely on natural sunlight and solar power can hinder time-sensitive research and development [1]. In these scenarios, the solar simulator device is objectively the preferred option in the development and production of renewable solar technologies because it is guaranteed to meet the customer's desired simulation metric at any given time, regardless of real-time environmental conditions. The sun emits almost all wavelengths of light, even some that we cannot see with our eyes such as radio waves, microwaves, infrared (IR), ultraviolet (UV), X-rays, and gamma rays. Before we talk about our specifications for irradiance, we must first describe what irradiance is. According to G2V optics, "Irradiance is the radiant flux shining on, or received by a specific surface area. Essentially, it's the received power of light per unit area. It has units of Watts per square meter (W/m2) or other variants like mW/cm2 (because most detectors have dimensional areas in the range of cm2 rather than m2)" [2]. Standards and practices have been put in place in the past to ensure that the specifications of the solar simulator meet common demands. For example, solar simulators are classed into categories such as A, B or C [3]. The requirements for a class A solar simulator are stricter than that of a class B. Class A solar simulators must reach an irradiance non-uniformity rating of < 2% [4]. In addition, the method by which you must test such specifications for non-uniformity is strictly laid out in standards as well [5].

The goal of this product, which makes it different from other solar simulators on the market, is that we created a more configurable solar simulator, one capable of displaying varying wavelengths of light at a time and singling out certain wavelengths. Before building a solar simulator, the target output spectra, target area, cost, and other constraints must be well defined [6]. Xenon arc lamps are the most used light sources among conventional solar simulators but there's a much wider variety of options available [7]. One instance that's of interest is the use of variable LED lights to recreate the spectrum. LEDs are beneficial because of the low cost, and low power consumption, however more control aspects need to be put in place to ensure full coverage and correct uniformity [8]. To emulate sunlight under different environmental conditions, the current that is sent to each individual LED can be varied in order to increase or decrease the intensity of the desired light output. This current can be controlled by user input and the user can also set predefined settings for their solar simulator if they find themselves testing specific conditions more often than others. In order to maintain accurate spatial uniformity, however, the LEDs are not repositionable and can only be altered in terms of their power output which is determined by the user input settings. One particular case study mentions that an LED-based solar simulator can be constructed from different types of high-power LEDs to provide a spectrum that matched the AM 1.5G spectrum of the sun [9]. This comes with potential health concerns as well, emphasizing the need for a controlled and protective environment to conduct research. Xenon lamps, which are almost always used in solar simulators, emit a dangerous amount of UVR. Without appropriate safeguards, the radiation on uncovered skin soon leads to burns, eye damage, and permanently enhances the risk for cancer. [10]

For comparison purposes, there are commercially available products by which we can come up with target specifications for our product. ABET technologies produce class AAA solar simulators which means they reach the class A specifications for spectral match, spatial non-uniformity of irradiance, and temporal instability [10]. Given that their products use Xenon arc lamps and not LEDs, our product should require much less power.

Our target customers are those seeking a low-power, low-cost solar simulator that can cover most of the same spectrum of light as the sun, while still allowing for the singling out of output spectrum and intensity. Important stakeholders include the product team as well as the project advisor. Renewable energy companies and research teams can greatly benefit from this solar simulator device [11]. This device is useful for renewable energy companies for not only testing and developing their products but also for demonstrating their product to their own shareholders and stakeholders. The simple user interface allows companies to test their products for a wide variety of environmental conditions and avoids the hassle of needing to test their devices using unpredictable natural sunlight [2]. Additionally, having access to this device reduces the risk of the product failing to operate in otherwise untestable natural sunlight conditions and therefore increases the quality and selling point of the renewable energy device. Likewise, research and development teams could also benefit from this solar simulator device. Researchers at renewable energy companies or at related educational institutions will likely already have access to a solar simulator device or a different product of the same caliber. Therefore, having access to the solar simulator device designed in this project will aid researchers in developing a more advanced version of the same product that can function more efficiently and assist with the overall goal of improving renewable energy machines [12]. In addition, our product is seeking to comply with government regulations for solar simulators, making them an important stakeholder as well. Not all stakeholders are interested in the success of our product, however, and it is very likely that energy producers using non-renewable energy such as fossil fuels would oppose the development of a product to benefit renewable energy.

Chapter 2. Customer Requirements

TABLE I: Customer Requirements and Engineering Specifications

Customer Requirements	Engineering Specifications	Justifications
D, F	1. Peak power < 200W	There are class A solar simulators on the market that operate with a 150W xenon lamp [13]
A, C	2. Housing Size < 1ft^3	Many commercially available solar simulators fit well within this range [13]
B, F	3. Irradiance 100mW/cm^2 (1 Sun) ±30%	The irradiance of one sun is approximately 1000W/m^2 [2]
B, F	4. 400 nm < Wavelength < 1,100 nm	This range of light covers the majority of the Sun's spectrum
E	5. Price < $500	The product must be affordable and fit within our budget
C	6. Working Plane of 1ft^3	A small working plane means we can focus more light into a smaller area, minimizing hot spots
B	7. Irradiance Non-Uniformity < 10%	Class A Irradiance Non-Uniformity is to be <2%, Class C is the target so this range of tolerance gives room to meet that goal [4]
A, D	8. Operating Voltage 120V, 60Hz	We would like to plug into standard outlets.
A	9. Weight < 25lbs	The average weight of commercial products was about 15lbs. We want to keep the device portable

Customer Requirements
A. Portable
B. Appropriately can model the irradiance of the sun
C. Compact
E. Low-cost
F. Adjustable spectrum and intensity output

TABLE II: Engineering Specifications Risk

Spec. #	Parameter	Target Units	Tolerance	Risk	Compliance	Test Equipment
1	Power	200W	Max	M	T	Watt Meter
2	Housing Size	$1ft^3$	±3 in.	L	I, A	Measurement Scale
3	Irradiance	$100mW/cm^2$	±30%	M	T	Light Irradiance Power Meter
4	Wavelength	400-1100nm	±50 nm	L	T	Spectroradiometer
5	Production Cost	$500	Max	L	A	N/A
6	Working Plane	$1ft^2$	Min	M	A, I	Measurement Scale
7	Non-Uniformity	10%	Max	H	T	Watt Meter
8	Operating Voltage	120V	50 V	L	A, T	Power Supply
9	Weight	20lbs	Max	L	A, T, S	Weighing Scale

Chapter 3. Functional Decomposition

3.1 Level 0 Breakdown

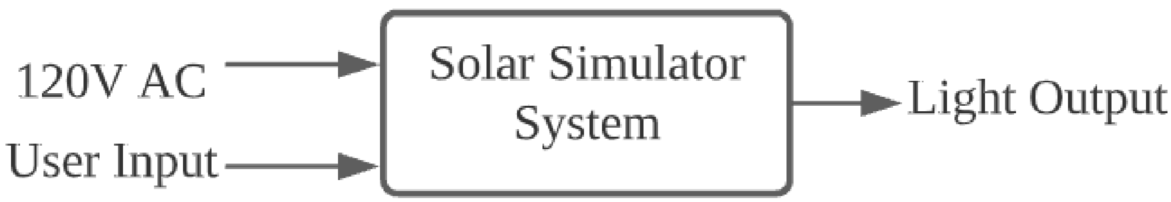


Figure 1. Level 0 Block Diagram of Product System

TABLE III. Level 0 Block Diagram I/O Description

Module	Solar Simulator
Inputs	- Power: 120 VAC rms, 60 Hz - User Spectrum Control: Variable Control
Outputs	Light Output - Tunable Spectrum of Light
Functionality	Output is an adjustable spectrum of light from 400nm to 740nm with adjustable intensity.

3.2 Level 1 Breakdown

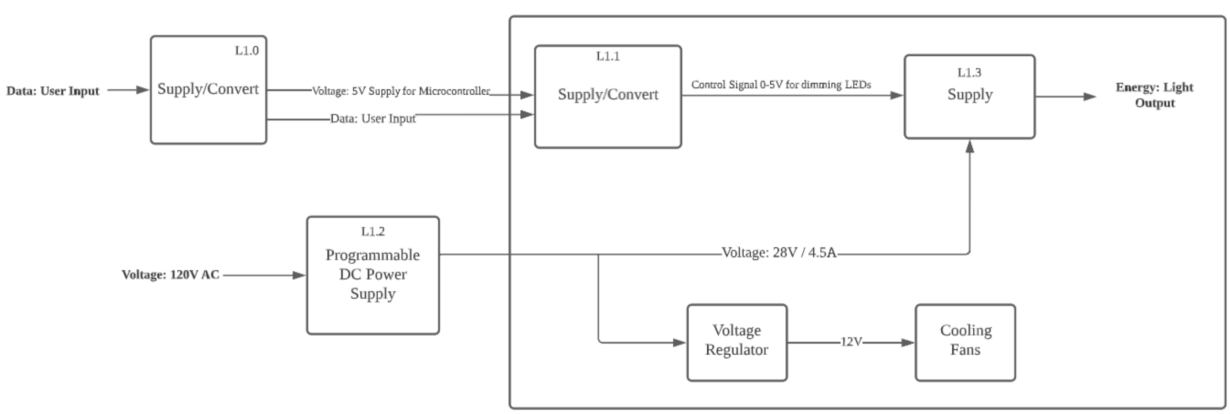


Figure 2. Level 1 Block Diagram of Product System

TABLE IV. L1.0 I/O Description

Module	Laptop
Inputs	User Input
Outputs	- Control Signal, Voltage for Microcontroller
Functionality	Output is a DC voltage supply for the microcontroller, and a control signal for the microcontroller.

TABLE V. L1.1 I/O Description

Module	Microcontroller
Inputs	- Power: 5 VDC - Control Signal from user
Outputs	LED Driver PWM Dimming Signals: 0-5 VDC, 490 Hz
Functionality	The microcontroller receives user input from the laptop and outputs a signal to the LED drivers to regulate current.

TABLE VI. L1.2 I/O Description

Module	Power Supply
Inputs	- Power: 120 VAC rms, 60 Hz
Outputs	DC Voltages • 28 V to Voltage Regulator, • 28 V to LED Drivers
Functionality	Receives AC power and converts it to DC and Voltage.

TABLE VII. L1.3 I/O Description

Module	LED Drivers and Array
Inputs	- 28 V - LED Driver PWM Dimming Signals: 0-5VDC, 490Hz
Outputs	Current / Light
Functionality	The LED drivers and array produce the variable intensity and variable spectrum light output.

