ECEN 403- 903: Photometer

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Concept of Operations

REVISION – Draft
3 December 2022

Concept of Operations
for
Photometer

Team <18>

Approved by:

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Project Leader Date

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Prof. Kalafatis Date

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T/A Date

Change Record

Rev.	Date	Originator	Approvals	Description
-	02/08/2022	Photometer		Draft Release
-	03/12/2022	Photometer		Final Release

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Executive Summary

OPTEC, a manufacturer of stellar measurement equipment, has recently discontinued its line of photometer products. This has created a need for high precision star measuring equipment in the market. Our objective is to create a cost effective photometer that can function as a replacement for one of the OPTEC models. Our primary customer is Mr. Don Carona, who will be using the photometer by attaching it to a telescope and measuring the intensity of a particular star known as Betleguse. We have many improvements in mind that were proposed in part by our customer. The durability of the photometer will be increased by using a modern op-amp over the the high-voltage photomultiplier used in the OPTEC model owned by Mr. Carona. We will expand the display screen from 12-bit to 16-bit and make the onboard navigation more intuitive. Finally, we will simplify the layout of the data acquisition software to be more user friendly – all while using far cheaper hardware than the SSP3 Photometer uses. There are alternative solutions to the problem, however, our approach is the one that best fits the needs of our customer and it is cost effective. Upon successful completion, our system would help provide our customer with the tool that he needs to research celestial bodies. Further, it could help fill the current gap in the photometer market and be cheaply manufactured and sold to amateur astronomers to aid in their research.

Introduction

This document is an introduction to the photometer, a photometer is a device that is used to measure light intensity from distant light sources. The one we will design will be used to measure an input from a celestial body. Upon processing, it should display a 16 bit value that represents the intensity of the measured celestial body. The higher the number the brighter the star or planet. Our primary customer is Mr. Don Carona, manager of the Physics & Astronomy Teaching Observatory.

Background

The photometer is used to measure the amount of photons that are being emitted from a light source. It has fast results and the one we are making can read from bright stars accurately. The main way our photometer will be able to measure light is through a photodiode. With this we can measure bright stars with great accuracy.

Our system will function as the replacement for an older model that was designed around 40 years ago by the company OPTEC. Recently, OPTEC discontinued their line of photometers. Our objective is to create a new and improved photometer that uses a photodiode instead of a photomultiplier tube

OPTEC had two different ways of measuring photons which was using a photomultiplier tube or a photodiode. The photomultiplier is very sensitive to light with intensity; it is usually used to measure 3rd magnitude stars or higher. The higher the magnitude of the star the less bright it is. The perk of a photodiode is that it is better at measuring brighter stars although it would have more noise.

○ ***Overview***

We will have 4 subsystems: the photodiode and amplifier, ADC, control systems and user inputs, and finally the chassis. The photodiode is the centerpiece of the project and will get input from the light directed from photons entering the telescope. The Amplifier part should amplify the signal for it to be a scalable value and for the ADC to read it. Then there is the ADC which is the analog to digital converter that gives a readable value. The backbone is the Control systems and user input. We want a hardware interface with buttons that would change the type of gain the Amplifiers give as well as the time integration. Last but not least is the chassis that will help contain all our project and will be set up in order to transfer light through the photodiode.

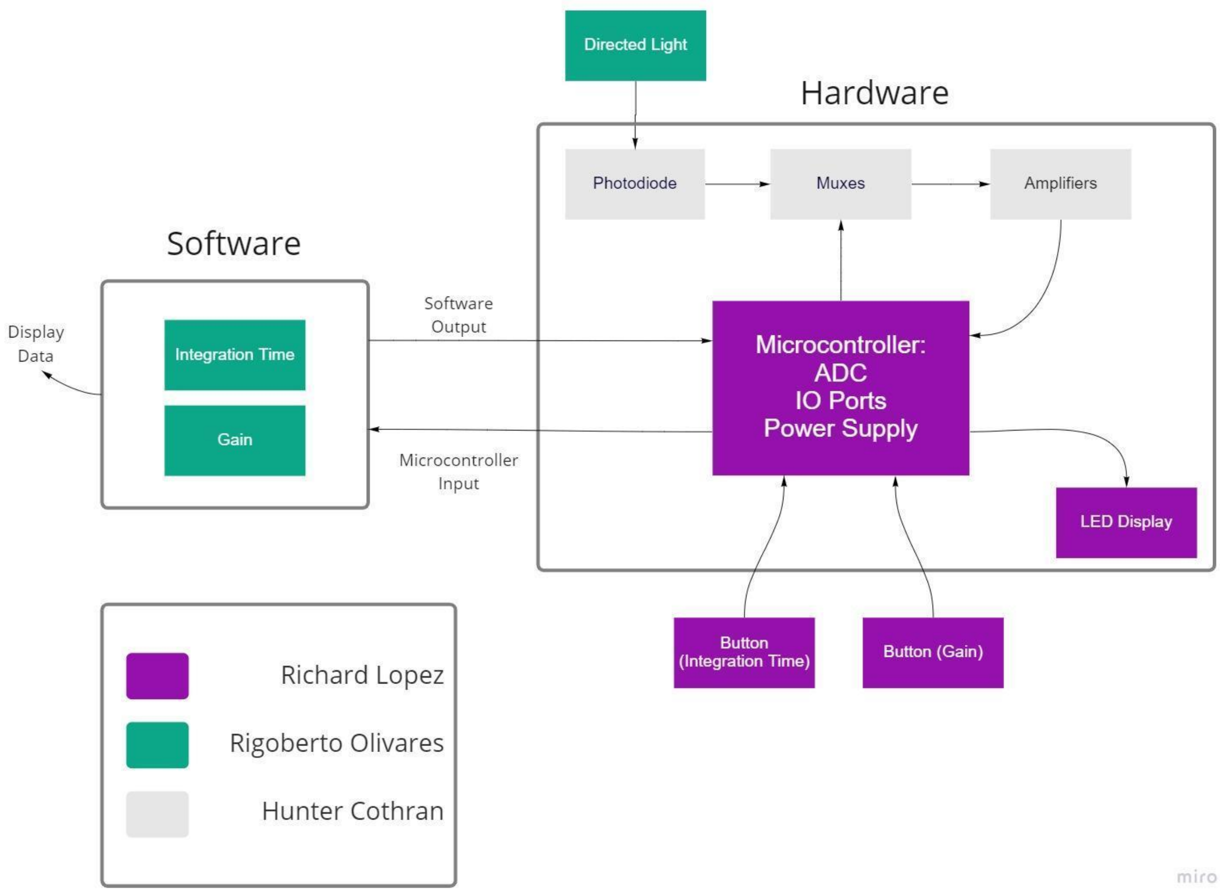

Figure 1: This diagram shows how our photometer will work from a broad point of view. Our subsystems are marked by different colors.

○ ***Referenced Documents and Standards***

SSP5 Photoelectric Photometer (Photomultiplier):
https://www.optecinc.com/astronomy/catalog/ssp/pdf/ssp_5_generation2.pdf

SPP3 Solid-State Stellar Potometer (Photodiode):

https://www.optecinc.com/astronomy/catalog/ssp/pdf/ssp_3_generation2.pdf

Magnitude of Stars:
https://earthsky.org/astronomy-essentials/what-is-stellar-magnitude/

Operating Concept

Scope

The scope of our project is very narrow, because our photometer design and methods of operation have been outlined for us by our customer. Our system is to be a specialized tool, to meet our customer's requirements. We will be designing and fabricating a photometer with specific design parameters for Mr. Don Carona, who will attach the photometer to his telescope and operate our system to take measurements of distant stars' light intensities, which is a way of measuring how bright a star is. This will be calculated by our system by directing light onto a photodiode and measuring the voltage which passes through. Then we convert that voltage into a number with an ADC system so a human can interpret the value. Our system must be able to integrate with software he uses, such that he may send commands to our system, and read data from our system with his laptop. He has given us specific communication protocols and data output formats he requires our system to use.

Operational Description and Constraints

Our project will be used by attaching it to a telescope operated by Mr. Carona, who will aim the telescope at a distant star and then activate a flip mirror, allowing our system to redirect light incident to the mirror to the system's photodiode. Our system will then generate data for Mr. Carona – providing ultimately a 16-bit integer as output. There will be three gain settings: 1, 10, 100 which will allow for more or less sensitive outputs to be displayed. Our system will, in its operation mode independent of a computer, have three exposure time settings of 1, 5, and 10 seconds. When connected to a laptop, a custom exposure time will be able to be set in addition to these three defaults. Some constraints of our system involve gain settings; we will be limited to a fixed number because our gain is determined by onboard circuit components that amplify the signal on a board level; not through software.

System Description

Our system can be described as a small device with an opening and an eyepiece. It must be able to attach to a telescope and, when aimed at distant stars, can by itself calculate, measure, and display the intensity of the incoming beam of light from the star, given specific gain and exposure settings. An internal circuit, microcontroller, and photometer allow for the intensity to be measured, and a A DB9 port allows for a computer to connect to our system and log the data recorded in a more robust way. A series of buttons on the device's exterior allow for gain and exposure time to be changed between one of three settings for each; and a display on the device allows for output to be read by a human in the event no laptop is used. Gain allows for more or less sensitive measurements to be taken and differing exposure times allow for a more reliable average to be taken, as higher exposure times reduce signal noise introduced from things like atmosphere conditions.

○ *Modes of Operations*

There will be two main modes of operation. One without a laptop connected and one with a laptop connected. Our system will come with the ability to be operated without any input from a laptop, and purely using human input from a series of buttons on the exterior of the chassis. Unlike the mode of operation with a laptop attached, exposure time will be limited to 1 ,5 ,10 seconds in this mode, and data output of measured intensity will be only displayed on a simple screen and not saved for later. This means that the laptop-connected operation mode will be more sophisticated, allowing for more robust options such as custom exposure time length and longer data readouts for intensity.

○ *Users*

The users for our system will be Mr. Don Carona. His desired features and functions have guided our decision making process as we design our systems. For example, our system must attach with a 1¼” nose piece to his telescope; it must have a DB9 male out connection port; and it must relay a light intensity reading in an unsigned 16-bit integer; and a laptop must be able to send commands to the system to change gain and exposure time. Adhering to these specifications will allow our user to perform the fullest operation of our device. Our user has also requested several things he would like to see such as a 5 digit display on the device and the ability to change gain and exposure without usage of a laptop. He would also like these values to be modified with more than two buttons total, asking that we produce a photometer with at least four buttons.

○ *Support*

For support, it will be necessary to create thorough documentation for our user such that basic operation and even troubleshooting is possible long after our project is finished. Our final project will include guides on basic operation and various flow charts of what to do if our system behaves in unexpected ways. We will need to thoroughly test our system and create documentation that walks the user through anticipated problems and explains solutions. And our documentation must also include a series of circuit diagrams, parts lists, and commented software code that explains how our system works fundamentally, in the event a future engineer wishes to study, modify, or add functionality to our system, replace a part, etc.

○ *Measuring Bright Stars*

The main use that a photometer could be used for is measuring the brightness of stars. Astronomers could use this to measure data very quickly given that it is a photometer and not a CCD camera. It is also safer to measure brighter stars because this photometer will have a photodiode instead of a photomultiplier tube, since a photomultiplier tube uses a lot of voltage and something that’s too bright will activate a safety mechanism.

○ *Measuring Reflection of light from planets*

Another use would be measuring the amount of light that is reflected from planets that other stars produce. Although it would not be as good as a photomultiplier tube it should still quickly give decent data.

- ***Scenarios***

  - ***Measuring Bright Stars***

The main use that a photometer could be used for is measuring the brightness of stars. Astronomers could use this to measure data very quickly given that it is a photometer and not a CCD camera. It is also safer to measure brighter stars because this photometer will have a photodiode instead of a photomultiplier tube, since a photomultiplier tube uses a lot of voltage and something that's too bright will activate a safety mechanism.

  - ***Measuring Reflection of light from planets***

Another use would be measuring the amount of light that is reflected from planets that other stars produce. Although it would not be as good as a photomultiplier tube it should still quickly give decent data.

• Analysis

  - ***Summary of Proposed Improvements***

The proposed improvements are:

1. **Use of a photodiode over a photomultiplier:** A photomultiplier is sensitive and if exposed to high intensity lighting could easily malfunction. By contrast, a photodiode can withstand high intensity light without problem.
2. **Decrease the size of the photometer:** With better technology at our hands, we plan for our photometer to be about half the size of the OPTEC model. This will make it more convenient for the user to store and use it.
3. **Improve onboard display:** Although the OPTEC model can compute values of up to 16 bits, it can only display a maximum of 12 bits. Our model will count with a 16 bit display.
4. **Improve onboard navigation:** The old model has two buttons used to control navigation, "display" and "mode". These are used to change integration time and gain. We were told by the owner of the Optec model that this is an unintuitive design. To fix it, we will instead have four buttons used for navigation, two of them will increase/decrease integration time and the other two will increase/decrease the gain.
5. **Improve software layout:** Currently, the software used to operate the Photometer contains a lot of unnecessary information on the screen. To make it easier for the user to understand the program, we will simplify the design of the software to include only the important information.

  - ***Disadvantages and Limitations***

The disadvantages and limitations in our system are:

2. **Photodiode Limitations:** Although photodiodes are more durable than photomultipliers, their durability comes at a cost. A photomultiplier's sensitivity allows for accurate measurement of faint stars.
3. **Sources of Error:** On a photodiode, changes in temperature could easily cause gain errors during observation. Additionally, since we will be amplifying very small currents, it is likely that leakage currents could affect the accuracy of the device.

○ *Alternatives*

The alternatives solutions to the photometer design are:

1. **Using a photomultiplier:** This would render a satisfactory photometer design, but it would fail to meet the requirements set by our customer and it would greatly complicate the design.
2. **Using a CCD camera:** CCD cameras are readily available for purchase and could be used for measuring light. However, we were informed by our customer that a CCD camera would be too sensitive for the task at hand.

○ *Impact*

After OPTEC discontinued its line of photometers, there was a gap left in the market that needs to be filled. If successful, our photometer could be manufactured and sold to astronomers to fill this gap and help in the research of celestial objects.

○ *Revisions*

The following is a list of Photometer characteristics that differ from the previously statements made about the device:

1. **Onboard Navigation:** The Photometer has three onboard buttons, one used to control Integration Time, one used to control Gain, and one last one used to Start/Stop the process of taking measurements.
2. **Software:** The software was determined not to be of any significant importance to the customer, and so its development was halted. Instead, a third party software is used to test the photometer protocol.

Team 18: Photometer

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INTERFACE CONTROL DOCUMENT

REVISION – Draft
3 December 2022

INTERFACE CONTROL DOCUMENT
FOR
Photometer

PREPARED BY:

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Author   Date

APPROVED BY:

____
Project Leader   Date

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John Lusher II, P.E.   Date

____
T/A   Date

Change Record

Rev.	Date	Originator	Approvals	Description
-	02/08/2022	Photometer		Draft Release
-	03/12/2022	Photometer		Final Release

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● Overview

This document lists some references and definitions useful in understanding the Photometer system. Additionally, a description of the physical characteristics of the photometer (weight and dimensions) will be provided. Finally, the document lists all device interfaces. These include electrical interfaces, such as the input power supply, and communication interfaces, like the protocol used between the software and microcontroller.

● References and Definitions

○ *References*

Refer to section 2.2 of the Functional System Requirements document.

○ *Definitions*

BIT	Built-In Test
GUI	Graphical User Interface
Hz	Hertz
ICD	Interface Control Document
DC	Direct Current
AC	Alternating Current
LED	Light-Emitting Diode
A	Amp
W	Watt
PCB	Printed Circuit Board
MCU	Micro Controller Unit
TBD	To Be Determined
Op Amp	Operational Amplifier
SSP	Solid-State Stellar Photometer

Physical Interface

Weight

Component	Weight
Chassis	1.0 lbs (Expected)
PIC24FV32KA302-I/SP	0.077603 oz

Table 1. System Weight

Dimensions

Component	Dimensions (L x W x H)
PIC24FV32KA302-I/SP	34.67 mm x 7.62 mm x 3.43 mm
LED 7 Segment Display	36.5 mm x 14 mm x 7.2mm
Chassis	TBD

Table 2. System Dimensions

Mounting Locations

The Photometer will be mounted onto the telescope located in the Texas A&M Physics and Astronomy Teaching Observatory and then manually calibrated through the use of a flip mirror.

Thermal Interface

The MCU we have chosen can operate at temperatures ranging from -40°C to 85°C. Similarly, other electrical components such as our photodiode and Op Amps can operate in a wide range of temperatures. As of now. There is no plan to implement a heat sink or any other type of cooling system. We expect passive cooling will be sufficient in regulating temperature.

Electrical Interface

Primary Input Power

The primary input power would be from a buck boost converter power supply module. The buck boost converter will obtain power either by being hooked up to a computer or through an AC Converter connected to an outlet.

Polarity Reversal

To reverse polarity we are using a buck boost converter in order to operate our Op Amps.

○ *Signal Interfaces*

The signals involved in the photometer will be coming from the laptop or from the onboard buttons. These signals will interact with MCU to choose which data to read from and which to output.

○ *User Control Interface*

The Microcontroller will display the LED 7 segment display. There will be buttons on the Photometer that can control the gain and the time integration. The other User Control Interface will be the Laptop which will also display the data as well as be able to control the photometer's gain and time integration.

Below can be found an image of our device, with three labeled buttons used for operation visible.

Figure 1: Photometer with buttons

● Communications / Device Interface Protocols

○ *Microcontroller*

The Microcontroller processes incoming data in the form of analog voltage and converts it into human-readable values. Additionally, it will take in human input in the form of button presses or commands sent from a connected computer, and change gain and integration time.

