Single Mode Autonomous Solar Spectrometry

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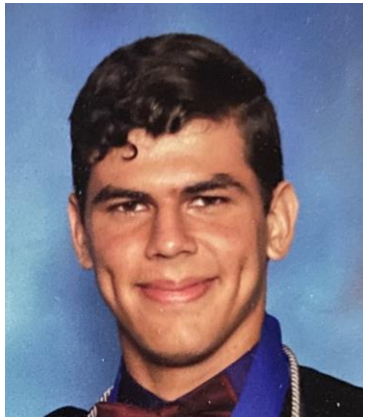

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Motivation

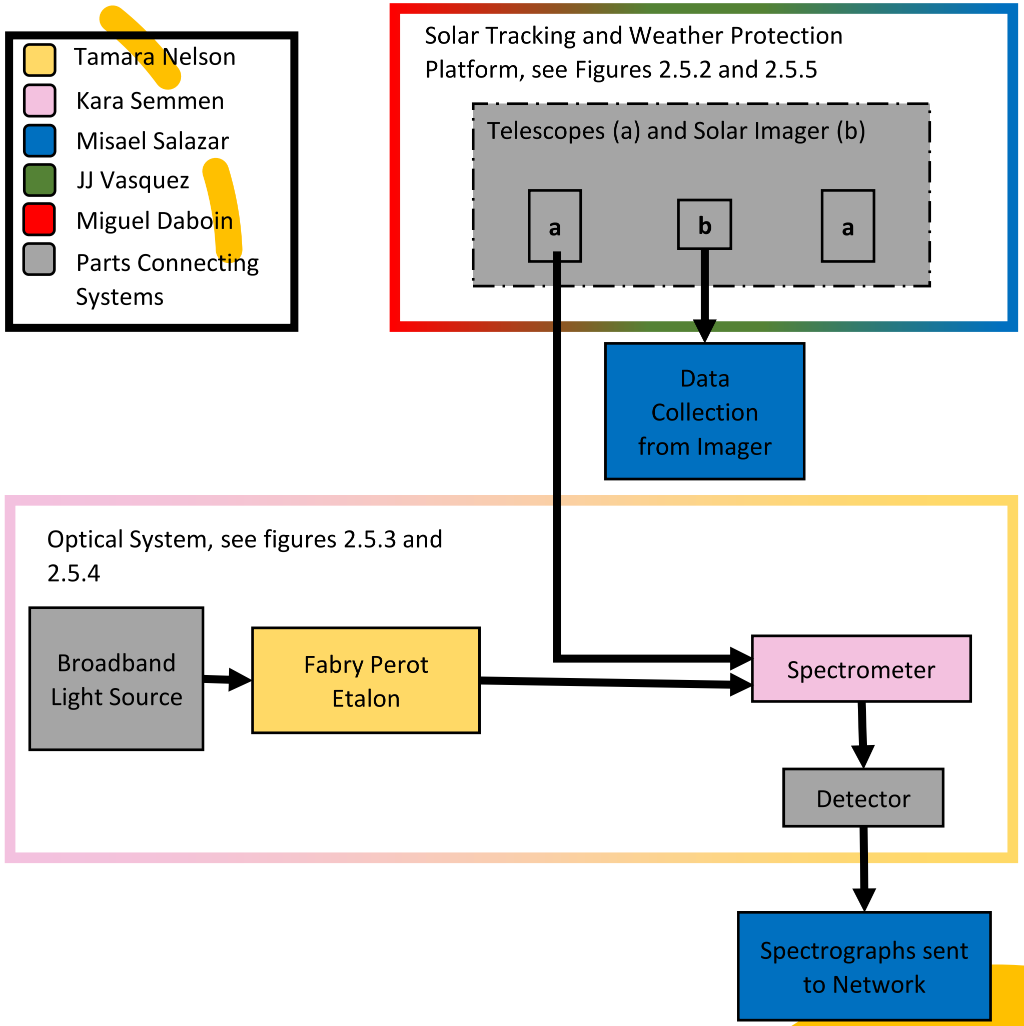
- Observing the sun and measuring redshift is important to studying the universe
  - Studying the sun aids in the discovery of extrasolar planets
- Unpredictable nature of the sun changed the measurements
  - Continuously monitoring and collecting data will account for this
- Spectrometry can be used to analyze the redshift of the sun
  - Most observatories use multimode fibers to observe the sun, but MMF have a lower resolution than single mode fibers
  - A SMF will be used instead to increase resolution
- The spectrograph needs a reference point to be properly analyzed
  - A Fabry-Perot Interferometer with a white light source is a low-cost option

Goals and Objectives

Goals		Objectives
Basic	Tracking of the sun	
	Weather protection of rooftop system	
	Spectrometer to output spectrum of sun	Implement a single mode fiber from telescope to spectrometer
	Spectrometer calibration	Filter broadband, continuum light source through a Fabry-Perot etalon as a parallel spectrometer input to create a comb-like pattern for comparison
	Spectrograph data sends to appropriate network	
Advance	Improve Fabry-Perot stability	Implement a thermostable mounting design with acoustic absorption
		Incorporate cross-dispersion in spectrometer to…
Stretch	Implement a second telescope and fiber connection	TBD

Overall Design

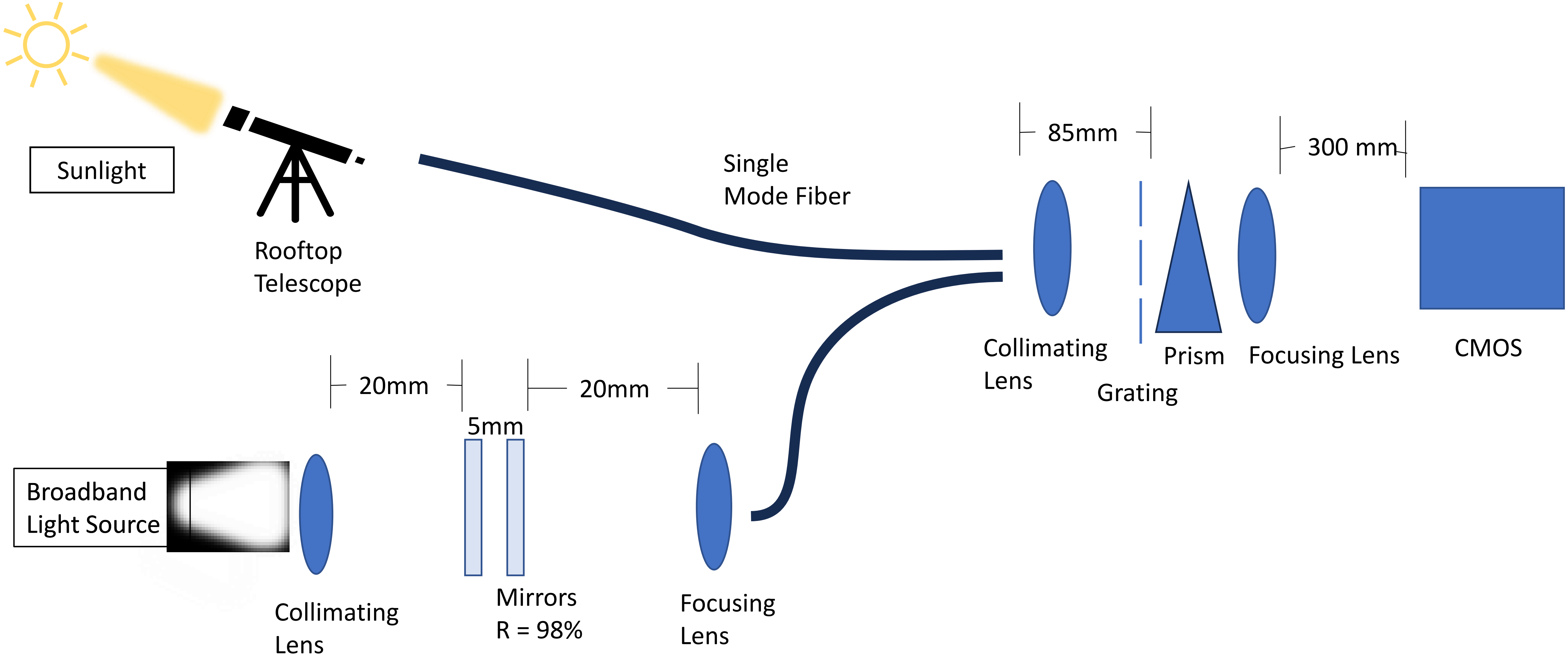
- Here is a diagram depicting the overall plan of the system, depicting how the optical, electrical, and software systems connect. Which also depicts with highligted colors the work distribution among the team.



