# Astronomical Polarimeter and Pulse Timer

Summer/Fall 2024 Group 3

# Introductions

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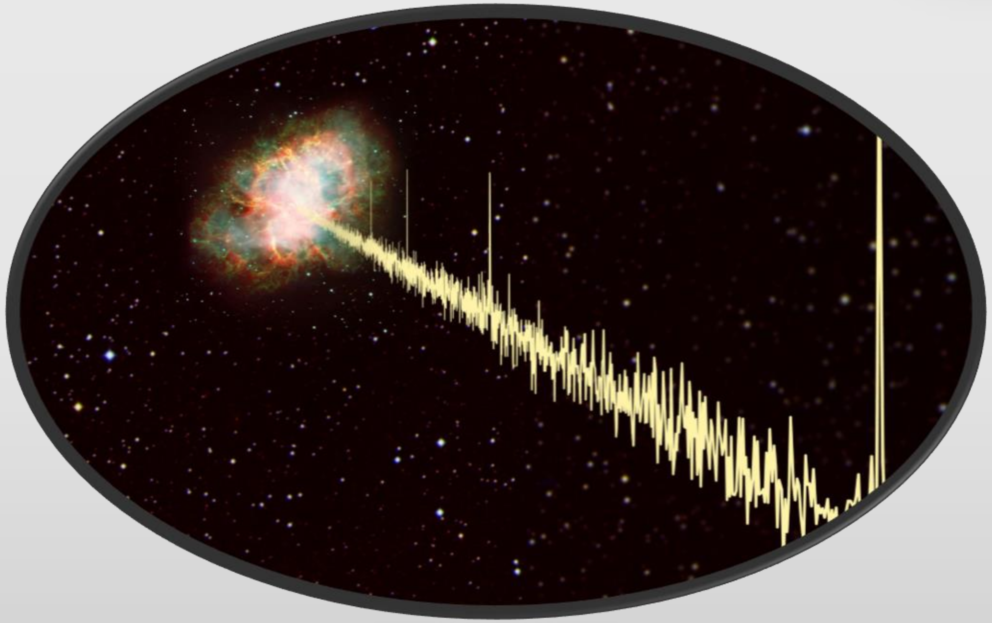
# Project Context and Scope

- Pulsars are spinning, which changes the intensity of the emitted radiation periodically with time.
- Most are in non-visible spectrums, but some – most notably the Crab pulsar – pulse in the visible spectrum
- Their pulsing behavior remains a mystery, but by measuring the polarization, astronomers may be able to learn more about them. Primarily using the data to understand the magnetic and gravitational field dynamics.

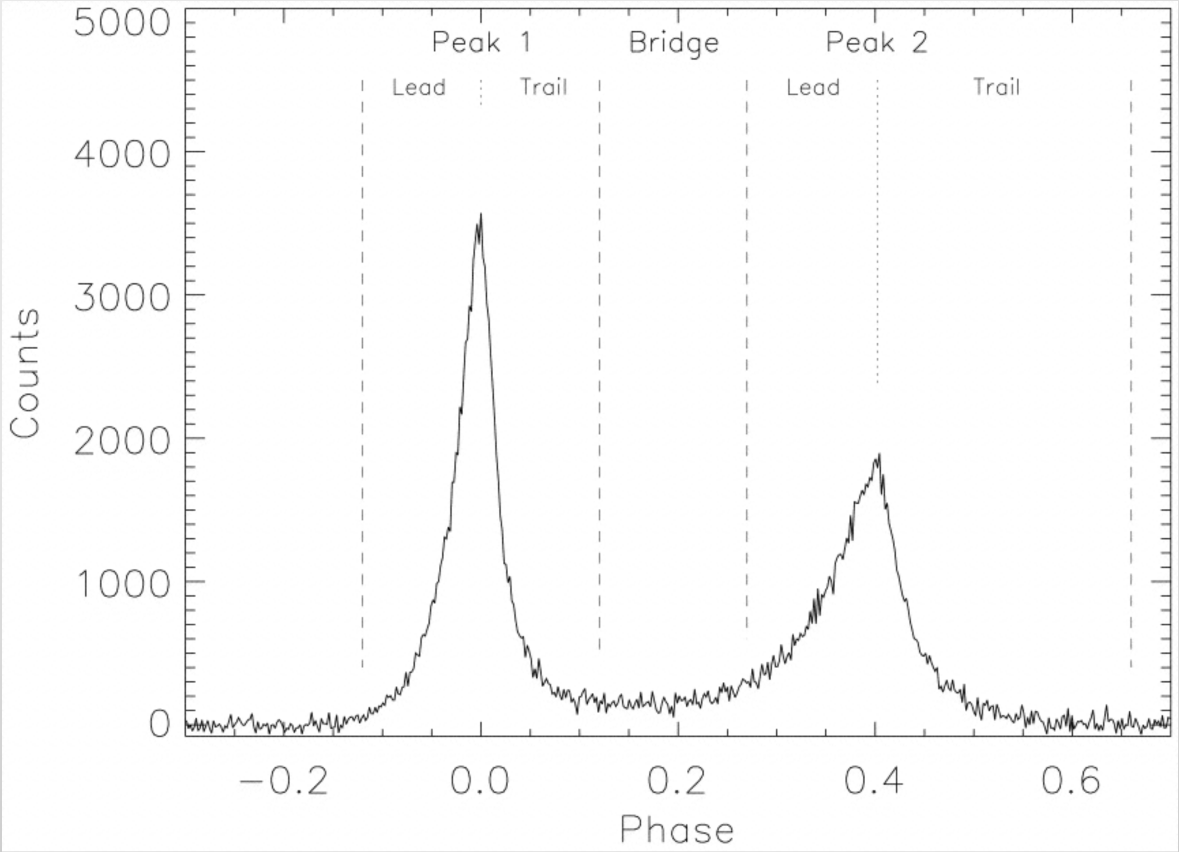


# Motivation

- The Crab Pulsar, located 7,000 light years away, provides a unique opportunity to study extreme space conditions.
- Measuring its polarization and pulse timing helps us understand its magnetic fields and rotation.
- Unlike most pulsars, it emits visible light, making optical polarimetry essential.
- Our project will capture and analyze this light, contributing to future discoveries about pulsars.

# The Crab Pulsar

- Located in the Crab Nebula
- The brightest optical pulsar (m = 16.5), but dimmer than most regular stars
- Two distinct peaks per pulse period, and each pulse is approximately 33ms.




*Crab Pulsar Pulse Profile*

# Our Goal

1. Design a telescope mountable stokes polarimeter that can sample photodetectors at a 1 MSPS.
2. Design a dual imaging system for tracking the star and imaging the pupil for alignment.
3. Design a software package which computes polarization and pulse timing.

# Objectives

- For goal 1 (polarimeter):
  - Reduce measurement errors through pupil imaging
  - Split light into distinct polarization components
  - Correct error in polarization measurements due to instrumental effects
- For goal 2 (dual imaging system):
  - Determine desired image size on detector for both paths (find magnification)
  - Define the problem paraxially, constrain the free variables (using magnification)
  - Optimize for real lenses (split power between > 1 element)
- For goal 3 (software package):
  - Develop an algorithm to accurately compute pulse arrival times based on polarization data.
  - Integrate the polarization data with the pulse timing software for real-time analysis.
  - Test the pulse timing software with real data to validate accuracy and performance

# Specifications

| Number | Description | Specification | Justification |
|---|---|---|---|
| 1 | **Polarization measurement** | Accurate to 1° | Measure polarization state to 1 degree of precision for high resolution data |
| 2 | **4 Output PSU** | 3.3V, 5V, ±12V | These voltages are required across the system for proper functionality |
| 3 | **Sample rate, ADC module** | 1 MHz, 1 MSPS | Enables us to detect signals at 1µs temporal resolution |
| 4 | **Sample duration/time** | 50ms | Allows for capture of full pulsar pulse |
| 5 | **Optical component power loss** | <10% | Light signals are weak, try to minimize possible loss |
| 6 | Optical power sensitivity | 10fW | The signals we intend to measure are weak |
| 7 | External memory size | ≥4GB | Allows for storing many samples worth of data |
| 8 | Instrument size | 6”x9”x15” | Instrumentation must fit onto the available telescope slot. |
| 9 | Internal data rate capacity | At least 8 MB/s | Sampling at 1µs for 4 sensors generates close to 8MB/s |

# Optical Technology Comparisons

Lookahead topics: lens types, beamsplitter types, waveplates

# Lens Type Comparison

- Singlets – single material, different shape factors
  - Cheapest, but also most aberrations
  - Good for multi-element systems where chromatic aberration not a concern
- Achromats – usually doublets, air-spaced or cemented
  - 2 materials to counteract chromatic aberration (dispersion)
  - Air-spaced has better performance, but cost goes up substantially
- Aspheric lens – non-spherical shape, harder to manufacture
  - Uses arbitrary conic constant/shape
  - Corrects spherical aberration
  - Doesn't counteract dispersion → chromatic aberration present
- Custom-designed lens
  - Paraxial lens prescription optimized in *Zemax*
  - Prescription is sent to manufacturer for custom order
  - Benefit is lens will have custom focal length, magnification, etc.
  - Downside is increased cost and time to manufacture

# Lens Type Comparisons

Common lens parameters:

Fields: 0°, 0.033° (1 arc-minute), and 0.5°

Wavelengths: F, d, C spectral lines, or 486 nm, 588 nm, 656 nm, respectively

$f = 50 \text{ mm}$

$f/\# = 2$, Diameter = 25 mm

Infinite conjugate (object at infinity)

| | Singlet (Plano-Convex) | Achromatic | Aspheric |
|---|---|---|---|
| RMS Spot Size (on-axis) | 140 μm | 13.295 μm | 46.661 μm |
| Spherical Aberration | 58.974 λ | 15.848 λ | 0.0532 λ |
| Coma Aberration | 0.650 λ | 0.046 λ | 1.482 λ |
| Chromatic Aberration (Chromatic Focal Shift) | 754.89 μm | 151.63 μm | 754.25 μm |
| Cost | $38.60 | $89.10 | $277.98 |
| Product # (Thorlabs) | LA1255-A | AC254-050-A | AL2550-A |

# Beam-Splitting Technologies

- Beamsplitter cube
  - Non-polarizing or polarizing with different split ratios
  - 10%:90% reflected/transmitted
  - AR-coated, $R_{avg} < 0.5\%$

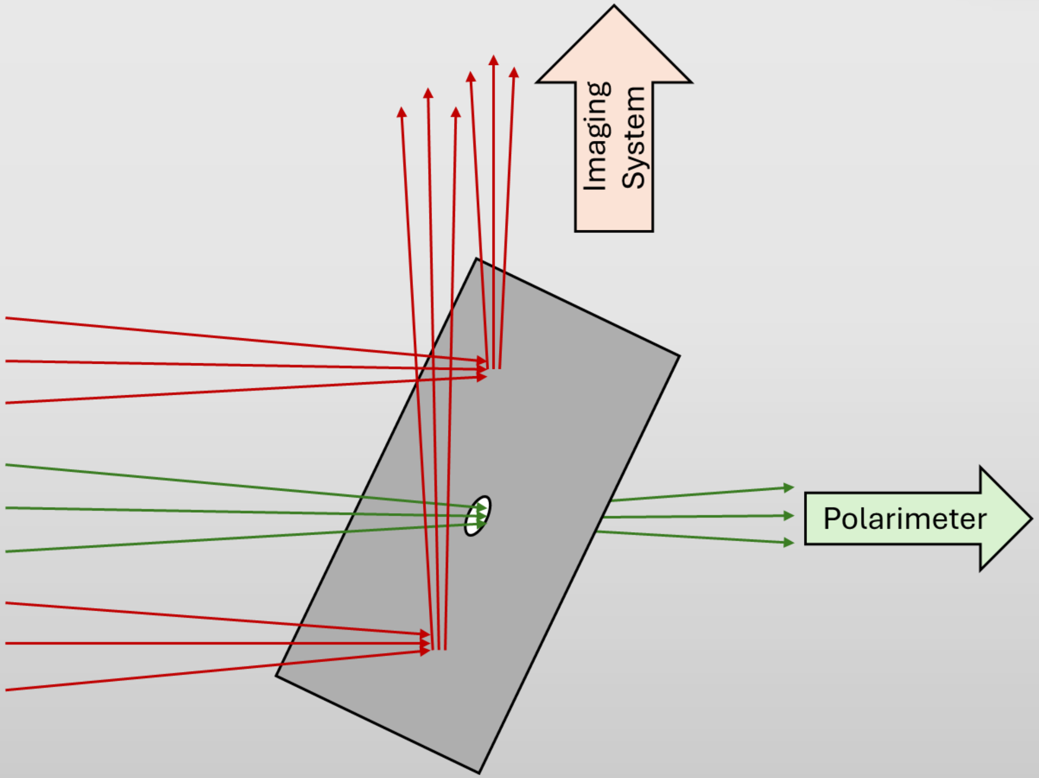
- Beamsplitter plate
  - Non-polarizing or polarizing, various splitting ratios
  - 10:90 R:T ratio
  - AR-coated back surface, $R_{avg} < 1\%$

Cube Beamsplitter
Image Credit: Thorlabs

Plate Beamsplitter
Image Credit: Thorlabs

# Beam-Splitting Technology – Pinhole Mirror

- A metallic mirror with a pinhole etched into the center, to allow a specific object to pass through (green).
- All other light is reflected (red)
- Splits light between guiding and polarimetry systems with minimal loss.



# Beamsplitter Technology Comparison

Commonalities between technologies:

Same splitting ratio: 10:90 reflection/transmission (R:T)

Same size / form factor

| | Cube | Plate | Pinhole Mirror |
|---|---|---|---|
| Angle of Incidence | 0° | 45° | 45° |
| Power Loss | < 15% | < 1% | < 1% (or zero) |
| Polarization Deviation | $\lvert T_s - T_p \rvert < 10\%$ <br> $\lvert R_s - R_p \rvert < 10\%$ | $\lvert T_s - T_p \rvert < 35\%$ <br> $\lvert R_s - R_p \rvert < 35\%$ | None* |
| Cost | $205.50 | $140.17 | Materials |
| Part Number (Thorlabs) | BS037 | BSN10 | - |

*Note: the pinhole in a mirror is empty space (air), so on-axis light passes through unimpeded, experiencing no change

# Waveplate Technologies

- Wavelength dependent retardance error is a critical issue, so we must use an achromatic waveplate. Must work for the full visible spectrum.
- Products of the chosen technology were all roughly equal in price and spectral range. Retardance error determined the final decision.

| | Liquid Crystal Variable | Multi-Order | Achromatic |
|---|---|---|---|
| Retardance Error (Single Wavelength) | λ/20 | λ/4 | λ/300 |
| Retardance Error (Wavelength Dependent) | >λ | >λ | λ/20 |
| Spectral Range | 350 – 700nm | Single Wavelength | 350 - 850nm |
| Cost | $1,300 | $500 | $1,000 |
| Can Be Electrically Modulated | Yes | No, requires mechanical rotation | No, requires mechanical rotation |
| Part Number (Thorlabs) | LC1611-A | WPMQ05M-633 | AHWP10M-580 |

# Photodetectors

- Imaging:
  - Monochromatic CCD
  - 4μm pixel size

- Polarimeter:
  - Silicon Photomultiplier single photon counters
  - Cost was the primary determining factor
  - 1.3mm active area


ASI220MM Mini(mono)


PDA44

# Hardware Comparisons

Lookahead topics: regulators, MCU,  storage

# Hardware Design: Component Selection and Comparison

**<u>Main HW components required</u>**:

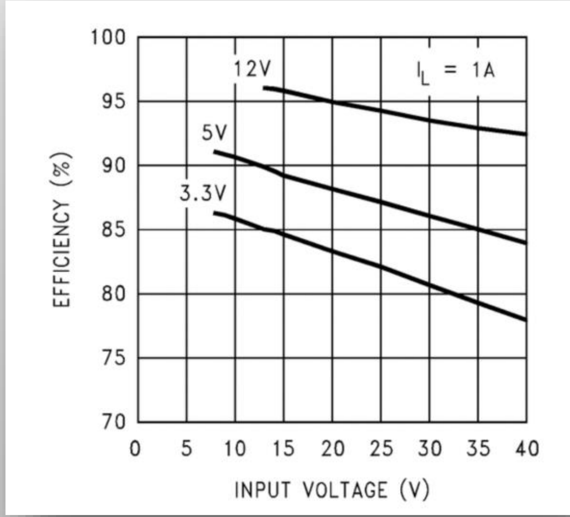
MCU for control & data acquisition; must have clock and ADC sampling rate that meet performance requirements

( >1 MHz clock frequency & >1MSPS ADC frequency). MCU processor we found was the ESP32_MINI-1U

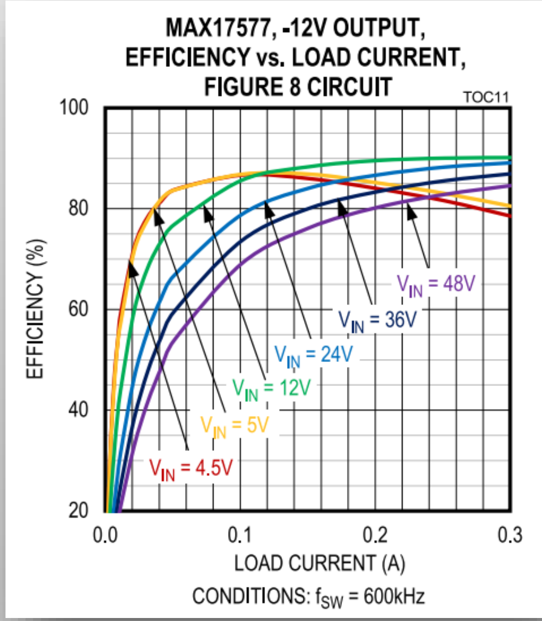
- 40 MHz internal crystal oscillator (Stable)
- ADC up to 2 MSPS (Plenty of headroom)

Use switching regulator to achieve all required voltages needed by system, 3.3V for MCU, 5V for servo & rotation mount, and ±12V for sensors and OA scheme.