○ *Device Peripheral Interface*

The DB9 port is in charge of the communication between the laptop and the MCU. The required communication protocol is as shown below:

```
'                       n       is any real integer 0 <= n <= 9
'                       x       is any character
'                       LF      is a line feed character, decimal 10, hex A
'                       CR      is a carriage return character, decimal 13, hex D
'                       "!"     is the exclamation character, decimal 33, hex 21
'
'       SSMODE          if in manual mode, this command will initiate the serial loop mode and
'                       only serial commands will control the instrument
'                       after the serial loop mode is entered, a "!" LF CR is sent on the
'                       serial port to acknowledge the mode change
'                       if the instrument is already in the serial loop mode, the
'                       acknowledgement code is sent again, "!" LF CR to confirm that the
'                       instrument is in the serial loop mode
'
'       SGAINn          sets gain of instrument of preamp stage. n can be 1, 2 or 3 only
'                       1 = gain of 1, 2 = gain of 10, 3 = gain of 100
'                       "!" LF CR is returned on serial port to acknowledge command
'
'       SInnnn          sets integration time in units of 0.01 seconds. 0001 <= nnnn <= 9999
'                        "!" LF CR is returned on serial port to acknowledge command
'
'       SCOUNT          start a reading with selected gain and integration time.
'                       after the count is completed, the results are displayed on the
'                       instrument and sent on the serial port in the following format:
'                       C=nnnnn LF CR, where 00000 <= nnnnn <= 65535, leading zeros are
'                       sent
'
'       SMnnnn          initiate a fast reading cycle with selected gain and integration time.
'                       nnnn is the number of readings to do, 0000 <= nnnn <= 9999, leading
'                       zeros must be added for number to be correct
'                       after each reading is done the value is sent on the serial in the
'                       following format: nnnn LF CR where 0000 <= nnnn <= 9999
'                       the fast mode sequence can be interrupted by sending a SS
'                       once the fast mode is successfully stopped, a "!" LF CR is sent
'
'       SENDxx          exits the serial loop mode and returns to manual mode.
'                       before leaving the serial loop mode, an "END" LF CR is sent
'
'       =======         serial error messages
```

Team 18: Photometer

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EXECUTION AND VALIDATION

REVISION – Final
3 December 2022

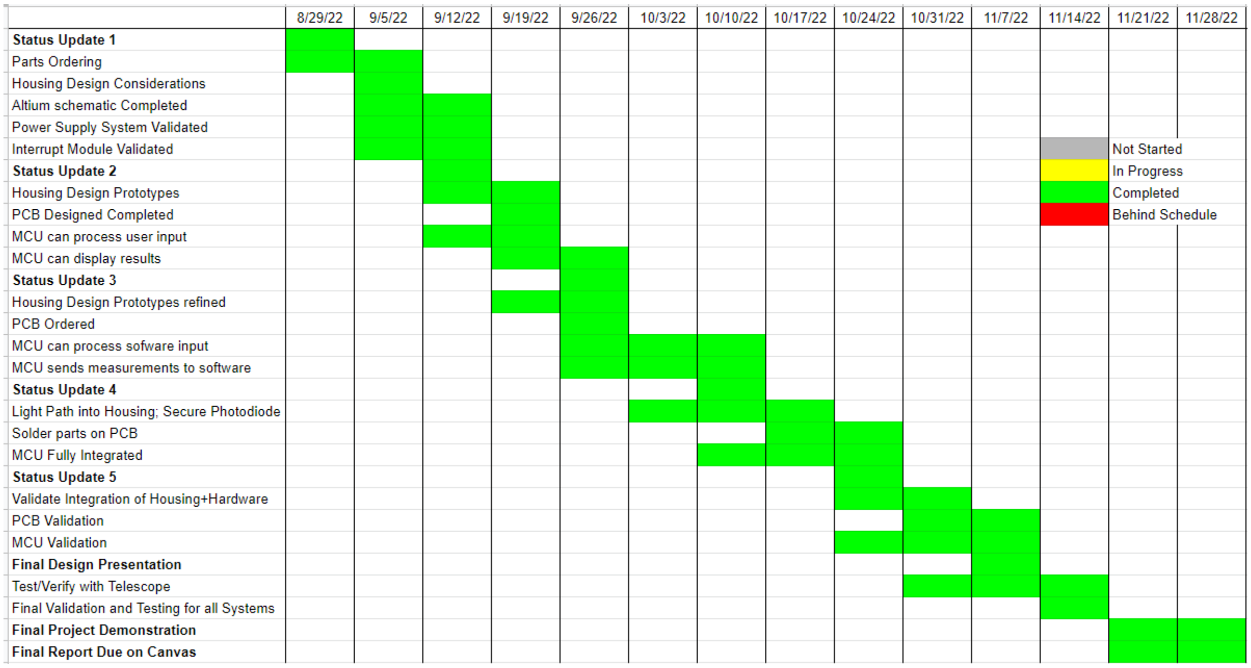
● Execution Plan for Semester One:

Work	End Date	Owner	Status	Date Complete
Concept of Operations	2/9/2022	ALL	Complete	2/8/2022
Interface Control Document	2/23/2022	ALL	Complete	N/A
Functional System Requirements	2/23/2022	ALL	Complete	N/A
GUI for photometer software should be created.	2/25/2022	Rigo	Complete	N/A
Learn the basics of a microcontroller and how to program it.	2/25/2022	Richard	Complete	N/A
Determine appropriate op-amps for acting as transimpedance amplifier and creating gain w/ minimal noise	2/25/2022	Hunter	Complete	N/A
Project Parts Ordered	2/21/2022	ALL	Complete	N/A
Midterm Presentation	2/28/2022	ALL		
Protocol should be implemented into the photometer software.	3/4/2022	Rigo	Complete	N/A
Work with the LED panel and get it to display numbers based off inputs	3/4/2022	Richard	Complete	N/A
Simulate and verify gain circuit design meets parameters	3/4/2022	Hunter	Complete	N/A
Start working with the microcontroller.	3/11/2022	Rigo	Complete	N/A
Work with the LED panel and get it to display	3/11/2022	Richard	Complete	N/A

numbers based off inputs				
Create and test circuit on breadboard with photodiode; procure false star set up	3/11/2022	Hunter	Complete	N/A
Microcontroller should recognize the appropriate protocol.	3/18/2022	Rigo	Complete	N/A
Set up the ADC so the microcontroller can read voltage input to digital	3/18/2022	Richard	Complete	N/A
Using false star; Create housing for photodiode and test environment for circuit	3/18/2022	Hunter	Complete	N/A
Test microcontroller and photometer can communicate through the protocol.	3/25/2022	Rigo	Complete	N/A
Set up ADC so it can make readable data to be outputted to the LED	3/25/2022	Richard	Complete	N/A
Ensure and verify measured light intensities are controlled and consistent	3/25/2022	Hunter	Complete	N/A
Progress Update 1	3/30/2022	ALL		
Continue testing the microcontroller and photometer can communicate through the protocol.	4/1/22	Rigo	Complete	N/A
Make sure the data getting outputted corresponds with the gain and time integration being inputted.	4/1/2022	Richard	Complete	N/A

Integrate housing and circuit and begin testing light and reading voltages	4/1/2022	Hunter	Complete	N/A
Debugging and creating test cases to ensure proper functionality.	4/8/2022	Rigo	Complete	N/A
Make sure buttons work according to time integration and the gain. Also making sure the laptop takes priority	4/8/2022	Richard	Complete	N/A
Verify photodiode can take in measured light and give expected voltage outputs	4/8/2022	Hunter	Complete	N/A
Microcontroller protocol should be finalized.	4/15/2022	Rigo	Complete	N/A
Last minute debugging and making sure everything works	4/15/2022	Richard	Complete	N/A
Ensure voltages and system operates expectedly	4/15/2022	Hunter	Complete	N/A
Final Presentation	4/20/2022	ALL		
Last minute testing input and outputs for the microcontroller protocol.	4/22/2022	Rigo	Complete	N/A
Last minute debugging and making sure everything works	4/22/2022	Richard	Complete	N/A
Ensure system demos expectedly	4/22/2022	Hunter	Complete	N/A
Final Demo	4/29/2022	ALL		

● Execution Plan for Semester Two:



● Validation for Semester One:

Test	Detail
Richard	
LEDS	Test if a certain segment lights up
	Test if a number gets displayed with segments
Buck Boost Converter	Test if it is receiving power and turning on
	Test if it is outputting power to on the breadboard
	Test if the buck boost converter can output negative Voltage
	See if it can raise or lower voltage
MCU	Test connection to LED
	Test if a number can be inputted to the LED with binary or decimal

	Test if ADC is can convert the data to digital
	Test if the microcontroller can make readable data
	Test if buttons are able to change gain and time integration
Rigoberto	
Software	Test GUI inputs perform the correct action.
	Test protocol is performing the correct operations.
	Test if software can communicate with MCU and change gain.
	Test if software can communicate with MCU and change integration time.
	Test if software can receive input measurements
MCU	Test if MCU protocol is performing the correct operations.
	Test if MCU can receive input from software.
	Test if MCU can output measurements to the software.
Hunter	
Transimpedance Amplifier	Test to make sure voltage, scales linearly from light intensity and within expected ranges
	Test to make sure voltages read as expected at maximum and minimum light
Photodiode	Test to make sure photodiode registers expected readings based on controlled light incident to it
	Test to make sure photodiode currents are as expected at maximum and minimum light

Op-Amp Gain Circuits	Test to make sure gain circuits reliably produce gain of 10,100
	Test to make sure gain circuits behave as we expect at maximum light and operate at safe voltage

- ## Validation for Semester Two:

Gain Increse (Hardware)	The gain increases with a button press and the LED corresponding to it turns on	See if the voltage is being sent to different pins based on which pos the button is on	TESTED
Time Integration Increase (Hardware)	The TI increases with a MOM button and the LED corresponding to it turns on	See if the voltage is being sent to different pins based on which pos the button is on	TESTED
Gain Increase (Software)	The photometer gain, on the software side, increases with a button press.	On a terminal, print out gain values to ensure correctness.	TESTED
Time Integration Increase (Software)	The photometer TI, on the software side, increases with a button press.	On a terminal, print out TI values to ensure correctness.	TESTED
Power On/Off	if the power button turns on and off the system	See if the MCU is powered on by seeing if LEDS turn on	TESTED
PCB	To see if the pcb connects all the parts properly	Final testing test for continuity and seeing if everything is working	TESTED
5 digit 7 Segment LED	To see if the output is being shown properly	Input numbers to be displayed from the MCU and see if it displays properly	TESTED
ADC	The output Digital Signal is being read properly	Change the input voltage and see if it matches the step function	TESTED
Photometer Protocol	MCU recognizes customer definded protocol signals	Send signals to the MCU to validate functionality.	TESTED
Housing Design	Design a housing for the device, bearing in mind other subsystems	Decide between prefab and CAD/3D print options	TESTED
Housing Implementation	Implement housing for the system	Create prototype housing based on previous choice	TESTED
Mounting	Secure a TPO M42 10mm female threading to our housing	Adhere TPO M42 10mm female threading to housing	TESTED
Rigidness	Ensure housing materials are fortified and sturdy enough to bear load	Test and verify parameters and hardiness	TESTED
Photometer Input Voltage	The input voltage for the photometer shall be 5V	Use multimeter to validate input voltage levels.	TESTED
Voltage Regulator Input Voltage	The input voltage for the DC to DC converter shal be 4.5V - 5.5V	Use power supply to validate working voltage range.	TESTED
Voltage Regulator Output Voltage	The output voltage of the power supply shall be 5V	Use multimeter to test validate output voltage levels.	TESTED
Input light	Secure light path to photodiode	Ensure photodiode is secure and recieves input	TESTED
Thermal Resistance	The Photometer shall effectively operate in temperatures ranging from 15 F - 120 F	Validate photometer by operating in different temperatures.	TESTED

Team 18: Photometer

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FUNCTIONAL SYSTEM REQUIREMENTS

REVISION – Draft
3 December 2022

Functional System Requirements

for

Photometer

Prepared by:

Author Date

Approved by:

Project Leader Date

John Lusher, P.E. Date

T/A Date

Change Record

Rev.	Date	Originator	Approvals	Description
-	02/08/2022	Photometer		Draft Release
-	03/12/2022	Photometer		Final Release

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1. Introduction

1.1. Purpose and Scope

The purpose of our project, and the photometer we design, engineer, and fabricate, is to ultimately provide Don Carona, an astronomer here at A&M, with a robust, custom-made tool which can attach to his telescope such that he can measure the light intensities from distant stars and get extremely reliable readings. Mr. Carona has expressed to us that modern hardware which performs this function has certain drawbacks that can create unreliable data, while relatively simple circuit components, when set up properly can create very reliable readings.

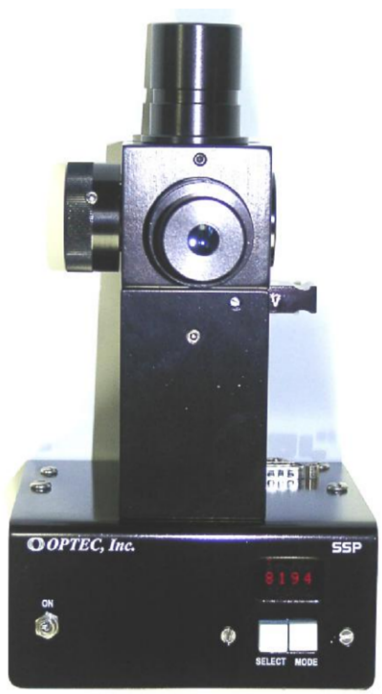

Figure 1. Our Photometer will be modeled after the OPTEC SSP 3 Photometer

1.2. Responsibility and Change Authority

Our team leader is Hunter, who oversees and ensures requirements are being met. Our client, Mr. Carona, has given us very particular system specs he would like to see in our designs, so there is not much room for changes. However, were changes necessary to be made, our team leader would correspond with Mr. Carona to ensure our changes were acceptable for Mr. Carona. However, ultimately, Mr. Carona would need to approve any changes from the original specifications he has outlined.

2. Applicable and Reference Documents

2.1. Applicable Documents

The following documents, of the exact issue and revision shown, form a part of this specification to the extent specified herein:

Document Number	Revision / Release Date	Document Title
DS30009995E	2011-2017	PIC24FV32KA304 FAMILY
KSPD1039E04	Apr 2021	SI Photodiodes S1087/S1133
mb102-ps	Rev 2 / Jan 2015	HiLetgo Breadboard 3.3/3.5 Power Supply
SLOS081M	Rev 1 / Dec 2021	TL08xx FET-Input Operational Amplifiers

Table 1. Applicable Documents

2.2. Reference Documents

The following documents are reference documents utilized in the development of this specification. These documents do not form a part of this specification and are not controlled by their reference herein.

Document Name / Document Number	Revision/Release Date	Document Title
ssp 3 generation2	Rev 5 / June 2012	SSP3 Generation 2 Solid-State Photometer
ssp_5_generation2	Rev 1 / June 2006	SSP5 Generation 2 Manual
Distance Modulus	Jan 2020	The Magnitude System
KSPD0001E15	Apr 2020	Si Photodiodes

Table 2. Reference Documents

2.3. Order of Precedence

In the event of a conflict between the text of this specification and an applicable document cited herein, the text of this specification takes precedence without any exceptions.

All specifications, standards, exhibits, drawings or other documents that are invoked as "applicable" in this specification are incorporated as cited. All documents that are referred to within an applicable report are considered to be for guidance and information only, except ICDs that have their relevant documents considered to be incorporated as cited.

3. Requirements

3.1. System Definition

Our photometer will be attached to a telescope and used to measure the light intensity of distant stars or other celestial objects. It will function as a replacement for an older model created by OPTEC, a manufacturer of stellar measurement equipment. The photometer has four main subsystems: Hardware, Microcontroller, Software, and Structure. The following block diagram portrays how the different subsystems interact with each other:

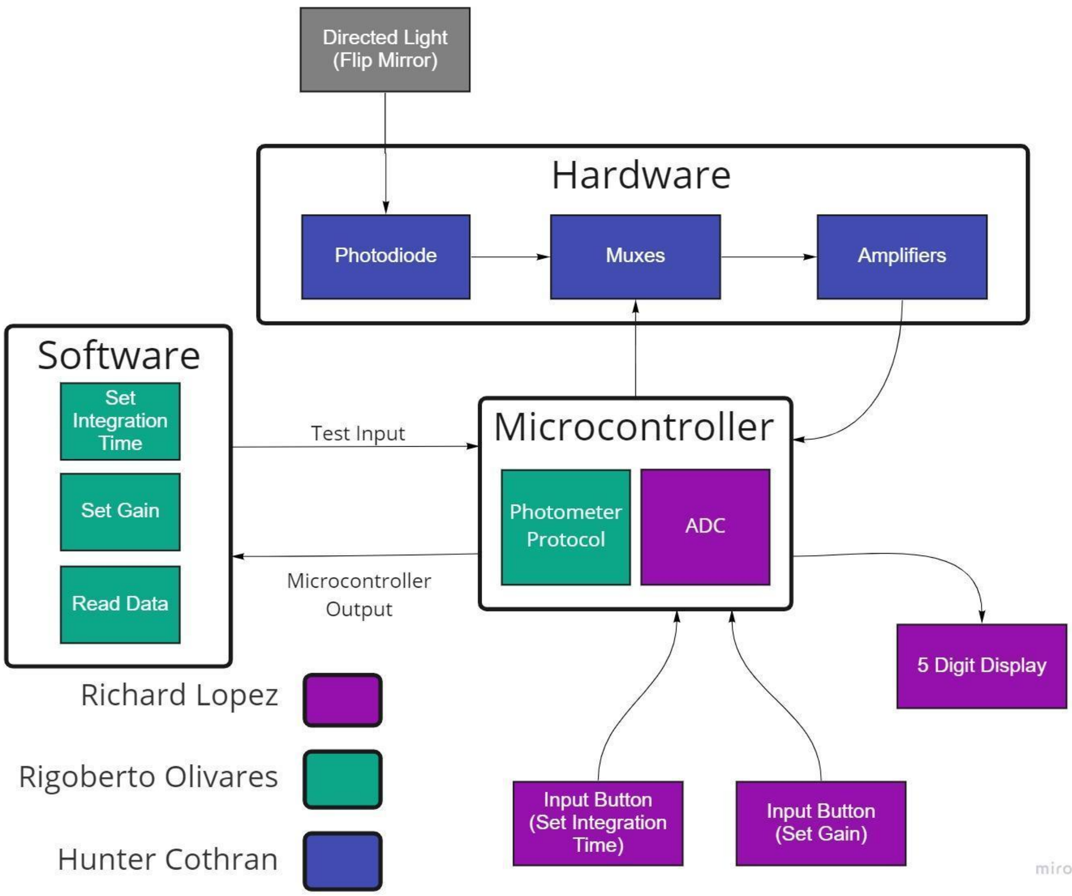

Figure 2. Block Diagram of System

The hardware subsystem consists of a photodiode and three op-amps. One op-amp, in combination with the photodiode, acts as a transimpedance amplifier which converts the current from the photodiode into a linear-scaling voltage with respect to light incident to the photodiode. The other two op-amps act as non-inverting amplifiers to create voltage gain. The microcontroller subsystem will then take this amplified signal and, based on user input (button or software), will take readings with a set integration time and gain. The software subsystem will be used mainly to test that the microcontroller protocol works as specified by our customer. The Structure subsystem is not shown in the block diagram, this subsystem refers to the framework that will be keeping all of the photometer components together (Hardware, Microcontroller, Display, and Input Buttons).

3.2. Characteristics

3.2.1. Functional / Performance Requirements

3.2.1.1. Minimum Magnitude of Measured Star

The photometer should, at a minimum, have the ability to accurately measure light emitted from stars of magnitude three or greater.

> *Rationale: Our customer will be using the photometer to measure stars such as Betelgeuse, which has a variable light intensity and its fluctuations are desired to be measured.*

3.2.2. Physical Characteristics

3.2.2.1. Mass

The mass of the photometer should be less than or equal to that of the model SSP 3 created by OPTEC.

> *Rationale: This is an implied requirement set by our customer since our photometer should be an improvement from the SSP 3 Model.*

3.2.2.2. Volume

The volume of the photometer should be less than or equal to that of the model SSP 3 created by Optec.

> *Rationale: This is an implied requirement set by our customer since our photometer should be an improvement from the SSP 3 Model.*

3.2.2.3. Mounting

The photometer should attach to the telescope through a 1.25-inch nosepiece. Additionally, the frame of the photometer should be sturdy to withstand usage in the field.

> *Rationale: This requirement was specified by our customer based on the characteristics of the telescope located in the Texas A&M Physics and Astronomy Teaching Observatory.*

3.2.3. Electrical Characteristics

3.2.3.1. Inputs

The presence or absence of any combination of the input signals in accordance with ICD specifications applied in any sequence shall not damage the Photometer, reduce its life expectancy, or cause any malfunction, either when the unit is powered or when it is not.

No sequence of command shall damage the Photometer, reduce its life expectancy, or cause any malfunction.

> *Rationale: In our design, we should ensure no damage or malfunction of the device will arise from any combination of user/technician input.*

3.2.3.1.1 Input Voltage Level

The input voltage level for the Photometer shall be within the range of 5 VDC to 9 VDC.

> *Rationale: Our Photodiode has a breakdown voltage of 10VDC, so we use 9VDC of power across it, and supply our op-amps with +/-5 VDC to get our desired non-inverting amplifier gain.*

3.2.3.1.2 Revised Input Voltage Level

The input voltage level for the Photometer shall be within the range of 4.5 VDC to 5.5 VDC. Additionally, the Photometer shall implement the appropriate system to supply -5 VDC and 5 VDC to the internal components.