Engineering Specifications

Description	Specifications
Spectrograph Resolution Element	6e9 Hz
Free Spectral Range of Etalon	18 – 30 GHz
Start-up Time	~1 minute
Weather Resistance	IP66 equivalent
Weather Model Accuracy	> 50%
Power Consumption	< 100W
Image Frequency	10 seconds

Optics: System Schematic

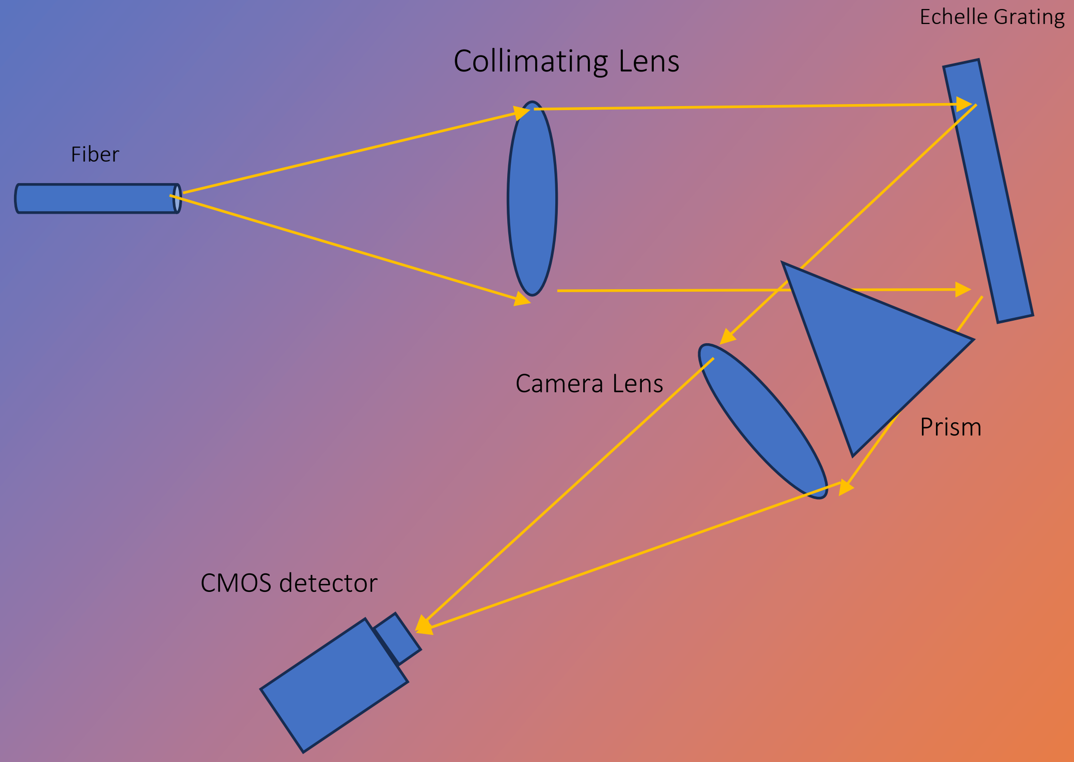


Overall Spectrometer Specs

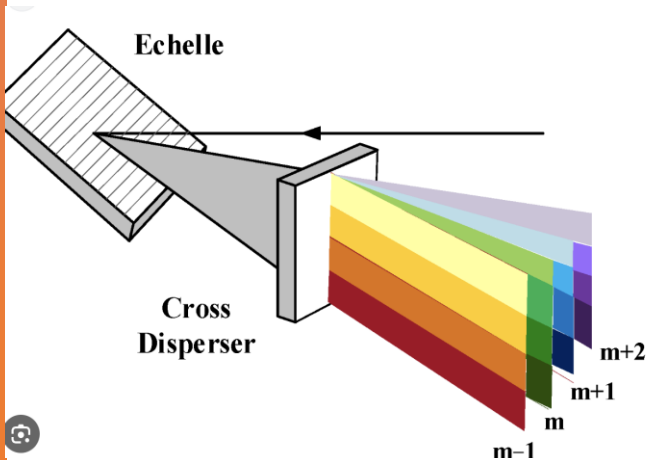
- 3.5x magnification
- Resolving power between 50,000 and 100,000
- Detector minimum 3 pixels across imaged spot
- Bandwidth of 400 nm to 700 nm

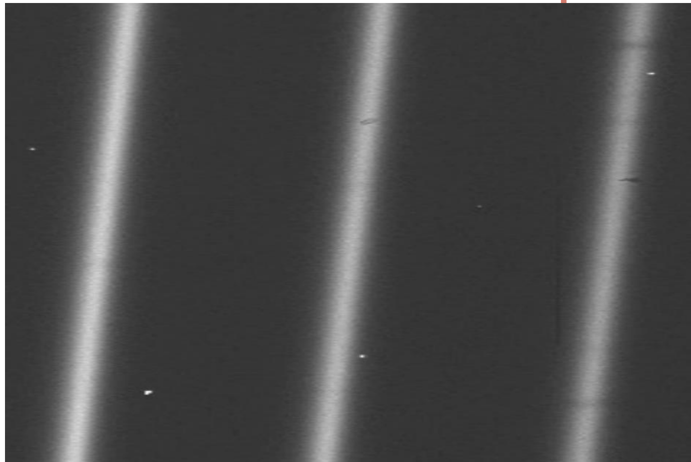
Optics: Spectrometer

Design



- Light is dispersed twice as it passes through the system. First by the grating and then by the prism
- First dispersion will result in a vertical line with a small range of spectrum varying by vertical distance from the center. There are many overlapping lines (diffraction orders) here.
- Second dispersion will spread out the overlapping lines to show a large bandwidth of color.





Optics: Spectrometer
Single Mode Fiber (SMF) Comparison and Selection

Fiber	Operating wavelength	Coating Diameter	Coating Material	Operating temperature (degrees Celsius)	Attenuation	Mode Field Diameter (MFD)	Numerical Aperture
Thorlabs SM400	405-532 nm	245 ± 15 µm	Dual Acrylate	-55 to 85 °C	≤50 dB/km @ 430 nm ≤30 dB/km @ 532 nm	2.4-3.5 µm	0.12-0.14
Newport: F-SAOptical	488-633 nm	245 µm	Dual Acrylate	Not Given	50 dB/km @ 488 nm	2.8-4.1 µm	0.1-0.14
Thorlabs SM600	633-780 nm	245 ± 15 µm	Dual Acrylate	-55 to 85 °C	≤15 dB/km	3.6 – 5.3 µm	0.1-0.14

Optics: Spectrometer

SMF Selection

Thorlabs SMF 400

- Chosen for smallest fiber core size (mode field diameter in table), to achieve high resolution.
- Also chosen for bandwidth. Designed for 532 nm, which is the peak wavelength we seek to measure in this system.
- Peak wavelength transmittance of 400-532 nm, MFD of 3µm, designed to operate at temperatures ranging from -55 to 85 degrees Celsius.

Optical Grating Specs

- Must be made for the visible to near infrared wavelength range (400 to 900 nm)
- Must have a pitch which allows for high resolving power (50,000 to 100,000)
- Bandwidth must fit on detector (roughly 35 mm across).
- Size must be large enough for incident beam to fit on grating
- The desire for large bandwidth with significantly high resolution leads us to solely compare echelle gratings whose blazed grooves are designed to maximize intensity of the higher diffraction orders (higher diffraction order provides spectral higher resolution).

