Crab Pulsar Polarimeter and Pulse Timer

Group 3

Vincent Miller (PSE), David Patenaude (PSE & CpE), Ethan Tomczak (EE), David Urrego (CpE)

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Sponsor: Dr. Stephen Eikenberry
Reviewers: Dr. Mark Maddox, Dr. Sonali Das, Dr. Stephen Eikenberry

Chapter 1 – Executive Summary

Chapter 2 – Project Description

2.1 Project Background and Motivation

2.1.1 Background

Our project is about making an instrument that can measure the polarization and pulse timing of pulsars, which are neutron stars that emit pulses. We plan to accomplish this by attaching our instrument to a pre-existing telescope. To measure the polarization, we intend to make a linear Stokes polarimeter. By attaching this instrument onto the telescope, we can analyze intensity of light after it passes through the polarizers and waveplates, which allows for the polarimeter to calculate the Stokes parameters. These parameters include light intensity, circular polarization, as well as linear polarization. This data reveals the degree and angle of polarization. Light from the Crab Pulsar will also be processed to determine how the light is polarized. Overall, our tool can be used to determine the orientation and degree of the pulsar's magnetic field and analyze the interactions between the pulsar's emitted light and its surrounding environment.

2.1.2 Motivation

The motivation for this project comes from Dr. Stephen Eikenberry, who is a professor at the University of Central Florida, College of Optics and Photonics. His research focuses on astrophysics and the development of instrumentation for Astrophotonics research.

At Dr. Eikenberry's request we are building an instrument to measure the pulse timing and polarization of light from the Crab Pulsar, an optical pulsar approximately 7000 light years from earth. Pulsars are a type of neutron star that emit bright, directed beams of radiation while simultaneously spinning at high speeds. This leads to a pulsing effect where the brightness of the star increases and decreases periodically, as the beam points towards and then away from astronomers on Earth. Among astronomical objects, this regular pulsing behavior is unique to pulsars, and it makes them a valuable tool for scientific research.

All neutron stars, pulsars included, are a highly unusual type of star with extremely fast rotational velocities, strong magnetic fields, and extreme densities. The polarization and pulse timing data provide astrophysicists with vital information needed to study the structure and dynamics of pulsars. Polarization data discloses details about the pulsar's magnetic field such as its structure and strength, this can help explain how the pulsar emits radiation and interacts with particles. Measuring pulse timing can provide the distance of a pulsar from Earth, it can give information on the pulsar's rotation and stability, and measuring changes in a pulsar's timing can indicate internal processes like starquakes and/or interactions with nearby objects. The combination of these two data points can serve astronomers by helping scientists understand the pulsar's behavior, structure, and the space around it. The extreme rotating magnetic fields near the surface of these types of stars interact with outgoing particles and produce linearly polarized light, which is what our project will be detecting. When synchronized with pulse timing measurements, our instrument will provide novel scientific data that will help scientists study these extreme and complex objects. Since pulses from the Crab Pulsar are detectable at visible wavelengths, our project will be built using visual spectrum optical components. It will be mounted onto the existing 20-inch telescope at the University of Central Florida's Robinson Observatory. It is uncommon for pulsars to emit visible light, as there are only a handful of such pulsars known. The Crab Pulsar, being one of these rare exceptions, provides a unique opportunity to study its properties in detail. By focusing on visible light, our project aims to capture high resolution data that can reveal new insight about its emission mechanisms and magnetic field structure, which are characteristics that would be difficult to obtain at other wavelengths. Having a better understanding of this pulsar could greatly contribute to the field of astrophysics in a variety of ways.

2.2. Existing Projects and Products Comparison

2.2.1 Mini-HIPPI (Miniature High Precision Polarimetric Instrument)

This telescope polarimeter developed by Jeremy Bailey, Daniel V. Cotton, and Lucyna Kedziora-Chudczer displays very similar functionality to the product we would like to develop. The Mini–HIPPI is a telescope mountable stellar polarimeter which has the following design properties: high precision measurements (0.1% error), compact footprint (weight of 650g), large wavelength coverage (nanometer range), and lastly sophisticated optical design coupled with sensitive detectors. The optics section of the module comprises a ferroelectric liquid crystal (FLC) modulator, a Glan Taylor Prism, and a collection of photomultiplier tube modules **[1]**. The use of a FLC modulator rather than a wave plate retarder is important to note. FLC modulators allow for fast, real-time application, whereas a half wave plate retarder may want to be selected for higher precision and reliability. Furthermore, for this polarimeter design, the team chose a Glan Taylor prism which limits the measurements to linear polarization states of the input signal. This prism was primarily chosen for simplicity and cost-effectiveness. In summary, the Mini-HIPPI is an excellent project to reference for our project design considering the optics design.