> *Rationale: Our Photodiode has a breakdown voltage of 10VDC, so we use 9VDC of power across it, and supply our op-amps with +/-5 VDC to get our desired non-inverting amplifier gain.*

3.2.3.1.3 Input Light Source

The Photometer shall make use of a model S1087-01 photodiode manufactured by Hamamatsu Corporation to measure the incoming light.

> *Rationale: This requirement was specified by our customer, this photodiode is known to be effective for taking stellar measurements, due to its low dark current.*

3.2.3.1.4 Input Integration Time and Gain

The photometer shall include onboard inputs that allow the user to control the integration time and gain of the photometer.

> *Rationale: This requirement was specified by our customer, the onboard inputs will allow them to control the photometer without interfacing with a computer.*

3.2.3.1.5 External Commands

The Photometer shall document all external commands in the appropriate ICD.

> *Rationale: The ICD will capture all interface details from the low level electrical to the high-level packet format.*

3.2.3.2. Outputs

3.2.3.2.1 Data Output

The photometer shall include an onboard 5-digit display for the user to view readings.

> *Rationale: This requirement was set by our customer, it will allow them to see data readings without interfacing with a computer.*

3.2.3.2.2 Diagnostic Output

The photometer shall include a diagnostic interface to test the correctness of output data.

Rationale: When programming the appropriate protocol onto the photometer, we will need an interface to test if the protocol is working as expected.

3.2.3.2.3 Peripheral Output

The photometer shall include a DB9 male output port for interfacing with a computer.

Rationale: This requirement was set by our customer, it will allow them to make use of data analysis software on his computer.

3.2.4. Environmental Requirements

The Photometer shall be designed to withstand and operate in the environments and laboratory tests specified in the following section.

Rationale: This is a requirement specified by our customer due to constraints of their system in which the Photometer is integrating.

3.2.4.1. Pressure (Altitude)

At a minimum, the photometer shall be able to function properly in altitudes ranging from sea level to 400 feet above sea level (the altitude in College Station, Tx).

3.2.4.2. Thermal

The Photometer shall be able to function properly at temperature ranges from 0°F to 110°F.

3.2.4.3. Humidity

The Photometer shall be able to function properly at humidity levels ranging from 0% to 80%.

3.2.5. Failure Propagation

The Photometer shall not allow propagation of faults beyond the Photometer interface.

3.2.5.1. Failure Detection, Isolation, and Recovery (FDIR)

The Photometer shall have a failure detection system in the form of output check during operation. If at any point while using the Photometer to take measurements the selected gain is too high to properly process an output measurement, the photometer will display an error message indicating that a different gain should be used. Additionally, the Photometer may have a system which allows for the calibration of the photodiode.

3.2.5.1.1 Built In Test (BIT)

The Photometer shall have an internal subsystem that will generate test signals and evaluate the responses to determine if all components are working as expected.

Rationale: This will allow us to test whether the photometer meets the requirements set by our customer.

3.2.5.1.1.1 BIT Log

The BIT shall save the results of each test to a log that shall be stored for retrieval and clearing by maintenance personnel.

Rationale: This will allow us to test whether the photometer meets the requirements set by our customer.

3.2.5.1.2 Isolation and Recovery

The Photometer should provide for fault isolation and recovery by enabling subsystems to be reset or disabled based upon the result of the BIT.

Rationale: This will allow us to test whether the photometer meets the requirements set by our customer.

4. Support Requirements

4.1. Telescope

The photometer requires a telescope to measure photons coming from a celestial body. This is because its purpose is to measure how bright stars or planets are.

4.2. Barrel Connector (AC to DC)

A Barrel Connector is needed we use a 2.1 x 5.5 mm connector in order send power to our buck boost converter to convert the proper voltages necessary for the system..

4.3. Laptop

A laptop is recommended because with a laptop the user would be able to store data and use it as they wish. It would also let them set specific time integration times in order to measure data at specific times.

4.4. DB9 Female

A DB9 Female port is required to receive and output data from the Photometer. Without this data cannot be saved and specific integration times cannot be inputted.

4.5. M42 Spacer Ring Extension

In order to properly fasten our photometer to the telescope, a spacer ring extension was necessary for this purpose

Figure 3. M42 Spacer Ring Extension

Appendix A: Acronyms and Abbreviations

BIT	Built-In Test
GUI	Graphical User Interface
Hz	Hertz
ICD	Interface Control Document
DC	Direct Current
AC	Alternating Current
LED	Light-emitting Diode
A	Amp
W	Watt
PCB	Printed Circuit Board
MCU	Micro Controller Unit
TBD	To Be Determined
Op Amp	Operational Amplifier
SSP	Solid-State Stellar Photometer

Appendix B: Definition of Terms

Op Amp	Operational amplifiers are circuits that have the ability to amplify an input voltage by a certain predetermined gain.
Si Diode	A diode that is made of silicone which is inexpensive and at room temp has little free electrons.

Team 18: Photometer

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Subsystem Reports

REVISION – Original
3 December 2022

Subsystem Reports
for
Photometer

Prepared by:

Author Date

Approved by:

Project Leader Date

John Lusher, P.E. Date

T/A Date

Change Record

Rev.	Date	Originator	Approvals	Description
-	02/08/2022	Photometer		Draft Release
-	03/12/2022	Photometer		Final Release

Table of Contents

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Introduction

Our project for this semester was to design separate subsystems for a photometer which behaves closely to the SSP3 OPTEC Photometer. To achieve these ends, our team decided on three separate subsystems that would be the most crucial components of the photometer: These subsystems are Light Measurement Hardware, the ADC and Controls, and Microcontroller and Software.

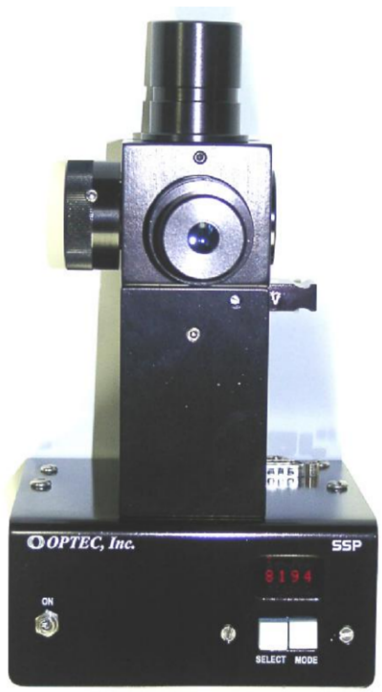


Figure 1.1 Our Photometer will be modeled after the OPTEC SSP 3 Photometer

Light Measuring Hardware Subsystem Report

Subsystem Introduction

As an introduction to our Light Measurement subsystem, it is important to first explain the goals we wish to achieve, and the methods and utilization of electrical engineering concepts this subsystem employs to meet those ends. First, our goal is to measure the intensity of incident light. We achieve this through the method of employing a photodiode which is placed under a light source we wish to measure. This photodiode is configured in a circuit, in tandem with a low-leakage op-amp, which creates a transimpedance amplifier; which then creates a relationship between voltage and current. This relationship is only possible because of the concept we know in Electrical engineering as the Photovoltaic effect. Due to the Photovoltaic effect, the material in our photodiode, when a voltage is placed across its terminals, acts as a current source.

- ### ***Subsystem Details***

The circuit I designed by the end of the semester which can reliably measure light and produce gains of 1, 10, and 100 at voltages we expect, is the following circuit:

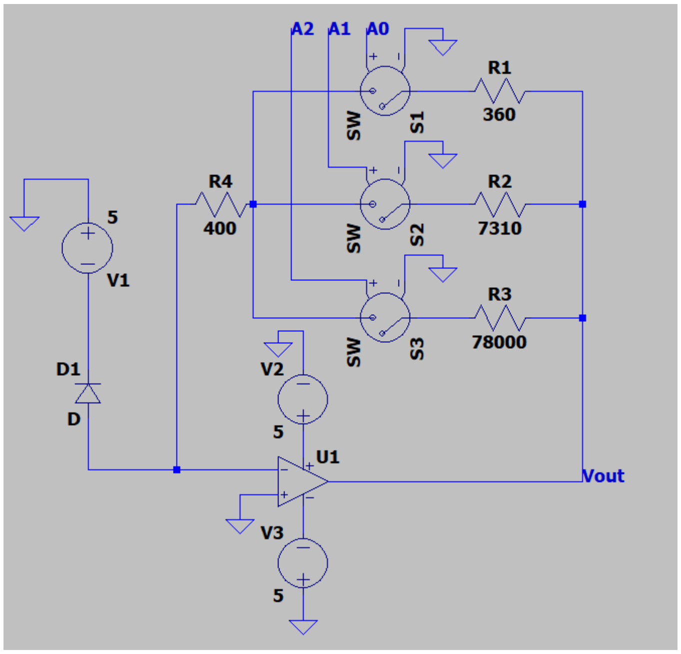


Figure 2.1 Circuit Implemented in LTSpice

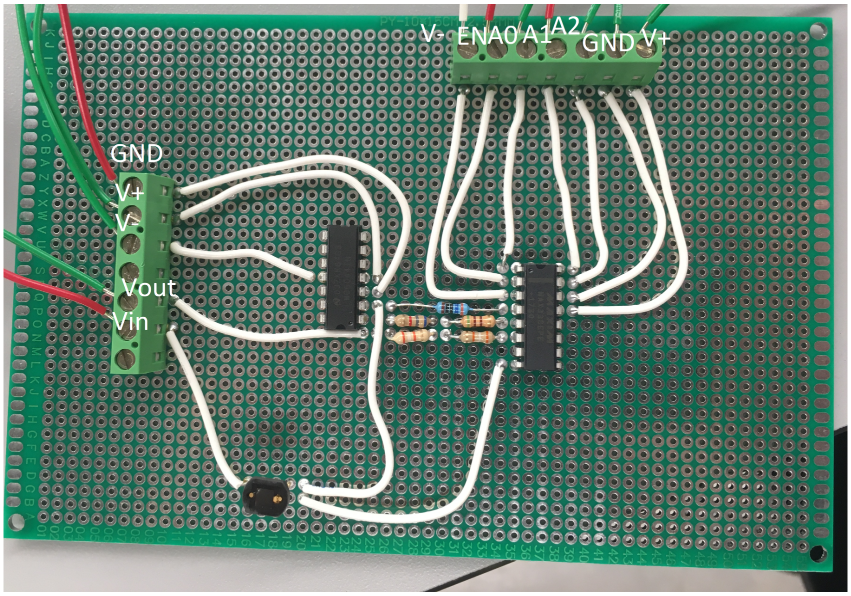


Figure 2.2 Circuit Implemented on Perfboard

To explain some design choices which were made, the LMC6044 op-amp was selected due to its extremely low input current (in the range of 2fA). Due to the nature of the transimpedance amplifier, we wish to preserve the current as much as possible and have as low current leakage as possible from our circuit components. Next, the MAX338 mux was selected for its low leakage current (20pA) and low On-Resistance of 400Ω (seen as R4 in the LTSpice simulation, in figure 2). The low On-Resistance value is ideal for our purposes because our gain 1 resistor must be around 770Ω. Multiplexers with lower leakage current exist, but have much higher On-Resistance values, making a gain of 1 impossible. The photodiode used is the Hamamatsu S-1087 model, which was selected for us by our customer, Mr. Carona.

After selecting the ideal circuit components for ourselves, it was necessary to find the maximum current our photodiode will produce, when exposed to very intense light.

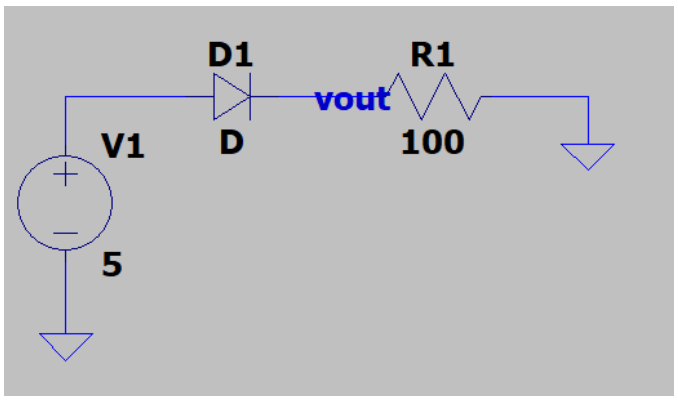


Figure 2.3 Designing Test Circuit for Reading Photodiode Current in LTSpice

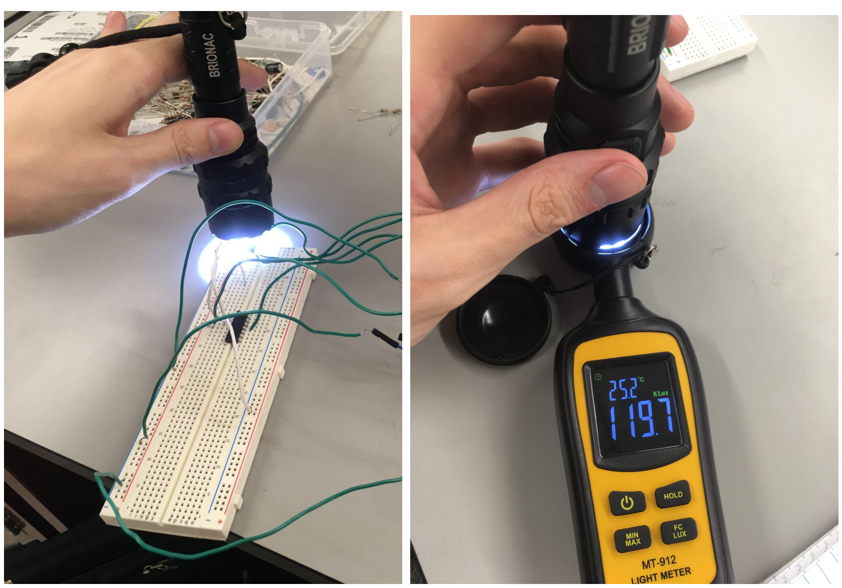


Figure 2.4 Exposing Test Circuit to high intensity light with Commercially Available Light Meter (~120kLux)

While measuring the Vout node experimentally, a value of <u>0.65V</u> was read by our voltmeter. Using basic KCL across the 100Ω resistor, we find that the current generated by our photodiode was 6.5mA. Using the following equation for finding resistance of transimpedance amplifiers in DC mode, we find what resistor value we need to create a gain of 1 for our circuit.

$$-I_{\text{in}} = \frac{V_{\text{out}}}{R_{\text{f}}}, \quad \longrightarrow \; 6.5mA \; = \frac{5V}{Rf}$$

With basic algebra we find that Rf = 770Ω. We also know to create gains of 10 and 100, we would need Rf to equal 7700Ω and 77kΩ respectively. Due to limited resistor access, we used the following resistors:

Nominal Gain	Calculated Resistance	Actual Resistance
1	770 Ω	760 Ω
10	7700 Ω	7710 Ω
100	77000 Ω	78400 Ω

Table 2.1 Calculated vs Actual Resistance Values

This behavior is consistent with our expectations, based on information provided to us by the Hamamatsu corporation from their s-1087 photodiode. At 120kLux (1.2*10^5), we observe 6.5mA current, which is very close to what we expect based on the graph below. Red lines are added to aid the viewer.

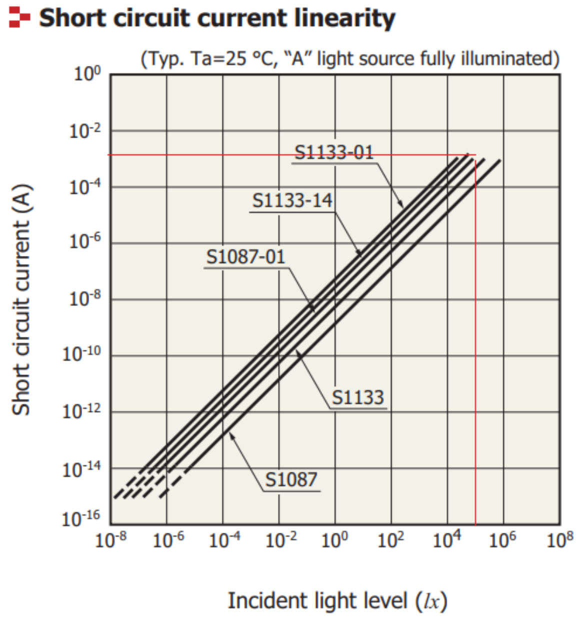


Figure 2.5 S-1087 Current Linearity Graph

This graph is important and we will reference it later.

- ***Subsystem Validation***

In order to validate our subsystem, we will need to validate two important behaviors. One, we will need to establish that our output voltage is consistent with the current linearity graph in Figure 7. Second, we will need to demonstrate that our gains behave in the way we expect. To begin, we will take a measurement with our light meter and test our system in Ambient Light. We measure around 82Lux with our commercially available light meter.

Figure 2.6 Commercially Available Light Meter

Next will look at our system's voltage readings at gains 1, 10, 100. We will expect to see appropriate gain values. And then, we will use simulation software to ascertain the photodiode current.