- 3.3V and 5V utilize LM2675-ADJ (low frequency switching regulator with 1A max o/p current)
- -12V utilize MAX17577 (meant for inverting and provides sufficient 0.3A max o/p current)


LM2675-ADJ typical performance



# Hardware Selection and Comparison

**Additional hardware requirements**:

- Controls and Display; start and menu select buttons, & rotary encoder
- Sensor input and analog processing; Op-Amps(OA): Going for low-noise and precision op-amps. Tested with TL084, project will utilize OPA188 which is an LNA and offers much more protection from unwanted noise, drift, and offset


| Specification | OPA188AIDBVT | TL084 |
|---|---|---|
| Supply Voltage Range | ±2V to ±18V (Single supply 4V to 36V) | ±3V to ±18V |
| Gain Bandwidth | 2 MHz | 3 MHz |
| Input Offset Voltage | 25 µV (maximum) | 5 mV |
| Slew Rate | 0.8 V/µs | 13 V/µs |
| Input Bias Current | 5 pA (typical) | 30 pA (typical) |
| Quiescent Current | 510 µA (maximum) | 1.4 mA per amplifier |
| Noise | 8.8 nV/√Hz | 18 nV/√Hz |
| Rail-to-Rail Output | Yes | No |

# FPGA vs. MCU Technologies

- FPGA
  - Highly customizable and support parallel processing
  - Great for real-time signal processing and low latency tasks
  - Complex development (HDLs), higher power consumption, and cost
- MCU
  - Low power consumption, ideal for use in remote locations
  - Easier and faster development with high-level languages (*C*)
  - Cost-effective with built in peripherals (ADCs, timers, etc..)
  - Suitable for real-time data acquisition with sufficient performance for our needs.
- Conclusion :
  - MCU selected due to power efficiency, cost, simplicity, and integrated peripherals, providing an optimized solution for real-time data processing

# MCU Selection

- ESP32C
  - High speed ADC (2 MSPS)
  - Integrated peripherals (ADC, UART, I2C)
  - Power Management (deep sleep mode)
  - Flexible communication options (USB, UART)
  - Dual core processor (240 MHz)

# Storage: Flash vs. PSRAM vs. SD Card

- Write speeds with MCU
- Must be fast enough to handle 8MB/s of data
  - Embedded flash is slow, external flash chip likely slow as well
  - Not enough RAM to store long enough samples. External PSRAM limited to 4MB, or 0.5 seconds of data
  - MCU supports 4-pin SDIO protocol, exploiting parallelism. Offers plenty of removable SD card storage

PSRAM Chip
Credit: ProtoSupplies


SD Card Reader
Credit: Adafruit

# Comparison of Storage Technologies

| Specs | Built-in Flash | ESP-PSRAM64H (PSRAM) | MicroSD Card |
|---|---|---|---|
| Storage Size | 4MB | 8 MB | 64 GB |
| Speed | 40-80 MB/s | ~200-400 MB/s (QSPI) | Up to 50 MB/s write (U3-rated) |
| Effective speed | 4-8 MB/s | ~50-100 MB/s | Target: 10-50 MB/s (based on 40 MHz clock with 4 lines: ~160 Mbps) |
| Integration method | Built-In | External (SPI/QSPI interface) | External via SDIO or SPI (removable from reader) |
| Cost | Included in MCU | $0.75 | $12 (for two cards) |

# Software Technology Comparisons

- Dev environments
  - ESP-IDF : Main framework for development, providing low level hardware control and FreeRTOS integration.
  - Arduino IDE : Used for quick prototyping and basic functionality during early development
- Software Used
  - Python : Used for data analysis, visualization, and interfacing with hardware via UART.
  - C : Core language for embedded programming, memory and hardware management

# Software Used

- Developer Environments:
  - Arduino IDE for simple test sketches
  - VSCode with ESP-IDF extension for native ESP32 development (in C)
  - GitHub for source control
- Design Software:
  - *Zemax* (optical design)
  - *SOLIDWORKS* (3D parts and assemblies)
  - *Fusion 360* (PCB schematics and layout)
  - *LTSpice* (circuit simulations)
- Other Software:
  - Microsoft Office
  - OneDrive
  - Discord

# Programming Languages

- Common languages: *C*, *C++*, *Java*, *Python*, *JavaScript*

| Language | HW Level | Formal Structure | Object-Oriented | Scripting |
|---|---|---|---|---|
| **C** | Low | ✓ | ✗ | ✗ |
| **C++** | Low | ✓ | ✓ | ✗ |
| **Java** | High | ✓ | ✓ | ✗ |
| **Python** | High | ✗ | Can be | ✓ |

# Optical Design

- The optical design can be broken into two parts:
  1. The Polarimeter
  2. Image Acquisition and Guide

The polarimeter separates the light into orthogonal polarizations, that can be measured to reconstruct the incoming light's polarization angle with respect to the instrument.

The image acquisition and guide system will image the object to a guide camera and feature a toggleable pupil imaging path.

# Imaging System Design

- The goal is to utilize 1 camera but image 2 paths
- Mirrors attached to servos are used to toggle which path the light takes
- One path will image the celestial object, the other the telescope's pupil

- Gaussian lens equation, magnification, and Gullstrand's equation:

$$\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$$

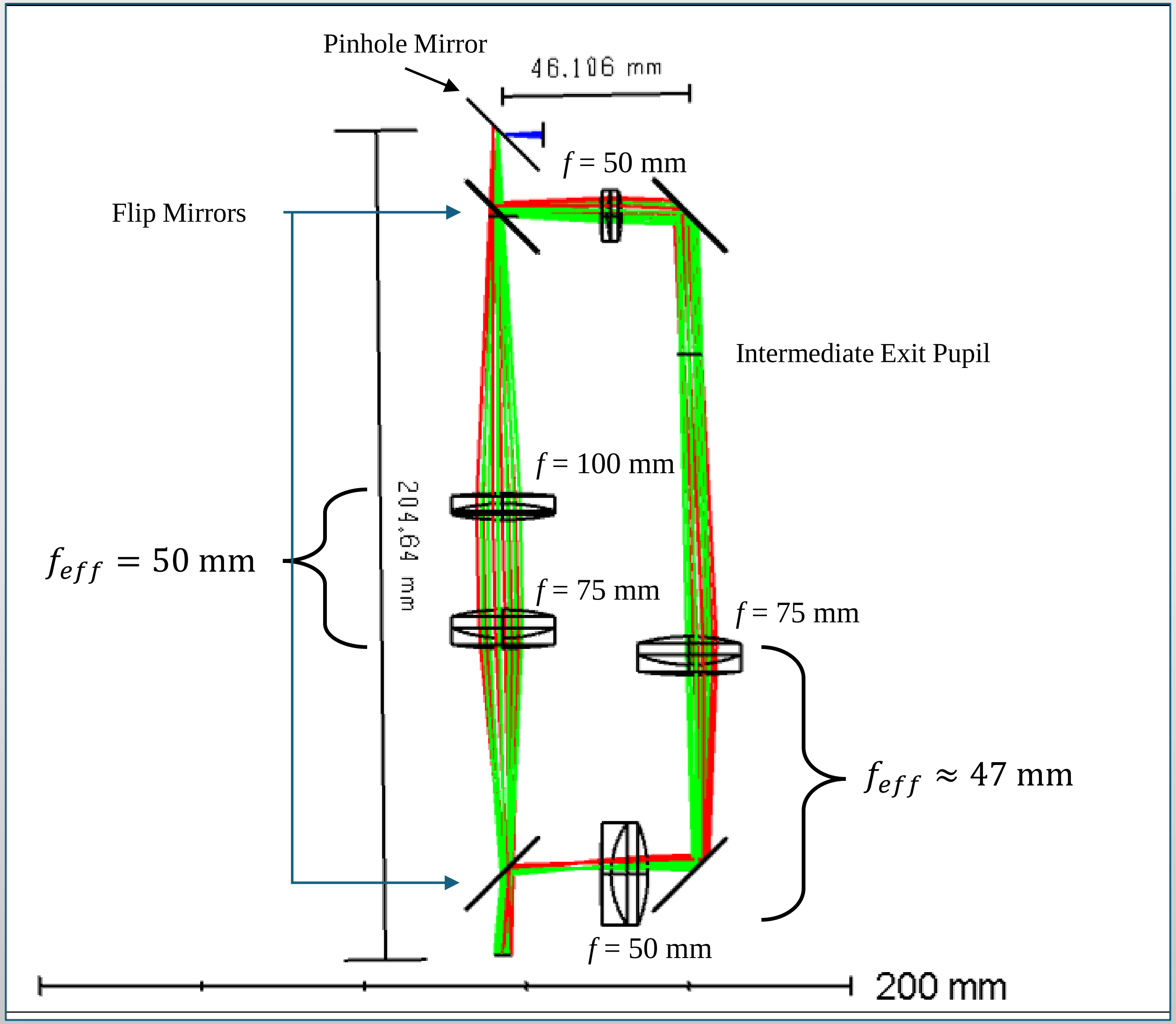
$$m = \frac{v}{u} = \frac{h_2}{h_1}$$

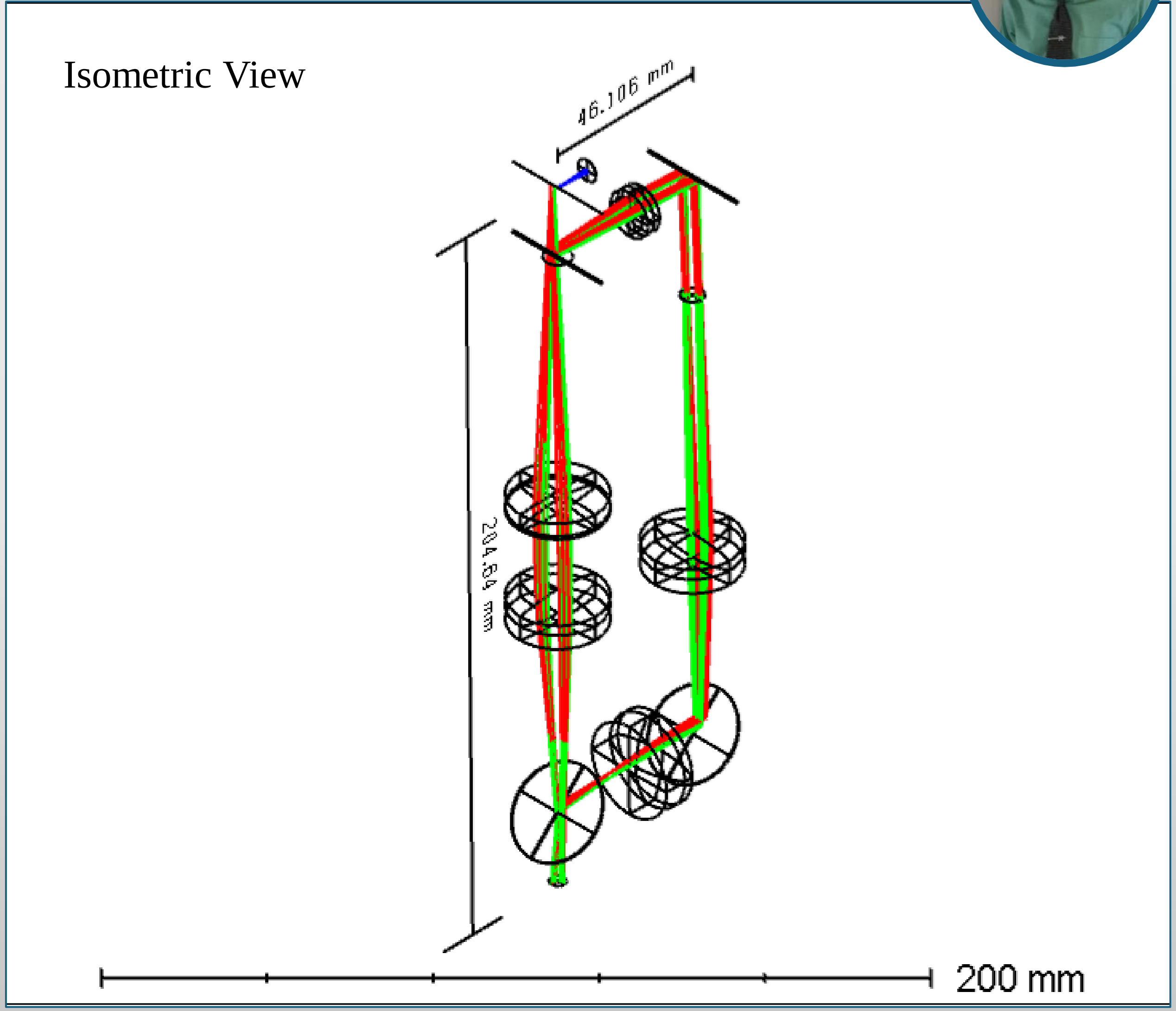
$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2}$$

# Imaging System Design Paraxial Constraints

- Magnification constrained to ensure images fit onto detector
  - For object imaging path, $m = 0.863$
  - For pupil imaging path, the 1st lens $m_1 = 0.0276$, 2nd lens $m_2 = 0.6848$
- The 2 optical paths were distance constrained so that their image planes aligned at the detector
- Focal lengths found from magnification and total distance
- After being constrained, *Zemax* is used to optimize RMS spot size

# *Zemax* Layouts of the Imaging System




The green and red rays are the off-axis 1 and 2 arcminute fields, respectively, while the blue on-axis rays pass through the pinhole mirror.

# Polarimeter

- Stokes polarimeter that measures the linear polarization state of light.
- Key Components:
  - Photodetectors
  - Wedged Double Wollaston Prism (WeDoWo)
  - Rotating Half Wave Plate
- The WeDoWo separates incoming light into two pairs of orthogonal polarization components. The photodetectors read the energy in each component.
- Rotating half wave plate used to negate instrumental polarization.