Chapter 4. Project Planning

4.1 Pre Construction Material Cost Breakdown

TABLE VIII. Pre-construction Cost Estimate

Part	Description	Unit Cost	Total Cost	Justification
4x4 Keypad Matrix	Keypad with 16 buttons	Optimistic: $6.95 Pessimistic: $9.95 Most Likely: $7.95 Unit Cost: $8.16	$8.16	Keypads range anywhere from $4 to $10 typically depending on the number of buttons and the material. This keypad will serve as the user input and corresponds with L1.0
MSP432P401R	Microcontroller	Optimistic: $18.99 Pessimistic: $26.00 Most Likely: $20.00 Unit Cost: $20.83	$20.83	The microcontroller is responsible for controlling the LED drivers and corresponds with L1.1
Power Supply 120VAC to 5VDC	Power Supply	Optimistic: $70.00 Pessimistic: $120.00 Most Likely: $85.00 Unit Cost: $70.30	$70.30	This power supply converts 120V ac into various DC voltages, one of which being 5V which we need to power our board. This is module L1.2
LEDs and Drivers	The LEDs emit the light, the Drivers control the intensity	Optimistic: $2.24 Pessimistic: $4.00 Most Likely: $2.85 Unit Cost: $2.94	$294	This is a ballpark number, we may require fewer LEDs than this but we won't know until testing. This is module 1.3
Enclosure	Housing for the Electronics	Optimistic: $50 Pessimistic: $100 Most Likely: $80 Unit Cost: $78.33	$78.33	We will likely have this fabricated by a manufacturer and sent to us, otherwise, we will 3D print it.
			Total Cost: $471.62	

4.2 Labor Cost Breakdown

EE 460	Optimistic			
HW 1.1	Pessimistic			
Resume	Most Likely			
Cover Letter	Labor Days			
Project 2.1				
Abstract	2	3	4	
Intro	1	2	3	
Customer Reqs.				
Engineering Specs	1	1	2	
References	2	2	3	
HW 1.2	1	1	2	
Monte Carlo	1	1	2	
Project 2.2	3	4	5	
Abstract				
Specs and Reqs. V2	2	3	4	
Functional Decomposition				
Cost Estimates	0	0	0	
Gantt Chart	0	0	0	
Project 2.3	1	2	3	
ABET Analysis	1	1	2	
Project 2.4	2	3	4	
Powerpoint				
HW 1.3	3	4	5	
Reverse Engineering				
	2	3	4	
	3	4	5	
Sum:	25	34	48	
				Total Estimate: 34.83

Figure 3. Labor for EE 460

EE 461	Labor Days			
Design V1				
Power Supply Design	4	5	6	
LED Part Picking	2	2	3	
PCB Design	3	4	4	
Design Review with Advisor	1	1	2	
Order Parts for V1	1	1	2	
Build V1				
Design Software V1	3	4	5	
Build LED Array w/ Drivers	3	4	5	
Design V2				
PCB Modifications V2	2	3	4	
Power Supply Modifications	2	2	3	
Advisor Review V2	1	1	2	
Order Parts for V2	1	1	2	
Order Parts for Enclosure	1	1	2	
Report — Sum:	24	29	40	
Report Review				Total Estimate: 30.00
Documentation				

Figure 4. Labor for EE 461

EE 462			Labor Days				
Build V2							
	Fine Tune Software		3	4	5		
	Assemble PCB with Hardware		4	5	6		
	Build Enclosure		3	4	5		
Test							
	Test Design Specifications		3	4	5		
	Fine Tune Hardware		3	4	5		
	Fine Tune Software		3	3	4		
	Test at Cal Poly		2	2	3		
Report							
	Finalize Report		12	13	14		
	Documentation	Sum:	33	39	47		
						Total Estimate:	39.33

Figure 5. Labor for EE 462

Total Labor Days for Product Estimate using 3-point System: 104.17

Labor Cost Summary:

In summary, using an average electrical engineering salary in California of $82,000 [11], we can correlate that to an hourly wage of about $39/hour. We define a workday of 3 hours for this product. Scaling the labor hours by the cost of labor per hour brings us to a total labor cost of $12,187 per person. Given that there are three partners working on this project, we estimate a total labor cost of $36,561.