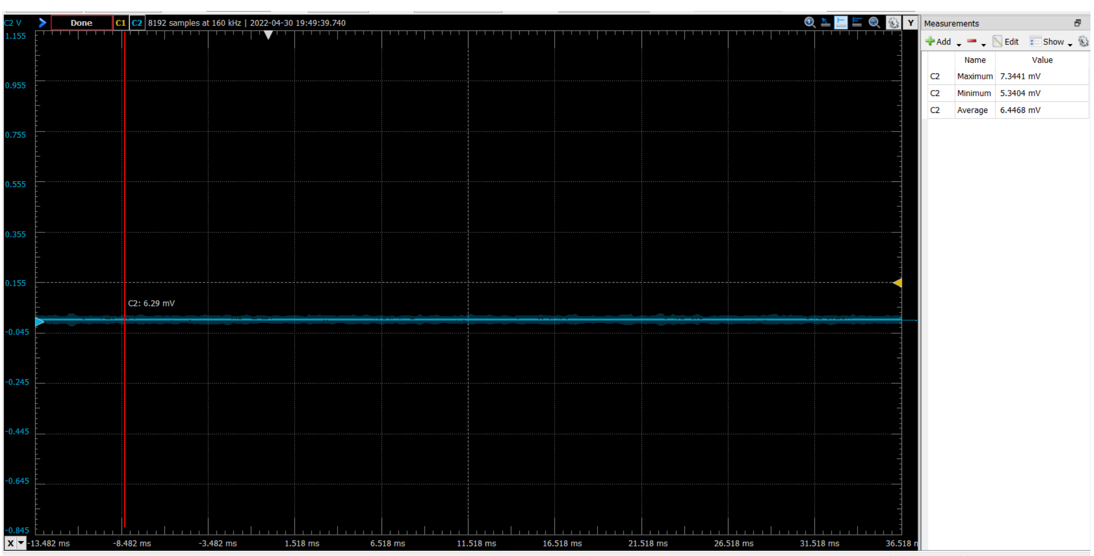


Figure 2.7 Voltage Output at Gain 1

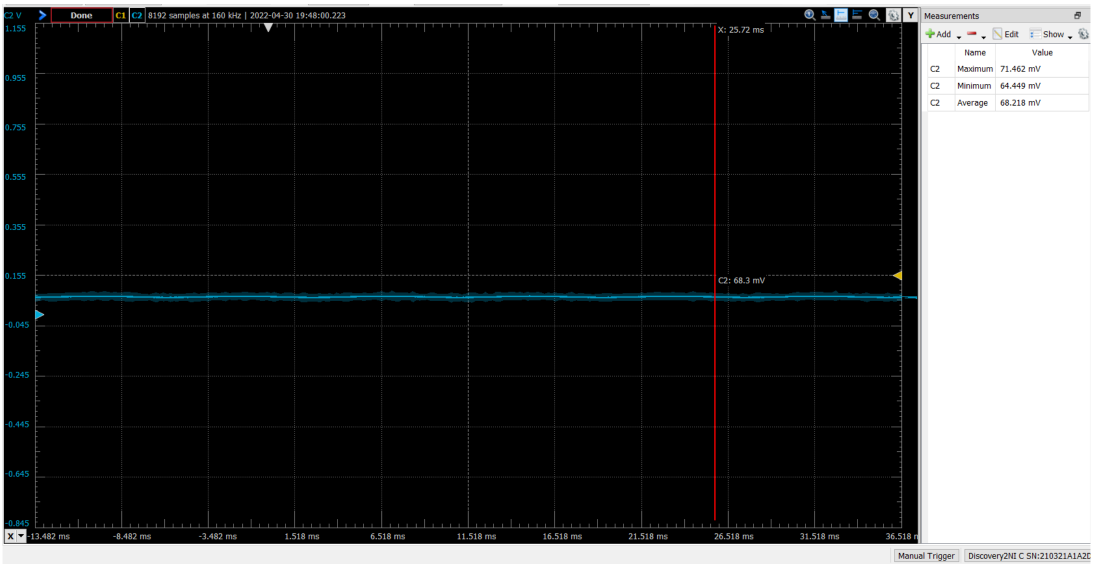


Figure 2.8 Voltage Output at Gain 10

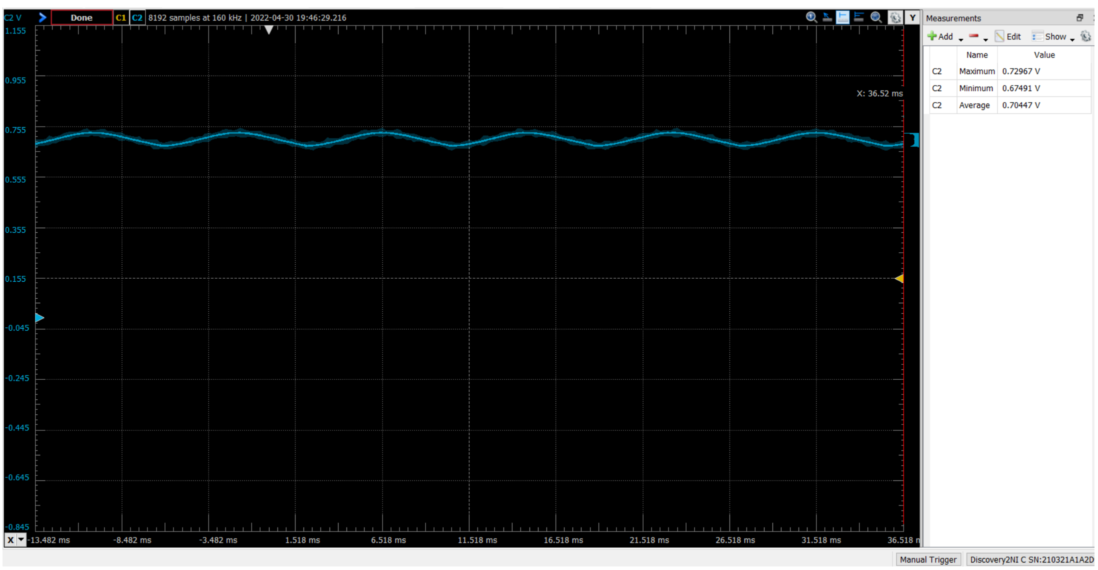


Figure 2.9 Voltage Output at Gain 100

Nominal Gain	Voltage (Averaged)	Gain (Estimated)
1	6.448 mV	1
10	68.218 mV	10.58
100	704.47mV	109.25

Table 2.2 Measured Voltages and Estimated Gains

In order to find out if this voltage is consistent with what we would expect, we must work backwards to find out the current which is flowing through our system. In order to achieve this, we must simulate our circuit and then find at what current the voltage we measured is produced by our transimpedance amplifier. We will simulate our circuit at gain 10 and then see what the current value is for 68mV.

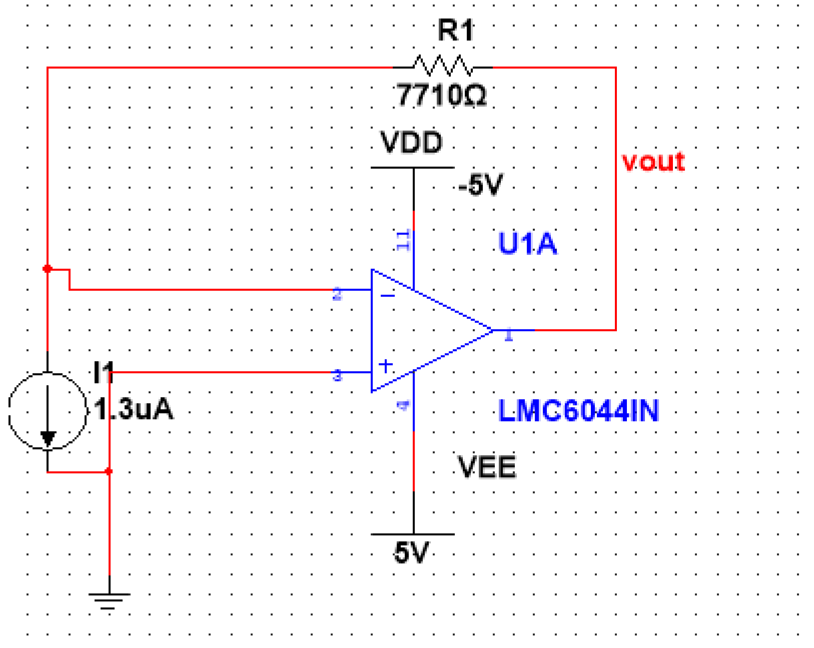


Figure 2.10 Multisim Gain 10 Circuit Simulation

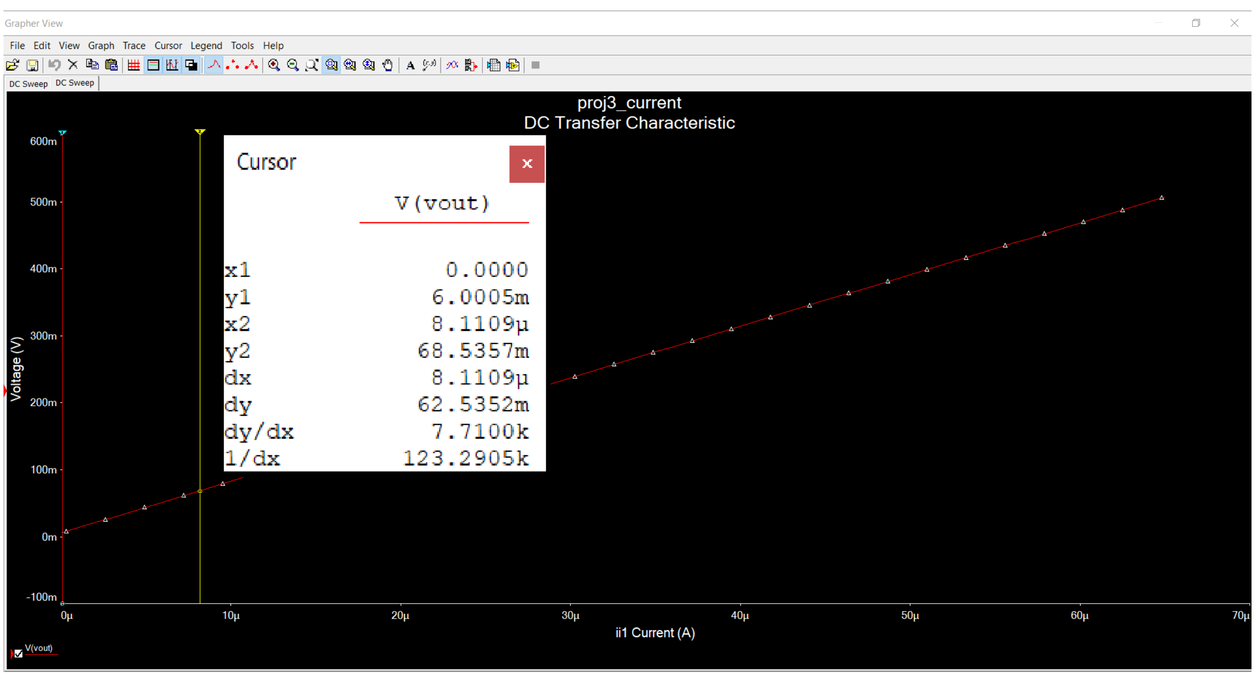


Figure 2.11 DC Sweep of Circuit at Gain 10

Looking at our simulation results, we find that at 68.53mV, our system would produce a current of 8.1uA. Next, we return to the Current Linearity graph from the Hamamatsu corporation for the S-1087 photodiode, and we hope to see a relationship between 8.1uA and 82 lux.

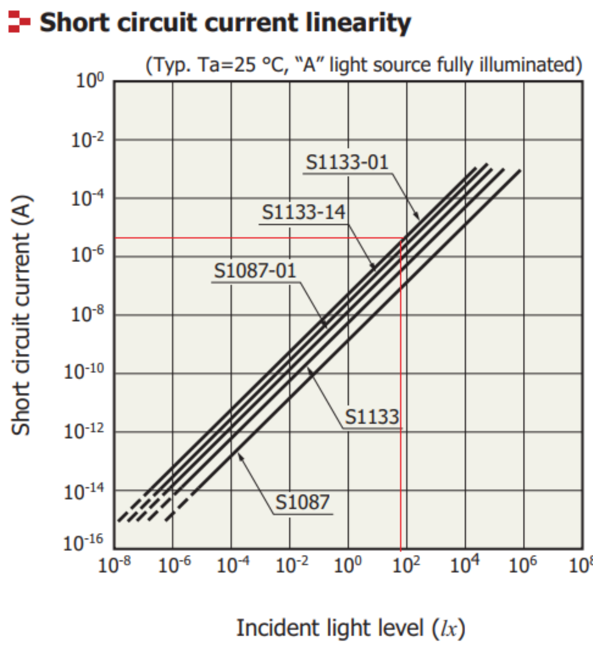


Figure 2.12 Current Linearity Graph with 82 lux and 8.1uA marked

Looking at the graph, we find that our markings of around 82 lux and 8.1uA, while not totally precise, do indicate that we are indeed very close to behaving as expected and that the current produced .

For completeness, we will be including some other test cases to display further verification of our subsystem The following screenshot is what our gain 1 mode looks like when completely covered. 0 lux. According to simulations, the minimal voltage should be 6mV. Indicating that at low light readings, current flows in the opposite direction in a small quantity.

	Name	Value
C2	Maximum	-1.00459 mV
C2	Minimum	-2.34039 mV
C2	Average	-1.61964 mV

Figure 2.13 Dark Voltage Values

We did not only test ambient light sources, we also tested more controlled light sources. The following tests are the results from a makeshift testbed constructed from a cardboard box with a hole poked through, with a flashlight resting on top. Approximately outputting

412lux. It is worth noting that our flashlight oscillates at 60Hz and so its waveform will appear as a square wave on our voltage scope.

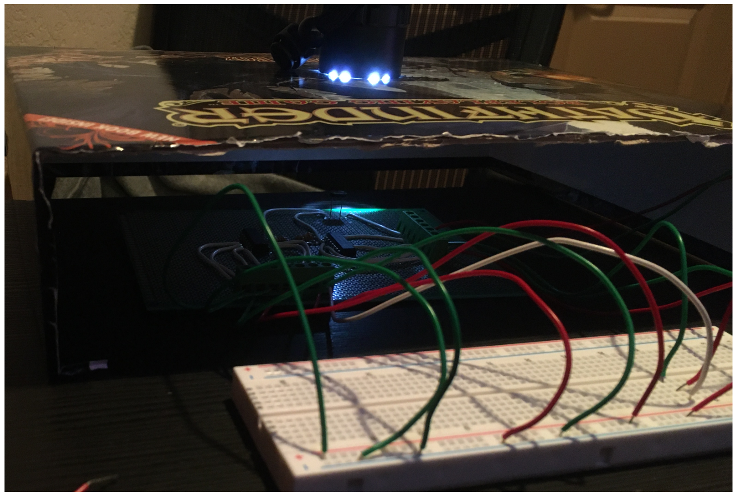


Figure 2.13 Controlled Light Source Testbed

Figure 2.14 Controlled Light Source Testbed Light Intensity Measurement

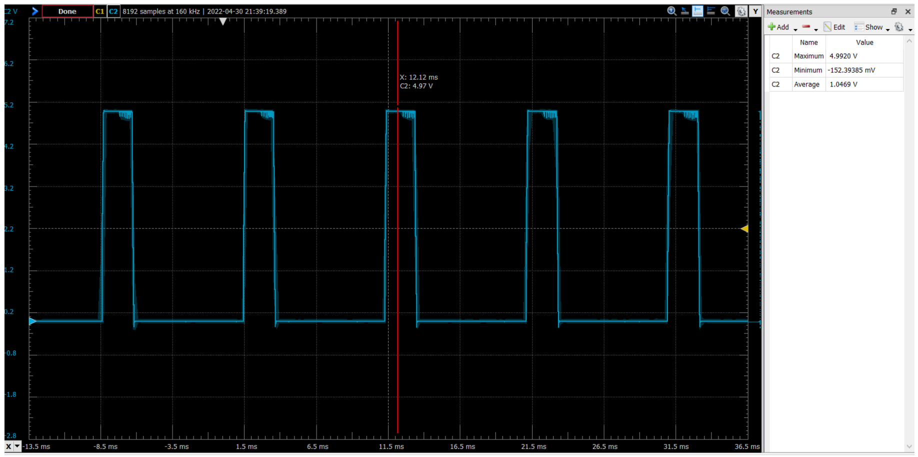


Figure 2.15 Voltage Output waveform at Gain 100

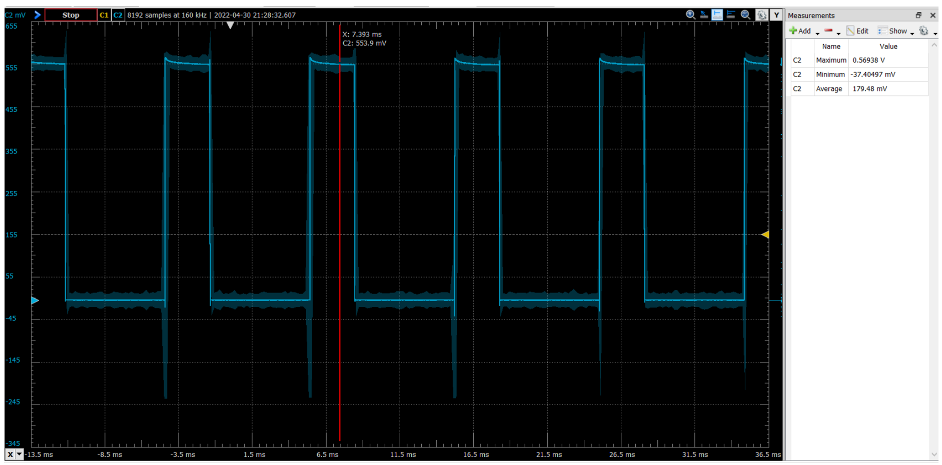


Figure 2.16 Voltage Output waveform at Gain 10

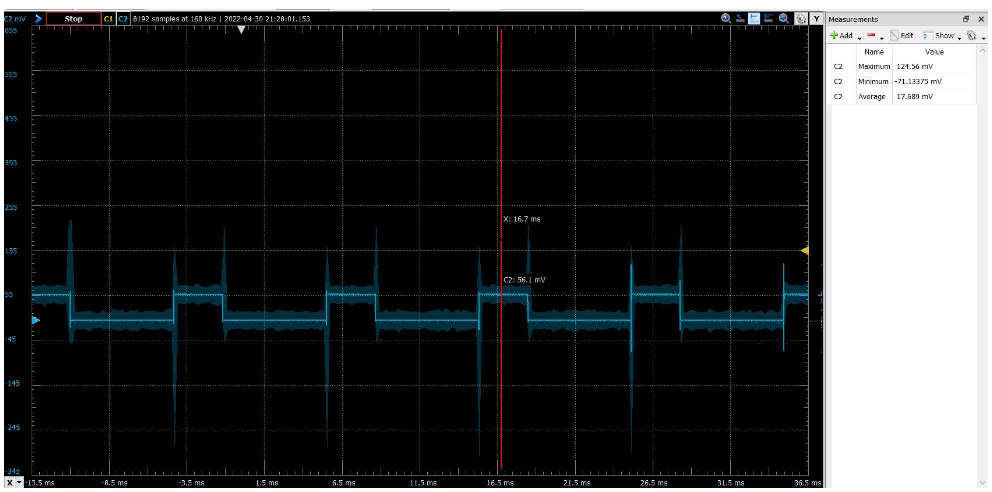


Figure 2.17 Voltage Output waveform at Gain 1

Gain Setting	Voltage Peak
1	56.1mV
10	553.9mV
100	4.97V* (Voltage Clipping)

Table 2.3 Measured Voltages and Gains

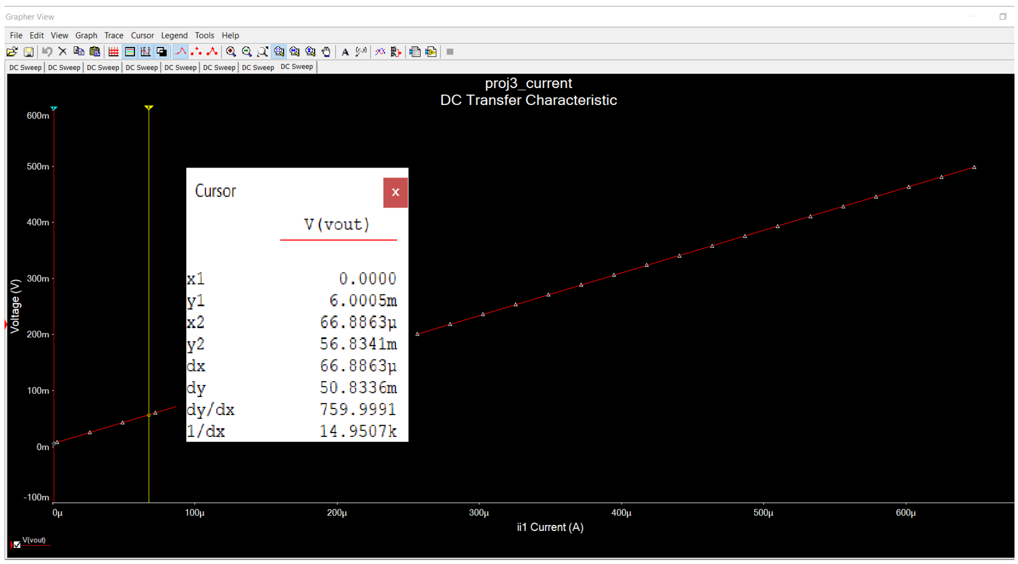


Figure 2.18 DC Sweep of Circuit at Gain 1

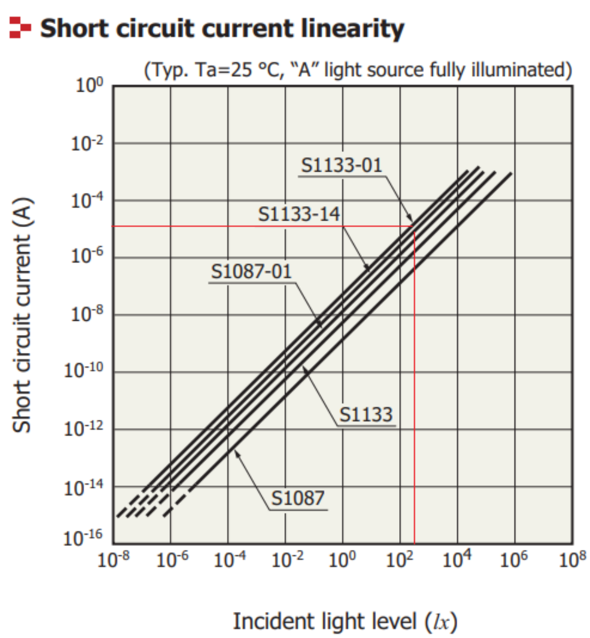


Figure 2.19 Current Linearity Graph with 412 lux and 66uA marked

Subsystem Conclusion

In conclusion, the Light Measurement Hardware measures lux consistent with what the manufacturer outlines for the photodiode on the spec sheet. In addition, we have a reliable gain of 1, 10, and 100. In 404, as we design and create the housing for our system, some attention will need to be paid to designing geometry which allows light to reach the photodiode unimpeded.