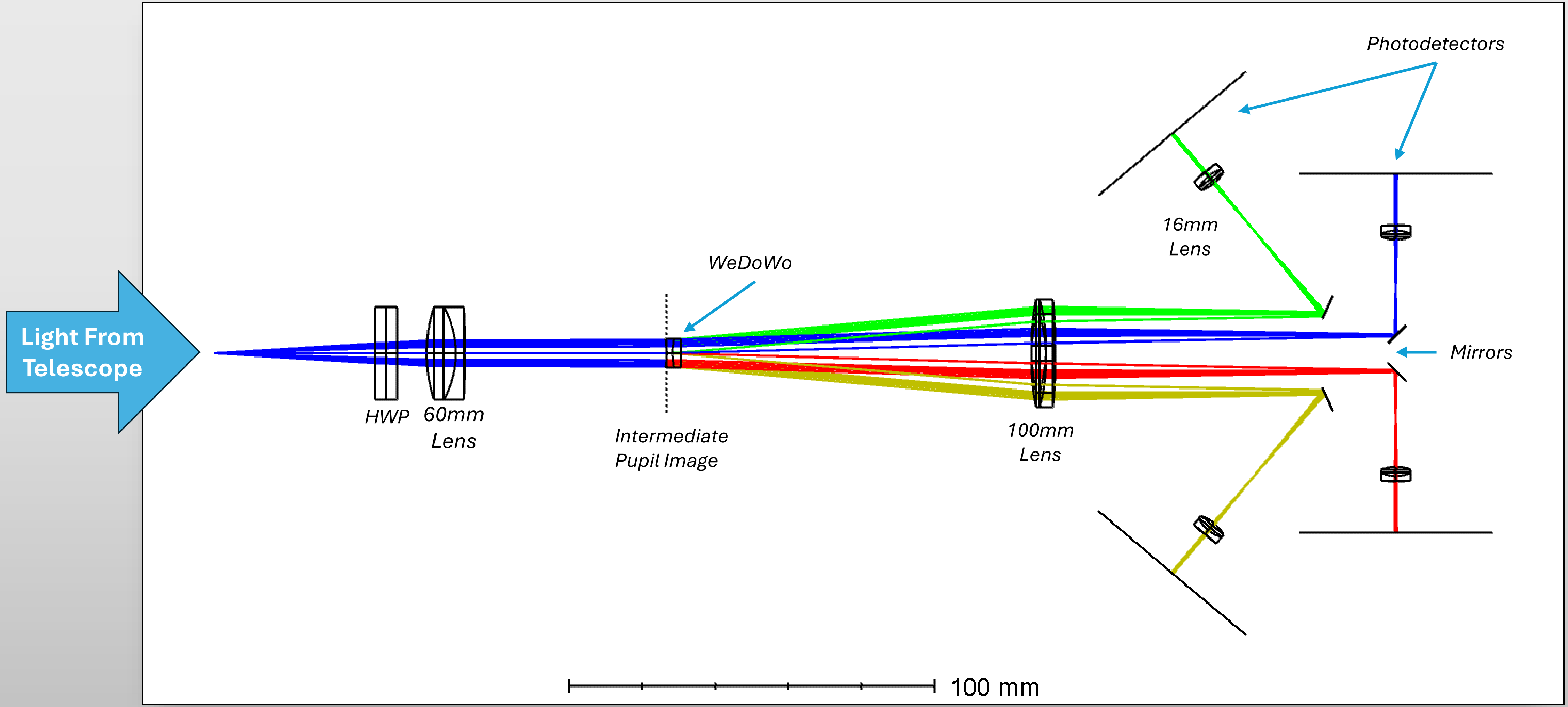
# Polarimeter System Design

- Bi-Telecentric optical system, each lens is one focal length away from the system pupil.

- System pupils are positioned at each of the four photodetectors, along with the front of the WeDoWo. Additionally, must leave enough space for all beam paths.

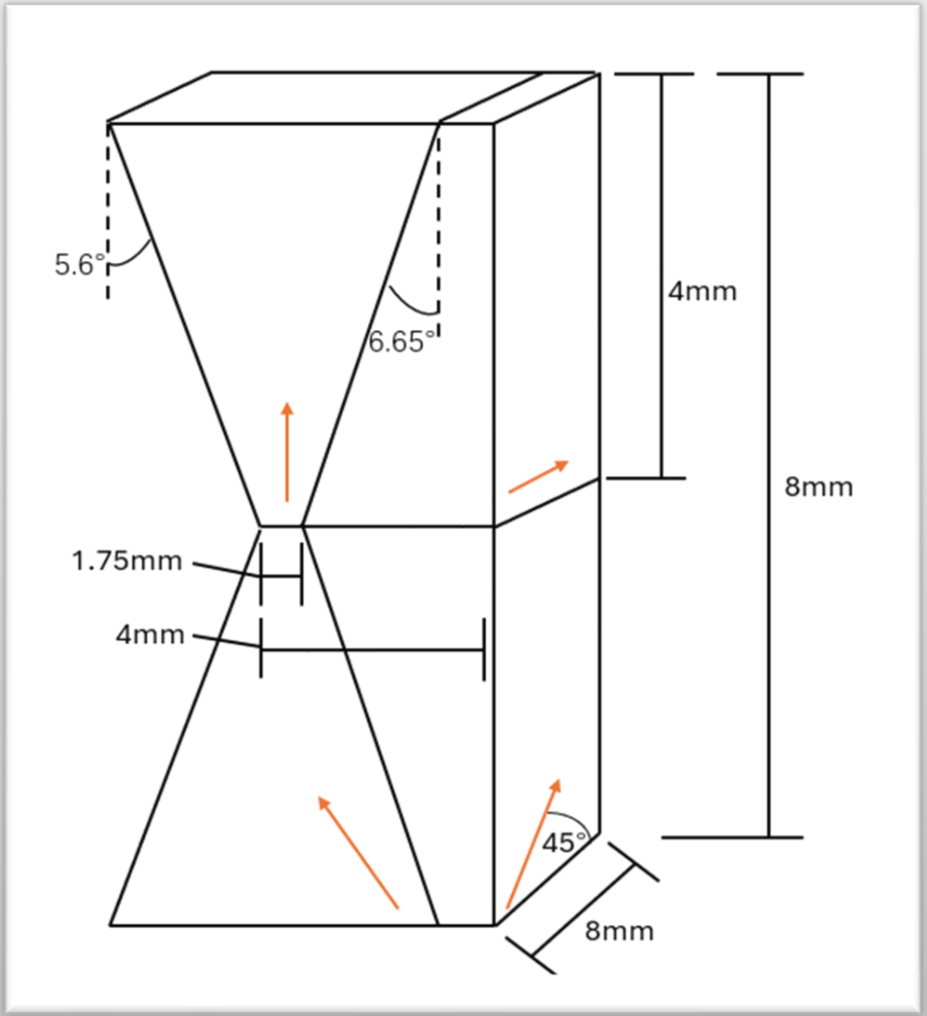
- Pupils must be positioned at the WeDoWo for precise beam splitting, and detectors for consistency in measurements.

# Polarimeter Schematic



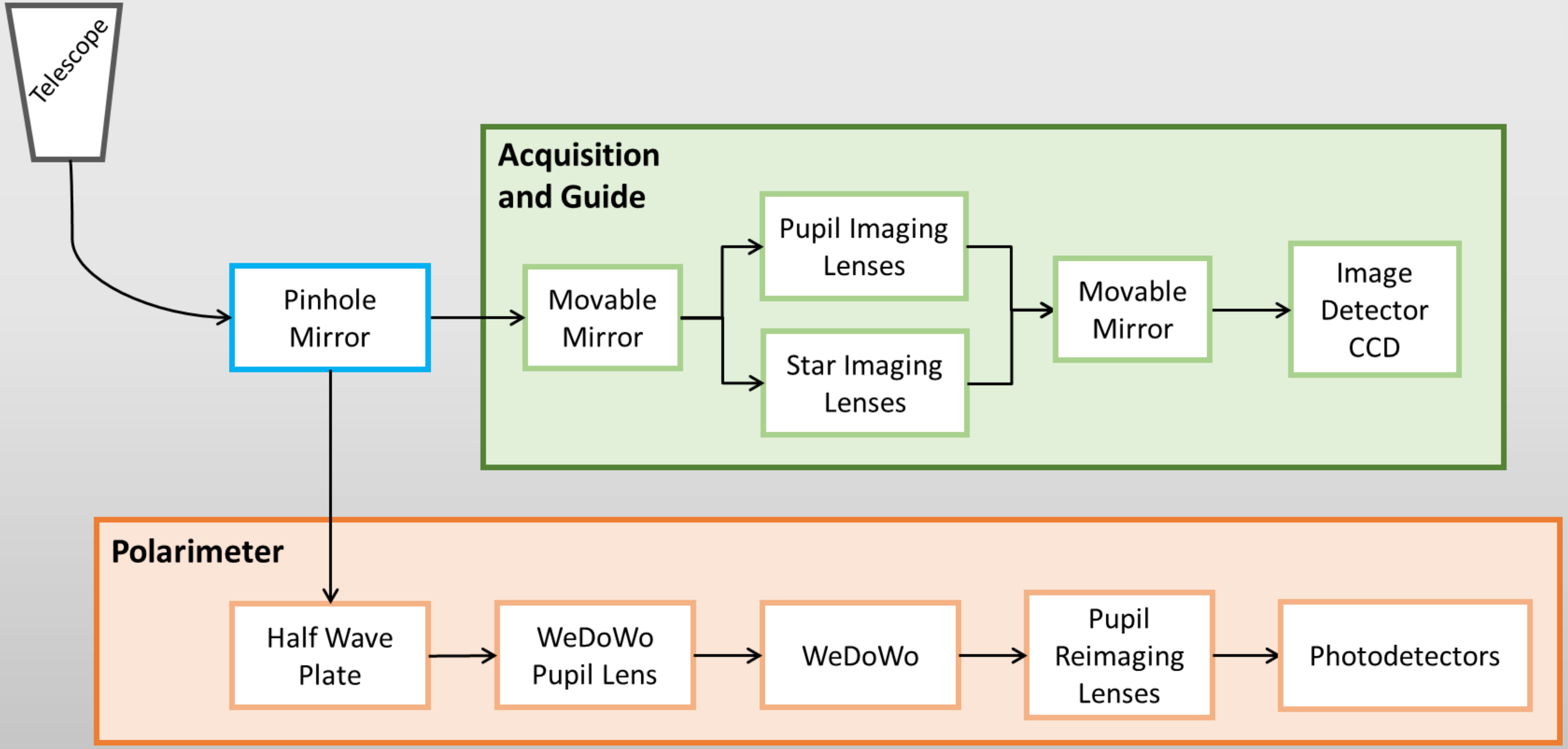

# Wedged Double Wollaston Prism (WeDoWo)

- Two Wollaston prisms mirrored across the optical axis, with an angled front face.
- Calcite crystal Axes (orange)of each half are 45° apart.
- Angles optimized to maximize output beam separation




*Drawing not to scale*

# Optical Block Diagram



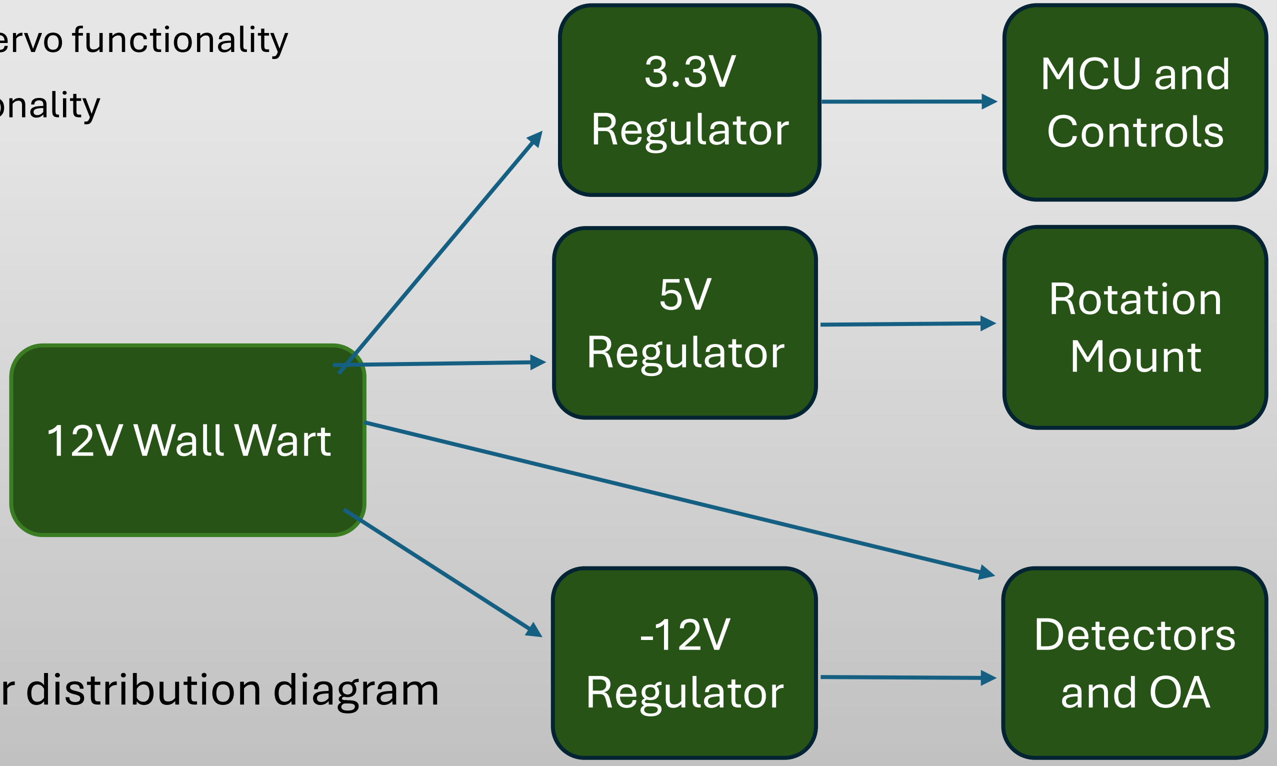

# Hardware Design: Power Supply Unit (PSU)

Design is to utilize a 3.3V regulator, 5V regulator, and three ±12V regulators.

All power is sourced from a 12V DC wall wart which can provide 5A max current output.