4.3 Gantt Charts

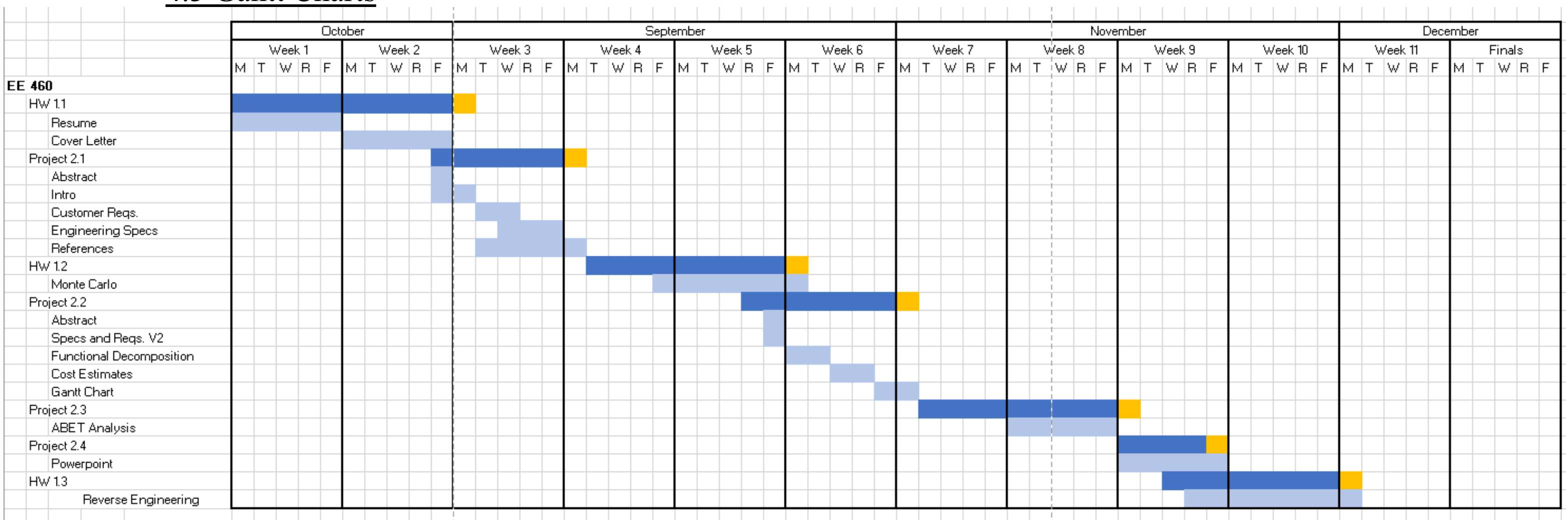


Figure 6. EE 460 Gantt Chart

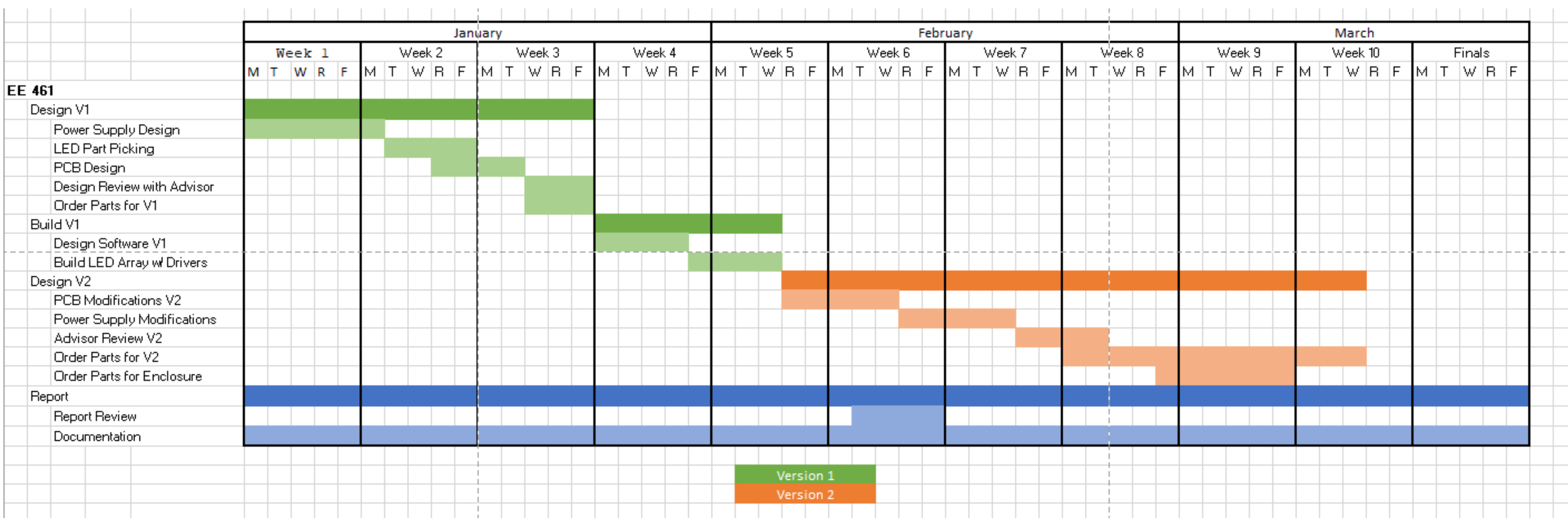


Figure 7. EE 461 Gantt Chart

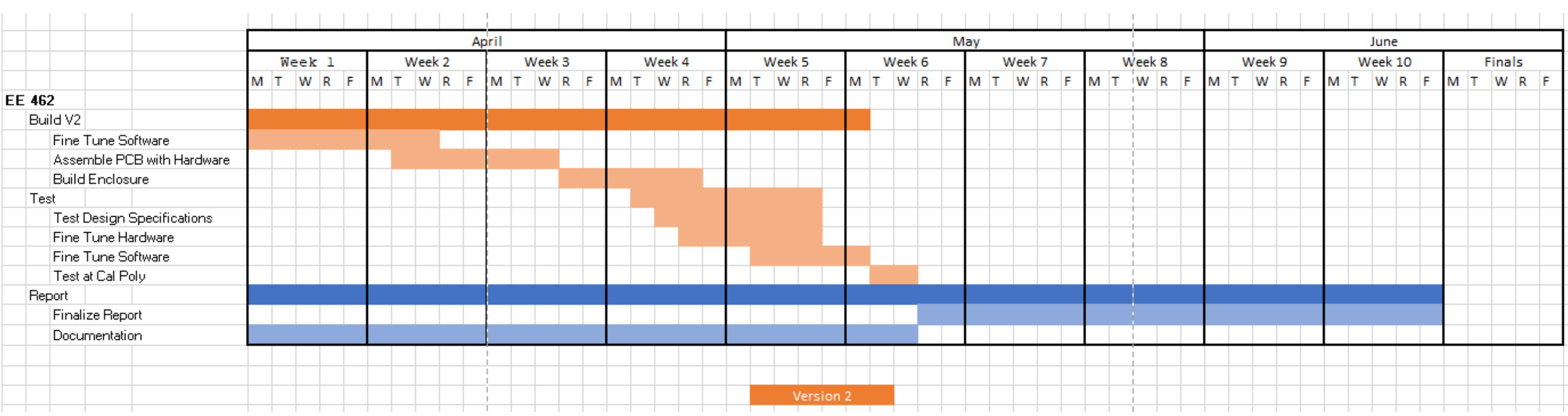


Figure 8. EE 462 Gantt Chart

Chapter 5. Implementation

5.1 Circuit Schematic and Finalized Bill of Materials

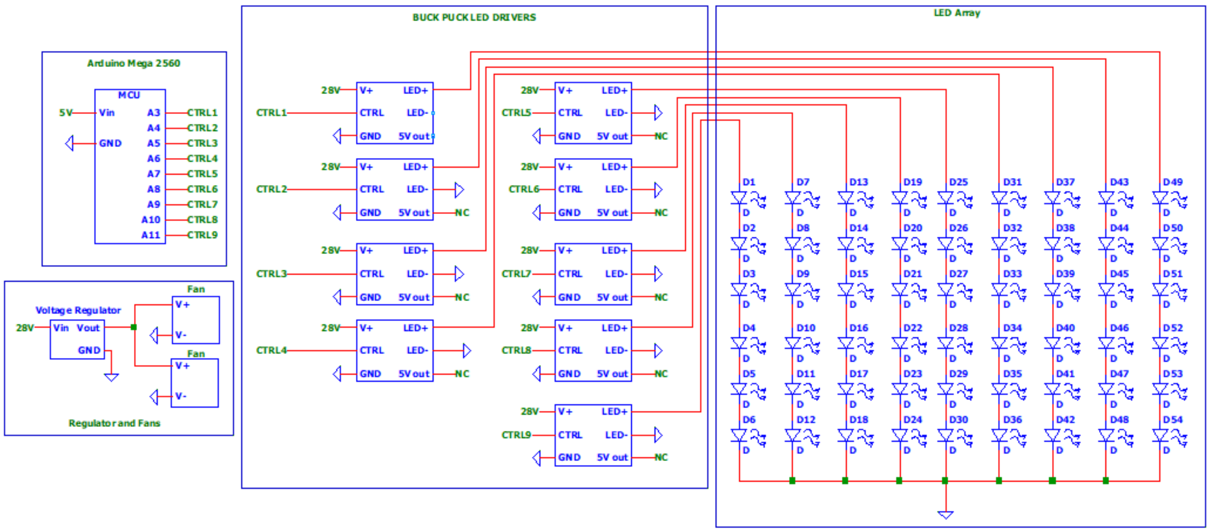


Figure 9. Circuit Schematic

TABLE IX. Finalized Bill Of Materials

Part	Description	Unit Cost	Quantity	Total Cost
Arduino Mega 2560	Microcontroller	$21	1	$21.00
Color LEDs	Luxeon C Color LEDs	$4.50	42	$189.00
UV LEDs	SemiLED UV LED	$8.00	6	$48.00
White LEDs	Luxeon C White LED Neutral 4000k	$4	6	$24.00
LED Current Drivers	700mA BuckPuck DC LED Drivers	$13	9	$117
Extrusion Kit with Fans	Housing for the Electronics	$50	1	$50.00
12 V Linear Voltage Regulator	Voltage Regulator	~$2	2	$4.00
Arduino Mega Proto Board	Protoboard attachment for Arduino for regulator circuitry	$10	1	$10.00
Male Header Pin Kit	Male Header pins to connect Arduino to	$5	1	$5.00
Metal Bars For Mounting	These provide the framing for the simulator	~$40	1	$40
				Total Cost: $508

TABLE X. LED Specifications

LEDS							
Color	Wavelength(nm)	Typical Drive Current(mA)	Max Drive Current(mA)	Forward Voltage	Output Power(mW)	Max Operating Temp (°C)	Radiometric Power (mW)
White 4000k		350	1225	2.75	962.5	85	171
Ultraviolet	400-410	500	800	3.2	1600	-	
Violet	425	350	1225	2.83	990.5	80	595
Blue	475	350	1050	2.84	994	80	43
Cyan	500	350	1050	3.05	1067.5	80	100
Green	530	350	1050	3.05	1067.5	80	141
Amber	600	350	1050	2.05	717.5	80	30
Red	630	350	1050	2	700	80	49
Far Red	735	350	700	1.9	665	80	340

5.2 LED Array Analysis

Design 1: Diagonal Strands

Column 1	Column 2	Column 3		Column 4	Column 5	Column 6
Blue	Amber	UV		Blue	Amber	UV
Red	Cyan	White		Red	Cyan	White
Green	Violet	Far Red		Green	Violet	Far Red
UV	Blue	Amber		UV	Blue	Amber
White	Red	Cyan		White	Red	Cyan
Far Red	Green	Violet		Far Red	Green	Violet
Amber	UV	Blue		Amber	UV	Blue
Cyan	White	Red		Cyan	White	Red
Violet	Far Red	Green		Violet	Far Red	Green

Figure 10. Original Array Layout

Design 2: Vertical Strands

Column 1	Column 2	Column 3		Column 4	Column 5	Column 6
Blue	UV	Amber		Blue	UV	Amber
Red	White	Cyan		Red	White	Cyan
Green	Far Red	Violet		Green	Far Red	Violet
Blue	UV	Amber		Blue	UV	Amber
Red	White	Cyan		Red	White	Cyan
Green	Far Red	Violet		Green	Far Red	Violet
Blue	UV	Amber		Blue	UV	Amber
Red	White	Cyan		Red	White	Cyan
Green	Far Red	Violet		Green	Far Red	Violet

Figure 11. Final Array Layout

The idea behind the first design was to optimize the spatial uniformity by having each color spread out diagonally across the six columns as seen above. We felt that by doing so we would maximize the area covered by each color and therefore minimize the number of square inches that were lacking in certain colors. The reason that we ultimately decided to implement design two was for simplicity's sake. It would have been difficult to wire the LEDs diagonally as originally suggested and it would not have been possible to efficiently interconnect the LED strands across the gap between the two separate extrusions. The only downside to designing two is that it sacrifices spatial uniformity because the colors are all concentrated in their own column. Another design consideration that was made was which LEDs would go on the middle columns two and five. We felt that the three most important LED strands were white, ultraviolet, and far-red so we put them in the middle column so that they would be able to span the most area. Additionally, we intentionally placed colors such as cyan and blue as far away from each other as possible since they have similar wavelengths. Overall, design two was an effective LED array because the wiring was simple and spatial uniformity was still sufficient.

5.3 Construction

The construction process began with first receiving one LED and one current driver. These were ordered prior to ordering large amounts of the materials since we wanted to first test the functionality of the driver and ensure it was what we wanted. After testing the operation of an individual current driver on a single LED, we found that the driver was operating as intended and proceeded to order the extrusion and LEDs. We screwed in the LEDs based on the LED array design as seen in the *LED Array Analysis* section and soldered the wires to the pads of the LEDs such that each wavelength was isolated from one another, where for every color of LED the six corresponding LEDs were in series. To confirm the electrical connection, we powered a single string of LEDs on a single panel before connecting the rest of the LEDs.

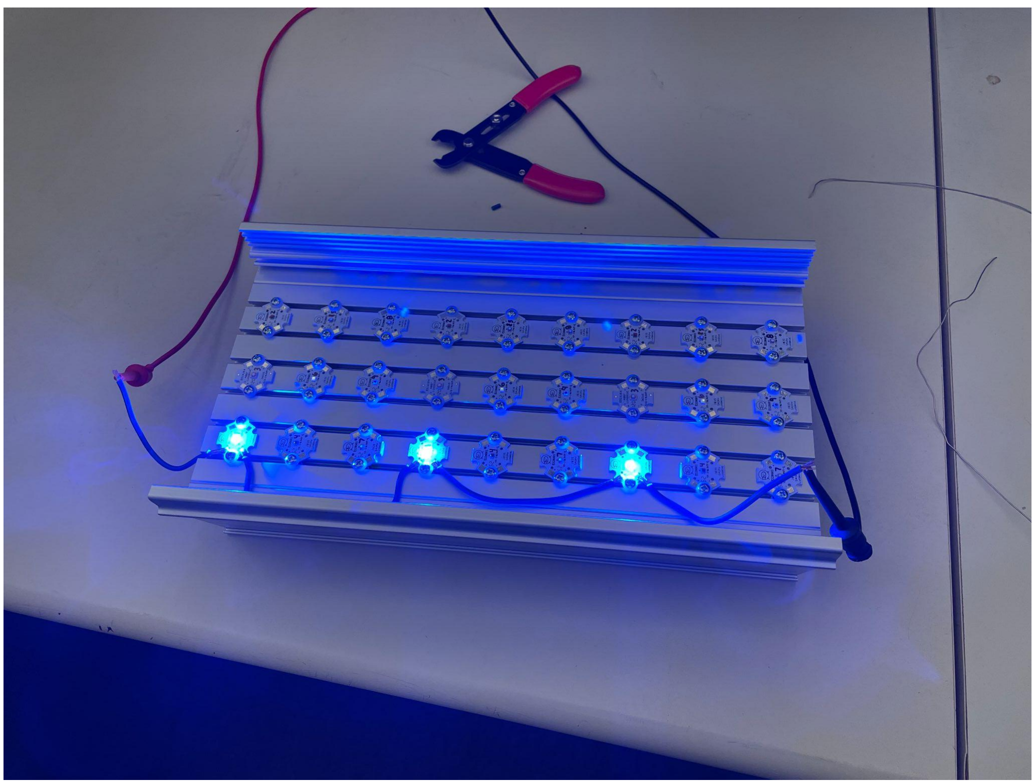


Figure 12. Testing a Single String of LEDs

Proceeding with the rest of the LEDs led us to the configuration below.

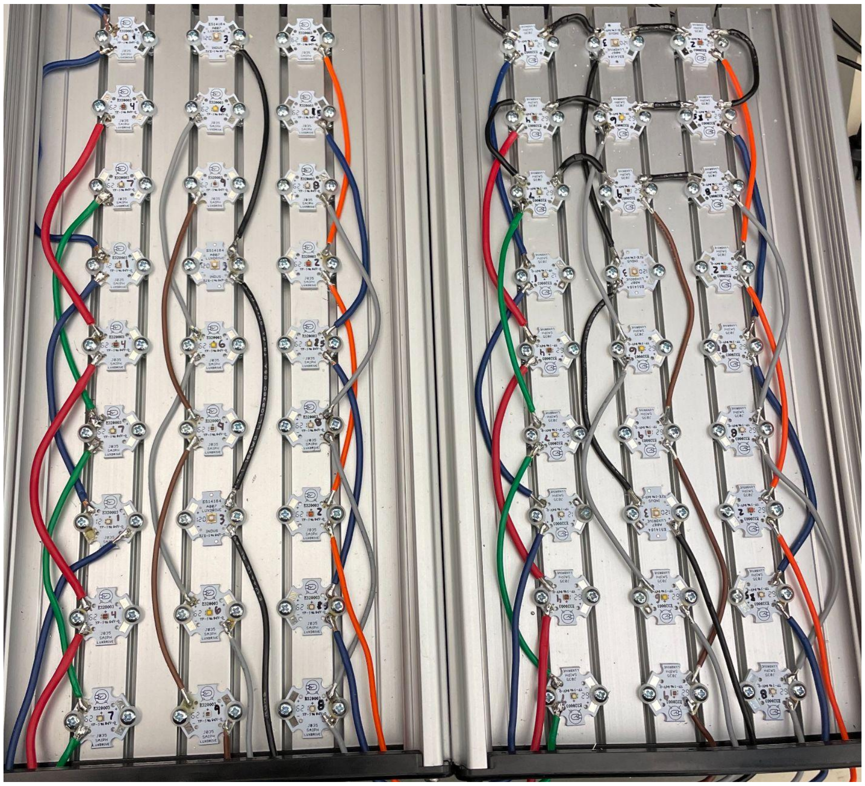


Figure 13. Both Arrays Constructed

The two separate panels were wired together by drilling holes in the plastic side panels and feeding the wire through one panel to the corresponding LEDs on the next panel. Metal cross bars were added in order to mechanically join the two panels together and provide structural support. The cross bars were also used to mount the illumination array to the final housing structure.