Subsystem Update

After 403, and as we miniaturized the design of the transimpedance amplifier subsystem into a PCB, the design remained largely unchanged, until we entered a phase of testing at the observatory, where we discovered that our system was nowhere near as sensitive as it needed to be, and was in fact around 1,400 times less sensitive than the SSP3 photometer we were attempting to imitate. In a last minute style hotfix, we removed and soldered on new resistors with compensated values that gave our design a much needed boost in sensitivity but regrettably added a lot more noise to our signal.

	Old Resistor Values (ohms)	New Resistor Values (ohms)
Gain 1	770	~1,000,000
Gain 10	7,700	~10,000,000
Gain 100	77,000	~100,000,000

Figure 2.20 Previous and Corrected Resistor Values for Gain

ADC and Controls Subsystem Report

Subsystem Introduction

The ADC and Controls subsystem interacts with the light measuring system as well as measure the input received from there and digitize it. It also should display the measurement that the light system would be measuring. The ADC will convert the output voltage received from the photodiode to an actual digitized number. This number will be sent to the computer as well as be displayed on the 7 segment display. There is also the controls part which sends a 2 bit signal to the mux. The second part of the controls is the 7 segment display. This all together makes the ADC and Controls subsystem.

Subsystem Details

The ADC subsystem uses an external ADC called LTC2470. LTC2470 is a single ended 16-bit adc that would convert voltage into readable data. It would send this readable data to the microcontroller through SPI (serial peripheral interface). SPI uses a slave device to send data from the slave device to master device which would be the microcontroller. The main reason to use an external ADC is to have accurate voltage conversion as well give it more bits for an accurate value

For the Controls subsystem an LED is being lit to show that there is an electrical signal which should be passed to the mux in the light measuring system. Another part is the 5 digit

7 segment display which is being multiplexed with 5 different NPN bjts. The code outputs a code which will light certain segments which are labeled A-G.

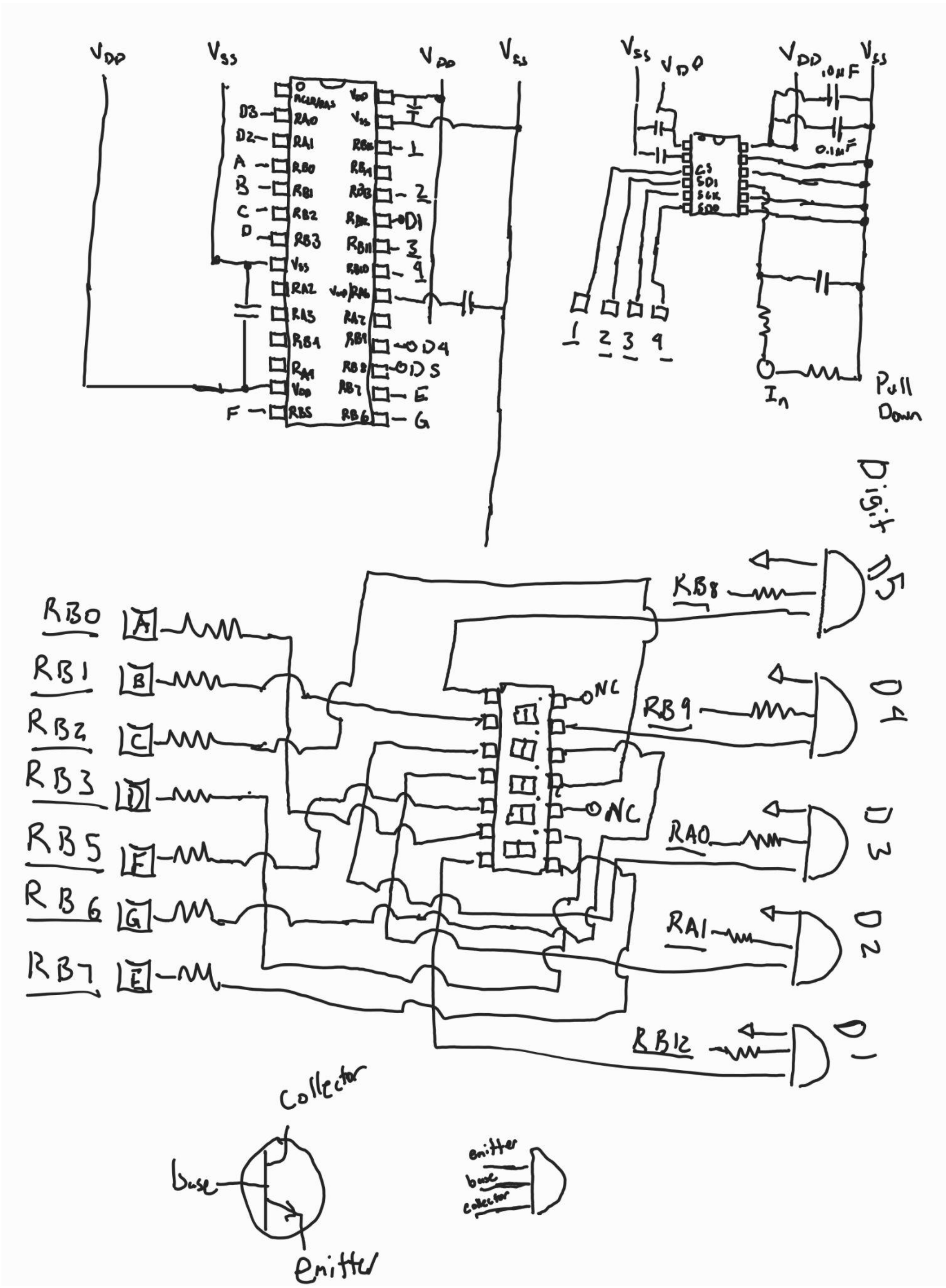
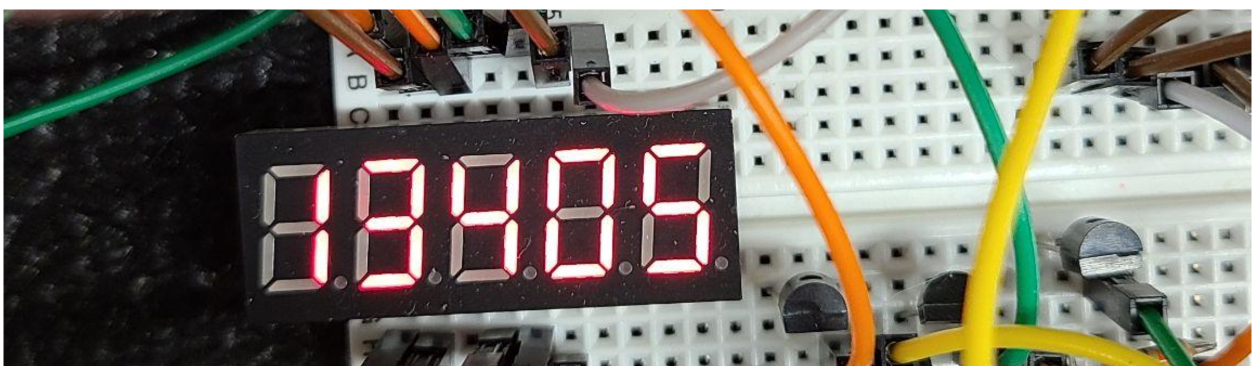


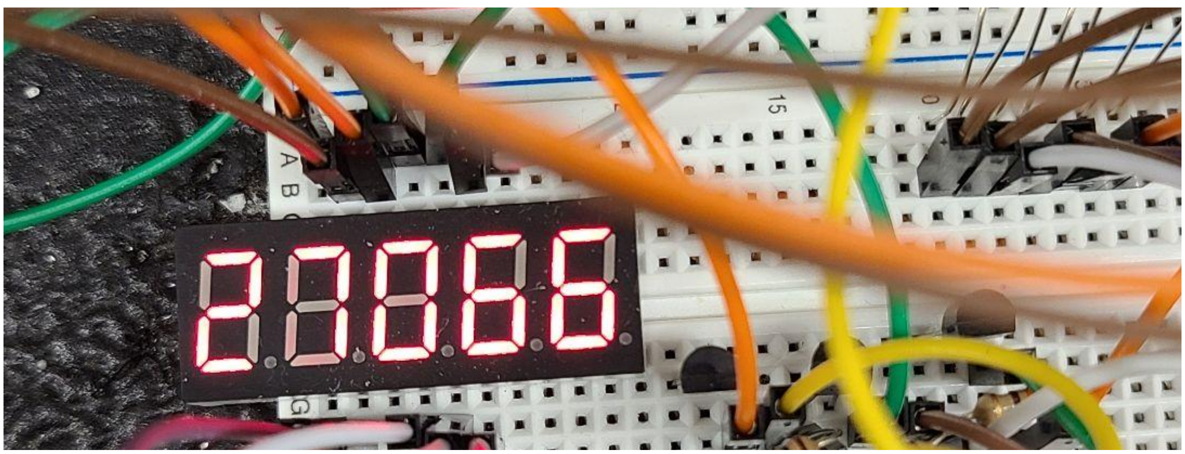
Figure 3.1 Diagram of ADC and 7 segment LED

○ *Subsystem Validation*

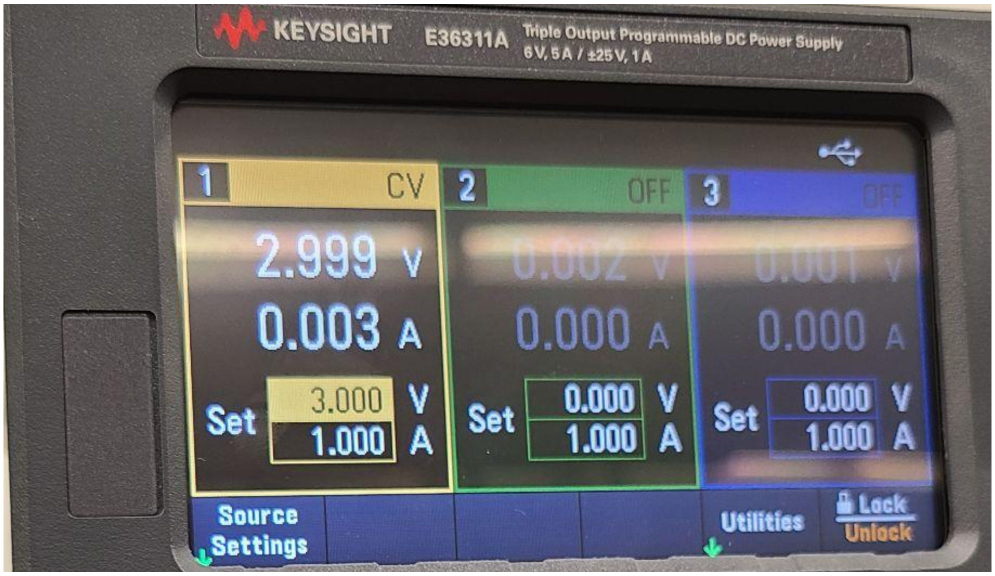
ADC: I took multiple measurements of the voltages and compared it with the digital bits that were outputted. The step-voltage comparison is used to show how stable the system is and how consistent the results are.

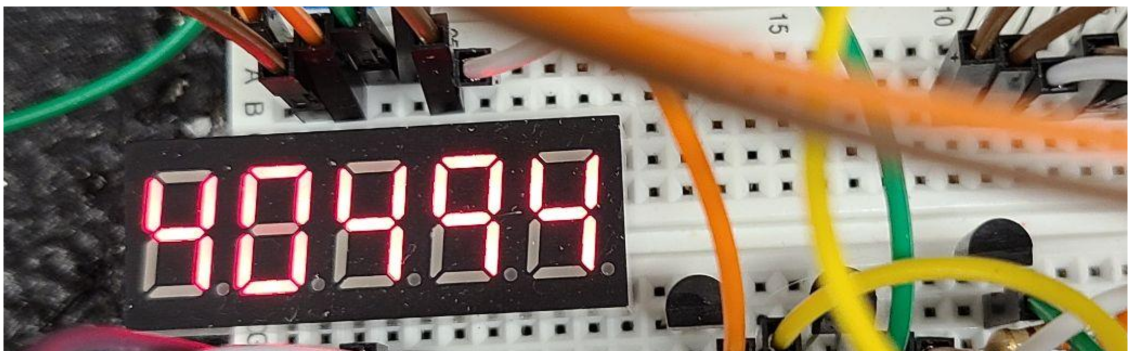


Picture 3.1 and 3.2 1 Volt and 5 digit 7 segment display

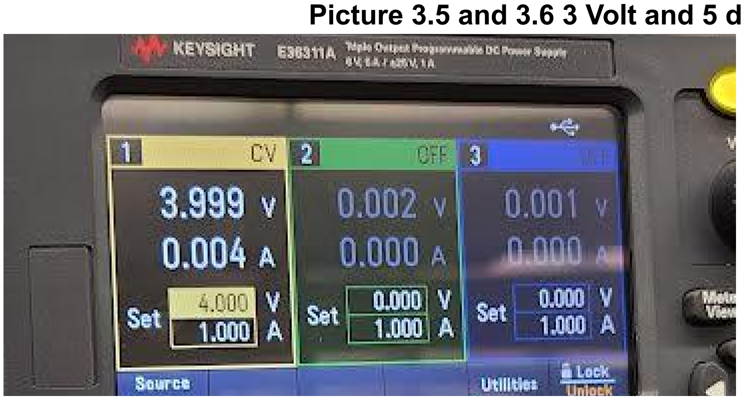


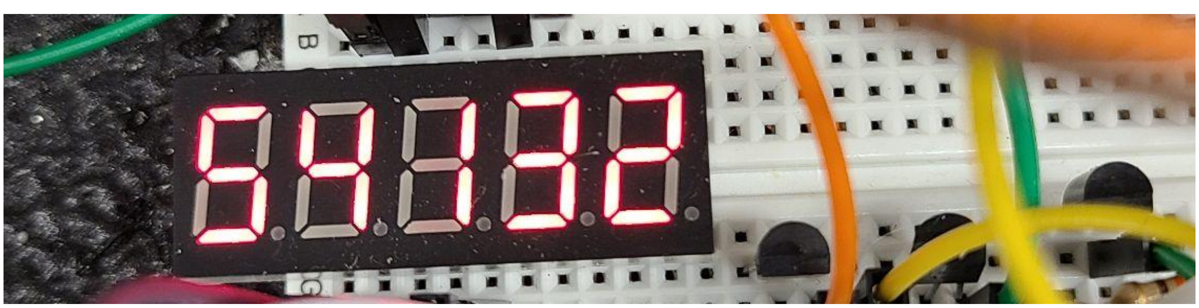
Picture 3.3 and 3.4 2 Volt and 5 digit 7 segment display



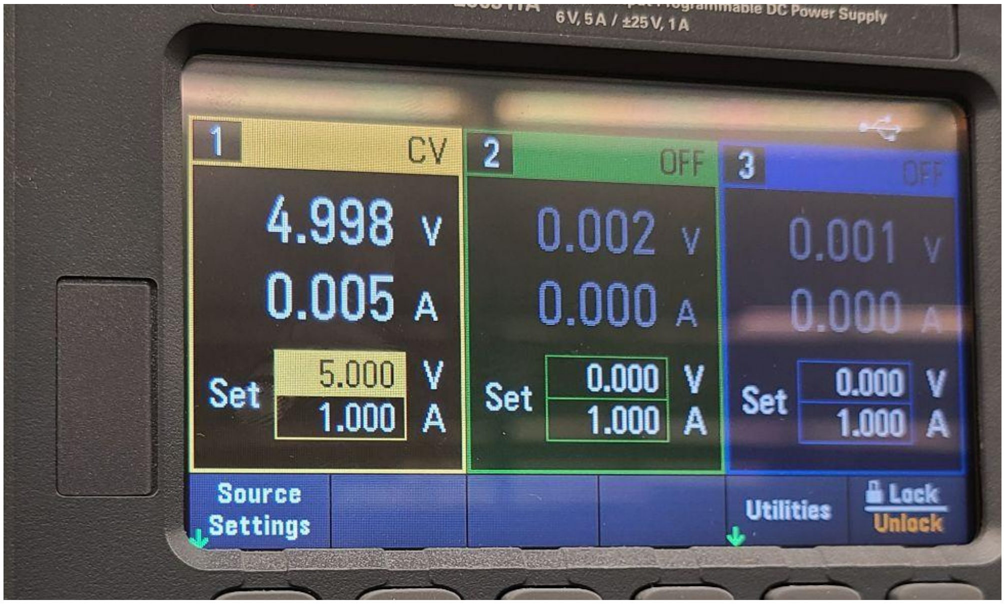


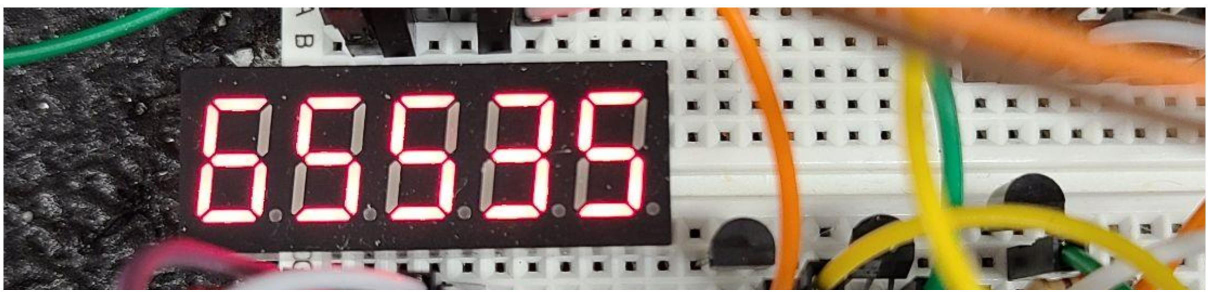
Picture 3.5 and 3.6 3 Volt and 5 digit 7 segment display