Optics: Spectrometer

Grating Comparison and Selection

Grating	Groove density	Dimensions	Blaze angle	Price
Echelle ruled reflective grating	31.6 grooves/mm	50x25 mm	63.9 degrees	$284
Echelle ruled reflective grating	79 grooves/mm	50x25 mm	63 degrees	$284
Echelle ruled reflective grating	79 grooves/mm	50x25 mm	74 degrees	$284
Echelle ruled reflective grating	316 grooves/mm	50x25 mm	63 degrees	$284

- Higher blaze angles result in a spectrum too large for detector
- 63.9 degree blaze angle sacrifices some resolving power but produces higher diffraction efficiency
- Reflective grating allows for a more compact design

Collimating and Camera Optics Specs

- The ratio of the camera lens focal length to the collimator focal length must be equal to the desired magnification, 3.5x
- Size of lens must be large enough to capture beam. This is only a concern for the camera lens, as it will be collecting dispersed light
- Lenses must have antireflective coating
- Lenses must be achromatic to diminish chromatic aberrations

Lenses Comparison and Selection

Lenses	EFL	CA	Diameter	Price	Part number	Wavelength
Collimating	88.9 mm	24.4 mm	25.4 mm	$114	#49-795	400-1000 nm
Collimating	85mm	24 mm	25 mm	$114	#49-359	400-1000 nm
Camera	300 mm	73.5 mm	75 mm	$341	#88-597	400-1000 nm
Camera	300 mm	49 mm	50 mm	$187	#49-394	400-100 nm

Prism

- Prism added to system to design a cross-dispersive spectrometer
- This will disperse overlapping orders to increase bandwidth range of device.
- No prism comparison necessary
- Edmund Optics equilateral prism used for this design
- F2 glass

Detector Specs

- The research group that funded this project already had a suitable detector in inventory. This saves money for the research group.
- Must detect light in the visible to near infrared wavelength range
- High Quantum efficiency
- Low read noise

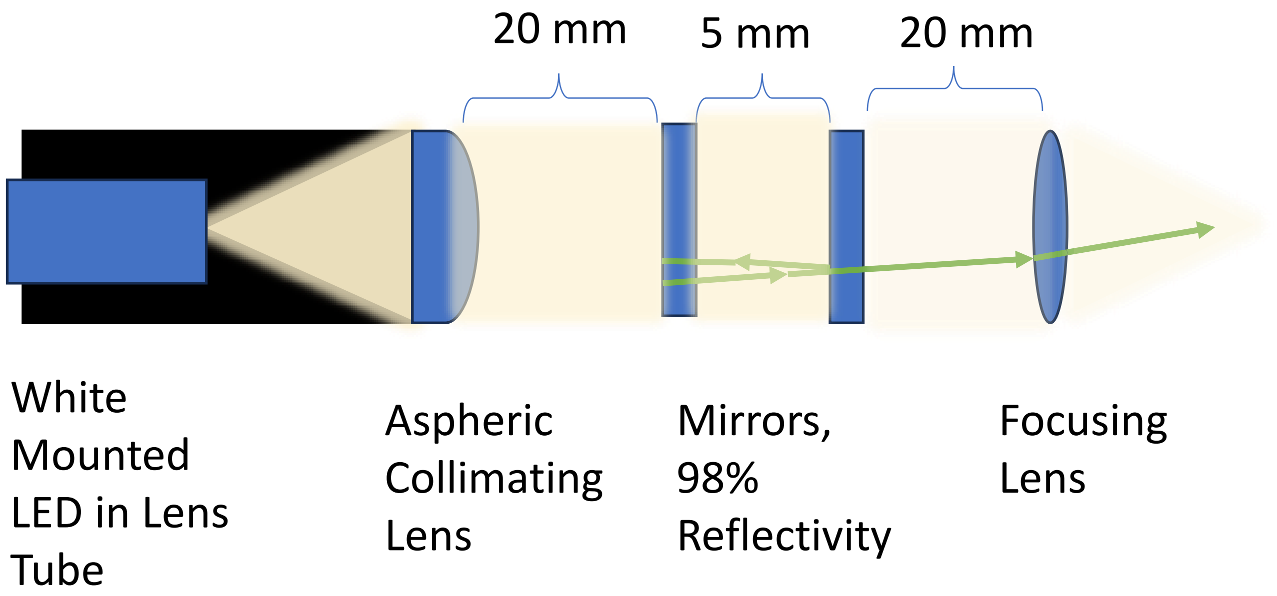
Detector	Pixel size	Detector size	Read noise	Frame rate	Price
ATIK APX60 CMOS detector	3.76 µm	36 mm x 24 mm	1.2 e-	2 fps	Won't cost the research group extra

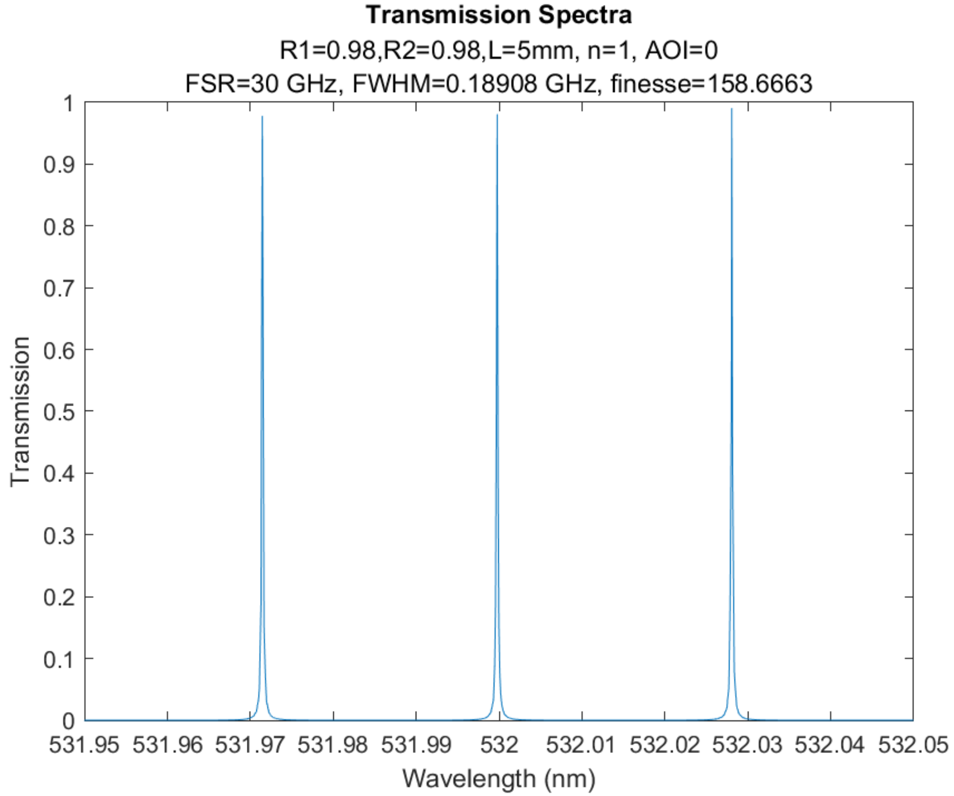
Fabry-Perot Etalon: Technology Comparison and Selection

	Frequency Comb	Hollow Cathode Lamp	Broadband Fabry-Perot Etalon
Precision and Stability	< 5 cm/s Potential for atomic clock stabilization	< 1 m/s	Dispersion shifts Sensitive to temperature and environment
Price, Availability, and Development	Expensive	Relatively Inexpensive Readily available	Inexpensive Easier development to match most spectrograph specifications since the FSR is a function of the cavity width
Spectral Range	Visible-Infrared	Visible-Infrared	Visible
Spectral Lines	Densely packed (spectrographs resolving power not high enough) More narrow wavelength coverage than spectrograph	Narrow lines Limited number of reference lines Irregular line distribution Undesirable spectral features from impurities Blending	Dense grid with uniform intensity over entire spectral range