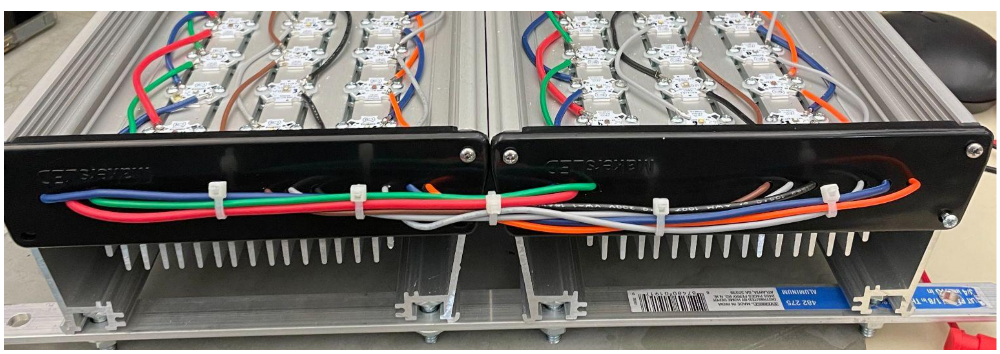


Figure 14. Side View of LED Array and Enclosure

The metal extrusion kit proved to be extremely useful because it not only provided a structural mount for the LEDs, but also acted as a large heat sink. An acrylic sheet was slipped over the LEDs to provide coverage and protection of the internal circuitry. Two fans slid in above the heatsink to recirculate air across the metal plates. The overall design was compact and efficient, allowing for adjustments to be easily made by tightening or loosening nuts and screws. More LEDs could be added to the array in the future by loosening and sliding LEDs closer together, making more room on the extrusion rails. The extrusion was cut to length in 6-inch increments and was 6 inches wide, therefore we ordered two 12-inch long panels to match our 1 sq. ft. customer requirement.

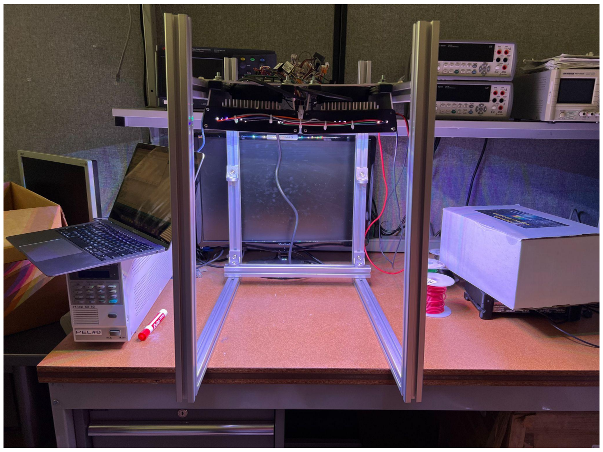


Figure 15. Housing for Solar Simulator

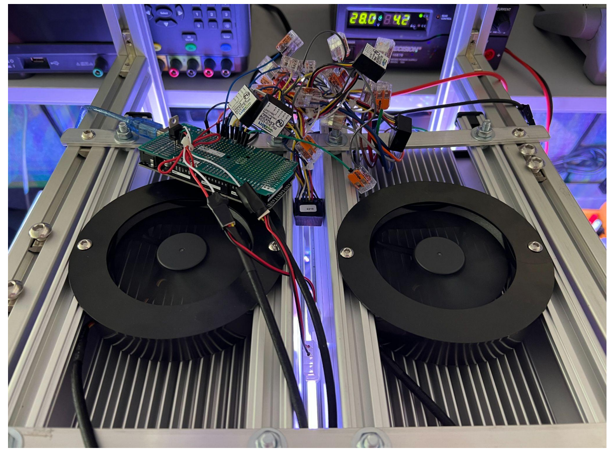


Figure 16. LED Arrays and Fans Wired to Arduino

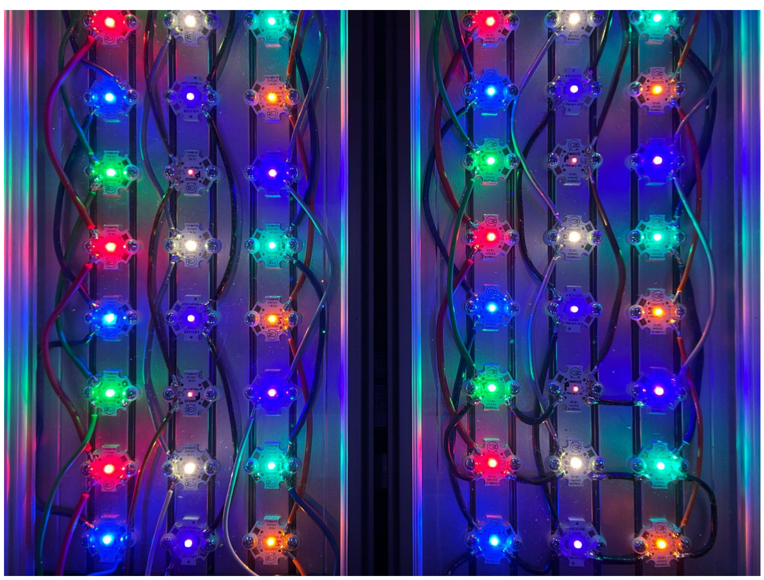


Figure 17. Powered LED Array

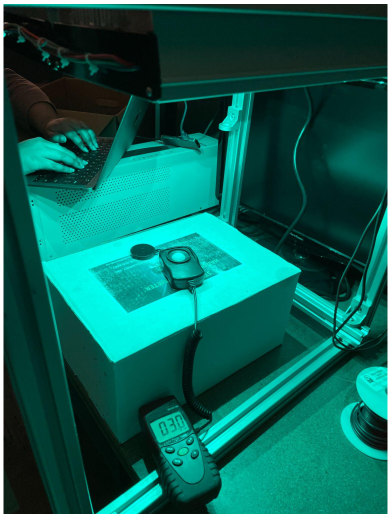


Figure 18. Cyan Light

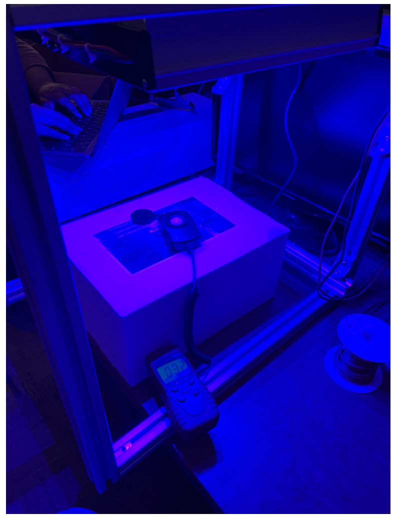


Figure 19. Violet Light

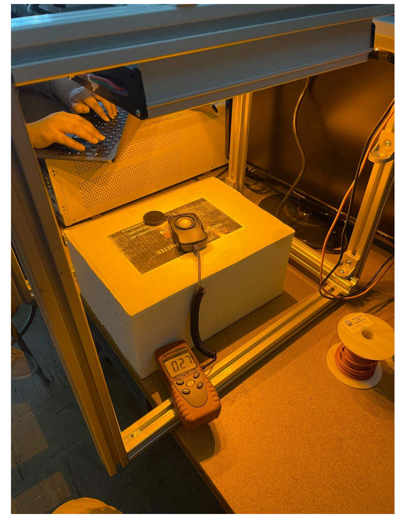


Figure 20. Amber Light

Figures 18, 19 & 20. Examples of a Single LED Color Powered On

5.4 Computer-Based Control Application

In order to quickly and easily tune the solar simulator's LED power intensity outputs, we created a computer-based control application using the Arduino Mega 2560 microcontroller via UART. For each individual LED color - for example, red, amber, UV, etc. - the user is able to enter any intensity from 0% to 100% in increments of 10%. These intensities correspond to an analog value that is then converted into a voltage which is outputted by the microcontroller to the pin corresponding to the LED color specified by the user. To specify the LED color, the user enters the first letter of the desired color - for example, 'r' for red, 'a' for amber, 'u' for UV, etc. - or the user can enter 'e' to set the same intensity for all the LEDs. Likewise, the user can also enter 's' to set the LEDs to the adjusted spectrum, which we determined as the closest actual solar spectrum output capable of being produced by the solar simulator as seen in the *Spectral Match* section below. The program is capable of checking for invalid inputs and will not perform any action until the user enters a valid input.

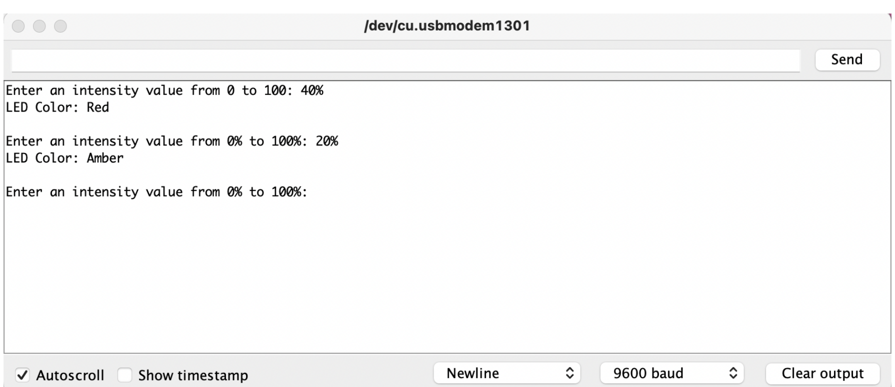


Figure 21. Sample Serial Monitor Output Given Two User Inputs

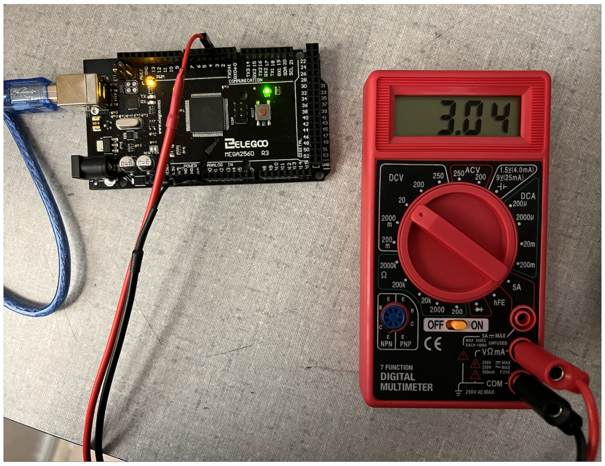


Figure 22. Red LED Array at 40% intensity

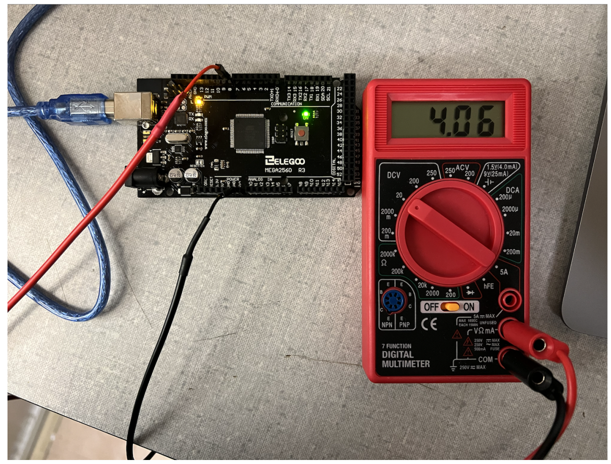


Figure 23. Amber LED Array at 20% intensity

Due to the solar simulator’s wiring, lower voltage outputs from the microcontroller correspond to larger intensities and vice versa.

Chapter 6. Data Collection

6.1 Measurement of Spatial Nonuniformity

For the measurement of spatial nonuniformity, we designated a two-dimensional coordinate axis originating from the bottom left corner of the solar simulator viewing array. Irradiance measurements were taken in 3-inch increments across the whole plane, at a distance of 6 inches from the LEDs. We chose this distance because we determined it would have a decent spatial distribution as well as irradiance. At a farther viewing distance, this array would have better spatial distribution, but less overall irradiance. All measurements were taken with all LEDs operating at 100% power. The raw data captured by the irradiance meter is listed in the table below.