Picture 3.7 and 3.8 4 Volt and 5 digit 7 segment display





Picture 3.9 and 3.10 5 Volt and 5 digit 7 segment display

V	Bits	Step Voltage (µV)
0.25	3309	75.55152614
0.5	6654	75.14277127
0.75	10065	74.51564829
1	13405	74.59903021
1.25	16752	74.61795606
1.5	20256	74.0521327
1.75	23689	73.87394993
2	27066	73.89344565
2.25	30455	73.87949434
2.5	33842	73.87270256
2.75	37222	73.8810381
3	40444	74.1766393
3.25	43872	74.07913931
3.5	47248	74.07720962
3.75	50752	73.88871375
4	54132	73.89344565
4.25	57508	73.90276135
4.5	60966	73.81163271
4.75	64363	73.80016469
5	65535	76.29510948

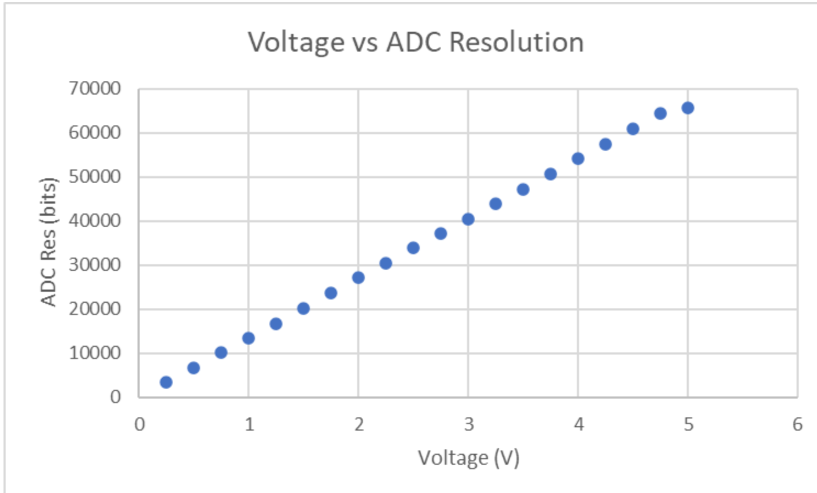
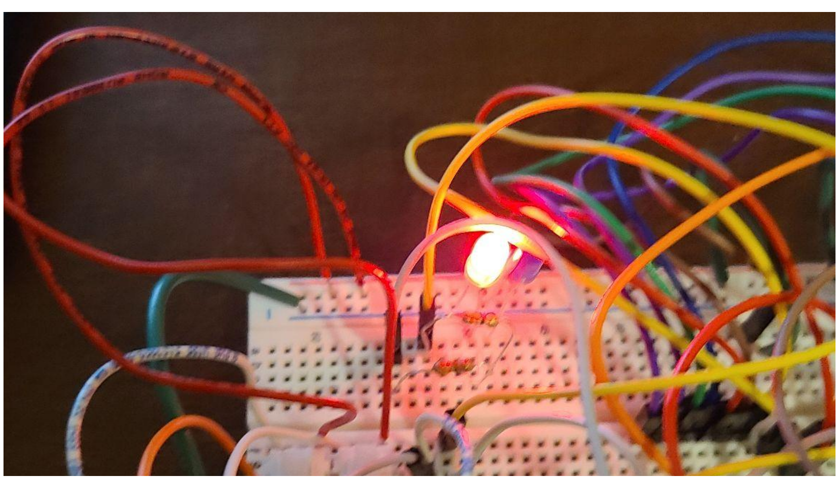


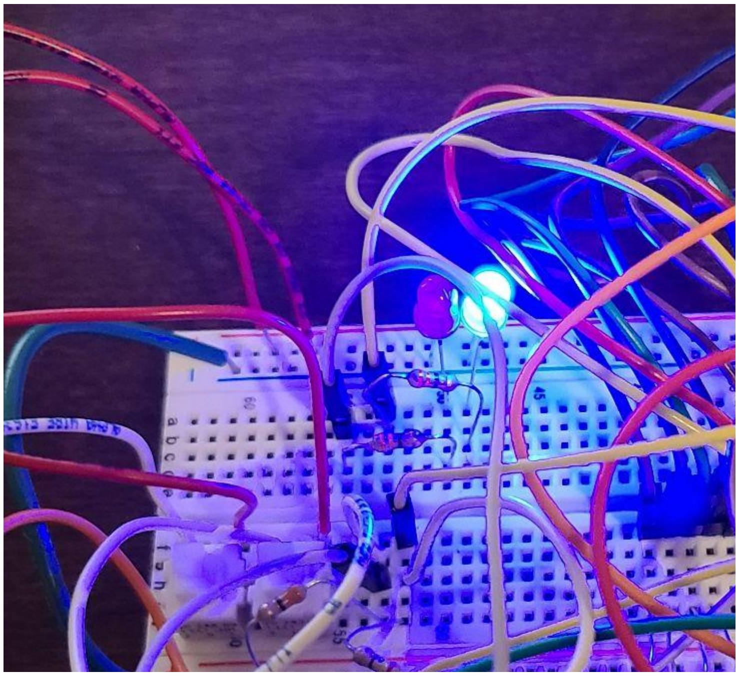
Table 3.1 and 3.2 Voltage vs Bits Chart and data w/ Step Voltage

As the voltage goes up linearly so does the number of bits involved. The step voltage should be around 74 microVolts.

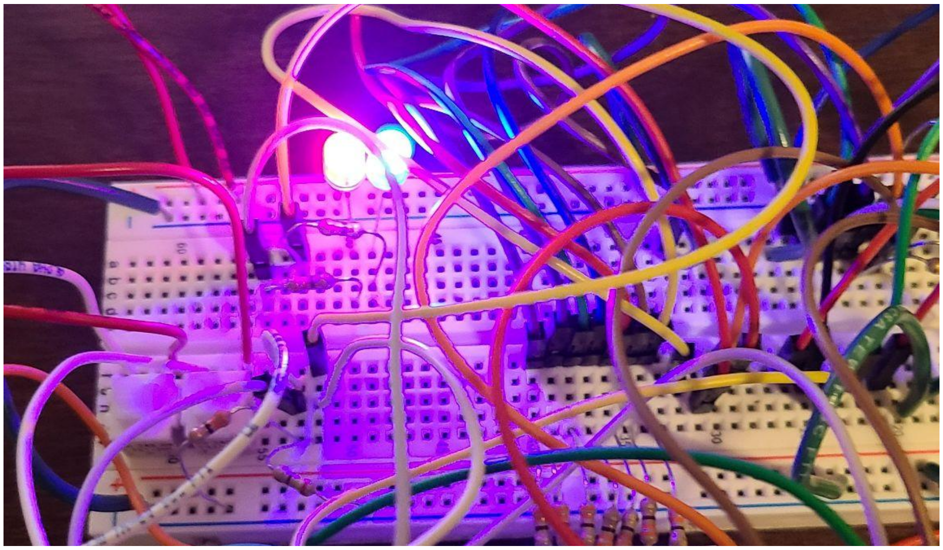
Controls: For the control system I have a button that outputs 2 bits of information. These two buttons will control the mux of the photodiode system and pushing one will turn on the first part of the mux on and the other will turn the 2nd part of the mux.



Picture 3.11 First button that lights up the first LED



Picture 3.12 Second button that lights up the second LED



Picture 3.13 Both buttons are on and both LEDS turn on

Having both on will take the one with the highest priority. The lights just show that a signal is being sent to the light measuring system.

- ### ***Subsystem Conclusion***

This subsystem's main duty is to communicate with the light measuring system and measure the output received from it and put onto The 7 segment LED and get the data ready to send to the laptop. The second part of the subsystem sends a two bit data input to the mux of the photodiode in order to choose which gain it needs. In conclusion this subsystem behaves accordingly.

- ### ***Subsystem Revisions***

The transition for ECEN 403 to ECEN 404 we changed the controls systems almost entirely while the ADC was kept the same. The 5 digit 7 segment display now gets data through a display board that uses a transfer SPI as a transfer protocol and gets decoded using SPI. The gain and time integration buttons are done with momentary buttons and each have two modes. The way to read the gains is also done on the 5 digit 7 segment display and will display the numbers for the various protocols For gain it is initially on a gain of 1 but there is also 10, 100, and after that it cycles back to 1. For time integration its default is 1 and cycles through 5, 10 and then goes back to 1 after 10. Lastly there is the start button which starts the actual readings of data.

Picture 3.14 All three different buttons

Picture 3.15 Initial Gain of 1

Picture 3.16 These are a gain of 10 and 100

Picture 3.15 Initial Time integration of 1

Picture 3.16 These are a time integration of 5 and 10

- # Microcontroller and Software Subsystem Report

  - ## *Subsystem Introduction*

Microcontroller - The main function of the microcontroller subsystem is to implement a protocol (details on the protocol are provided in the Subsystem Details section) that will allow our customer to gather data from our photometer using data acquisition software. Additionally, the protocol will allow the customer to control the integration time and gain properties of the photometer with more flexibility.

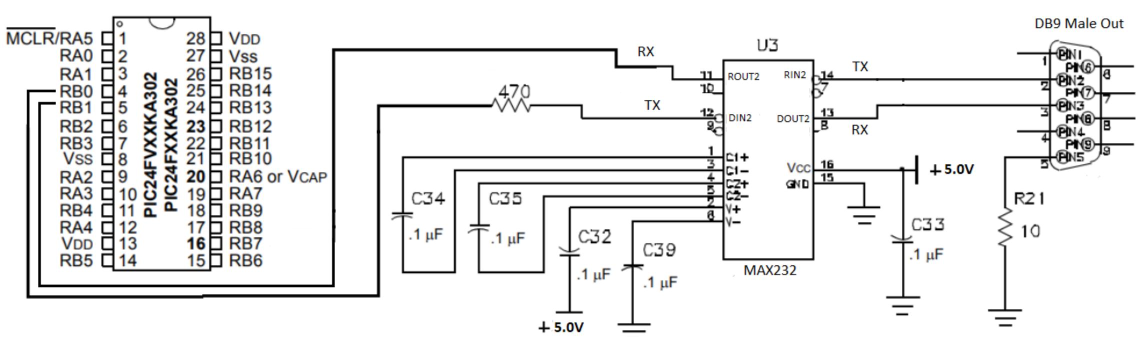


Figure 4.1 Schematic for Microcontroller Subsystem

Software - The software's purpose is to help us validate the protocol implementation. It does this by establishing a UART connection between a PC and the microcontroller, once a connection is established, various commands can be sent to the microcontroller that can be used to test the appropriate functionality of any of the features of the photometer. More details on the software are provided in the following sections.

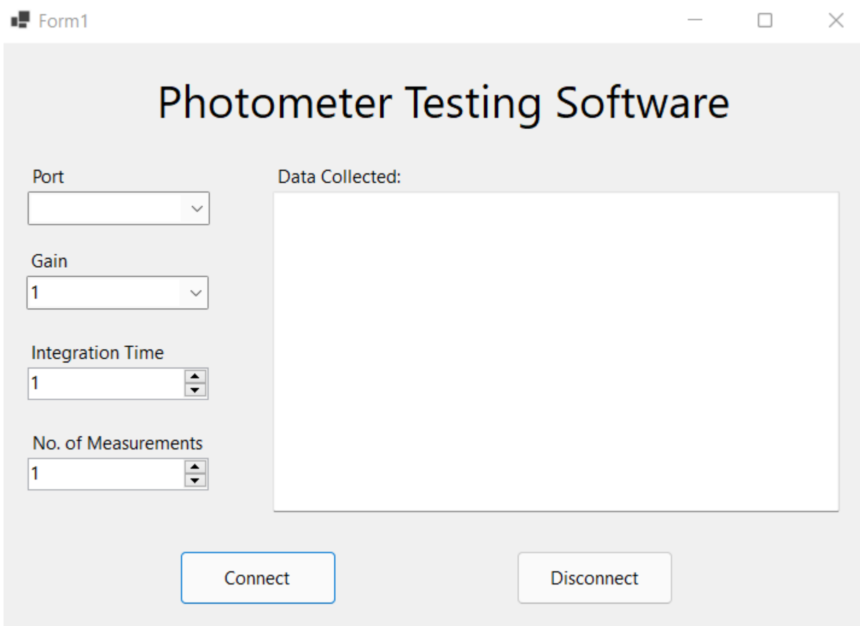


Figure 4.2 General Design for the Software Subsystem

- ### *Subsystem Details*

Microcontroller - The hardware part of the microcontroller subsystem consists of three parts, (1) a PIC24FV32KA microcontroller used to implement the protocol, (2) a MAX232 which is in charge of converting TTL to RS232 logic, and (3) a DB9 Male output port which allows connection between the microcontroller and a PC. These components and their interconnections are shown in Figure 4.1.
Like mentioned before, the main functionality of the microcontroller is to implement a protocol that will allow our customer to operate our photometer using data acquisition software. The commands implemented by this protocol and their descriptions are shown below:

```
'                   n       is any real integer 0 <= n <= 9
'                   x       is any character
'                   LF      is a line feed character, decimal 10, hex A
'                   CR      is a carriage return character, decimal 13, hex D
'                   "!"     is the exclamation character, decimal 33, hex 21
'
'       SSMODE      if in manual mode, this command will initiate the serial loop mode and
'                   only serial commands will control the instrument
'                   after the serial loop mode is entered, a "!" LF CR is sent on the
'                   serial port to acknowledge the mode change
'                   if the instrument is already in the serial loop mode, the
'                   acknowledgement code is sent again, "!" LF CR to confirm that the
'                   instrument is in the serial loop mode
```

```
'
'       SGAINn      sets gain of instrument of preamp stage. n can be 1, 2 or 3 only
'                   1 = gain of 1, 2 = gain of 10, 3 = gain of 100
'                   "!" LF CR is returned on serial port to acknowledge command
'
'       SInnnn      sets integration time in units of 0.01 seconds. 0001 <= nnnn <= 9999
'                    "!" LF CR is returned on serial port to acknowledge command
'
'       SCOUNT      start a reading with selected gain and integration time.
'                   after the count is completed, the results are displayed on the
'                   instrument and sent on the serial port in the following format:
'                   C=nnnnn LF CR, where 00000 <= nnnnn <= 65535, leading zeros are
'                   sent
'
'       SMnnnn      initiate a fast reading cycle with selected gain and integration time.
'                   nnnn is the number of readings to do, 0000 <= nnnn <= 9999, leading
'                   zeros must be added for number to be correct
'                   after each reading is done the value is sent on the serial in the
'                   following format: nnnn LF CR where 0000 <= nnnn <= 9999
'                   the fast mode sequence can be interrupted by sending a SS
'                   once the fast mode is successfully stopped, a "!" LF CR is sent
'
'       SENDxx      exits the serial loop mode and returns to manual mode.
'                   before leaving the serial loop mode, an "END" LF CR is sent
'
'       =======     serial error messages
```

Two parts of this protocol are yet to be implemented, these are the serial error message "=======" and the stop command "SS". The rest of the commands have been fully implemented and tested for proper functionality.

Software - The software was developed using C#, this programming language provides libraries and functionalities that make it easy for the programmer to quickly design desktop applications and make use of PC peripherals such as USB ports. The app itself runs on windows operating systems and consists of the following functions:

Port	Used to select the port on the user's computer that will be used for data acquisition.
Gain	Used to select the photometer's gain property to 1, 10, or 100.
Integration Time	Used to select the photometer's integration time property to a value between 1 and 9999.
No. of Measurements	Used to select the number of measurements to be taken by the photometer, the number of measurements can be anywhere from 1 to 9999.

Data Collected	Displays data received from the photometer.
Connect	Initiates a connection with the photometer and sends the appropriate command based on the selected gain, integration time, and No. of Measurements.
Disconnect	Serial mode ends and the photometer goes back to operating in handheld mode.

Table 4.1 Software Feature Definitions

The actual layout of these functions on the software can be seen in Figure 4.2.

○ Subsystem Validation

Microcontroller - The first step in validating the microcontroller subsystem was to build the hardware and establish a UART connection. Figure 4.3 shows the layout that was used to validate the hardware. Once the hardware was built, different signals (characters) were sent to and from the microcontroller, using an oscilloscope (Figure 4.4) we verify that the baud rate and signals received for all of our components are as expected.

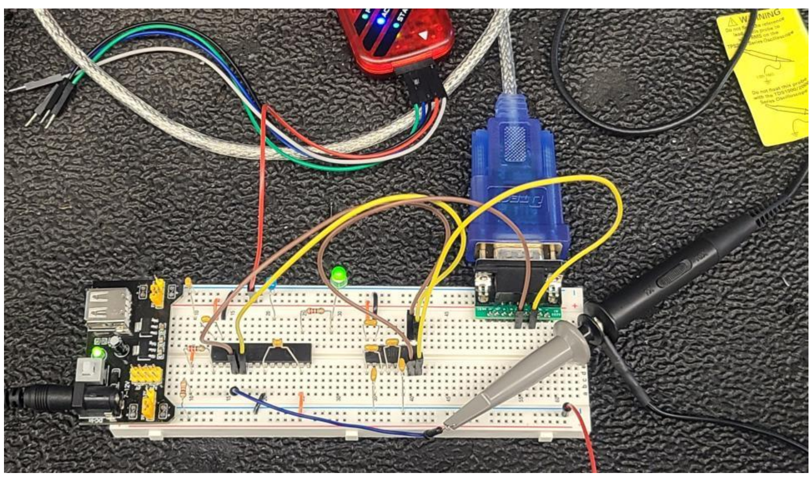


Figure 4.3 First Circuit Layout on a Breadboard

Figure 4.4 Example of Oscilloscope Output at TX Pin

The following table summarizes the results obtained while validating the microcontroller hardware:

	Expected Output	Actual Output	Expected Baud Rate	Actual Baud Rate
MCU RX Pin	a - b - c	a - b - c	19.2 Kbps	19.214 Kbps
MCU TX Pin	a - b - c	a - b - c	19.2 Kbps	19.212 Kbps
MAX232 RX Pin	a - b - c	a - b - c	19.2 Kbps	19.321 Kbps
MAX232 TX Pin	a - b - c	a - b - c	19.2 Kbps	19.312 Kbps
DB9 RX Pin	a - b - c	a - b - c	19.2 Kbps	19.199 Kbps
DB9 TX Pin	a - b - c	a - b - c	19.2 Kbps	19.201 Kbps

Table 4.2 Data Results from Hardware Validation

Once the hardware is validated, we can begin to validate the appropriate operation of the protocol. Validation was done through the use of Proteus, a circuit simulation software (Figure 4.5). After confirming the operation of the protocol through simulations, we implemented it on the physical device, validated a second time, and soldered all the components together (Figure). More details on the validation results for the protocol are provided in the “Software” section.