Fabry-Perot Etalon Design

	FSR (GHz)	FWHM (GHz)	Finesse	Reflectance	Cavity Length (mm)	Wavelength Range (nm)
Goals	18 - 30	< 0.6 - 3	>25-50	86%-95%	5 - 8 mm	400 - 700
Actual	18.75 - 30	0.12 - 0.19	160	98%-99%	5 - 8 mm	400 – 750





Fabry-Perot Etalon: Part Comparison and Selection

Mirrors:

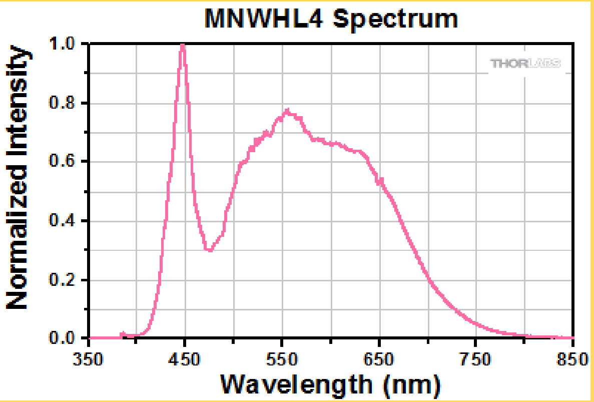
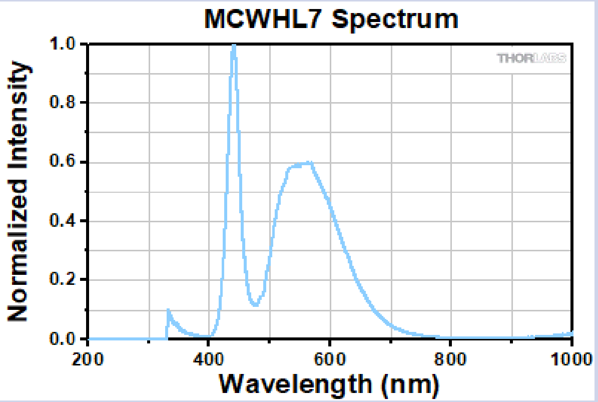
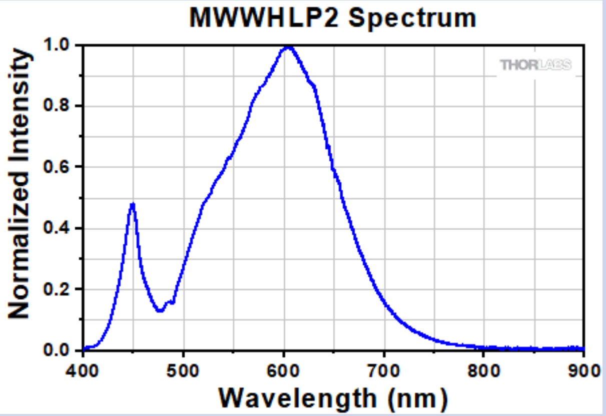
- Back Polished Surface, Front surface partially reflective
- Zerodur – low thermal expansion

	Identifier	Reflectance	Cavity Length (mm)	FSR (GHz)	FWHM (GHz)	Finesse	Notes
Thorlabs	BB1-E02P	99% @ 400-750 nm	5	30	0.095	315.738	Good range, FSR = goal Finesse >> goal, FWHM << goal,
	PF10-03-P01P	97% @ 450 nm – 2 µ	5	30	0.282	106	Slightly limited visible range, FWHM< goal Finesse>goal
***Edmund Optics**	24-029	98%-99% @400 - 750 nm	5	30	0.19	158	Middle ground between the Thorlabs options, Zerodur

Fabry-Perot Etalon: Part Comparison and Selection

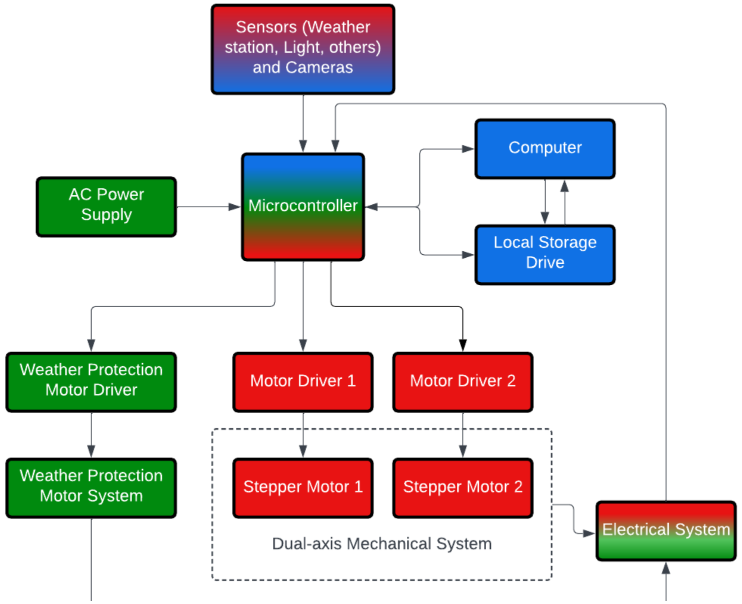
Broadband Source Selection: 4900 K, 740 mW Mounted LED

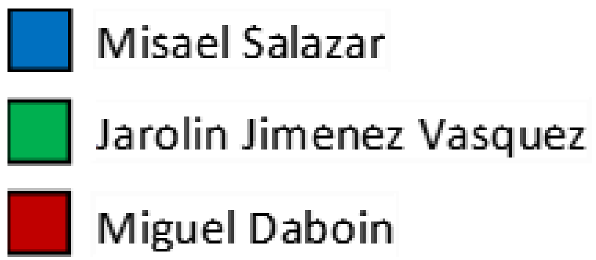
Collimation Lens Selection: Aspheric Condenser Lens, 1” 350-700 nm AR coating

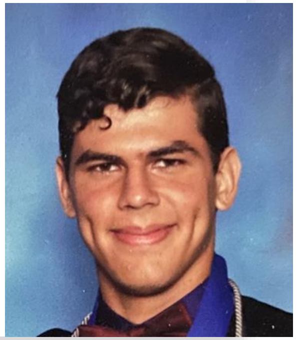
	MNWHL4	MCWHL7	MWWHLP2
Output Power (mW)	740	930	1713
Color Temperature (K)	4900 (Neutral White)	6500 (Cold White)	3000 (Warm white)
Spectrum			

Hardware Block Diagram

- Here we are depicting the way we are planning to implement the hardware of our system. With color coded work distribution, we are depicting each component that will be integrated into our system and who is responsible for it.

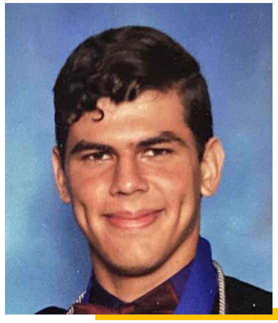






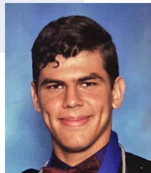
Microcontroller Requirements

- Our observatory needs a computer capable of handling multiple tasks concurrently
- We need to be able to connect to our weather station, solar camera, light sensor, and motors
- The computer will receive and transmit the data collected from its sensors