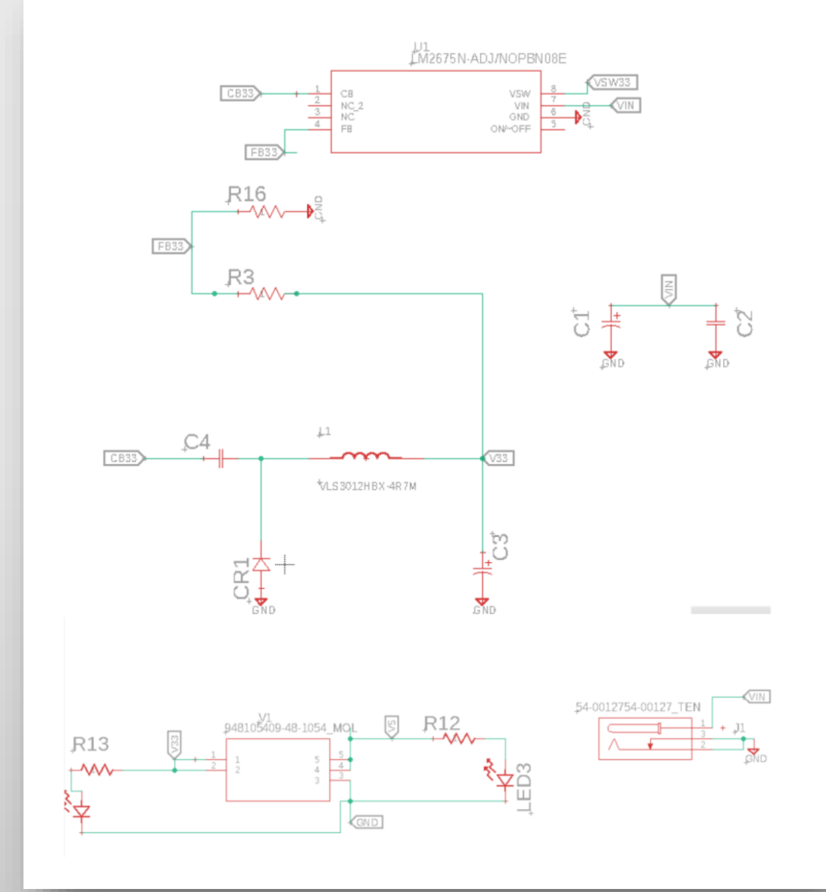
**Required Voltages**:

- 3.3V @ 250 mA for MCU functionality
- 5V @ 800 mA for waveplate mount and mirror servo functionality
- ±12V @ 250 mA/detector & <500 μA /OA functionality

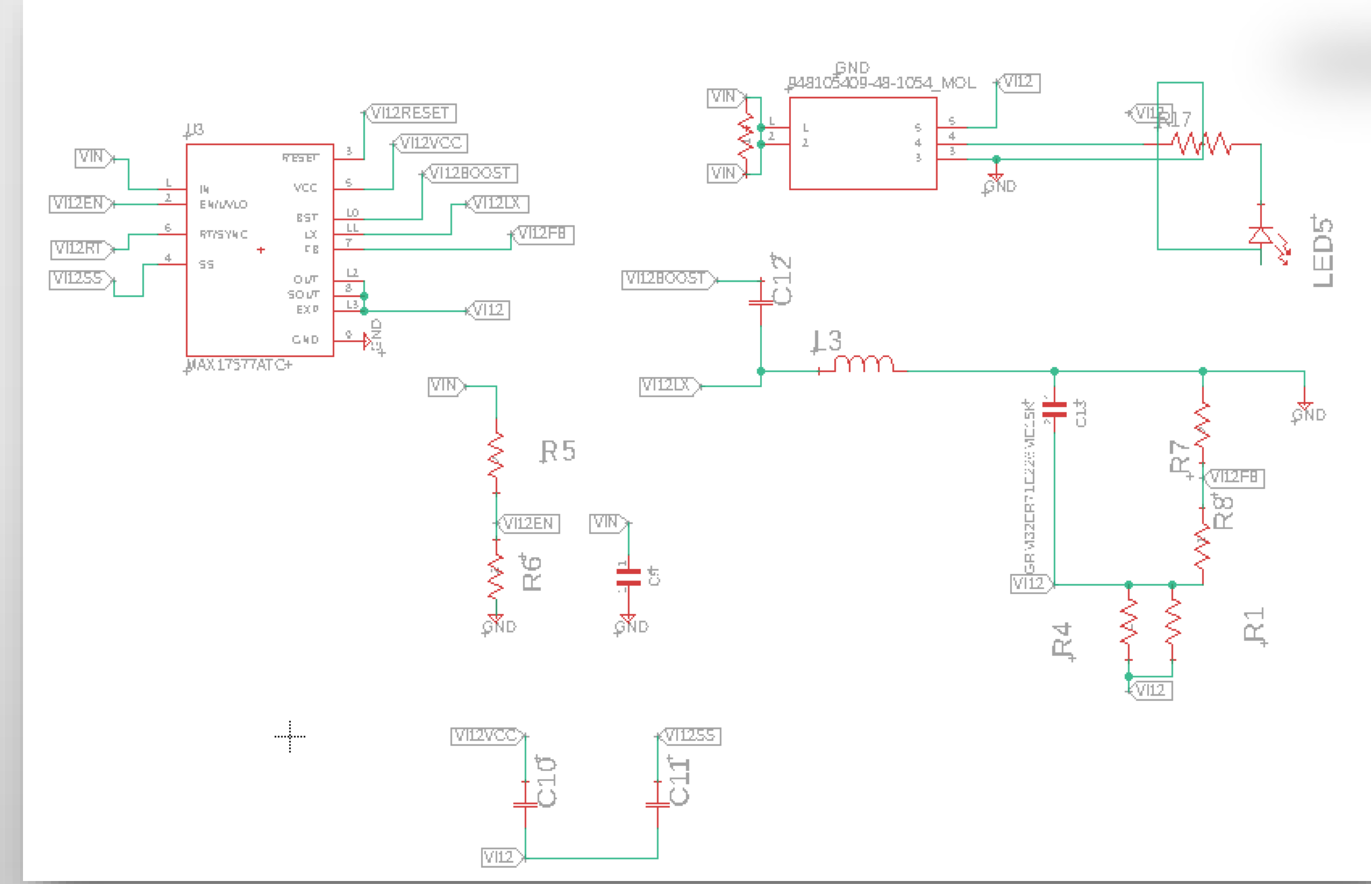



Power distribution diagram

# Hardware Design: PSU Schematics

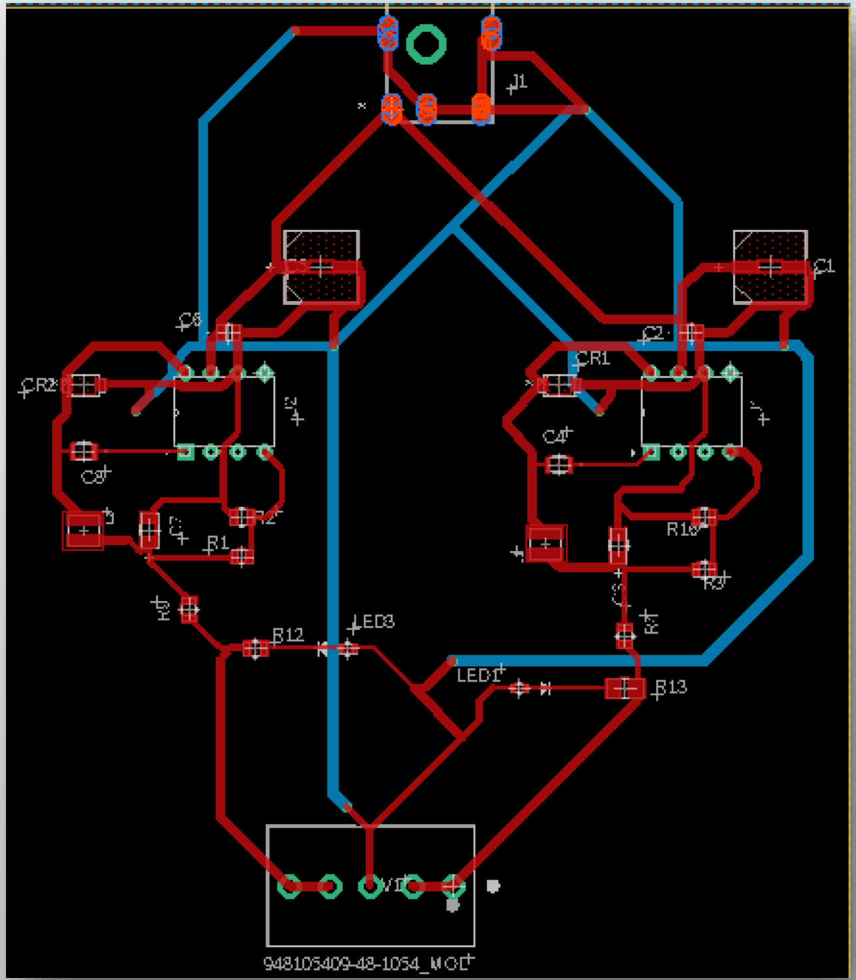


3.3V and 5V regulator scheme using LM2675-ADJ (Same topology, different feedback resistances)

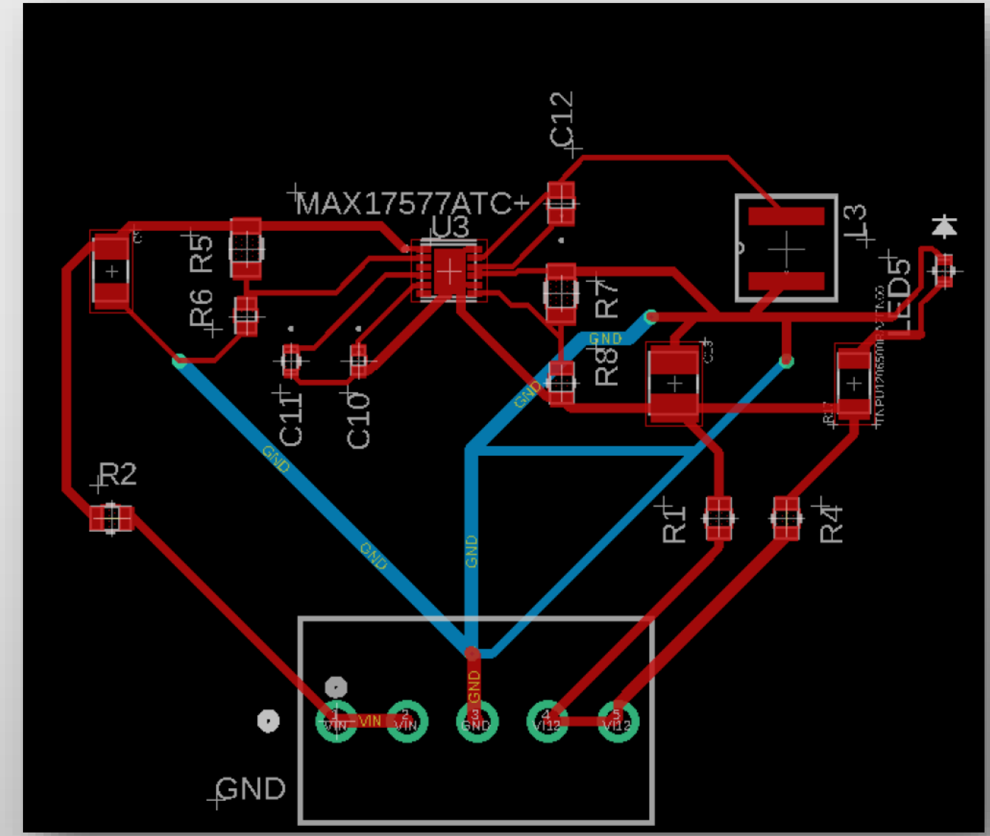


-12V regulator scheme using MAX17577

# Hardware Design: PSU Layout




5V and 3.3V regulator layout




-12V inverting regulator layout

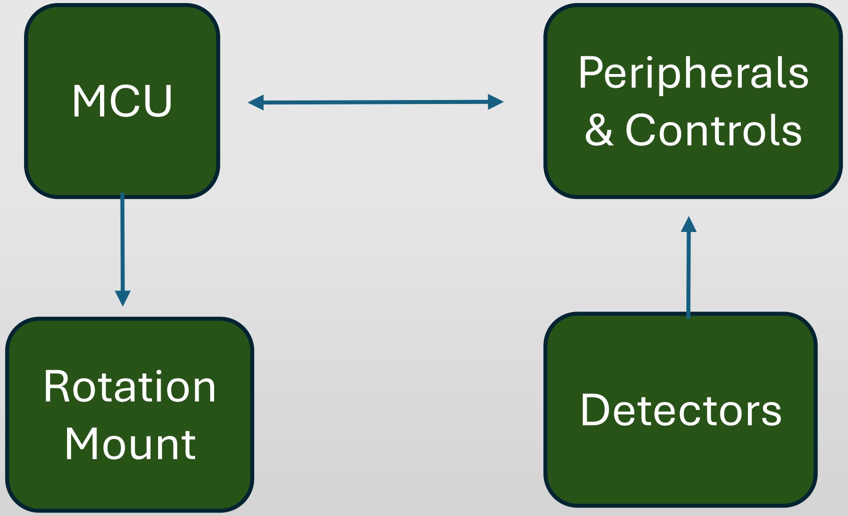
# Hardware Design: MCU and Peripheral Boards

Design of the MCU board was to create a breakout board to make prototyping easier to troubleshoot. The MCU will be placed on a board which will include the following:

- USB port to serial communication using a bridge (CP2102)
- BOOT and EN buttons for flashing and start-up debugging
- Jumpers/Connection to GPIO used for sensor input to ADC, I2C communication for display, UART for terminal and waveplate communication, and rotary encoder and button controls.
- Power input

Design of external peripherals board is separate for same reason. Peripheral board must include:

- Sensor input and analog front-end (AFE)
- Start and menu buttons, rotary encoder for sampling adjustment
- Connection for rotation mount rs232 communication.
- Power Input