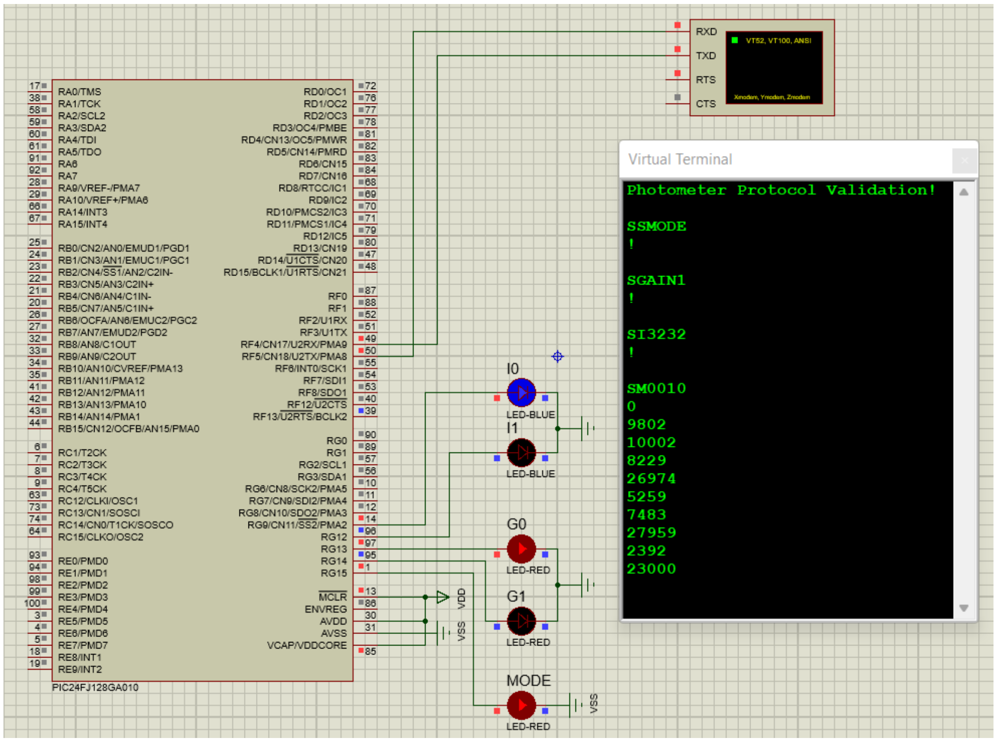


Figure 4.5 Protocol Validation Using Proteus

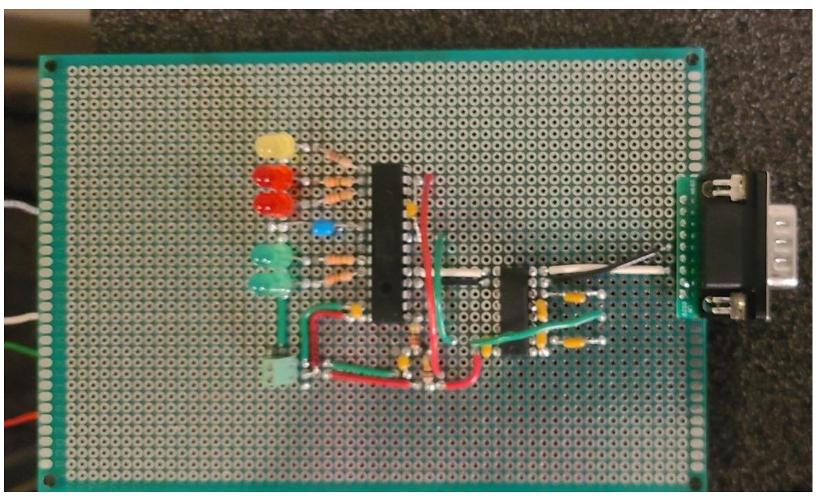


Figure 4.6 Final Microcontroller Design on a Perfboard

Software - Software validation is fairly straightforward, we send various commands to the microcontroller and verify that they are recognized and the appropriate data is sent back to the computer. Figure 4.6 shows an example of what it looks like when we use the software to validate the protocol and acquire data, and Table 4.3 shows a summary of various test cases.

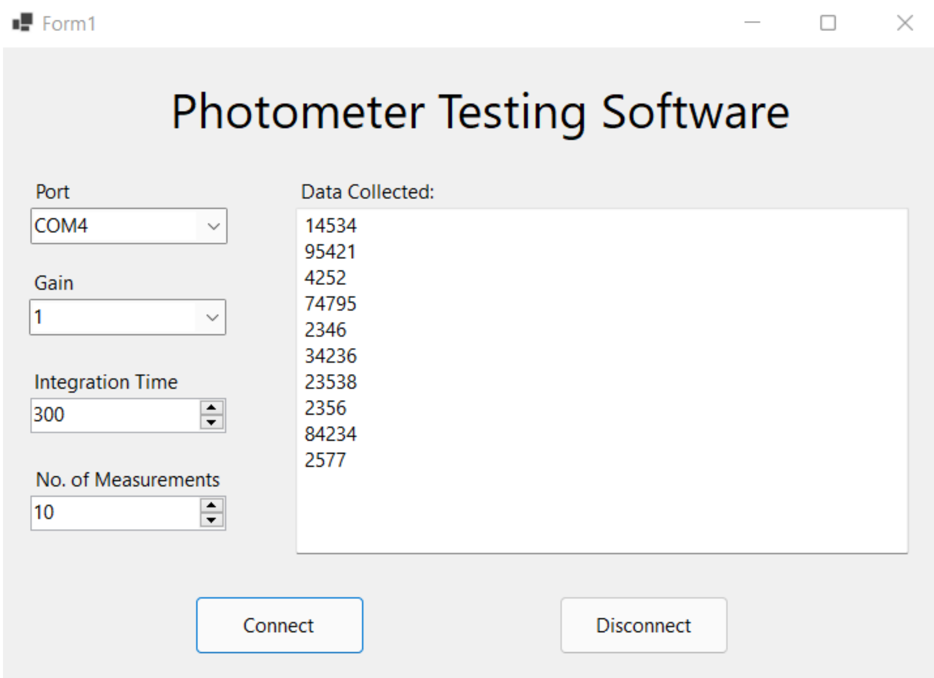


Figure 4.7 Example of Software Inputs and Data Received

Comand	Expected Result	Actual Result
SSMODE	SSMODE LED on in the hardware	SSMODE LED on in the hardware
SGAIN1	GAIN LEDs set to 01 in the hardware	GAIN LEDs set to 01 in the hardware
SGAIN3	GAIN LEDs set to 11 in the hardware	GAIN LEDs set to 11 in the hardware
SI0010	INTEGRATION LEDs set to 01 in the hardware	INTEGRATION LEDs set to 01 in the hardware
SI9999	INTEGRATION LEDs set to 11 in the hardware	INTEGRATION LEDs set to 11 in the hardware
SCOUNT	One reading on the “Data Collected” box of the software	One reading on the “Data Collected” box of the software
SM0001	One reading on the “Data Collected” box	One reading on the “Data Collected” box
SM0100	One hundred readings on the “Data Collected” box	One hundred readings on the “Data Collected” box
SENDxx	SSMODE LED off in the hardware	SSMODE LED in the hardware

Figure 4.8 Example of Software Inputs and Data Received

○ Subsystem Conclusion

In the end, my subsystem behaves as is expected and meets all of the requirements set by our customer. In the future, I will have to meet with our customer to ensure the protocol is compatible with his data acquisition software. Furthermore, I will be designing a simple voltage regulator that will serve as the power source for my and the other subsystems and working on designing a PCB during the summer.

○ Subsystem Revisions

After discussing with our customer, it was determined that the Photometer software would not be of any significant importance to the project and its development was halted. Testing for the Photometer protocol was instead done using a third party software. This software allows for all aspects of the protocol to be thoroughly tested and validated. A sample of the testing done using this third party software is shown below.

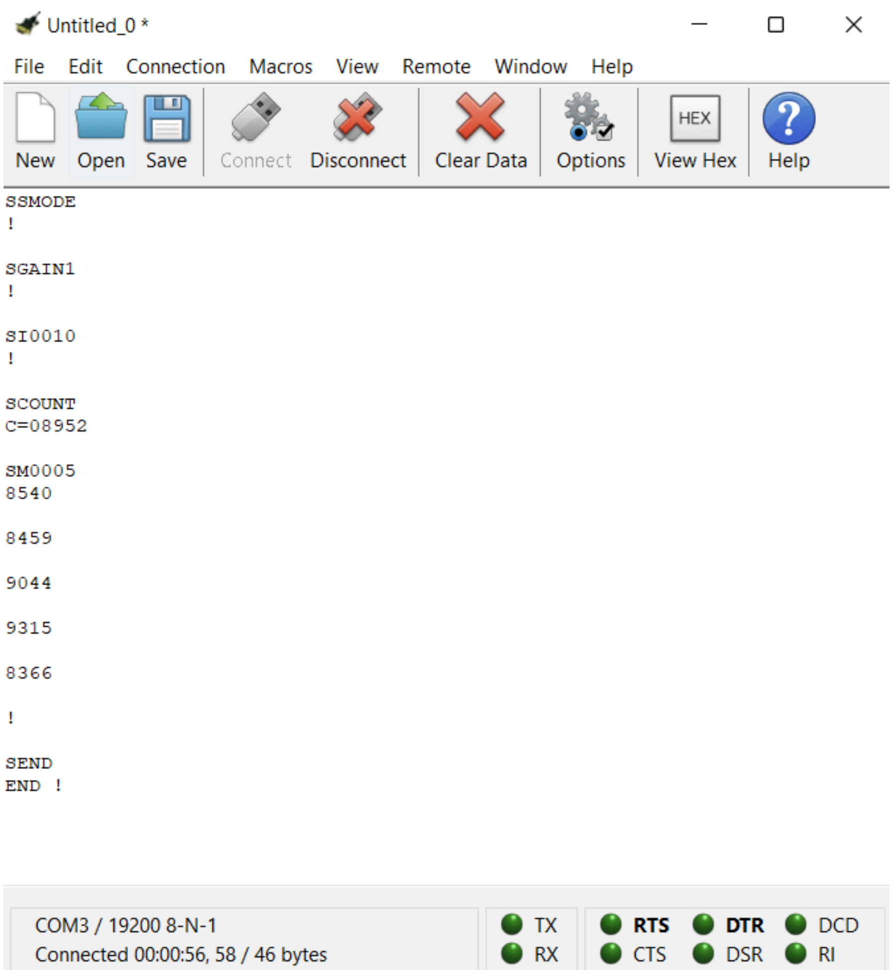


Figure 4.9 Example of protocol testing using third party software.

- ## Enclosure Subsystem Report

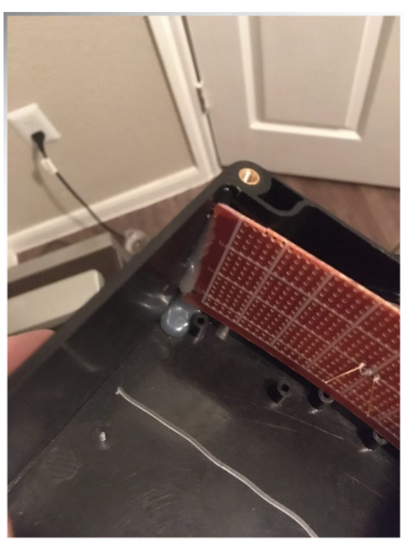
    - ### *Subsystem Introduction*

It is very important for our hardware to have a secure enclosure with which to stay stable and be transported within, in addition to being securely fastened to a telescope during operation. For these reasons, it was necessary to design and fabricate an enclosure with commercially available parts and integrate them together with FEDC hardware such as the dremel tool and hot glue.

    - ### *Subsystem Details*

The enclosure we decided on is a rectangular enclosure measured to be 200 x 120 x 75mm of ABS plastic. In order to fashion this plastic enclosure for our purposes, we needed to dremel a hole roughly 42mm in diameter, so that our 42mm spacer ring extension could fit. We then superglued it in place and for additional support applied DB Weld epoxy. We also hot glued a strip of perfboard into the enclosure near the hole and paid close attention to center the photodiode as much as possible.






- ### Subsystem Validation

To ensure our system was stable and could support its weight and the weight of the PCB, we first tested ~250g of evenly distributed weight (left) which is approximately how much our PCB weighs, and then we applied a 500g weight centered at the end of the enclosure (right) with much more torque forces applied to the device. This test shows our enclosure design can support significant weight, more than our roughly 250g PCB.

ECEN 404- 905: Photometer

Rigoberto Olivares
Richard Lopez
Hunter Cothran

SYSTEM REPORT

REVISION – Final
3 December 2022

System Report
for
Photometer

Team 18

Approved by:

____
Project Leader Date

____
Prof. Kalafatis Date

____
T/A Date

Change Record

Rev.	Date	Originator	Approvals	Description
-	02/08/2022	Photometer		Draft Release
	12/03/2022	Photometer		Final Release

Table of Contents

List of Figures

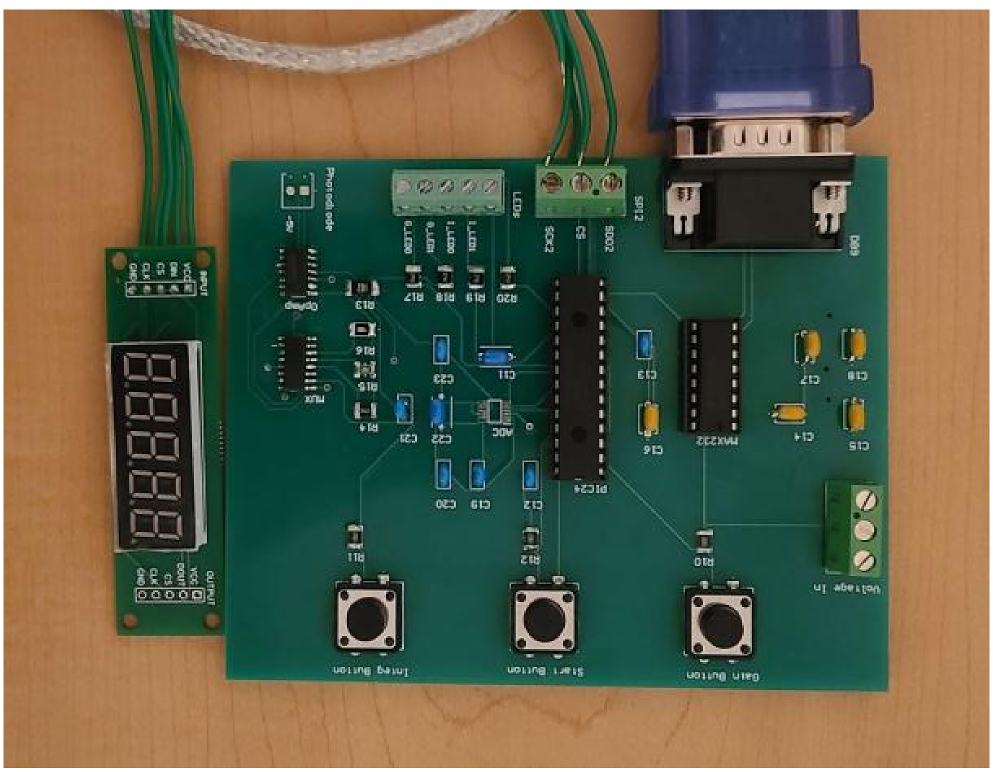
● Overview

The Photometer is a device that is used to measure the light intensity of celestial objects. Its compact and lightweight design allows it to easily be attached to telescopes of various sizes. The main objective of this project was to create a modernized version of older photometer models. Internally, the device consists of five major subsystems, Photodiode, Amplifier, Microcontroller, Input/Outputs, and Enclosure. The proper integration, validation, and testing of all subsystems yields the final Photometer design. Upon completion of the design process, the Photometer was ready to be used in conjunction with our customer's telescope for data collection.

● Development Plan and Execution

○ *Design Plan*

The goal of the design is to mimic the design of the SSP3-Photometer but use a safer operating voltage, making it cheaper, and more modernized by having newer parts as well. We designed our photometer around the Hamamatsu photodiode which would get a certain current based on how bright the incoming light is. Then the goal is to transform that current into a voltage which an Analog to Digital converter would then convert into a digital signal that the pic microcontroller can read. This would then transfer any data that the pic has sent to the customers laptop and display to a 5 digit 7 segment display.

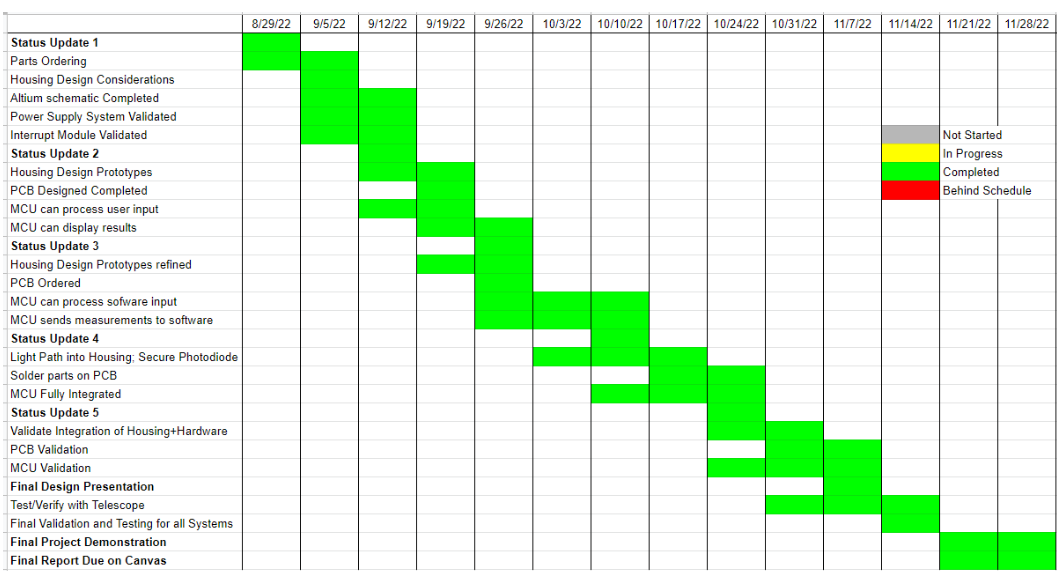


○ *Execution Plan*

The execution plan for the first half of this project involved obtaining the proper functionality for each of the five different subsystems. Ensuring each of the subsystems has been properly tested and validated is an integral part of achieving a working project (refer to previous sections for more information on subsystem test and validation). One semester was allocated for the completion of this step in the process. The following tables show our progress in this step of the project throughout the semester:

Work	End Date	Owner	Status	Date Complete
Concept of Operations	2/9/2022	ALL	Complete	2/8/2022
Interface Control Document	2/23/2022	ALL	In Progress	N/A
Functional System Requirements	2/23/2022	ALL	In Progress	N/A
GUI for photometer software should be created.	2/25/2022	Rigo	In Progress	N/A
Learn the basics of a microcontroller and how to program it.	2/25/2022	Richard	In Progress	N/A
Determine appropriate op-amps for acting as transimpedance amplifier and creating gain w/ minimal noise	2/25/2022	Hunter	In Progress	N/A
Project Parts Ordered	2/21/2022	ALL	In Progress	N/A
Midterm Presentation	2/28/2022	ALL		
Protocol should be implemented into the photometer software.	3/4/2022	Rigo	Planned	N/A
Work with the LED panel and get it to display numbers based off inputs	3/4/2022	Richard	Planned	N/A
Simulate and verify gain circuit design meets parameters	3/4/2022	Hunter	Planned	N/A
Start working with the microcontroller.	3/11/2022	Rigo	Planned	N/A
Work with the LED panel and get it to display numbers based off inputs	3/11/2022	Richard	Planned	N/A
Create and test circuit on breadboard with photodiode; procure false star set up	3/11/2022	Hunter	Planned	N/A
Microcontroller should recognize the appropriate protocol.	3/18/2022	Rigo	Planned	N/A
Set up the ADC so the microcontroller can read voltage input to digital	3/18/2022	Richard	Planned	N/A
Using false star; Create housing for photodiode and test environment for circuit	3/18/2022	Hunter	Planned	N/A
Test microcontroller and photometer can communicate through the protocol.	3/25/2022	Rigo	Planned	N/A
Set up ADC so it can make readable data to be outputted to the LED	3/25/2022	Richard	Planned	N/A
Ensure and verify measured light intensities are controlled and consistent	3/25/2022	Hunter	Planned	N/A
Progress Update 1	3/30/2022	ALL		
Continue testing the microcontroller and photometer can communicate through the protocol.	4/1/22	Rigo	Planned	N/A
Make sure the data getting outputted corresponds with the gain and time integration being inputted.	4/1/2022	Richard	Planned	N/A
Integrate housing and circuit and begin testing light and reading voltages	4/1/2022	Hunter	Planned	N/A
Debugging and creating test cases to ensure proper functionality.	4/8/2022	Rigo	Planned	N/A
Make sure buttons work according to time integration and the gain. Also making sure the laptop takes priority	4/8/2022	Richard	Planned	N/A
Verify photodiode can take in measured light and give expected voltage outputs	4/8/2022	Hunter	Planned	N/A
Microcontroller protocol should be finalized.	4/15/2022	Rigo	Planned	N/A
Last minute debugging and making sure everything works	4/15/2022	Richard	Planned	N/A
Ensure voltages and system operates expectedly	4/15/2022	Hunter	Planned	N/A
Final Presentation	4/20/2022	ALL		
Last minute testing input and outputs for the microcontroller protocol.	4/22/2022	Rigo	Planned	N/A
Last minute debugging and making sure everything works	4/22/2022	Richard	Planned	N/A
Ensure system demos expectedly	4/22/2022	Hunter	Planned	N/A
Final Demo	4/29/2022	ALL		

At the end of this time frame, the project moved on to the next step in the process, which involves designing an Enclosure, PCB, and integrating all subsystems both at the hardware and software levels. Once again, one semester was allocated for the completion of this step. The following Gantt Chart shows our progression through the second part of the project in the duration of the semester:



○ ***Validation Plan***

The Validation Plan for our 403 semester is as follows:

Test	Detail
Richard	
LEDS	Test if a certain segment lights up
	Test if a number gets displayed with segments
Buck Boost Converter	Test if it is receiving power and turning on
	Test if it is outputting power to on the breadboard
	Test if the buck boost converter can output negative Voltage
	See if it can raise or lower voltage
MCU	Test connection to LED
	Test if a number can be inputted to the LED with binary or decimal
	Test if ADC is can convert the data to digital
	Test if the microcontroller can make readable data
	Test if buttons are able to change gain and time integration
Rigoberto	
Software	Test GUI inputs perform the correct action.
	Test protocol is performing the correct operations.
	Test if software can communicate with MCU and change gain.
	Test if software can communicate with MCU and change integration time.