TABLE XI. Irradiance at Different Positions Under the Array

x	y	Irradiance (w/m^2)
0	0	39.2
3	0	51.8
6	0	58.5
9	0	54.8
12	0	41.1
0	3	45.2
3	3	66.8
6	3	70.1
9	3	66.2
12	3	43.9
0	6	49.8
3	6	66.6
6	6	74.8
9	6	69.6
12	6	53.3
0	9	44.1
3	9	55.8
6	9	62.7
9	9	59.1
12	9	48.2
0	12	35.3
3	12	49.6
6	12	56.4
9	12	54.1
12	12	40.7

The following figure represents the irradiance measurements across the viewing plane.

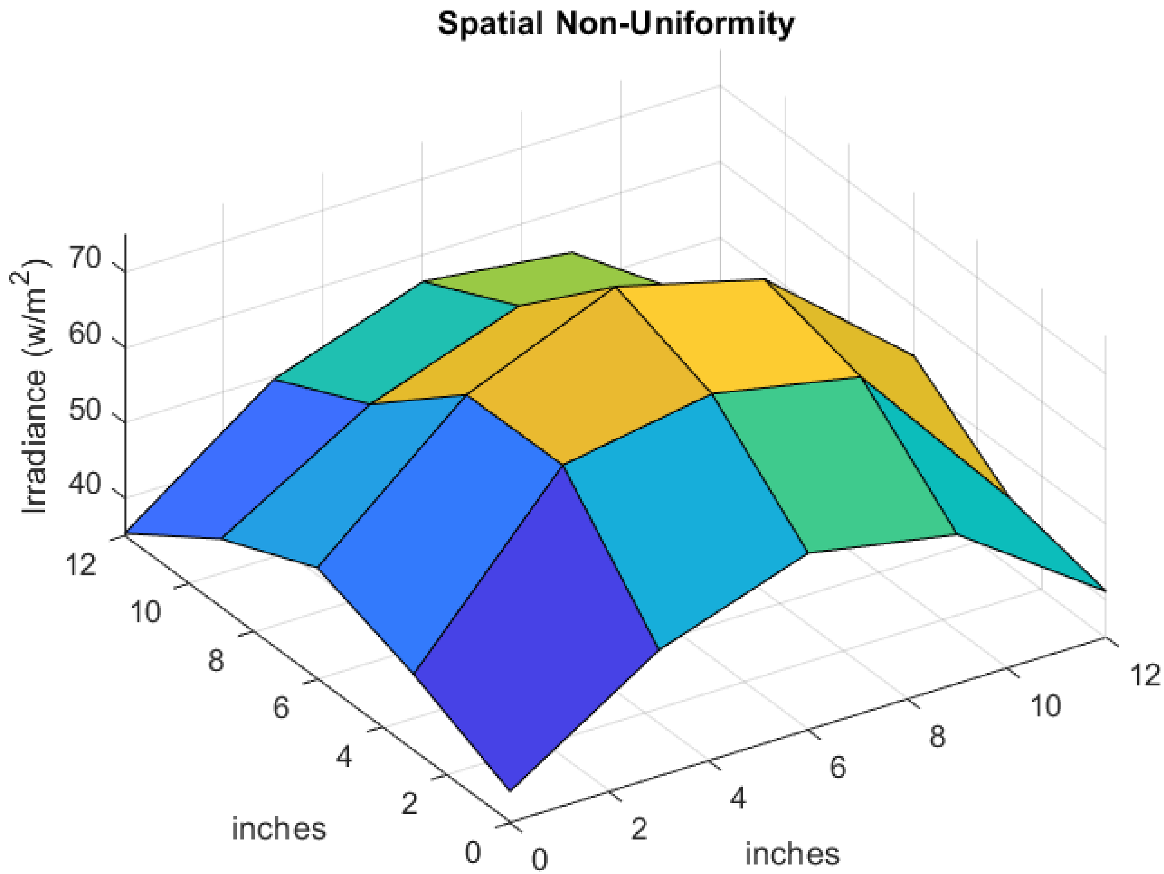


Figure 24. Graph of Spatial Non-Uniformity

As noted in the figure, towards the center of the array viewing plane (the center of the LED array), we observe a higher overall irradiance measured. This is expected because more of the light emitted from the LEDs is overlapping in the center. As we get farther away from the center of the array, and especially at the corner, irradiance drops somewhat significantly. The variation in irradiance can be reduced by moving the viewing plane farther away from the LED array so more light is overlapping across the area. Performing a calculation for overall spatial non-uniformity using the data in the table leads to this:

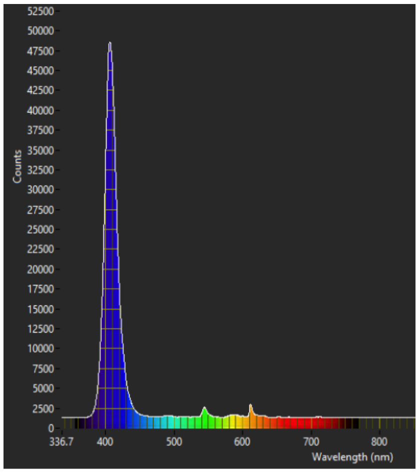
$$\%\, Spatial\ Nonuniformity\ =\ \frac{Max\ Irradiance - Min\ Irradiance}{Max\ Irradiance + Min\ Irradiance}\ x\ 100\%\ =\ 14\% \qquad (Eq.\ 1)$$

Considering this data was collected at only 6 inches away from the viewing plane, we are pleased with the result. Our original target for the solar simulator was to meet 10% spatial nonuniformity as denoted by ASTM class C solar simulator requirements. Seeing as we very closely met the class C requirement, it is safe to assume that <10% spatial nonuniformity can be achieved if the viewing plane is moved farther away.

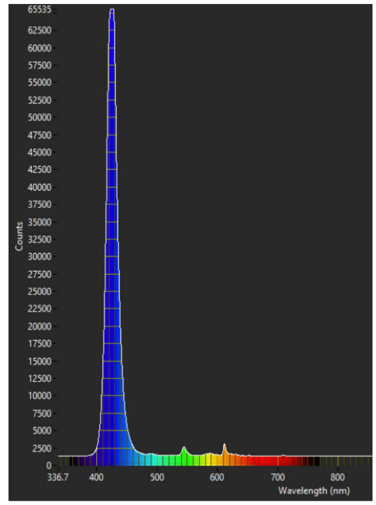
6.2 Spectral Match

TABLE XII: Individual LED Spectrum Measurements

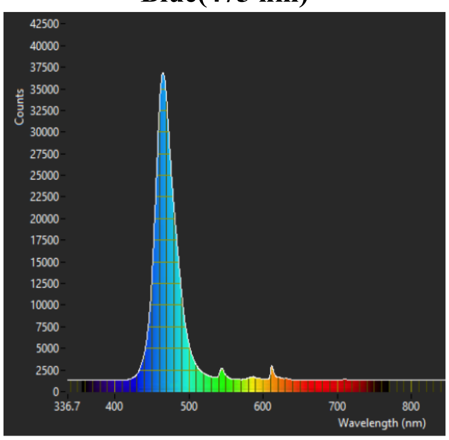
Ultraviolet (400-410 nm)



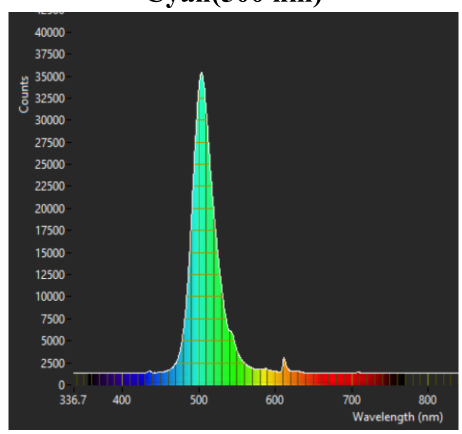
Violet (425 nm)



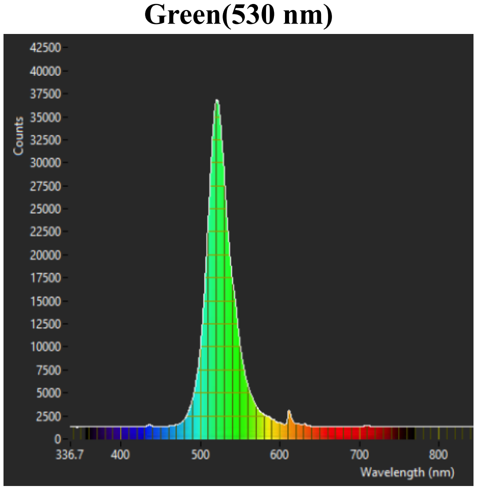
Blue(475 nm)



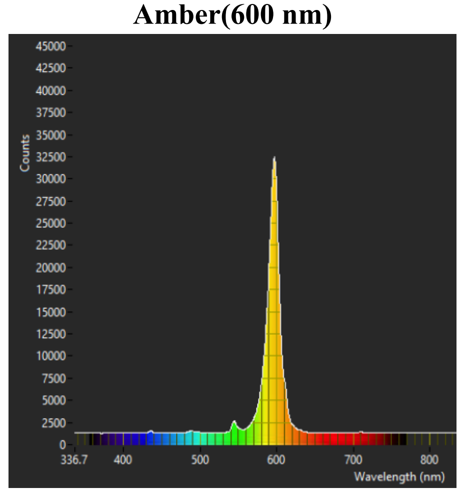
Cyan(500 nm)



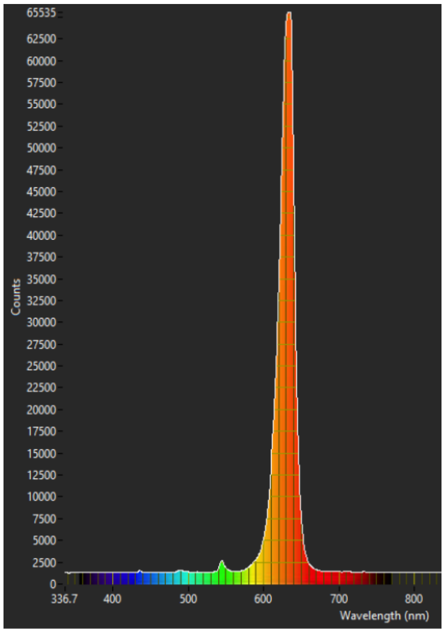
Green(530 nm)



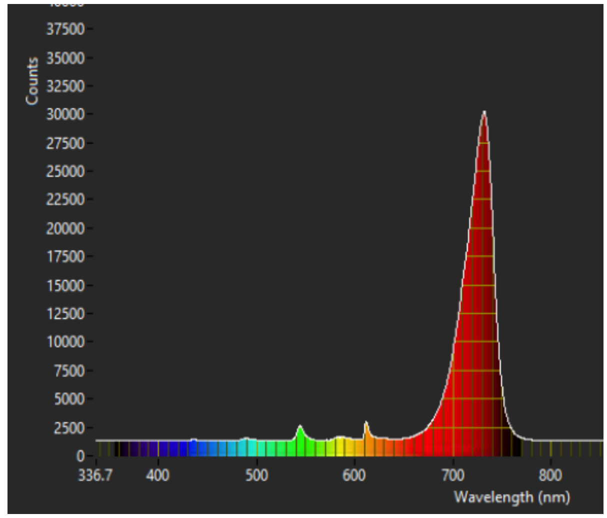
Amber(600 nm)



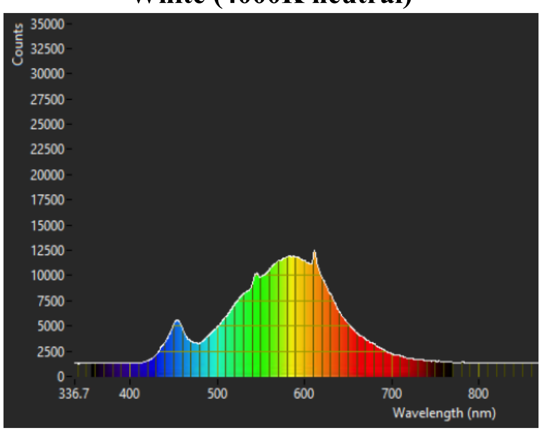
Red(630 nm)