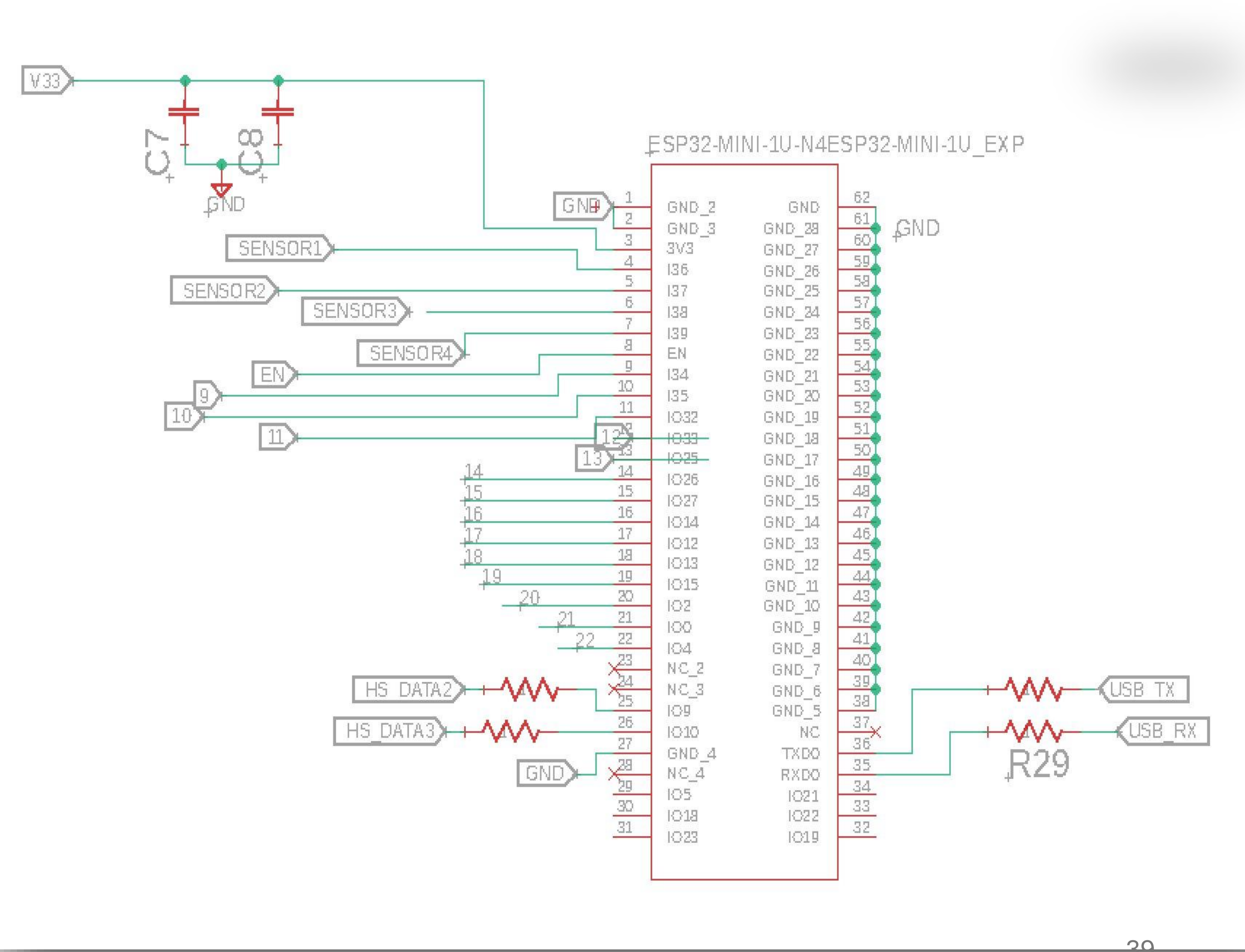

MCU and peripheral board implementation

# Hardware Design: MCU Breakout Board

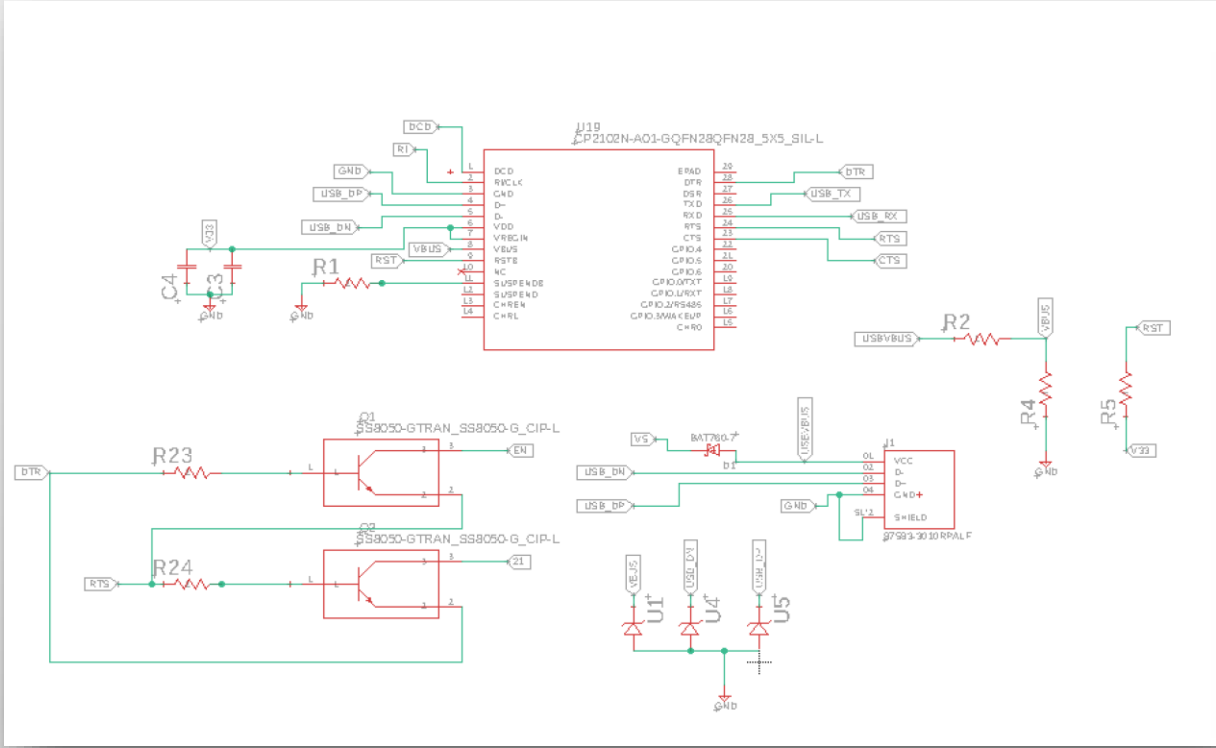
MCU is going to be placed on separate board for troubleshooting.

**<u>MCU Breakout board must include</u>**:

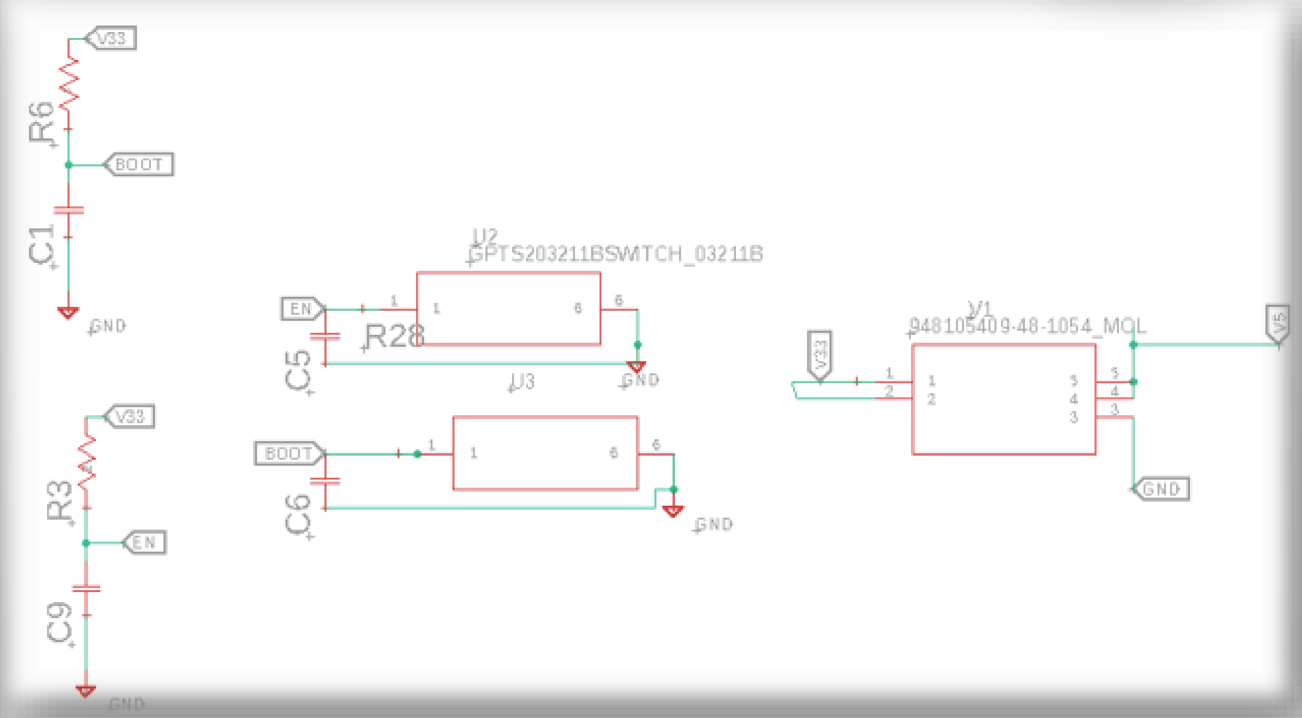
- USB communication for data TX/RX
- BOOT and EN buttons installed for flashing
- GPIO, power, and ground jumper ports.
- GPIO pins must have 0Ω resistor for isolation
- Connection to 3.3V power from PSU



# Hardware Design: MCU Breakout Board

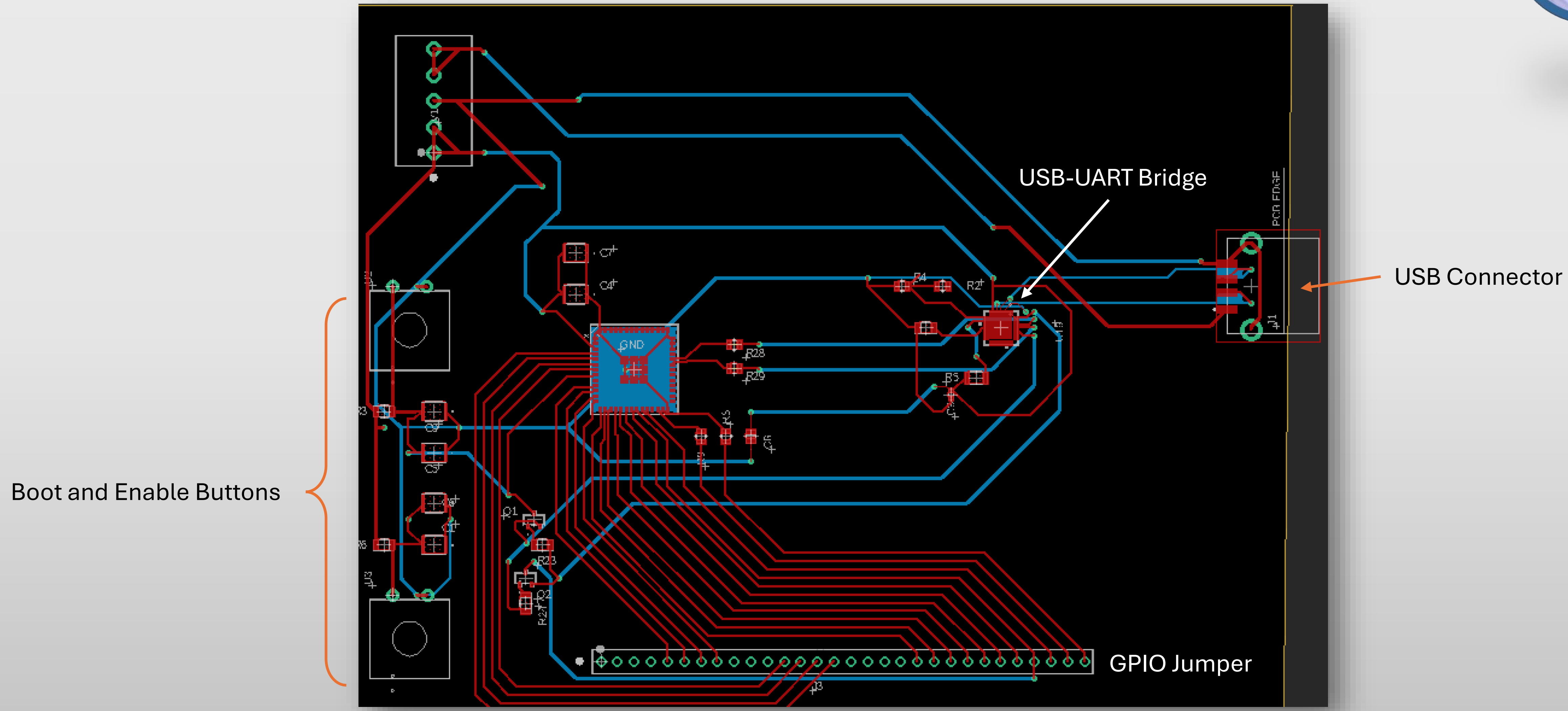



USB to serial bridge CP2102




BOOT and EN buttons for MCU flashing

# Hardware Design: MCU Breakout Board Layout

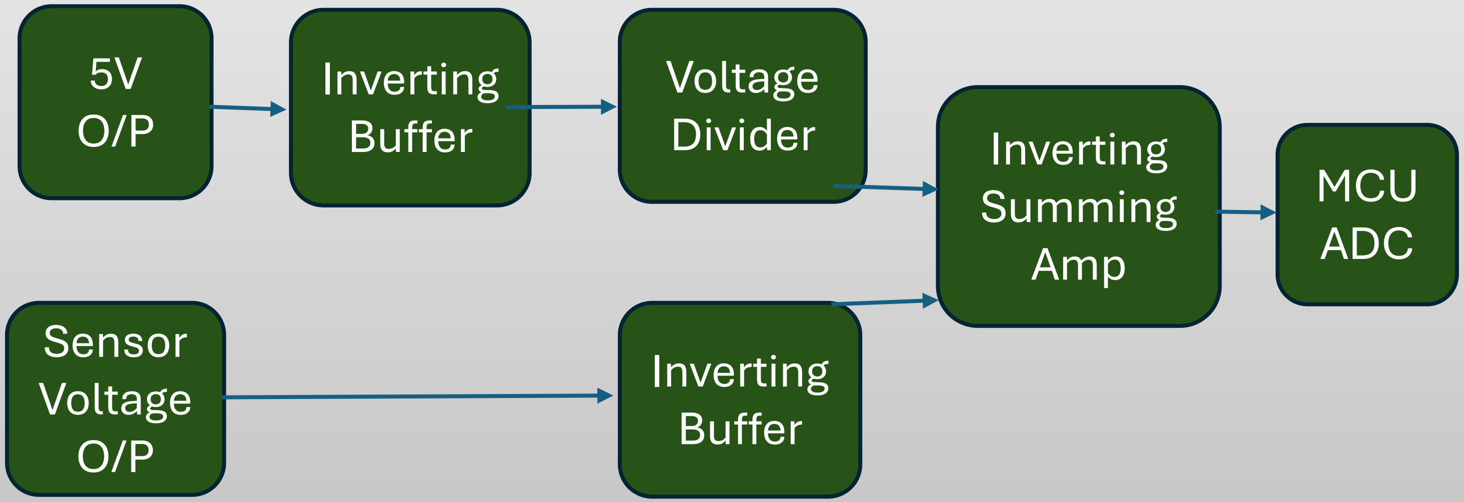


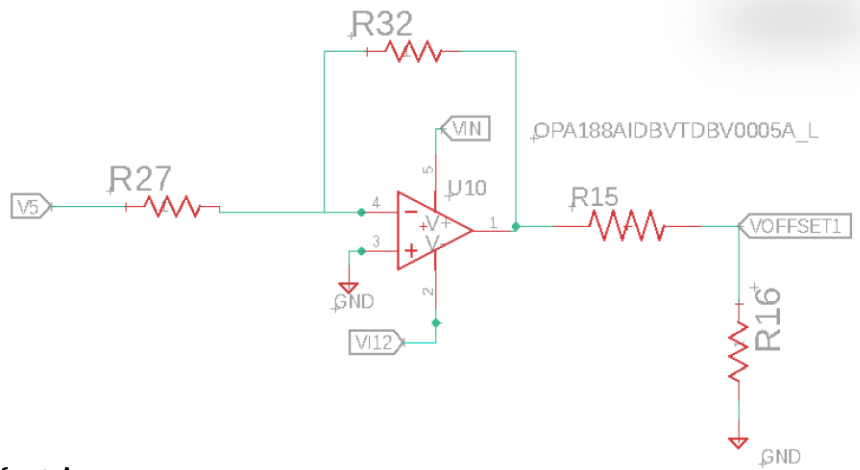

Breakout board with GPIO pin jumpers and USB connection

# Hardware Design: Peripherals Board

An analog front-end (AFE) module must be attached to every sensor output (O/P max ±2V) such that the ADC module can sample the signal within its sampleable range (0-1V ideally, 0-2V practically). Each detector signal must go through their own analog processor/AFE unit.