Microcontroller Comparison

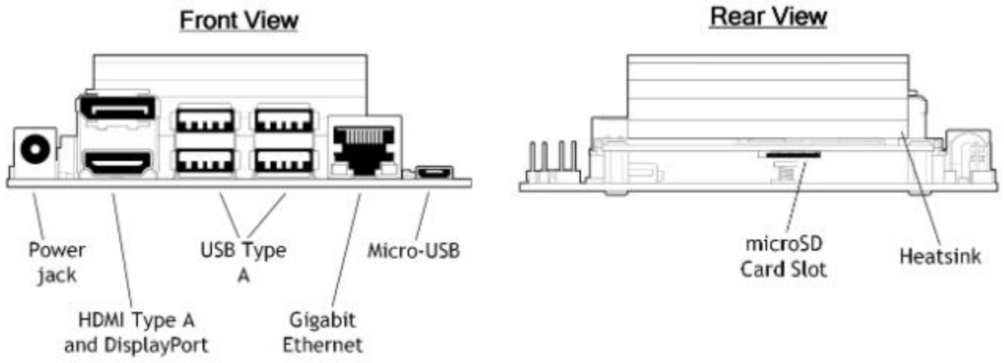
	Jetson Orin Nano series		Raspberry Pi		
	Jetson Orin Nano Developer Kit	Jetson Orin Nano 8GB	Raspberry Pi 4 Model B	Raspberry Pi Zero	Raspberry Pi Pico
CPU	6-core Arm® Cortex®-A78AE v8.2 64-bit CPU 1.5 GHz		Broadcom BCM2711, Quad core Cortex-A72 (ARM v8) 64-bit SoC 1.8 GHz	single-core CPU 1 GHz	Dual-core Arm Cortex-M0+ processor 133 MHz
Memory	8GB 128-bit LPDDR5		8GB LPDDR4-3200 SDRAM	512 MB RAM	264kB on-chip SRAM
USB*	USB Type-A Connector: 4x USB 3.2 Gen2, USB Type-C Connector for UFP	3x USB 3.2 Gen2 (10 Gbps), 3x USB 2.0	2x USB 3.0, 2x USB 2.0	micro USB On-The-Go (OTG)	1x USB 1.1
Display	1x DisplayPort 1.2 (+MST) connector	1x 4K30 multi-mode DP 1.2 (+MST)/eDP 1.4/HDMI 1.4**	2x micro-HDMI	Mini HDMI	
Other I/O	40-Pin Expansion Header(UART, SPI, I2S, I2C, GPIO),	3x UART,	40-pin header	40-pin header	26 GPIO pins,
	12-pin button header,	2x SPI,			3 Analog inputs,
	4-pin fan header,	2x I2S,			2 UART,
	microSD Slot,	4x I2C,			2 SPI,
	DC power jack	1x CAN,			2 I2C,
		DMIC & DSPK,			16 PWM
		PWM,			
		GPIOs			
Power	7W - 15W	7W - 15W	15 W		
Mechanical	100 mm x 79 mmx 21 mm	69.6mm x 45mm	56.5mm x 85.6mm	65mm x 30mm	51mm x 21mm
	(Height includes feet, carrier board, module)	260-pin SO-DIMM connector			

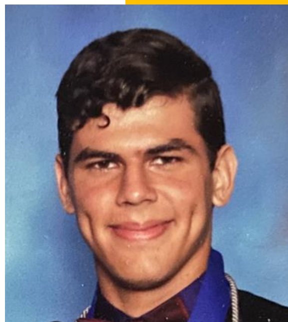


Microcontroller Selection

- Our team decided to go with the NVIDIA Jetson Nano development kit as the main computer for our project. The Jetson Nano offers great computing power, a comprehensive software development environment and a large community of developers.

- The Jetson will perform the computations necessary to track the sun, capture images, and predict incoming weather to protect the observatory platform.





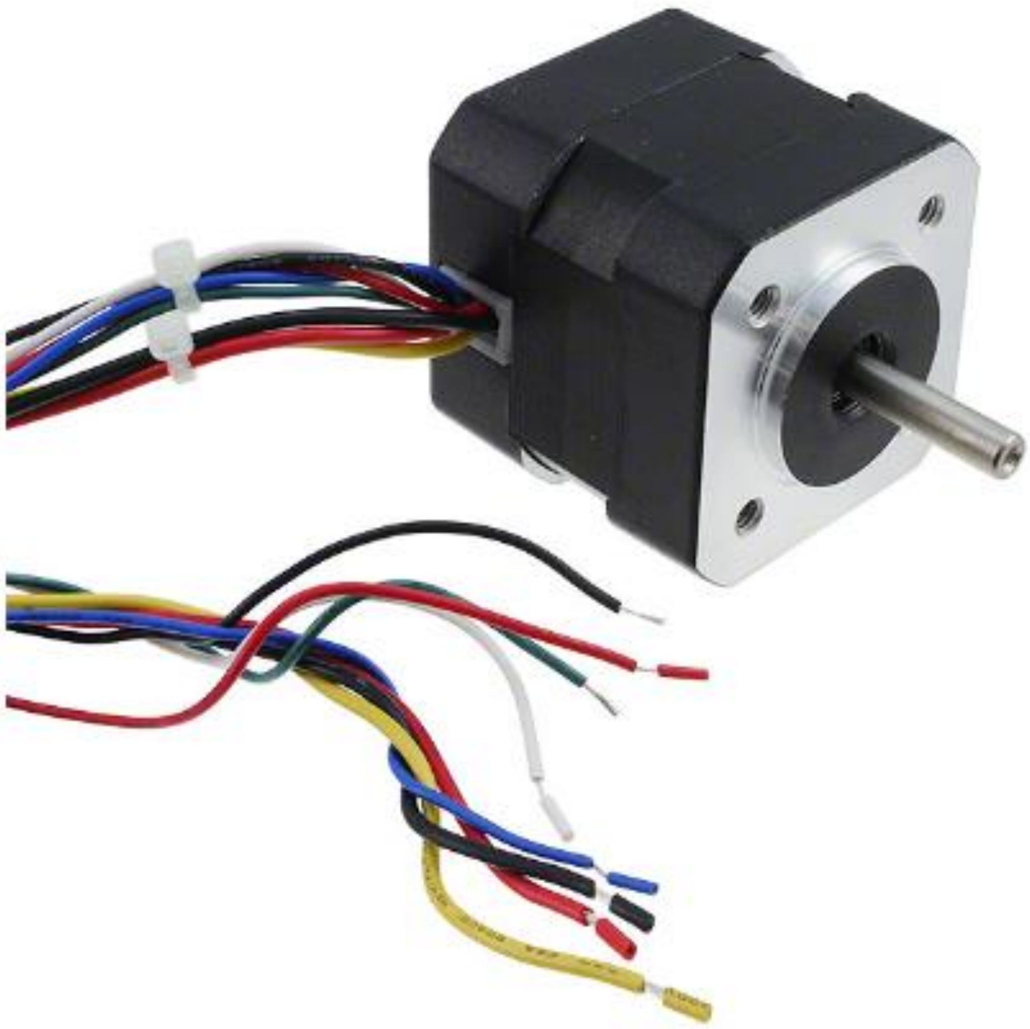
Motor Comparison and Selection

- After doing all the necessary research to pick the right motor for the attachment of the weather machine that will be in our system, we concluded that the best choice for this would be the DC brushless servo motor. Which will give us longer lifetime and a high efficiency, with meeting the requirement of at least 24 V rating. Which will help us get the torque necessary to close the lid of our system for weather protection.