Far Red(735 nm)



White (4000K neutral)



Spectroradiometer Measurement of LED Array at Full Power

Measured in Counts:

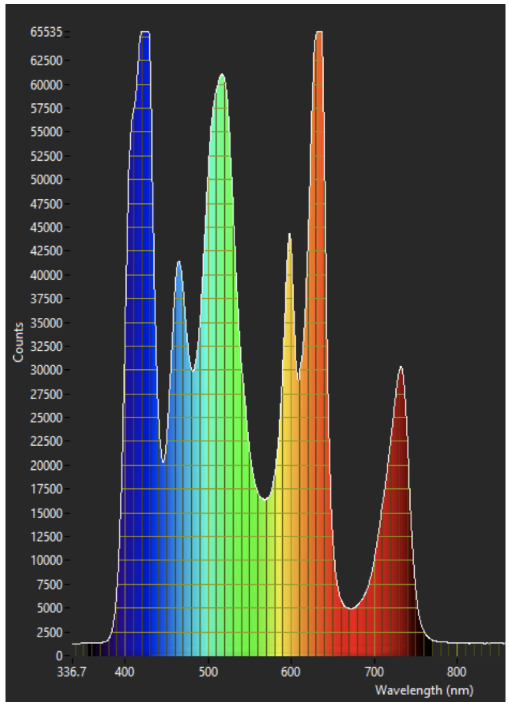


Figure 25. LEDs at Max Power, Measured in Counts

Measured in W/m^2:

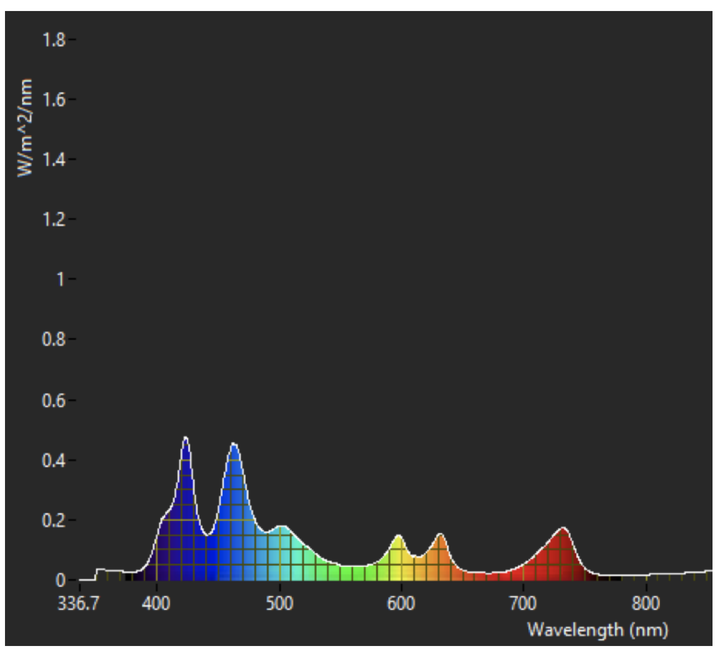
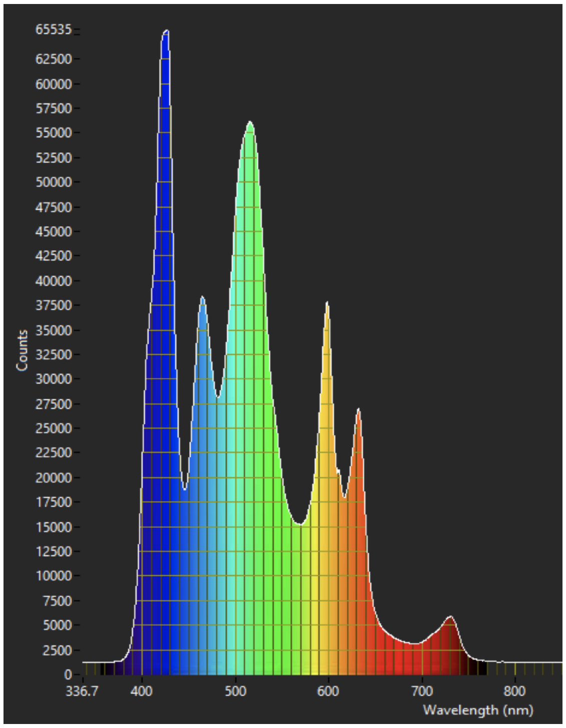


Figure 26. LEDs at Max Power, Measured in W/m^2

Solar Spectrum Matching via Spectroradiometer

Using data from light irradiance power meter:



The following are the percentages at which each LED strand was powered up:

Far Red - 10%

Red - 20%

Amber - 100%

Green - 80%

Cyan - 100%

Blue - 100%

Violet - 90%

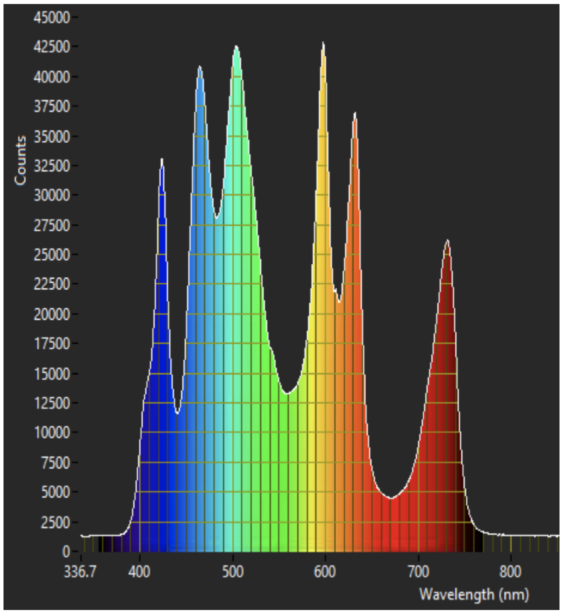
UV - 60%

White - 100%

Figure 27. Remastered Solar Spectrum Based Solely on Irradiance Data

The light irradiance power meter we used to collect our original data recorded the presence of UV and violet light, leading us to overestimate the need for UV and violet light in order to achieve an accurate spectral match. The converse is true for red and far-red light, which is what led to there being insufficient amounts of each wavelength present in this spectral match.

Adjusting the spectroradiometer:



The following are the percentages at which each LED strand was powered up:

Far Red - 80%

Red - 30%

Amber - 100%

Green - 10%

Cyan - 90%

Blue - 100%

Violet - 30%

UV - 20%

White - 100%

Figure 28. Visually Adjusted Spectrum for Better Spectral Match

By adjusting the percentages of each LED strand, we were able to improve our spectral match. Further improvement could be made by adding LEDs located in the gaps and adding more white light.

6.3 Irradiance Measurements

TABLE XIII. Irradiance of Individual LED Strands in W/m^2

Color	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Red	1.7	2.7	3.7	4.6	5.6	6.6	7.5	8.4	9.3	10
Green	1	1.2	1.5	1.8	2.1	2.4	2.7	3	3.2	3.4
Blue	0.8	1.1	1.4	1.6	1.9	2.2	2.4	2.7	2.9	3.1
White	1.2	1.8	2.4	3	3.7	4.3	4.9	5.6	6.2	6.7
Amber	0.8	1.1	1.4	1.6	1.9	2.1	2.3	2.5	2.7	2.8
Violet	0.7	1	1.3	1.6	1.9	2.1	2.4	2.7	3	3.2
Cyan	0.8	1	1.3	1.6	1.8	2.1	2.3	2.6	2.8	3
Far Red	2.6	4	5.5	7	8.4	9.9	11.3	12.8	14.2	15.1
UV	0.7	0.9	1.2	1.4	1.6	1.9	2.1	2.3	2.5	2.7

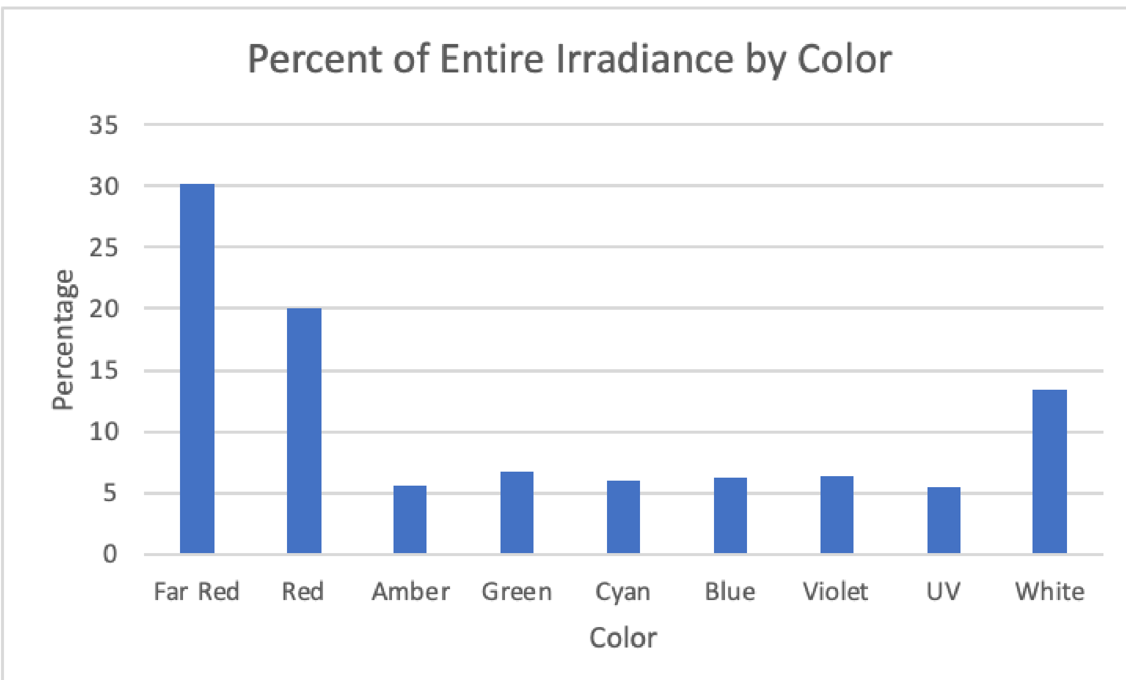


Figure 29. Representation of Each LED Strand's Contribution to Overall Irradiance at Full Power

6.4 Temporal Instability Measurements

TABLE XIV: Instability Measurements at the Center of the LED Array

Time [Minutes]	0	5	10	15	20	25	30	35	40	45	50	55	60
Irradiance [W/m^2]	45	45	45	45	45	45	45	45	45	45	45	45	45

Using the data measured by the irradiance meter, we can determine that our solar simulator has a temporal instability of 0% at the center of the LED array. Over the period of an hour, the irradiance meter only ever read 45 W/m^2. However, we believe that with a device that calculates to more significant figures, we would have seen small fluctuations over time. The reason for us believing this is that at other locations of the LED array, the irradiance meter would flicker between 44 and 45 W/m^2, leading us to believe that at certain areas of the LED array the true irradiance was fluctuating between 44.4 and 44.6 W/m^2. Nonetheless, our solar simulator has negligible temporal instability.