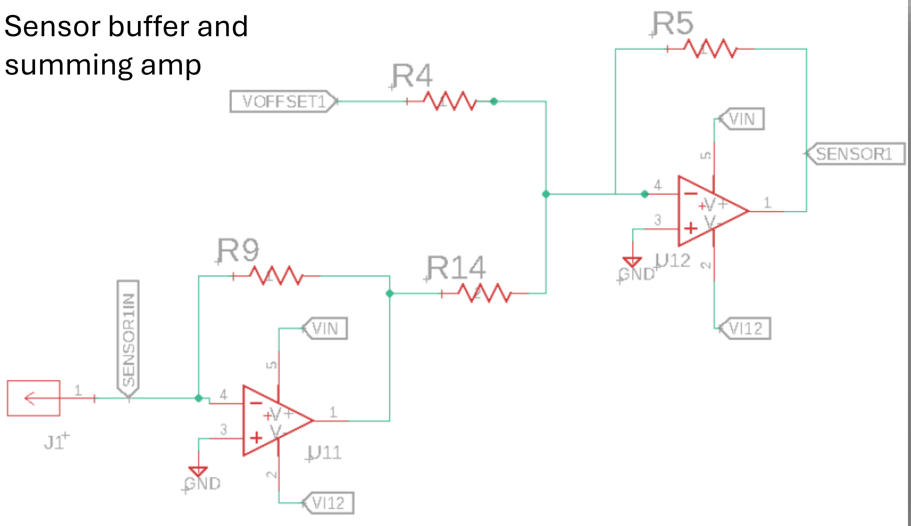
The testing source will be low intensity therefore our predictable output range is in the hundreds of millivolts, which the ADC module can sample with precision. The signals simply need to be buffered, and DC offset before being sampled by the ADC




Offset Amp

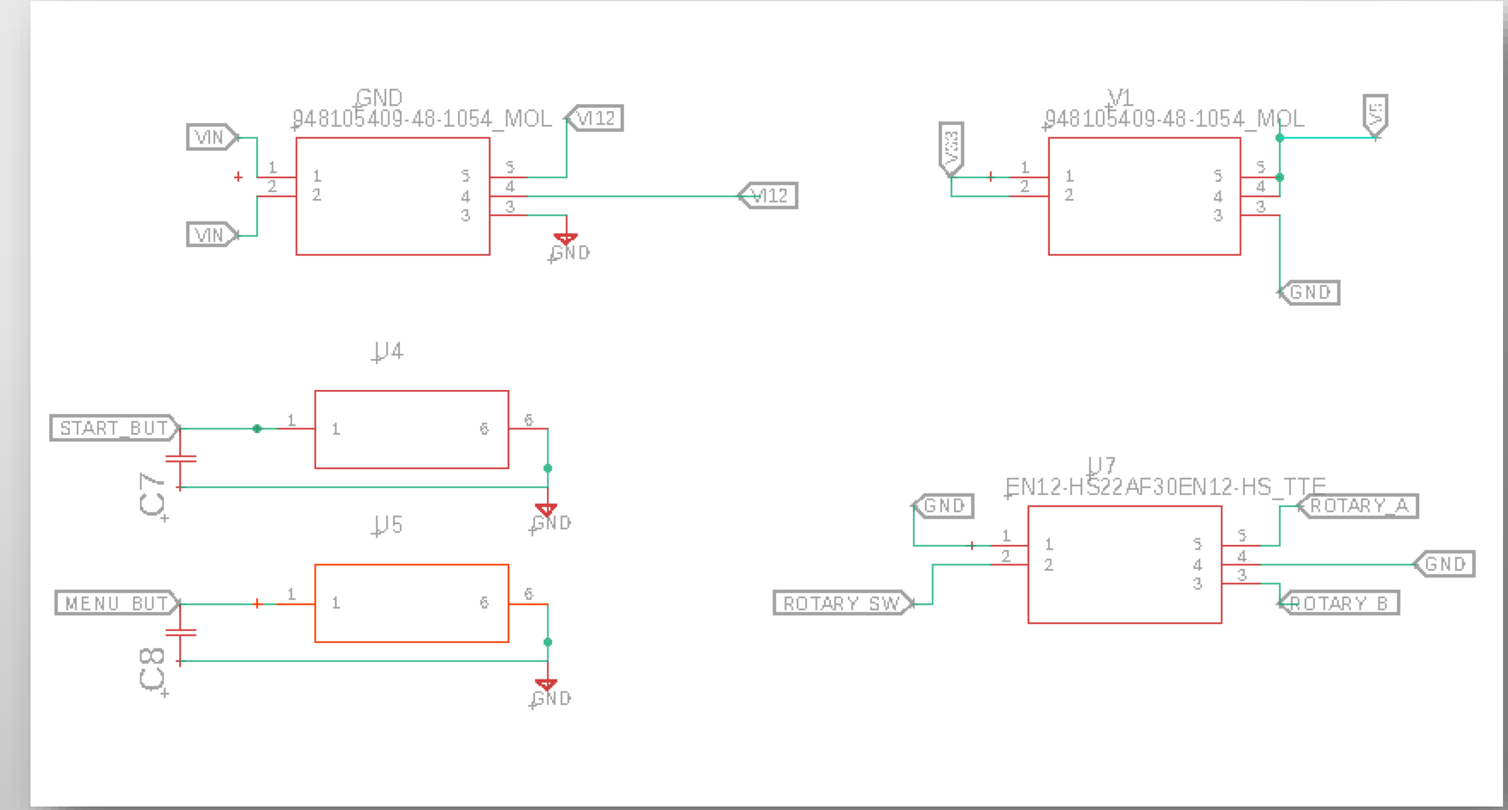
Sensor buffer and summing amp



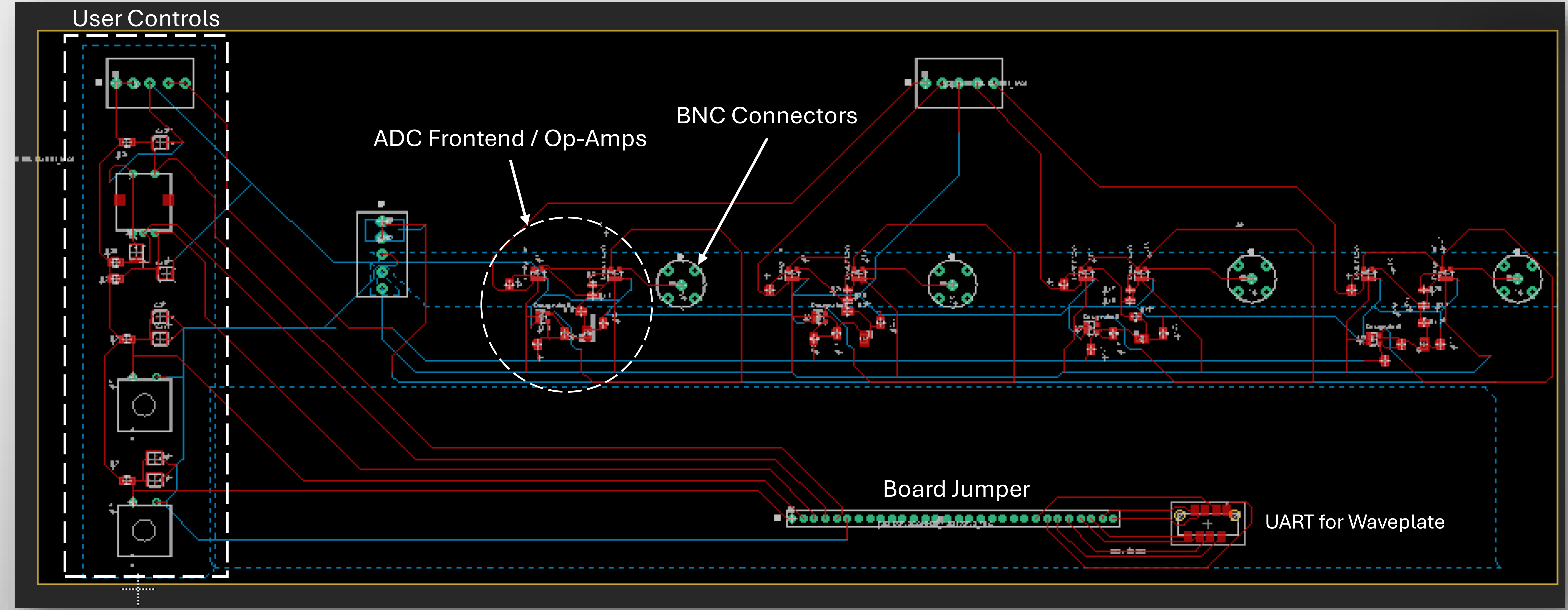
# Hardware Design: Peripheral Board

**<u>Controls, display, & power connection</u>:**

- Rotary Encoder for sampling duration adjustment (bottom right)
- Buttons for sampling start & menu select (bottom left)
- 3.3V, 5V , ±12V, and GND connection (top left and right)



# Hardware Design: Peripheral Boards



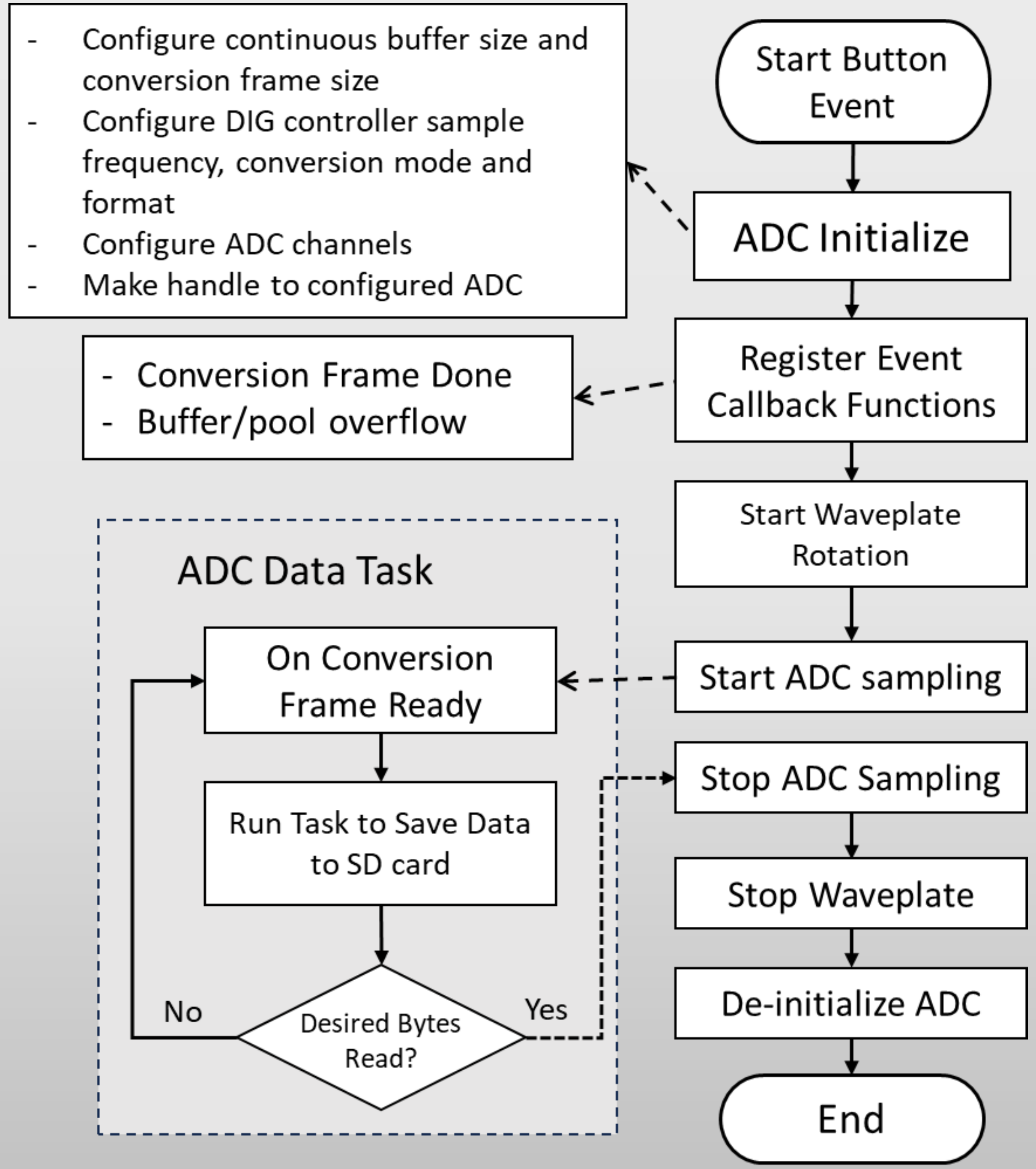

AFE and Controls implemented in conjunction on peripherals board

# Software Design

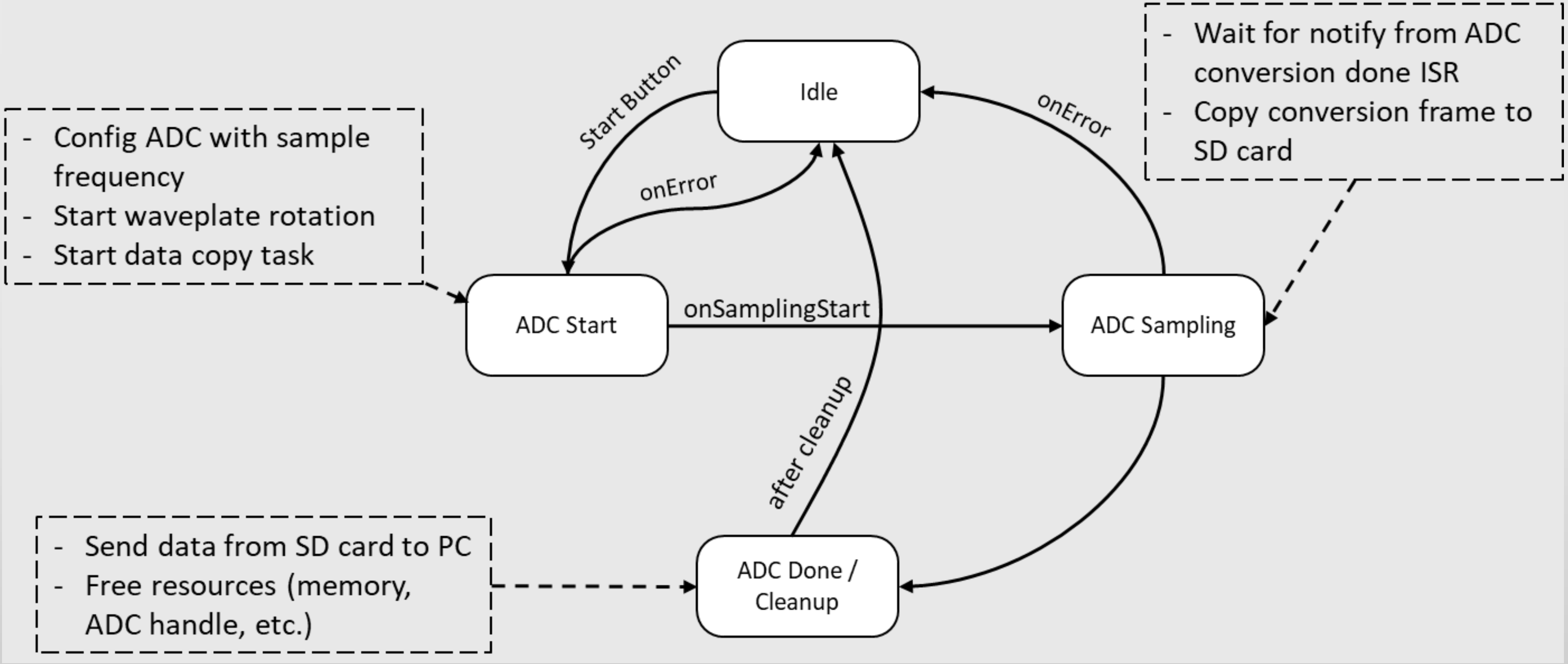
- Native ESP32 developer environment
- Peripherals used:
  - ADC
  - Motor PWM (MCPWM) – Servo Control
  - Pulse Counter (PCNT) – Rotary Encoder Dial
  - UART – Waveplate and PC communication
  - LCD I2C Library
  - SD Card
- Python data processor
  - Get and store data
  - Find polarization
  - Find pulse time

# Sampling Flow

- ADC Sampling starts on button press
- Uses user-defined parameters to configure
- Counts bytes of data read
- Starts waveplate for sampling, stops when done