Comparisons	Trinamic Motion Control Gmbh	AC, DC & Servo Motors Brushless DC Motor
Torque rating (oz-in/mNm)	8.85/62.58	46.73 minimal
Power rated rated (W)	26.2	700
Efficiency (%)	85	95
Voltage rating (VDC)	24	160
Price range	$90.00	$306.15
Weight (lbs)	0.662	4.771

Motor Specifications

- Trinamic Motion Control Gmbh
- Standard Motor 4000 RPM 24V
- Part number QBL4208-41-04-006
- DC brushless motor (BLDC)
- Voltage rated 24VDC
- Torque rated (oz-in/mNm) 8.85/62.5
- Power rated 26.2 W
- Weights 0.662 lb

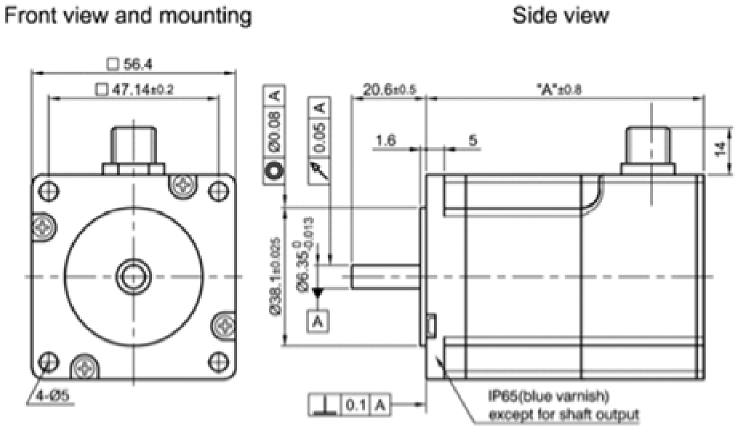


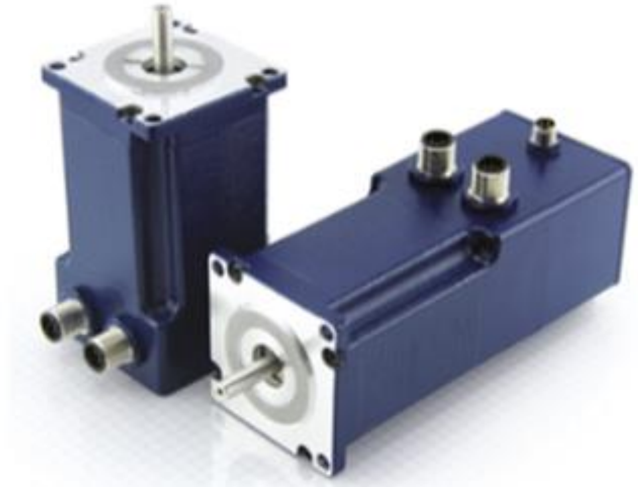
Stepper Motors for Dual-axis tracker

Technical Data	Value
Size	2.2 in
IP-Protection Motor (Except Shaft Output)	IP65
Holding Torque	264.81 oz-in
Inductance per Winding	1.9 mH
Length "A"	3.9 in
NEMA	23
Current per Winding	4.2 A
Resistance per Winding	0.58 Ohm
Rotor Inertia	480 gcm²
Weight	2.3 lb

Table 7.4.1.1: Hybrid Stepper Motor 24-48VDC IP65

- 5V 4.2A each. These stepper motors will be responsible to point out the main platform with telescopes and camera to the sun while the system is operating (dual axis tracker)





Weather Station Requirements

- To get the best predictions possible, we need a weather station capable of measuring:
    - Barometric Pressure
    - Ambient Temperature
    - Humidity
    - Wind speed and wind direction
    - Rainfall
    - Solar radiation

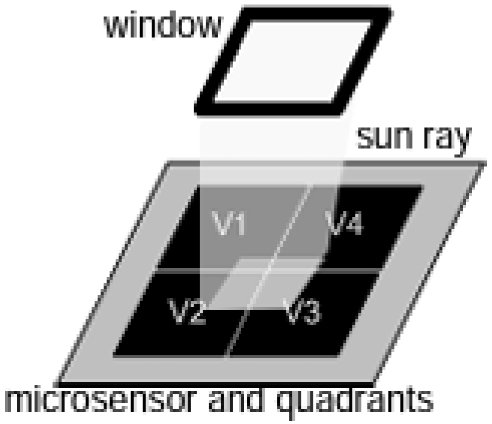
Weather Station Selection

Brand	Product model	Sensors	Features	Price
Ambient Weather	WS-2000	Anemometer, rainfall, UV, solar radiation, barometric pressure, temperature, humidity, dew point, wind chill	LCD display tablet, Water/dust resistant, Wi-Fi, 5V DC adaptor, Power Consumption 0.5W and 1.25W during Wi-Fi config mode	$299.99
AcuRite	Atlas 01108M	Anemometer, rainfall, UV, Light intensity, barometric pressure (from the screen), temperature, humidity, Lightning detection	Non-WiFi HD Display, 5V power adapter, battery option for backup, lightning detection 1 to 25 miles, Water/dust resistant	$218.16
Davis Instruments	SKU 6357	Anemometer, Rain detection, temperature, humidity,	Solar-powered with lithium battery backup, extreme testing, corrosion protected, UV protected	$350
Oregon Scientific	WMR89A	Anemometer, rainfall, optional UV, humidity, barometric pressure, heat index, dew point, wind chill	Water/dust resistant, LCD screen, long-range transmission 330ft., AC adapter and battery for backup	$199.99

- After a deep research on weather stations with the required capabilities for data acquisition and weather protection system, we selected the Ambient Weather WS-2000 due to its reliability and weather resistance.

Solar MEMS Device

- The Solar MEMS device measures the incidence angle of a sun ray in both azimuth and elevation based on a quadrant photodetector device. The sunlight is guided to the detector through a window above the sensor. Dependent of the angle of incidence, the sunlight induces photocurrents in the four quadrants of the detector.



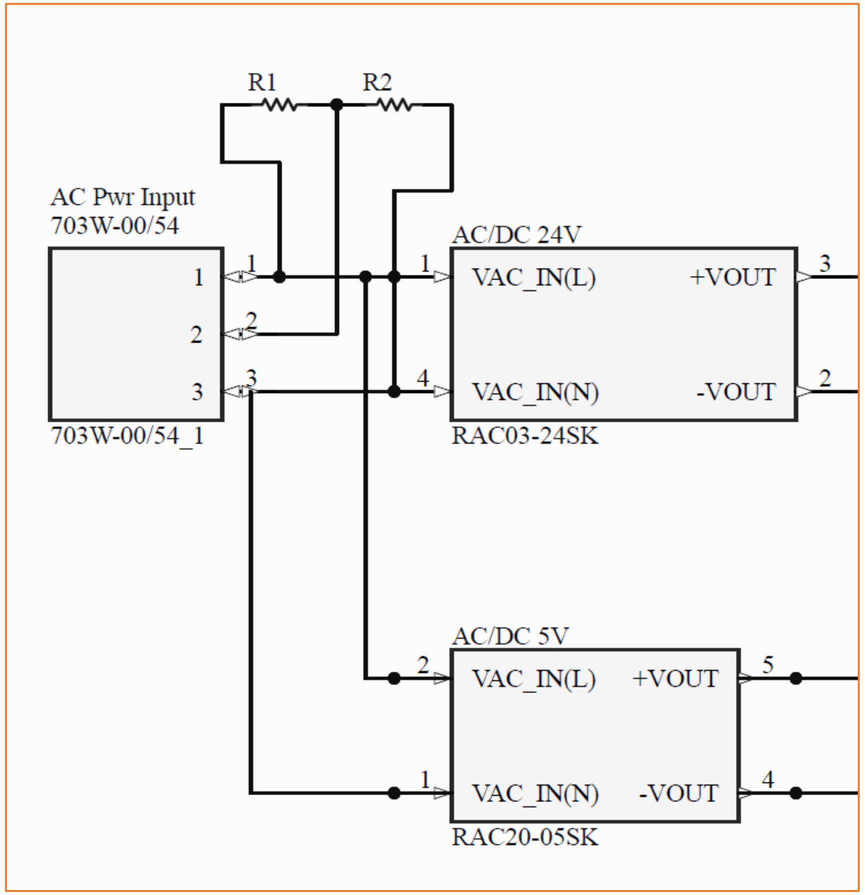
Power Distribution

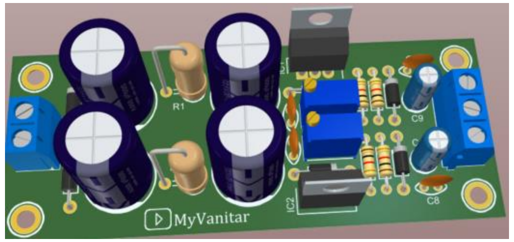
Component	Voltage Requirement	Current Requirement
MCU Nvidia Jetson	5 VDC	2 A – 4 A
Stepper Motors	5 VDC	4.2 A
Servo Motor	24VDC	1.79 A
Camera	5 VDC	500 mA
Solar MEMS	5 VDC	33 mA
Totals	**5 – 24 VDC**	**10.08 – 12.08 A**

- One of the main challenges we faced is figuring out how to distribute power across the many components.
- Based on these requirements we comply with one of the design requirements to have a <100W electrical system.