Test	Detail
	Test if software can receive input measurements
MCU	Test if MCU protocol is performing the correct operations.
	Test if MCU can receive input from software.
	Test if MCU can output measurements to the software.
Hunter	
Transimpedance Amplifier	Test to make sure voltage, scales linearly from light intensity and within expected ranges
	Test to make sure voltages read as expected at maximum and minimum light
Photodiode	Test to make sure photodiode registers expected readings based on controlled light incident to it
	Test to make sure photodiode currents are as expected at maximum and minimum light
Op-Amp Gain Circuits	Test to make sure gain circuits reliably produce gain of 10,100
	Test to make sure gain circuits behave as we expect at maximum light and operate at safe voltage

For the 403 semester, we spent a large amount of time studying the problem of how to convert light into a readable voltage with a transimpedance amplifier design, then how to take the voltage and convert it into a human-understandable 16-bit value with an ADC. We also had to study and find the best way to use a microcontroller to operate the entire system. Next, the Validation Plan for our project for the 404 semester is as follows:

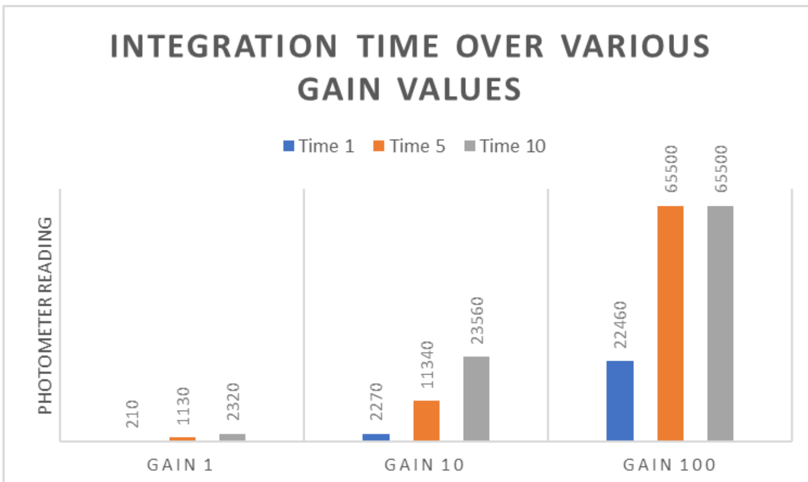
Gain Increse (Hardware)	The gain increases with a button press and the LED corresponding to it turns on	See if the voltage is being sent to different pins based on which pos the button is on	TESTED
Time Integration Increase (Hardware)	The TI increases with a MOM button and the LED corresponding to it turns on	See if the voltage is being sent to different pins based on which pos the button is on	TESTED
Gain Increase (Software)	The photometer gain, on the software side, increases with a button press.	On a terminal, print out gain values to ensure correctness.	TESTED
Time Integration Increase (Software)	The photometer TI, on the software side, increases with a button press.	On a terminal, print out TI values to ensure correctness.	TESTED
Power On/Off	if the power button turns on and off the system	See if the MCU is powered on by seeing if LEDS turn on	TESTED
PCB	To see if the pcb connects all the parts properly	Final testing test for continuity and seeing if everything is working	TESTED
5 digit 7 Segment LED	To see if the output is being shown properly	Input numbers to be displayed from the MCU and see if it displays properly	TESTED
ADC	The output Digital Signal is being read properly	Change the input voltage and see if it matches the step function	TESTED
Photometer Protocol	MCU recognizes customer definded protocol signals	Send signals to the MCU to validate functionality.	TESTED
Housing Design	Design a housing for the device, bearing in mind other subsystems	Decide between prefab and CAD/3D print options	TESTED
Housing Implementation	Implement housing for the system	Create prototype housing based on previous choice	TESTED
Mounting	Secure a TPO M42 10mm female threading to our housing	Adhere TPO M42 10mm female threading to housing	TESTED
Rigidness	Ensure housing materials are fortified and sturdy enough to bear load	Test and verify parameters and hardiness	TESTED
Photometer Input Voltage	The input voltage for the photometer shall be 5V	Use multimeter to validate input voltage levels.	TESTED
Voltage Regulator Input Voltage	The input voltage for the DC to DC converter shal be 4.5V - 5.5V	Use power supply to validate working voltage range.	TESTED
Voltage Regulator Output Voltage	The output voltage of the power supply shall be 5V	Use multimeter to test validate output voltage levels.	TESTED
Input light	Secure light path to photodiode	Ensure photodiode is secure and recieves input	TESTED
Thermal Resistance	The Photometer shall effectively operate in temperatures ranging from 15 F - 120 F	Validate photometer by operating in different temperatures.	TESTED

Here, we shifted gears from studying the various sub-systems, to integrating our sub-systems and miniaturizing our designs from breadboard/perfboard to PCB. We also needed to construct an ideal enclosure that was capable of housing the PCB and spent significant time ensuring the enclosure would be able to support the weight of the device and keep all components secured.

- ## Critical System Data

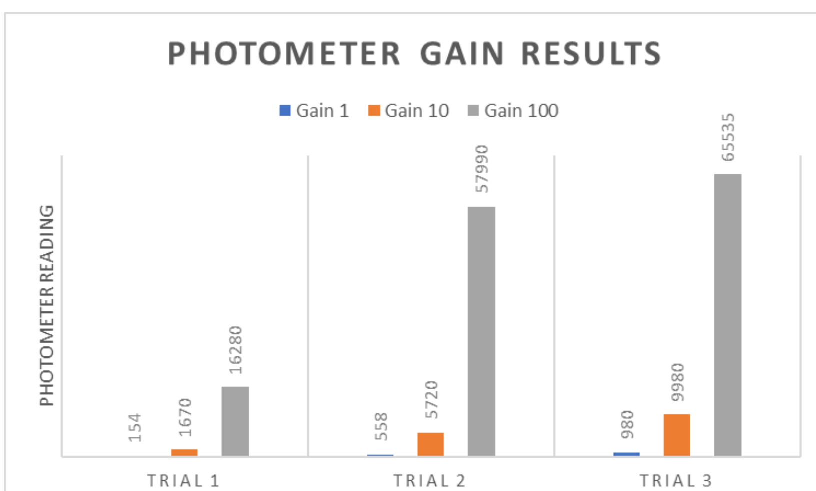
  - ### *Integration Time Data*

Integration Time is a function in the Photometer that allows it to collect readings over a period of time. There are three different time intervals available for selection, one second, five seconds, and ten seconds. For each of these time intervals, the Photometer will collect a data point every one second. At the end of the time interval, the Photometer will display the total value obtained from adding each of the data points sampled.



  - ### *Gain Data*

Gain is a function of the Photometer that allows it to amplify a measurement taken. The available amplification values are one, ten, and one-hundred. These amplifications occur at the hardware level and are done using operational amplifiers. A reading taken with a gain set to ten is equivalent to ten times the same reading taken with a gain set to one. A reading taken with a gain set to one-hundred is equivalent to one-hundred times a reading taken with a gain of one.



○ *Display Data*

The display focused on a 5 digit 7 segment display because the customer, Don, wanted the device to display up to 16 bits of data which is 65535. The way the display receives data from the PIC is through SPI transfer protocol. The main decoder for the data incoming to the display is a MAX 7219. The MAX would run Decode mode which would decode the SPI signal into a readable format for the 5 digit 7 segment display to display

○ *Photodiode Data*

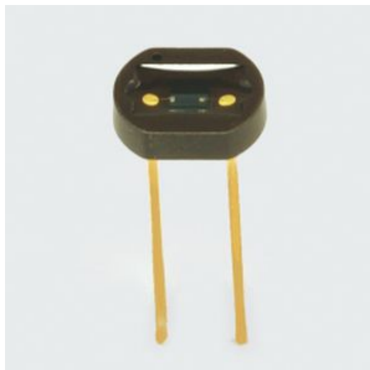


Figure: Hamamatsu S-1087-01 Photodiode

The photodiode our system uses as a piece of critical hardware is the Hamamatsu S-1087-01 photodiode. This photodiode was recommended to us by our customer, Don Carona, as an ideal photodiode for our photometer. It was used in the SSP3 photometer we seek to emulate, and has been used in many astronomy applications and designs since then. The S-1087-01 photodiode is desirable for many reasons, one of them being that it has a very small dark current which means the photodiode allows for high granularity and can precisely detect small instances of light.

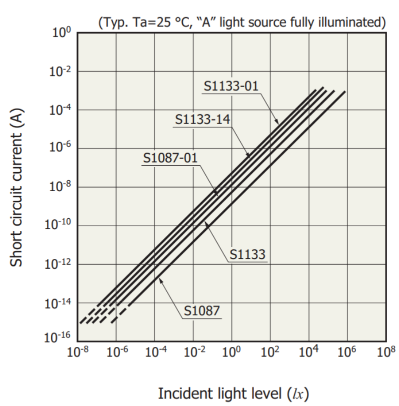


Figure: Short Circuit Current Linearity of S-1087-01 Photodiode

In the figure above, we see a chart plotting the short circuit current of the S-1087-01 photodiode as well as other photodiodes in the same family, showing the current they generate, which scales linearly with incident light as it increases in lux.

○ *Power Data*

The Photometer can operate with voltage inputs in the ranges from 4.5V to 5.5V. The power supply subsystem will then take in the input voltage and convert it into a constant 5.5V and -5.5V. These voltages are propagated throughout the rest of the subsystems to provide a steady source of power. The following graph shows the Power Supply's performance under different input voltage ranges:

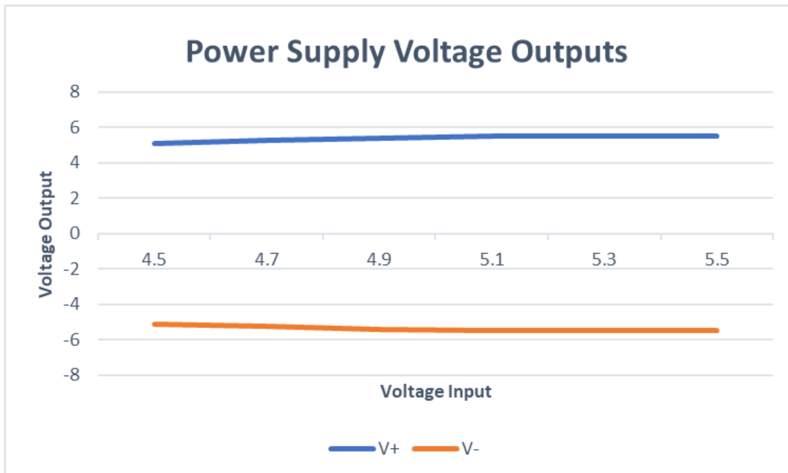


Figure: Power Supply Voltage Outputs

● System Testing

○ *Hardware Testing (Bench)*

After successfully synthesizing all subsystems and placing the PCBs into the enclosure, we began bench testing to ensure our device behaved as expected in preparation for our eventual experiments and measurements at the observatory with real hardware. Below is a graph that shows how our system responds and quantifies the data after a light is being shown at our photodiode with an intensity of 0.4 kilolux at a distance of 10cm.

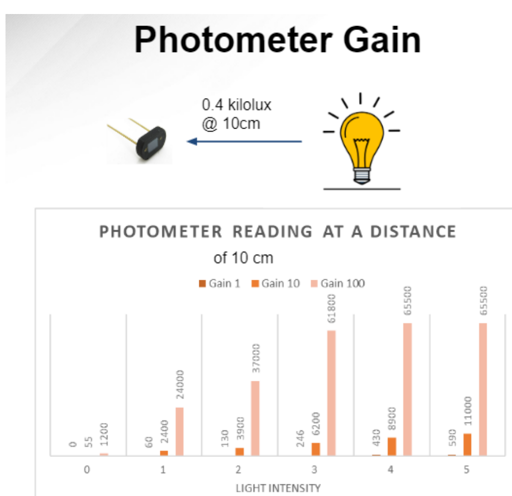


Figure: Photometer measurements with a bright light up close

Below is a graph that shows how our system responds and quantifies the data after a light is being shown at our photodiode with an intensity of 0.16 kilolux at a distance of 20cm.

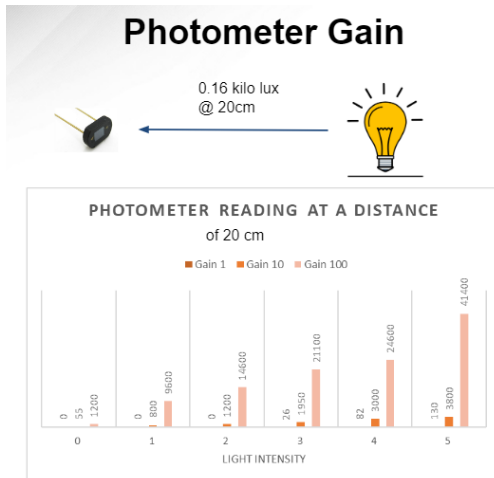


Figure: Photometer measurements with a low light far away

The two graphs above demonstrate that our system behaves in expected ways and we find that with brighter lights, and closer light sources, that we find an increase in voltage readings. Furthermore, we find that our gain circuits operate as intended and properly scale in various lighting conditions.

- ### *Hardware Testing (Experiment)*

After our bench testing, it was time for us to test our hardware in a real application with hardware at the observatory. We successfully attached our photometer and attempted several test cases, observing various celestial bodies.

Figure: Our photometer attached to a 11mm telescope located at A&M's observatory

○ *Hardware Testing (Failure and Iteration)*

After our first trial run at the observatory, we noticed that our gain values were nowhere near as sensitive as they needed to be. With an ambient light source, the SSP3 photometer measured approximately 7000 ADU/sec (ADU being Analog to Digital Conversion Units) at gain 1, while our system read 500 ADU/sec at a gain of 100. (This data was not recorded but was confirmed by our customer, Don Carona via email with Max). We returned to the FEDC and changed our gain resistors to account for this disparity, multiplying all resistances by approximately 1,400. Our resistor values went from 770, 7,770, and 77,000 to approximately 1, 10, and 100 megaohms.

This change created a far more sensitive photometer, but due to the lack of compensation, also introduced a lot of noise to our signal, because we had no circuit components (e.g. capacitors) in place on our PCB to reduce signal noise from the high resistance. Nevertheless, we returned to the observatory and took measurements.

Below is a graph of two different stars measured with our modified design, the stars Deneb and Alderamin were measured with 5 second integration times at gain 10. Deneb is a brighter star, of approximately 1 magnitude more intense than Alderamin. Don explained to us that the exact magnitude we calculate is not important, but rather, the difference in magnitudes is what we should be interested in.

Don supervised our measurement taking and he gave us the following formula to see how accurate our photometer's readings were when it came to measuring two distant stars and their relative brightnesses.

$$m = -2.5 * log(flux)$$

Where m is magnitude and flux is our measured ADU voltage. Following this formula, we found the difference in magnitude between the stars was Deneb being brighter by a difference of 0.15, but not 1. Our photometer therefore was able to show that Deneb was indeed a brighter star than Alderamin, but not by the correct magnitude.

Star name	ADU (5 Sec Integration @ Gain 10	calculated magnitude	difference in magnitude	expected difference
Deneb	6573	-9.54	0.15	~1
Alderamin (Gain 10)	5273	-9.39		
m=-2.5*log(flux)				

Figure: Measurements and calculated magnitude and comparisons

To further demonstrate our system, we took measurements at gain 10 while looking at empty sky, which has an expected low value, and then looked at the moon to demonstrate our system was capable of differentiating the lower light and brighter sources of light

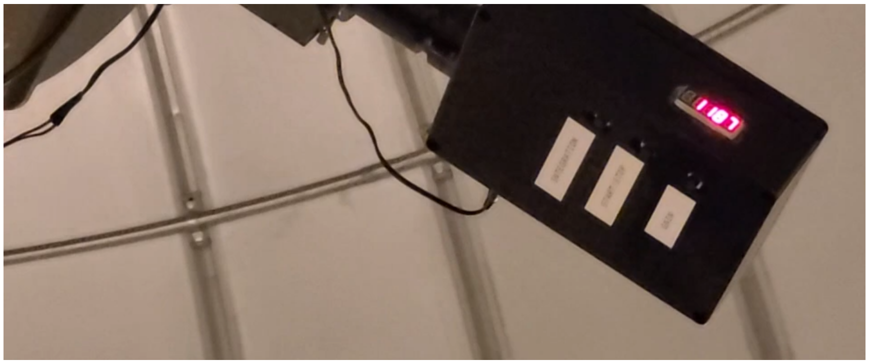


Figure: Our photometer measuring empty sky while attached to 11mm telescope, Gain 10

Figure: Our photometer measuring the moon while attached to 11mm telescope, Gain 10

As we see, we find a reading of 1187 ADU/sec when observing empty sky at gain 10, and 5825 ADU/sec when observing the moon at gain 10. According to our customer Don, the sky reading is a low enough value that we could come to expect. However, although it is true we find ourselves reading a higher ADU/sec when observing the moon compared to empty sky, according to Don, we should have a much, much higher reading– easily capping out at max voltage at 65,000. Which is not behavior we observe.

- ## Conclusion

In conclusion, we find that our design is imperfect, and is still not as sensitive as the SSP3 photometer we attempted to imitate with cheaper hardware. However our system came with some advantages in that it is also safer to operate compared to the original OP-tech design which relies on using high voltage photomultiplier tubes, while our system uses a 5v power supply. While we could measure bright celestial objects such as the moon, we struggled to measure fainter bodies like distant, dim stars. If our issues were fixed, our system would have many advantages over the SSP3 photometer.