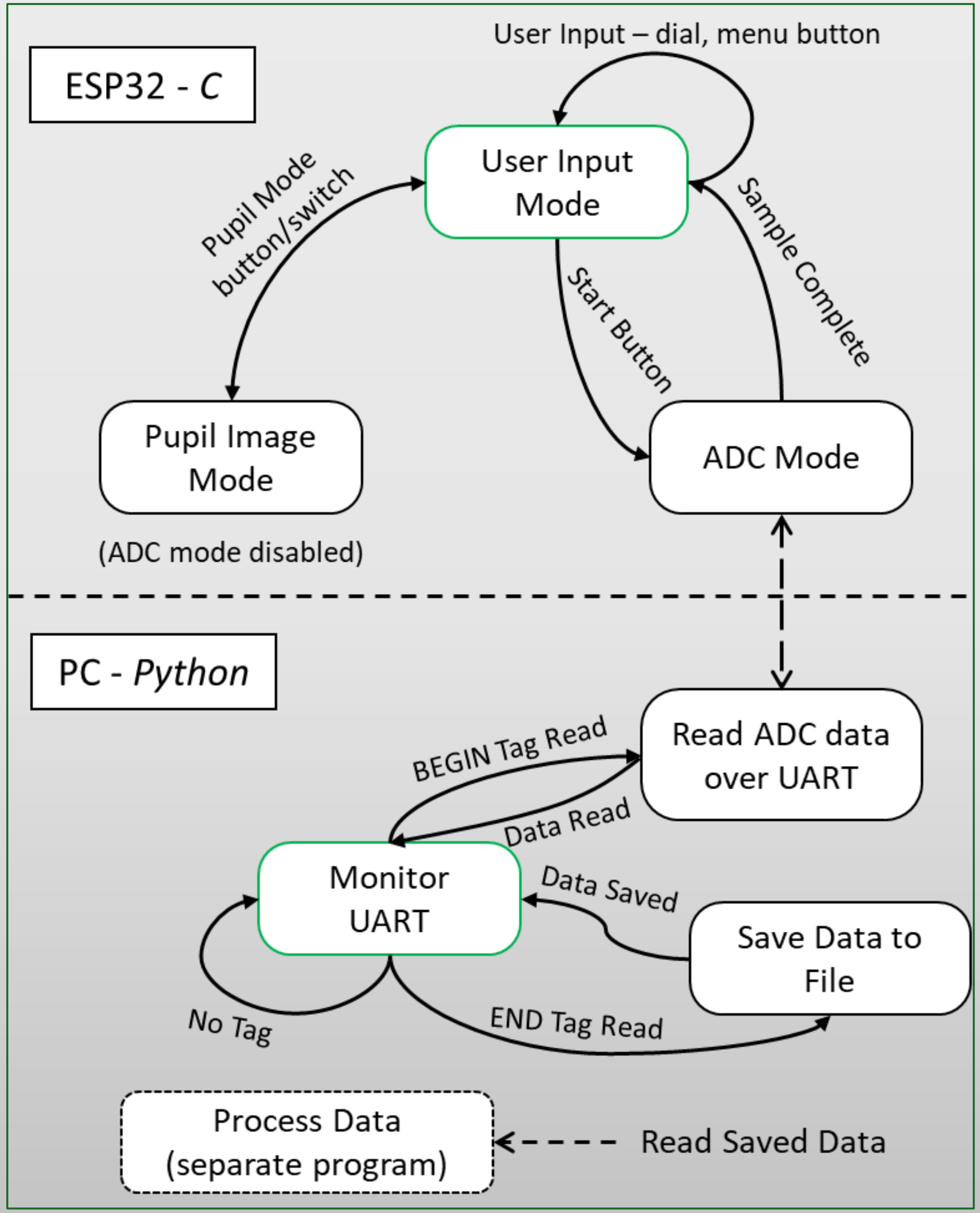



# Sampling State Machine



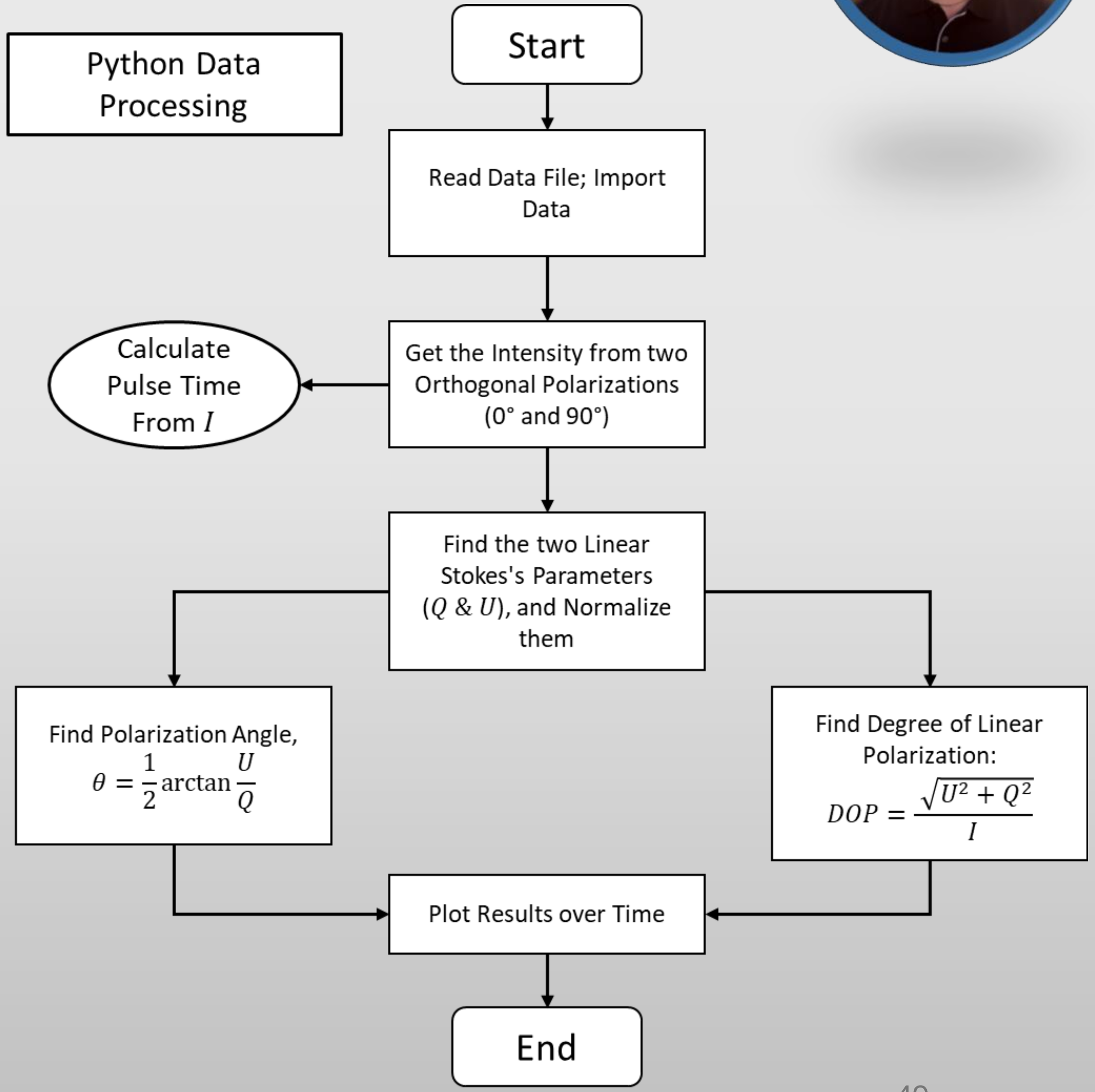
# Broad State Diagram

- Green border is starting state
- Top section are states for ESP32
- Bottom section are states for Python
- Communicates occurs through UART to USB bus




# Data Processing

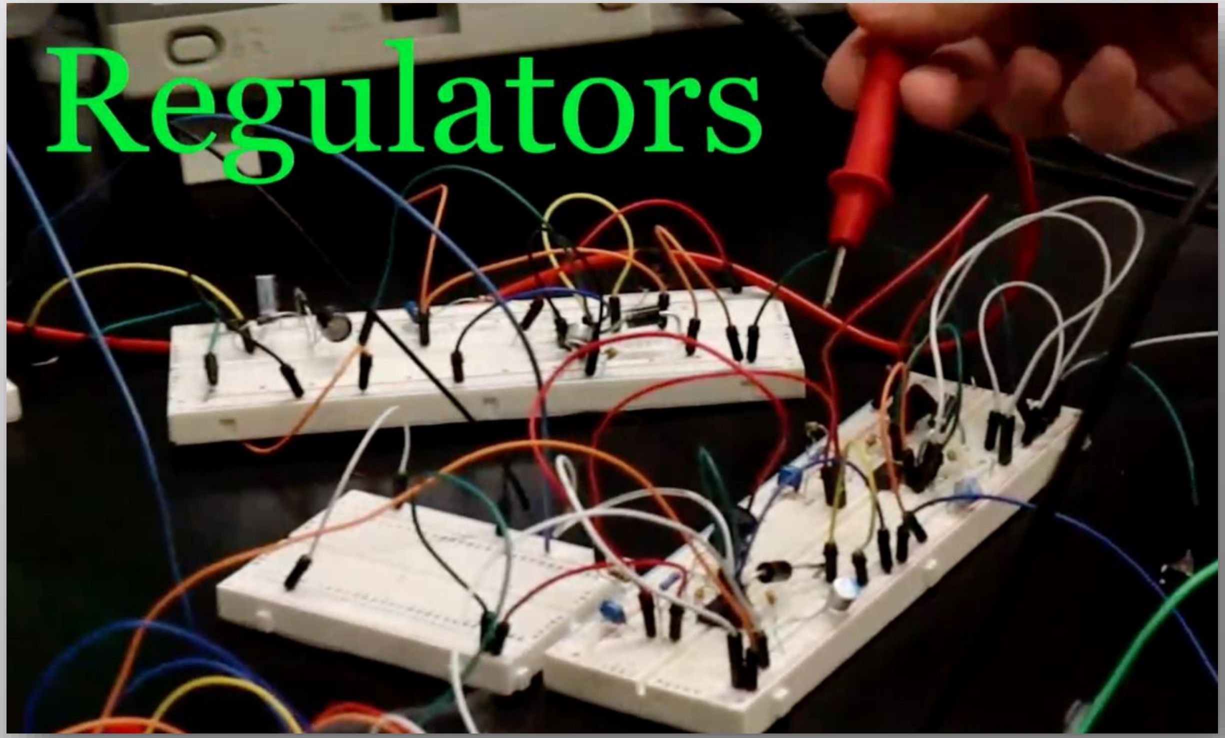
- Gives meaning to the data:
  - Angle of polarization
  - Degree of linear polarization
  - Pulse time and plot
  - Fourier transform
- Export data into .FITS file format
  - Preferred format for astronomers

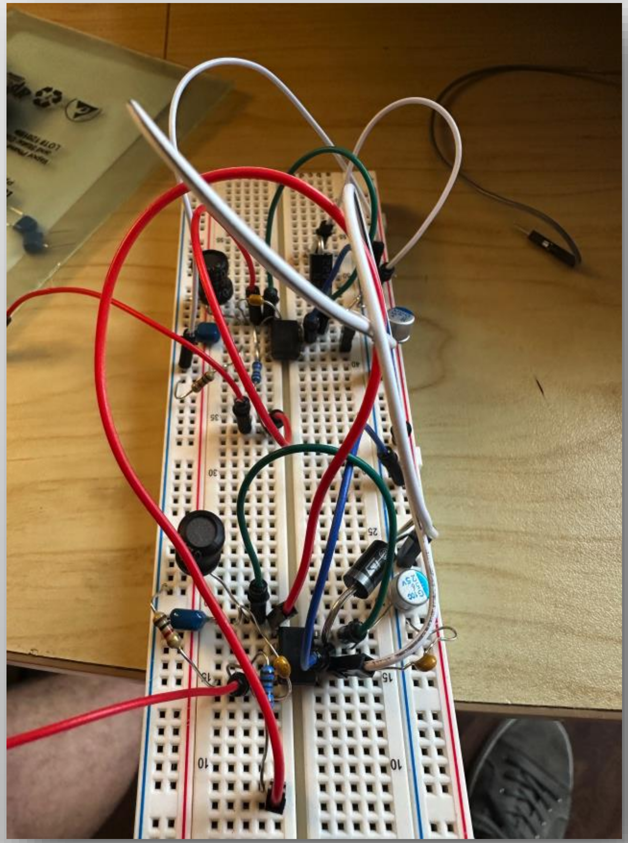


# Prototyping: Power Supply Unit

Regulator scheme breadboard construction 3.3V, 5V, and –12V

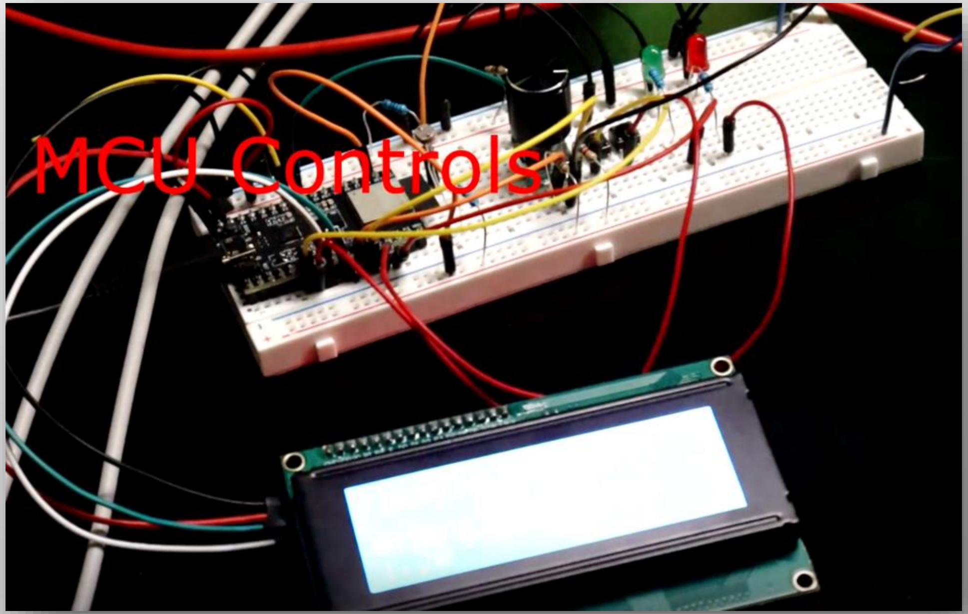
Utilized through-hole components with values as specified by the regulator manufacturer and following application instructions

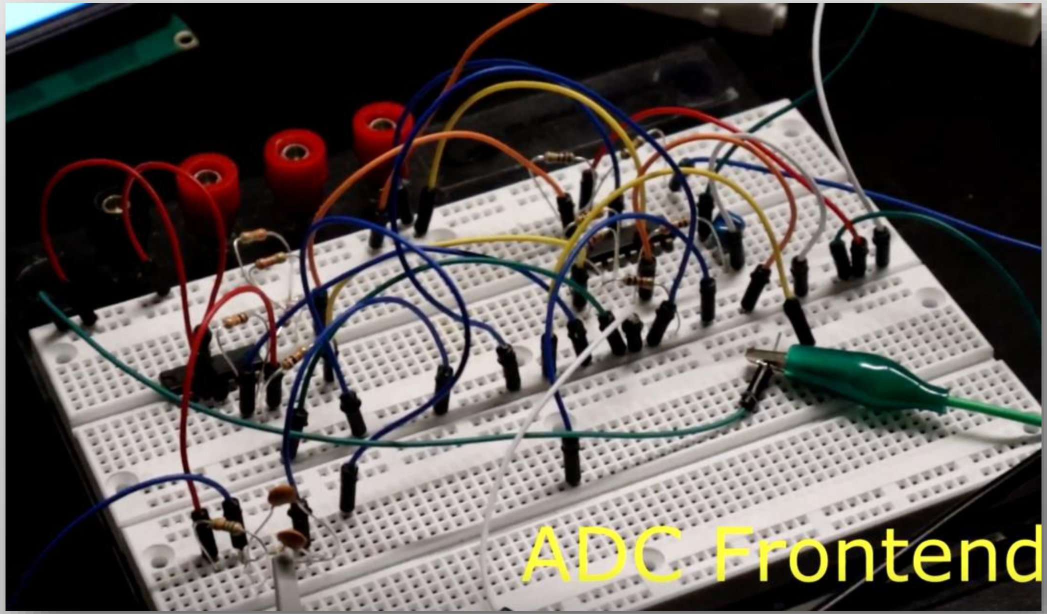


# Prototyping: MCU Interfaced With Controls and Peripherals

- Electronics: AFE circuit construction, and MCU Dev board interfacing.