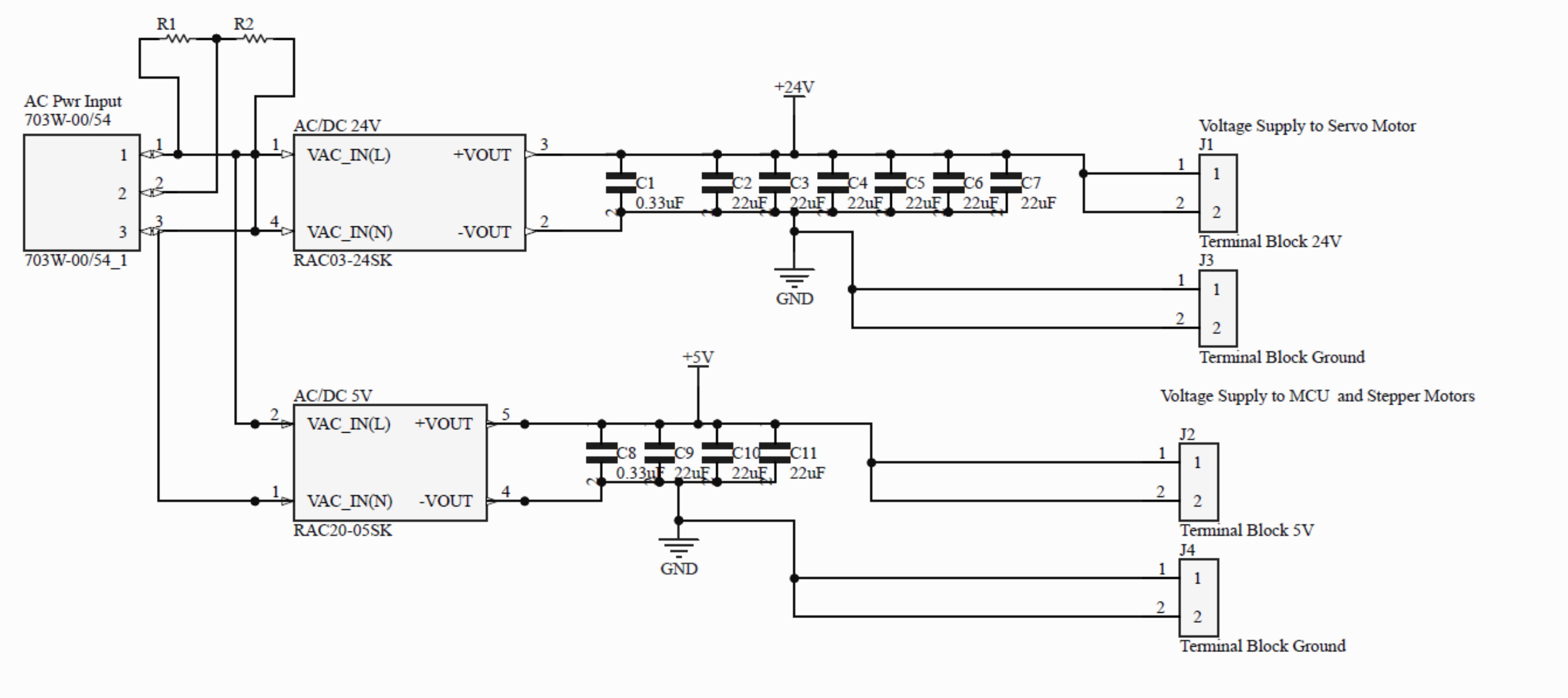
Voltage Regulators

- There are two voltages that are needed to supply our system. We are supplying 5V to the Stepper Motors and the Jetson Orin Nano Developer Kit (MCU). At the same time, our Solar MEMS device and the Camera will be connected directly to the MCU. On the other hand, 24V is required for our Servo Motor that will be in charge on opening and closing the weather protection case that will protect our core devices.