6.5 Satisfaction of Engineering Specifications and Customer Requirements

TABLE XV. Overall Satisfaction of Customer Requirements

Specification/Requirement	Satisfied	Partially	Unsatisfied
Portable	✓		
Compact		✓	
Low-cost	✓		
Adjustable spectrum and intensity output	✓		
Peak power < 200W	✓		
Housing Size < $1ft^3$		✓	
Irradiance $100mW/cm^2$ (1 Sun) ± 30%			✓
400 nm < Wavelength < 1,100 nm		✓	
Price < $600	✓		
Working Plane of $1ft^2$	✓		
Irradiance Non-Uniformity < 10%		✓	
Operating Voltage 120V, 60Hz	✓		
Weight < 25lbs	✓		

The two specifications that we did not meet can be seen above. The first regarding housing size is not a particularly large issue. Our entire system did meet this specification until we attached it to the metal beam structure provided by Dr. Dolan. This specification might not have been reasonable to begin with because we knew we were going to have a structure that held the LED array off the ground. The second specification that we did not satisfy is achieving the same irradiance as the sun. If we spent more money to buy more LEDs and switched to the more expensive 3-Up Luxeon LEDs, we would have been able to achieve this goal. However, in order to meet the other specification of keeping the cost below $600, we decided to sacrifice irradiance. As for the partially satisfied requirements, we have a UV LED with a wavelength of 400-410 nm but the highest wavelength we have is far-red at 735 nm. It was difficult to find an affordable infrared LED, which is why we did not purchase any. Additionally, the insufficient irradiance is why the “Appropriately can model the irradiance of the sun” requirement is checked partially. As for uniformity, our measurements show that spatial uniformity is approximately 10%, making that specification partially satisfied. In general, we met most of the engineering specifications and customer requirements and as expected, money was a binding factor that prohibited us from meeting more of them.

Chapter 7. Conclusion

7.1 Summary of Results and Reflection

In this project, we constructed a tunable LED-Based Solar Simulator using six parallel LED arrays composed of nine separate LED colors which were chosen based on the maximum ultraviolet to visible light spectrum we were able to cover (400 nm-735 nm). Our goal was to create an LED-based solar simulator that replicated natural solar irradiance which could be further fine-tuned to emit specific wavelengths of light and intensities. In general, our end product goals were to design a solar simulator that was capable of achieving an adjustable spectrum, an adjustable intensity, and spatial uniformity. Overall, the solar simulator was able to output 5% of the sun's irradiance with all of the LEDs on at their maximum intensities. Ideally, we aimed to output 100% of the sun's irradiance within the solar simulator's working plane, but due to constraints detailed in the following *Future Improvements* section, this output was not feasible due to budget and device size constraints. Additionally, we were not able to meet the 1,100 nm specification we sought to cover which is also detailed in the following section.

The solar simulator was designed to be tunable using a microcontroller and PC-based user input to control the outputted wavelengths and intensities. As a result of this addition, we were able to meet two of our general project criteria: having an adjustable spectrum and an adjustable intensity. With this application, we were able to measure the contributed power from each individual LED color spectrum at its maximum intensity and how much it contributed to the total output of the solar simulator at maximum power. From these measurements, we found that the far-red and red LED spectra contributed to approximately 50% of the device's total irradiance with the white LED spectrum contribution trailing close behind. The rest of the LED spectra contributed roughly 5% each toward the device's total irradiance. Using these values in addition to the spectroradiometer, we were able to fine-tune the intensities of each individual LED color spectrum to match the actual solar output spectrum as can be seen in the *Solar Spectrum Matching via Spectroradiometer* section.

Ideally, we aimed to achieve a uniform spectral irradiance within the solar simulator's working plane with a 10% tolerance. Using the 25 unique spectral irradiance data points we collected as a result of measuring every 3-inch increment under the simulator's working plane, we calculated a spectral non-uniformity of 14% as detailed in the *Data Collection* section, which is fairly close to our 10% non-uniformity goal. As a result of refactoring our LED array layout as shown in the *LED Array Analysis* section, we were able to strategically place the LEDs such that the spectral irradiance at each location within the working plane of the solar simulator would be as equal as possible in order to form a uniform distribution. As a result of this process, we were able to partially meet our last general requirement: spatial uniformity.

One area that our solar simulator excels in is its temporal instability. Measuring at the center of the LED array, the device has a temporal instability of 0%. As mentioned before, certain locations of the LED array have fluctuations in irradiance, but no more than $1 W/m^2$. With a more sensitive irradiance meter, we could have more accurate temporal instability measurements, but in general, our solar simulator's temporal instability is negligible.

Overall, our solar simulator device was able to meet or partially meet a substantial amount of our original project constraints. With further improvements, our solar simulator can be capable of meeting several more solar output characteristics, including achieving the full solar spectrum output and a uniform irradiance.

7.2 Future Improvements

When it comes to future improvements, there are a variety of ways that this simulator can be expanded upon or improved. First and foremost, the overall irradiance of the device did not come close to our target specification. This caught us off guard because we failed to take into account that the power absorbed by the LEDs may vary heavily from the radiometric power output depending on the efficiency of the LEDs. One significant limiting factor in the amount of light we are outputting is the overall budget. In total, we purchased 54 LEDs, each valued at about $4.50. These LEDs were a “1-up” configuration meaning that there was one LED on each LED star package. One immediate improvement would be to purchase the “3-up” configuration which has three LEDs one each LED star. This is a quick way of tripling the radiometric power output, but not sacrificing space as the LED star packages are the same size. Unfortunately, purchasing 3-up LEDs in as large of a quantity as we needed would put us over budget or close to it, causing us to make sacrifices in other areas of the design.

Likewise, LED optics were something that we played with before creating the whole array. Optics have the ability to focus the light emitted by the LEDs into a more compact area. Buying enough optics for every LED would have also put a huge dent in the budget, as well as potentially negatively affecting the spatial non-uniformity.

To cover more of the spectrum, it would be beneficial to purchase LEDs that go deeper into the infrared section as well as ultraviolet, but LEDs like this are both very expensive as well as difficult to find in the LED star package that we were using. The LED star package was useful because it allowed for easy mounting to the extrusion.

In addition, when we originally were hardcoding the intensity of the LEDs, we were able to get precision down to 1% increments of power, however, when we configured the UART communications for the Arduino, our code limited us to 10% increments. Luckily, 10% increments seemed to be fine-tuned enough to get a general representation of the solar spectrum. Any finer tuning would likely be unnoticeable.

Finally, the wiring for the current drivers is extremely messy and tangled, making it difficult to diagnose issues. It would be beneficial to solder extensions to the wires on the BuckPucks so that a cleaner wiring job can be done, and also the BuckPucks could be mounted to a large heat sink so that they do not get as hot after operating for long periods of time.

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Appendices

Appendix A: ABET Analysis

1. Summary of Functional Requirements

This product is an LED-based solar simulator. The function of the solar simulator is to illuminate a small square area with the same spectrum of light output by the sun. In addition to covering the full spectrum of light, a solar simulator mimics the irradiance, or intensity per unit area, of the sun as well. Solar simulators are used in laboratory settings to determine the strengths of products like sunscreen or to test the efficiency of solar panels. The device offers variable settings that can be set according to the user-desired specifications. These settings include an adjustable spectrum, an adjustable intensity, and spatial uniformity. According to the user-provided specifications, the solar simulator will replicate these settings in a manner comparable to natural sunlight if exposed to the same simulated environmental conditions.

2. Primary Constraints

The main limiting factors for this product were sizing and spectral match. Given the product was implemented solely with LEDs, a variety of LEDs that corresponded with different wavelengths of the light spectrum needed to be purchased. Due to a large number of various LEDs, the layout of the LEDs themselves became incredibly important. With the uneven distribution of LEDs, the solar simulator could end up with uneven irradiance, and spectral non-uniformity. High amounts of spectral non-uniformity mean there is no longer an accurate representation of sunlight. Doing all of this in an enclosure that is both small enough to be portable but large enough to cover large portions of a solar cell made this product difficult.

3. Economic

The main funding for this product will come from the EE department. There is an allocated $200 per student, giving the team a total budget of $600. This fits within the estimated cost for the product given in the parts list ($471). In terms of human capital, the product will require roughly 100 labor days to complete with a team of three.

Most of the cost accrues through the final stage of the product development where construction begins. None of the required funding is dedicated to research, all of it goes straight into parts and testing. Testing equipment may also require large amounts of funding if the testing equipment is not already readily available.

In addition to having an impact on natural capital, this device also has a significant impact on human capital. The solar simulator will aid researchers in gaining a more thorough understanding of renewable energy and how to eventually implement solar panels on a grand scale worldwide. This process of establishing and spreading awareness about renewable energies will result in the general public also learning about the importance and necessity of such resources.

The LED target lifespan we are shooting for is 10,000 hours, so at the end of the product lifetime the LED array will need to be replaced or the product entirely will need to be replaced. To ensure that the

LEDs are always operating at peak performance, it is recommended that the LED array be replaced entirely every 5000 hours of operating time. This long lifespan minimizes economic strain.

In terms of cost-benefit analysis, the benefits of this device significantly outweigh the costs. Because the solar simulator device is constructed with fairly simple elements, such as LEDs, a microcontroller, and basic sensors, the actual device is not expensive when compared to the benefits it is able to produce. The total cost of these component parts will amount to roughly $400 to $500. Since Cal Poly will provide $200 for each senior project, the project developers will likely need to produce at most $300 of their own.

4. If manufactured on a commercial basis

This product has an estimated manufacturing cost of $474 dollars. After parts optimization and wholesale purchasing, if manufactured on a commercial basis the team expects to manufacture each unit for about $400. The retail price of this product would begin at $800. The reasoning for this is that many class AAA solar simulators are priced for thousands of dollars. The product will be close to AAA specifications but closer to class B. In addition, materials that are relatively cheap in the industry will be utilized to make the product more affordable.

In terms of variable costs, the number of workers on the product is subject to change if manufactured on a commercial basis, hence labor costs may increase. In addition, LEDs when purchased on a massive scale decrease in price. If 500 solar simulators were sold in a year, which is a rather conservative number, then the estimated profits would be $200,000. Most of this profit would have to be then distributed in the form of labor costs to employees.

5. Environmental

The environmental costs of this product are like those costs created by most electronics. Printed circuit boards require copper, as well as other metals and chemicals to develop. Circuit boards like this are not easily recyclable due to how expensive it would be to disassemble them on a mass scale. Luckily, this product uses just one printed circuit board and a microcontroller. If necessary, the microcontroller can be removed and easily repurposed as something else.

To continue, the enclosure of the product is plastic, which can be recycled but only with harmful emissions to the air. This product also utilizes power from the grid, which is generated primarily from fossil fuels. Fossil fuels are obviously nonrenewable, hence the negative impact on the environment as we waste material burning them and emitting pollutants to the air.

All these considerations are prices that must be paid in order to have the convenience of testing in a laboratory setting. Anybody can work and test outside under the actual sun, but they lack the ability to be configured which we offer with our product.

6. Manufacturability

As stated earlier the primary component for the device housing is plastic. PCBs are made from materials such as Silkscreen, Solder mask, Copper, and Substrate. Cheaper boards do exist which are manufactured with cheaper materials however they are more susceptible to temperature. Our product is going to be operating at high temperatures due to the large power dissipation hence it is important we work with materials that can withstand such heat.

The most significant concern with manufacturing this device would involve some aspect of timeliness and how the process can be streamlined in order to produce the final product quickly but also ensure that its durability is maintained. In order to efficiently develop the device, a division of labor needs to be established which blocks out times for each stage of assembly, including the production of the PCBs, testing the board, assembling the final product and then testing the device for quality control prior to shipping it out to consumers. There needs to be a rigid checklist of criteria that need to be met before each individual device is approved for public use.