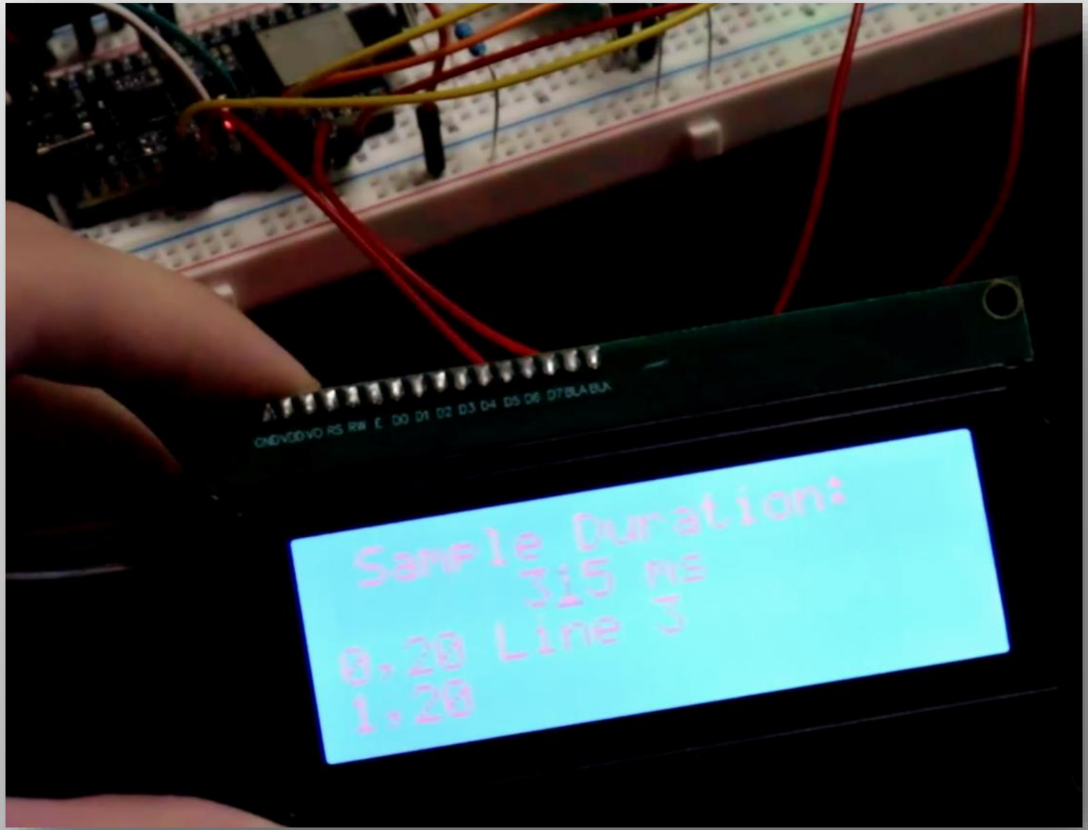



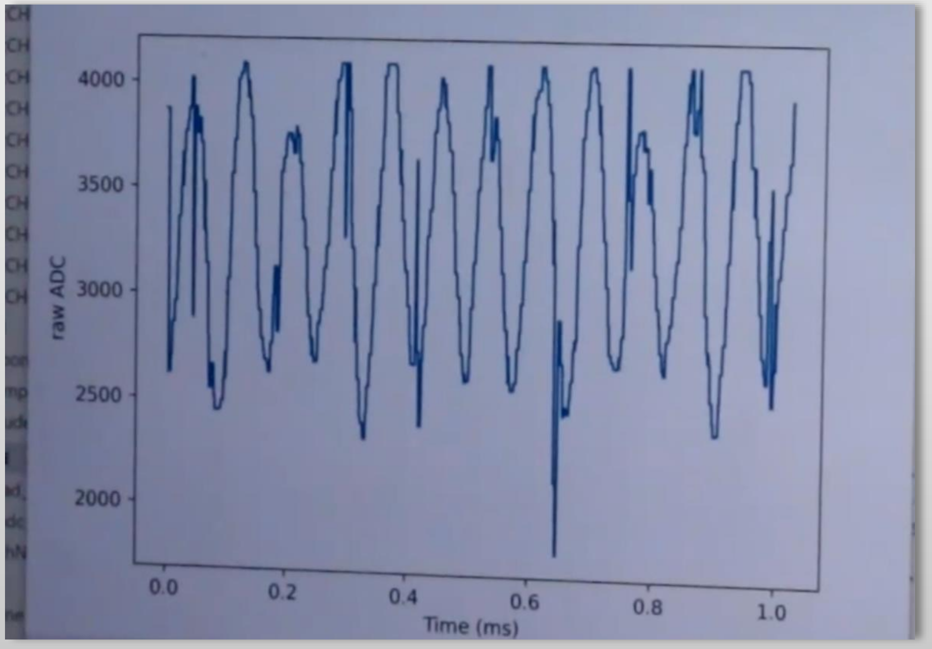
# Prototyping: Optics

- Use of lenses to match the telescope's f/# and simulate its output.
- Use of a Wollaston prism to take polarization measurements of a test light source, in combination with a rotating half wave plate to affect polarization at a rate of 1 Hz.
- Measuring the response of photodetectors to a known source.
- Demonstrating multiple imaging paths by use of a flip-able mirror.

# Testing: MCU, Peripherals, and AFE Prototype

- Controls and display, AFE testing, ADC sampling at 1 μs, Rotation mount testing
- What we learned: AFE adjustment, ADC buffer/memory management




Plotted data from the ADC sampling at 1MHz for a 100kHz sine wave

# Testing: PSU Prototype

- 3.3V and 5V regulators had successful output
- 3.3V and 5V worked when implemented with the MCU prototype board
- Inverting scheme using LM2576 failed, using inverting charge pump off a 12V LM2675-ADJ regulator failed
- MAX17577 was ideal regulator for allowing inverting output with sufficient current output. Multiple inverting modules will be needed in final project to meet requirements

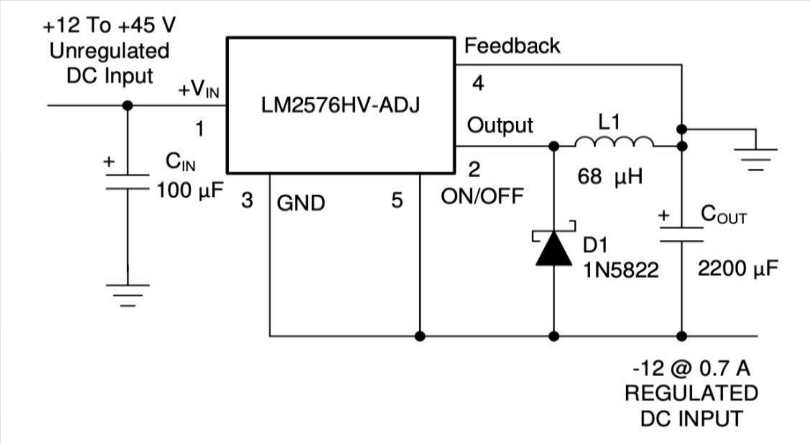
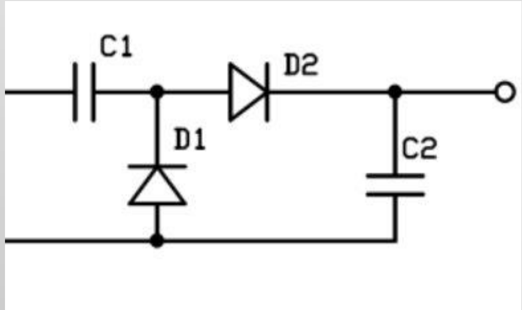
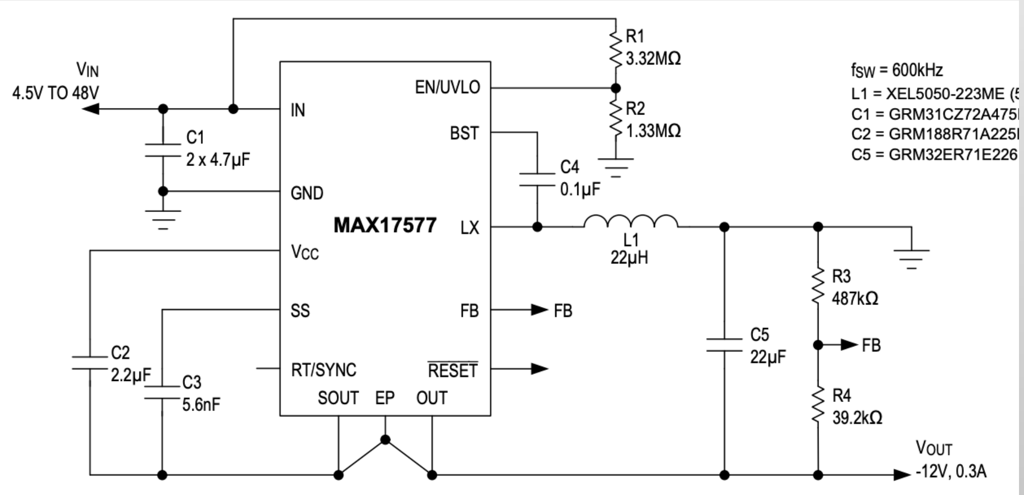



**Figure 8-1. Inverting Buck-Boost Develops −12 V**

LM2576 inverting output scheme
Original design (failed)




Inverting charge pump which connected to LM2675-ADJ PWM output
Secondary plan (failed)




MAX17577 inverting output scheme

# Testing: AFE Prototype

Tested AFE by looking at the FFT Frequency transform, in hope of showing noise reduction. Input to the AFE was a10 kHz sine wave  with 200 mVp-p from a function generator. A 1 MHz RC filter was used at the output of the AFE


Input Signal FFT


Output Signal FFT

# Budget

| Item | Qty. | Cost |
|---|---|---|
| Photodetectors | 4 | $6400 |
| Lenses / Mirrors | 18 | $600 |
| WeDoWo | 1 | $2500 |
| Waveplate | 1 | $1600 |
| Camera | 1 | $250 |
| Chips | | $20 |
| PCB Printing | 5 | $70 |
| Circuit Components | - | $100 |
| Housing Materials | 1 | $100 |
| Mechanical Components | 3 | $650 |
| **TOTAL** | **-** | **$12,290** |

# Distribution of Labor/Work

General Breakdown:

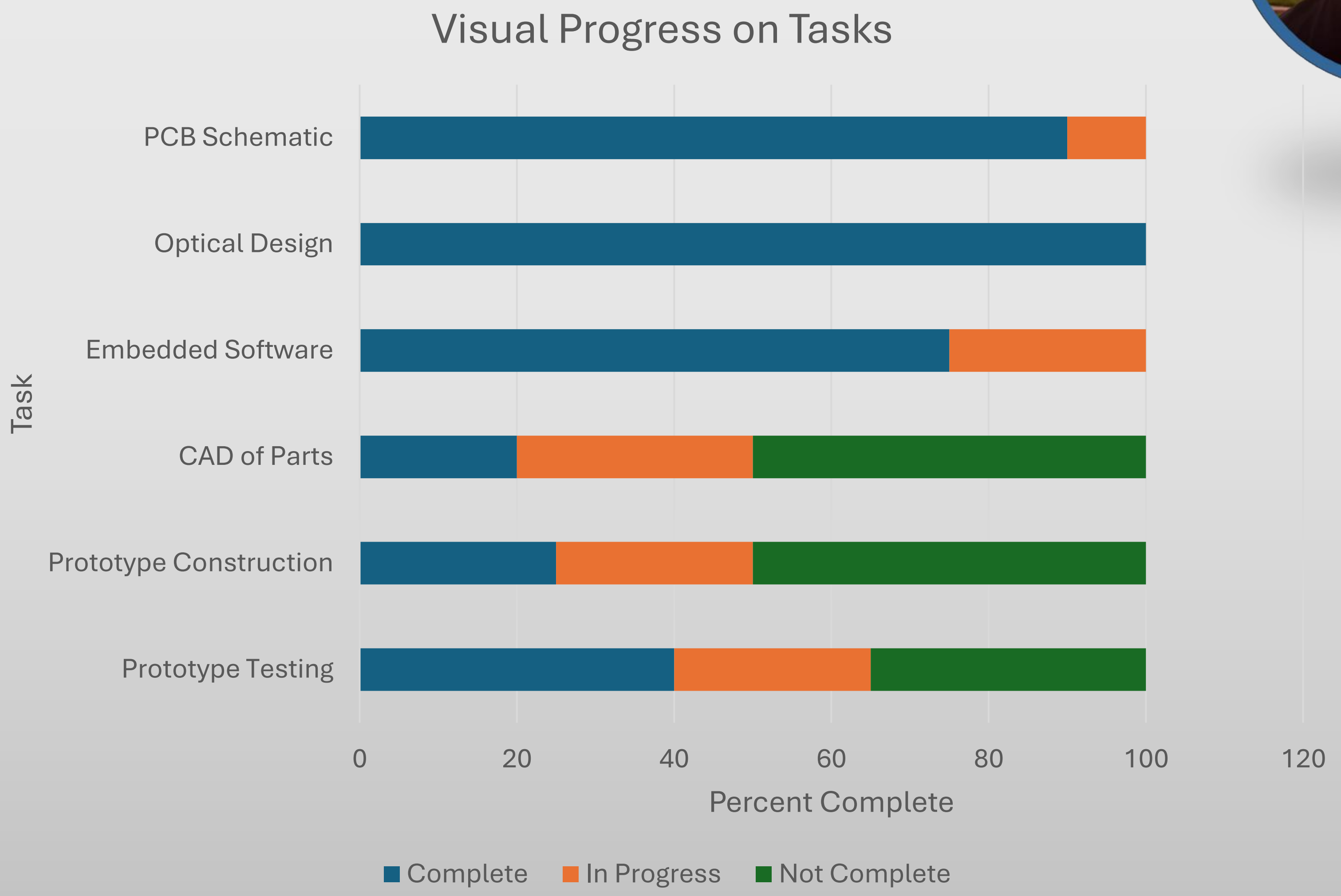
- Optics Design: Vincent Miller (Polarimeter) and David Patenaude (Dual Imaging System)
- Hardware Design: Ethan Tomczak (Analog processing and PCB design)
- Software Design: David Patenaude and David Urrego

Detailed breakdown:

| **Area** | **Primary** | **Secondary** |
|---|---|---|
| Project Manager | David P. | Vincent |
| Website Design & Management | David P. | David U. |
| Polarimeter | Vincent | David P. |
| Image Acquisition | David P. | Vincent |
| Embedded Coding | David P. | David U. |
| Python Package | David U. | David P. |
| Power Supply | Ethan | David U. |
| PCB | Ethan | David P. |

# Progression

- PCB acquisition and board assembly
- Software testing and debugging
- About to order boards
- Finish last few tests
- Communication between MCU and Waveplate
- Construct Optical Prototypes




# Plan to Finish

- Weekly tasks planned out
- Testing and integration activities included
- Includes submission deadlines

| | | |
|---|---|---|
| #4, 9/9 | - PCB Review Meeting by 9/13 | - CDR power point<br>- Waveplate w/ MCU<br>- MCU ADC -> sample desired amount and print<br>- (SW) Testing of the above |
| #5, 9/16 | - CDR Presentation (video) Due 9/18<br>- Our CDR Presentation Lecture 9/20 | 1. Record CDR slides<br>2. SD card speed testing/implementation<br>3. Start housing assembly?<br>4. Start designing/CAD of assemblies. |
| #6, 9/23 | - CDR Lecture part 2 | - Start Assembling optical components |
| #7, 9/30 | | - Start Assembling electrical components (mounting and wiring)<br>- Test Optical.<br>- Test electrical<br>- Schedule Midterm meeting |
| #8, 10/7 | | 1. Film midterm demo video<br>2. Integration testing carry over |
| #9, 10/14 | - **Midterm Demo (video) due 10/19 (5pm)** | - Filming carry over |
| #10, 10/21 | - Midterm Demo Meeting (from 10/21 to 10/23) Zoom | - |
| #11, 10/28 | | |
| #12, 11/4 | - Conference Paper due 11/8 (12pm) | - BE DONE BY NOW!! |
| #13, 11/11 | - Reserve Time Slot for Final Pres. by 11/15 | - |
| #14, 11/18 | - **Live Demo (CREOL) Friday, 11/22** | - |
| #15, 11/25 | - Final Documentation due 11/26 (12pm) | - |

# Questions?