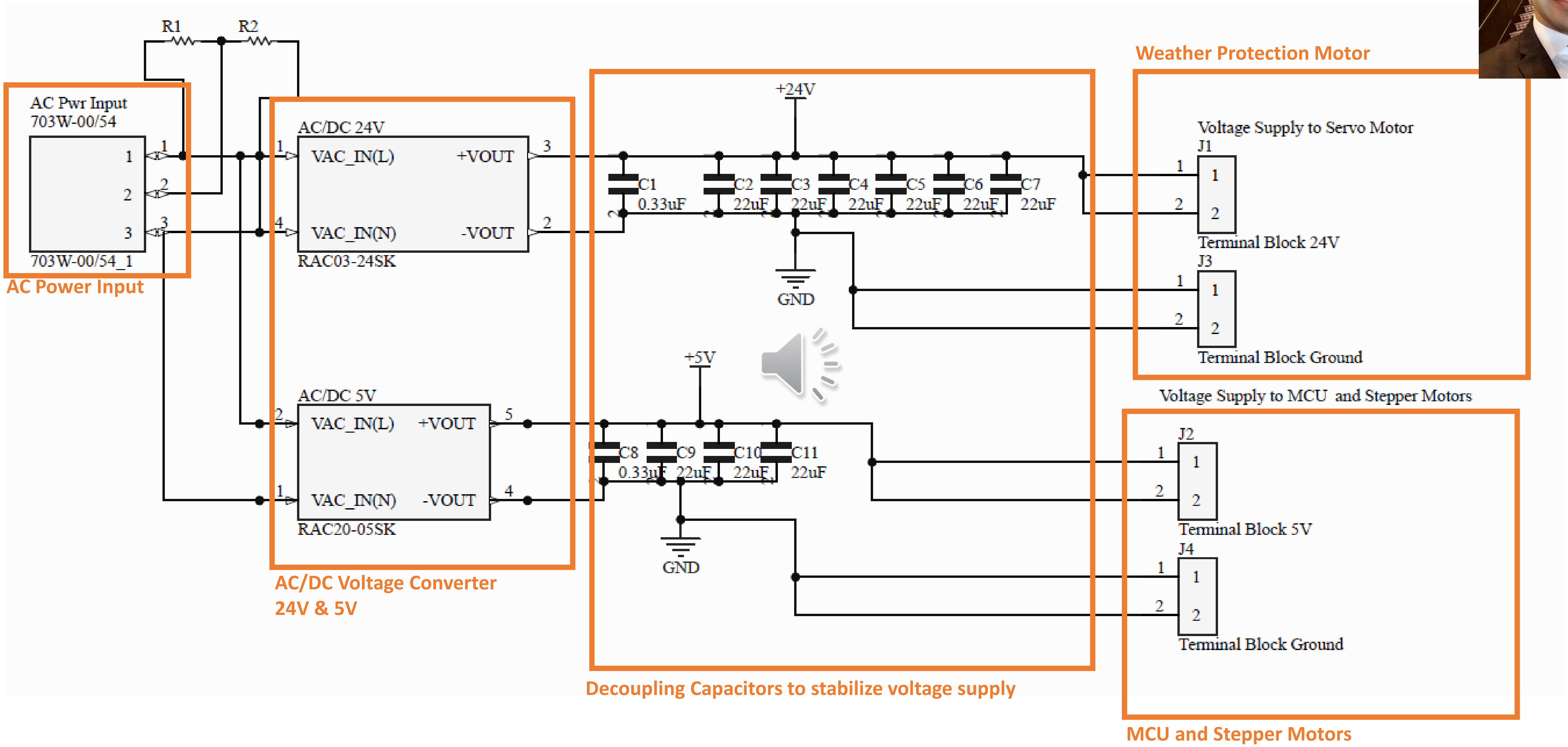




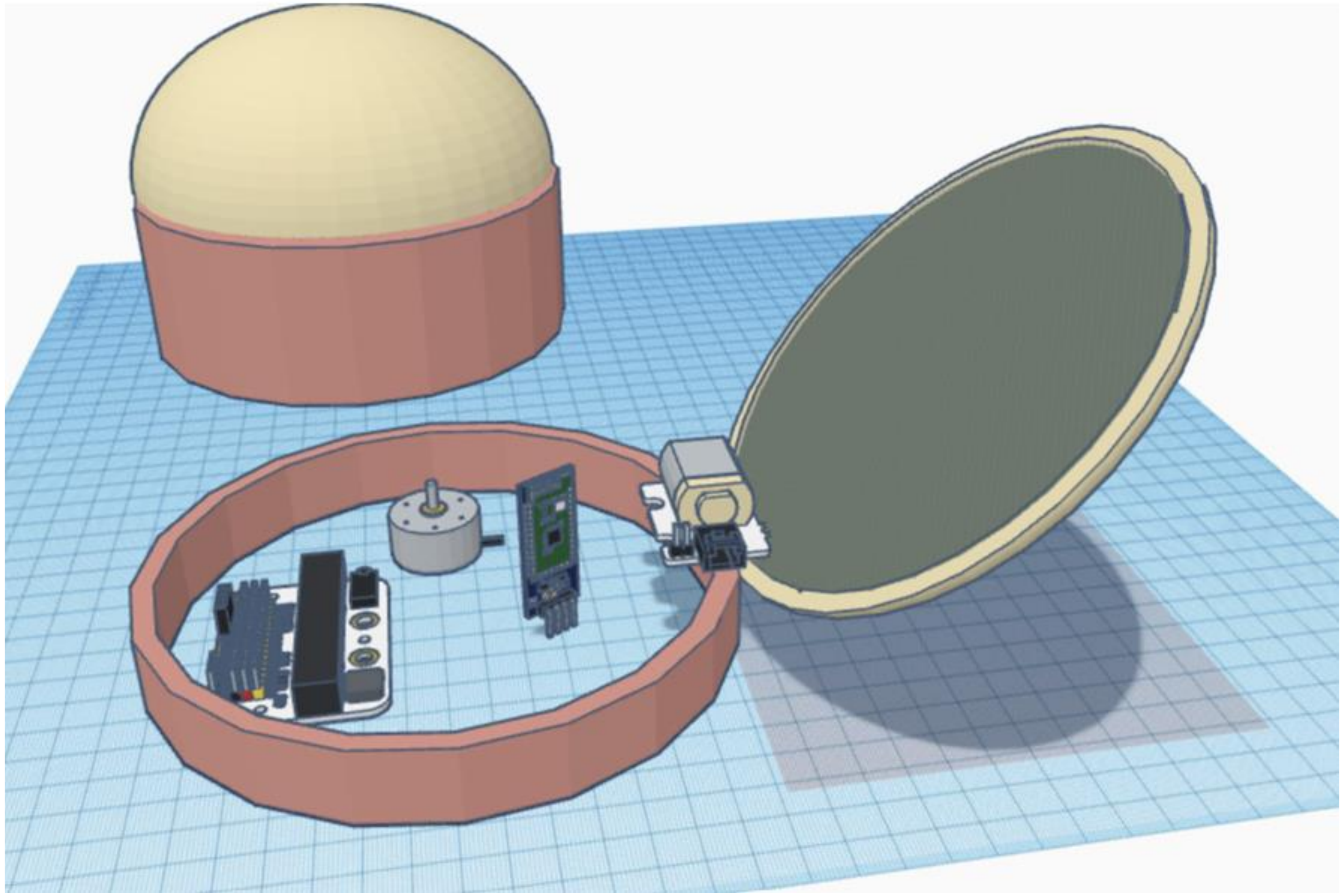
PCB Schematic



PCB Schematic

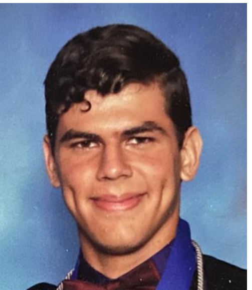


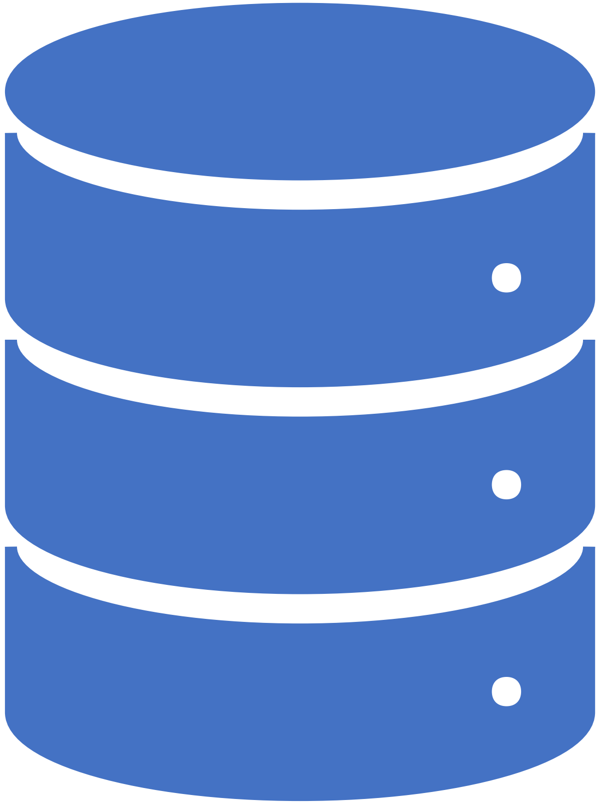
Structural (Mechanical) Design



- For our weather protection system design, we decided to go with a cylindrical dome that will as of right now be made of Plexi glass, since it was one of the material types that we founded to be durable, not too heavy so that we can stay withing the weight specifications that we need to meet and water resistant. Inside all the main components: the Servo motor that will be for closing and opening of the dome, the MCU that will be taking care of the telling the components what to do, the stepper motor that will be taken care of the platform, and solar spectrometry equipment.

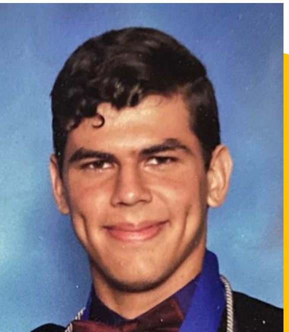
Software Diagram





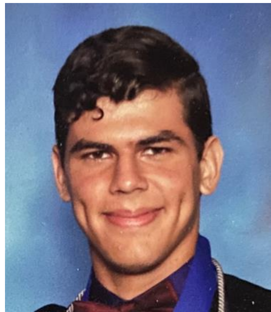
Software Requirements

- Our software needs to be able to do a variety of things
- We need to use a model to predict incoming rainfall
- We need to capture images from our solar imager
- We need to move the motors to open and close the observatory
- We need to move the motors to be able to track the sun



Software Tools

- The main software for our observatory was written in Python.
- We used the PyCharm IDE to write the Python programs.
- Progress was saved using GIT as our VCS.
- We set up an SSH client to allow remote access of the observatory's computer.



Administrative Content

- Budget
  - Base on what our sponsor suggested and the parts that has been ordered we can end up with a range expenditure of 10k-20k.
- Work distribution
  - From the CREOL department Kara and Tamara are the ones responsible for the Fabric-Perot and Spectrometer aspect of the project.
  - For the electrical, power and sensor part of the project Miguel and Jarolin are the ones responsible.
  - For the data collection, the MCU and software Misael is the one responsible for this part of our project.

Name	Primary	Secondary
Misael Salazar	Software, MCU	Hardware
Kara Semmen	Spectrometer	Fabry-Perot
Tamara Nelson	Fabry-Perot	Spectrometer
Miguel Daboin	LDR & Sun light sensor, Stepper Motors, Weather Station	Power Supply, WPS Motor, MCU, Camera
Jarolin Jimenez	WPS Motor, Power Supply	Hardware, MCU