7. Sustainability

Thankfully due to the very long lifespan of LEDs, we can ensure the product won't need to be replaced or upgraded during its lifespan. LEDs are low power relative to gas bulbs and hence decrease the energy consumption of our product. LED's output relatively low amounts of heat compared to Xenon arc lamps which are commonly found in solar simulators; hence we further decrease the energy consumption when it comes to providing sufficient cooling.

The housing for the product itself is recyclable however the PCB itself is going to need to go to a landfill. Unfortunately, there is little way around this without raising capital to properly dispose of it. In addition, properly calibrating our microcontroller to accurately sense variations in temperature allows the system to respond better to temperature increases. The product is modular so that if an upgrade is needed, it can be done so easily. Fortunately, the product does not require batteries which contribute to landfill pollution.

8. Ethics

One potential ethical dilemma with this product is regarding code 1 from the IEEE code of ethics [15]. Code one states that the health safety and welfare of the public should be held paramount. In addition, sustainable practices will be conducted. An ethical dilemma arises here because we are creating something that uses power from the grid only to mimic a natural phenomenon. We must ask ourselves whether it is ethical to use energy generated primarily by non-regenerative fossil fuels rather than just conduct tests outside under the actual sun.

Looking at the product from a utilitarian ethical framework, however, it can be argued that this product would benefit most of the people hence it is morally right. Products like sunscreen need to be tested in a lab setting to prove they are effective for people. This is for the safety of the public. In addition, this product will be used to test solar cells which are used to replace non-renewable energy.

9. Health

The health of the people is always the most important aspect when making a product. There are without doubt health implications with solar simulators. To begin, high amounts of exposure to UV-light can pose danger to human skin. UV light is known to cause skin cancer in people who are over-exposed to it. Hence, operators of the solar simulator need to be educated about how to mitigate UV exposure.

To continue the device is high power operating off 120VAC. It turns out 120VAC can prove to be fatally dangerous if not properly handled. The enclosure and all circuits inside must be properly grounded to prevent any malfunctions.

10. Social and Political

This product is related to energy production, which happens to be a politically polarizing topic itself. Most people are on board with renewable energy, but some aren't willing to spend the money on it. Things like nuclear energy and windmills are two prime examples of energy generation where there is a major disagreement between political parties. Solar panels are no different, and one use for our product is for testing solar panels.

Stakeholders in our product that are hoping it succeeds include solar panel companies as well as sunscreen companies. Conversely, coal power plant companies will likely be very against the product as they are typically against renewable energy in general. Their reasoning for not supporting renewable energy is because they make very large sums of money off coal. There isn't much money to be made in renewable energy because it is so expensive to manufacture.

In order to account for consumers in other countries, the device needs to be designed in a manner that can use transformers to account for different power supply values. Additionally, users with impaired vision would be accommodated by providing options to change font sizes and colors on the digital device which controls the solar simulator device settings.

11. Development

Over the course of this product, we have honed our abilities in MATLAB simulation tools as well as soldering. Soldering is something we had only practiced in one class up to this point, so we are glad that we got to improve those skills. In addition, PCB design was entirely foreign to us, and we had never done it on our own. This product pushed us to understand PCB design further.

Probably the most important benefit that the team gained from completing this project is an improved ability to problem solve independently. Compared to lectures and scripted lab experiments, the steps taken to design and implement a working LED-based solar simulator were nearly autonomous. Other than the advisor checking progress and making subtle suggestions, the project was researched, designed, implemented, and tested solely by the team. The team was faced with many decisions and problems, and through hard work and perseverance all were overcome. All team members gained valuable experience in conducting technical research, specifically being able to determine the credibility of a source. A piece of equipment that all team members became familiar with is a light uniformity measurement device. It was used to determine whether or not the specification of an irradiance spatial non-uniformity of less than ten percent was being met. The technique of functional decomposition was also instrumental to the success of the project in the sense that it broke down exactly what certain modules needed to achieve.

Appendix B: Arduino Code

```
// Solar Simulator LED Intensity Code
// Tanvi Kharkar, Mitchel Hutcheson, Jake Meyers EE 461/462 'Design of an LED Based
Solar Simulator'

// LED color and corresponding Arduino pin
const int RED = 3;
const int GREEN = 4;
const int WHITE = 5;
const int FAR_RED = 6;
const int BLUE = 7;
const int AMBER = 8;
const int UV = 9;
const int CYAN = 10;
const int VIOLET = 11;
const int A_HIGH = 255;

float LED_output;

char key;
String press_key;
int num_key;

void setup() {
  Serial.begin(9600);

  pinMode(FAR_RED, OUTPUT);
  pinMode(RED, OUTPUT);
  pinMode(GREEN, OUTPUT);
  pinMode(UV, OUTPUT);
  pinMode(VIOLET, OUTPUT);
  pinMode(WHITE, OUTPUT);
  pinMode(BLUE, OUTPUT);
  pinMode(AMBER, OUTPUT);
  pinMode(CYAN, OUTPUT);

  Serial.print("Enter an intensity value from 0 to 100: ");

  while (!Serial){
    // Wait until a user input is entered from the computer keyboard
  }
}

void loop() {
  if (Serial.available() > 0){  // If a key is pressed
    key = Serial.read();  // Reads key press
```

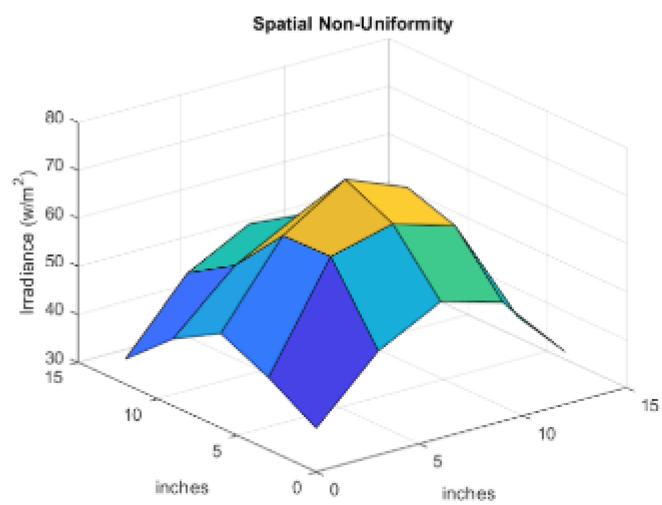
```
    // LED INTENSITY CONTROL
    // Key press '0' = 0% intensity, '1' = 10% intensity, ... , '9' = 90% intensity
    // '$' = 100% intensity. LED intensity can be changed in increments of 10%
    if (key == '0' || key == '1' || key == '2' || key == '3' || key == '4' || key
== '5'
        || key == '6' || key == '7' || key == '8' || key == '9' || key == '$'){

      if (key == '$'){
        String press_key = "10";
        Serial.print(press_key.toInt() * 10);
        Serial.print("%");
        num_key = press_key.toInt();
      }

      else{
        String press_key = String(key);
        Serial.print(press_key.toInt() * 10);
        Serial.print("%");
        num_key = press_key.toInt();
      }
      LED_output = (1 - (float(num_key) / 10)) * A_HIGH; // Formula for controlling
LED intensity based on user input
      Serial.print("\nLED Color: ");
    }

    // LED COLOR CONTROL
    // Far Red
    else if (key == 'f' || key == 'F'){
      Serial.print("Far Red");
      analogWrite(FAR_RED, LED_output);
      Serial.print("\n\nEnter an intensity value from 0% to 100%: ");
    }

    // Red
    else if (key == 'r' || key == 'R'){
      Serial.print("Red");
      analogWrite(RED, LED_output);
      Serial.print("\n\nEnter an intensity value from 0% to 100%: ");
    }

    // Green
    else if (key == 'g' || key == 'G'){
      Serial.print("Green");
      analogWrite(GREEN, LED_output);
      Serial.print("\n\nEnter an intensity value from 0% to 100%: ");
    }
```

```
// UV
else if (key == 'u' || key == 'U'){
  Serial.print("UV");
  analogWrite(UV, LED_output);
  Serial.print("\n\nEnter an intensity value from 0% to 100%: ");
}

// Violet
else if (key == 'v' || key == 'V'){
  Serial.print("Violet");
  analogWrite(VIOLET, LED_output);
  Serial.print("\n\nEnter an intensity value from 0% to 100%: ");
}

// White
else if (key == 'w' || key == 'W'){
  Serial.print("White");
  analogWrite(WHITE, LED_output);
  Serial.print("\n\nEnter an intensity value from 0% to 100%: ");
}

// Blue
else if (key == 'b' || key == 'B'){
  Serial.print("Blue");
  analogWrite(BLUE, LED_output);
  Serial.print("\n\nEnter an intensity value from 0% to 100%: ");
}

// Amber
else if (key == 'a' || key == 'A'){
  Serial.print("Amber");
  analogWrite(AMBER, LED_output);
  Serial.print("\n\nEnter an intensity value from 0% to 100%: ");
}

// Cyan
else if (key == 'c' || key == 'C'){
  Serial.print("Cyan");
  analogWrite(CYAN, LED_output);
  Serial.print("\n\nEnter an intensity value from 0% to 100%: ");
}

// Everything
else if (key == 'e' || key == 'E'){
  Serial.print("Everything");
  analogWrite(FAR_RED, LED_output);
```

```
      analogWrite(RED, LED_output);
      analogWrite(GREEN, LED_output);
      analogWrite(UV, LED_output);
      analogWrite(VIOLET, LED_output);
      analogWrite(WHITE, LED_output);
      analogWrite(BLUE, LED_output);
      analogWrite(AMBER, LED_output);
      analogWrite(CYAN, LED_output);
      Serial.print("\n\nEnter an intensity value from 0% to 100%: ");
    }

    // Adjusted Spectrum
    else if (key == 's' || key == 'S'){
      Serial.print("Adjusted Spectrum");
      analogWrite(FAR_RED, (1 - 0.8) * A_HIGH);
      analogWrite(RED, (1 - 0.3) * A_HIGH);
      analogWrite(AMBER, (1 - 1.0) * A_HIGH);
      analogWrite(GREEN, (1 - 0.1) * A_HIGH);
      analogWrite(CYAN, (1 - 0.9) * A_HIGH);
      analogWrite(BLUE, (1 - 1.0) * A_HIGH);
      analogWrite(VIOLET, (1 - 0.3) * A_HIGH);
      analogWrite(UV, (1 - 0.2) * A_HIGH);
      analogWrite(WHITE, (1 - 1.0) * A_HIGH);
      Serial.print("\n\nEnter an intensity value from 0% to 100%: ");
    }
  }
  // If a valid key is not pressed, program will wait for a valid user input before
it performs an action
}
```

Appendix C: MATLAB Code

```
clearvars
x = [0 3 6 9 12; 0 3 6 9 12; 0 3 6 9 12; 0 3 6 9 12; 0 3 6 9 12]
y = [0 0 0 0 0; 3 3 3 3 3; 6 6 6 6 6; 9 9 9 9 9; 12 12 12 12 12]
z = [39.2 51.8 58.5 54.8 41.1; 45.2 66.8 70.1 66.2 43.9; 49.8 66.6 74.8 69.6 53.3;
44.1 55.8 62.7 59.1 48.2; 35.3 49.6 56.4 54.1 40.7]
figure(1)
surf(x,y,z)
title('Spatial Non-Uniformity')
xlabel('inches')
ylabel('inches')
zlabel('Irradiance (w/m^2)')
non_uniformity = (max(z)-min(z)) / (max(z)+min(z)) * 100
```




```
non_uniformity = 14.0836
```