2.2.2 ThorLabs High-Dynamic Polarimeter

An existing product on the market is a pre-built polarimeter. These polarimeters come with different wavelength ranges and an accuracy of ±0.25°. They operate on the principle of using a rotating quarter-wave plate and a linear polarizer hooked up to a photodiode. The use of a quarter-wave plate allows for the instrument to detect circularly polarized light. This particular polarimeter from ThorLabs has a max sampling rate of 400 samples/s [2]. In our case, we would require a higher sampling rate to achieve the temporal resolution to see the pulse features. We are also dealing with incoherent light, which this polarimeter cannot handle.

2.2.3 Radio Astronomy Polarimetry

Polarimetric measurements of various pulsars have been taken before and are most commonly done using radio frequencies. This is simply because, of the over 3000 known pulsars, the overwhelming majority pulse at radio frequencies. Additionally, radio polarimetry in astronomy can often be done without specialized measurement devices, since radio antennas are inherently susceptible to the polarization of the received signal. Specifically, this is the case with the ALMA radio telescope [3]. Unfortunately, radio frequency polarimetry cannot be used to replace visible spectrum polarization data. Visible spectrum light and higher energy light provide unique information about the high energy interactions and mechanisms taking place within pulsar magnetic fields.

2.2.4 Summary

Overall, it is critical that we do research on existing products and projects related to our project to compare design measures and locate potential obstacles that may slow developmental and prototyping processes. Through the work of others, we can also see if certain methods should or should not be considered regarding our design specifications. Additionally, the research opens the avenue into new technologies that may suffice a requirement we desire. Using this approach will aid our development timeline and will improve the overall quality of our final product.

2.3 Goals and Objectives

2.3.1 Goals:

Our basic goals:

- <u>Optics:</u> high fidelity optical coupling to the telescope; beam-splitting along optical paths; minimal power loss.
- <u>Hardware:</u> Power supply unit with rechargeable battery; PCB contains data path from peripherals, oscillator, physical control panel containing LCD, sampling start/stop button, and oscillator control; MCU to direct control flow and data flow; On-board memory and USB I/O for data processing.
- <u>Software:</u> Control flow for hardware; sampling start/stop and wave plate oscillation adjustment.

Then some advanced goals:

- <u>Optics:</u> Exit-pupil imaging for alignment; high temporal and angular resolution measurements.
- <u>Hardware:</u> Adjustable sampling rate and duration; Variable frequency oscillator for waveplate; Physical controls (buttons, dials, LCD, etc.) on physical instrument.
- <u>Software:</u> Effective and logical data management and precision processing of pulse timing and polarization intensity; program UART for external (PC) control.

Our stretch goals:

- <u>Optics:</u> Better than 0.1% polarization angle error.

- Hardware: 1 hour battery run time without connection to outlet source; Remote sampling and oscillator controls; Low power mode.
- Software: Full GUI program.

2.3.2 Description of Features and Specifications

The expected pulses from pulsars will be on the order of 30ms, but in order to see the features of the pulse, we will sample every 1µs. The detectors will therefore have to be fast and sensitive due to the faintness of the incident light. To measure polarization, the design will feature a modulated waveplate and Wollaston prisms to separate the light into 4 beams, which go through a polarizer before the detector. This set up describes a linear Stokes polarimeter.

To track the pulsar in the night sky, an image is captured and sent to the telescope's built-in tracking software. The input light is split upon entering the instrument using a beamsplitter, allowing an image to be taken on one path, while the other path continues into the instrument. As an optional feature, we will also save the camera's image to our internal storage. This makes it more convenient for the astronomer to retrieve the image for viewing.

Some other features we will implement are the ability to adjust the sampling frequency and the sample duration. By default, we will design for a 1MHz sampling rate, and 50µs duration. We will allow the sampling rate to increase to 2MHz and decrease to 100kHz while allowing the sample duration to increase to 250ms and decrease to 25ms. The sampling rate will dictate how fast of an analog-to-digital converter we will need. The sample duration dictates how much storage is needed, although this isn't a huge issue as memory chips are cheap. The main issue is ensuring that the memory is fast enough to not bottleneck the data acquisition. This feature will be implemented by adding some buttons or dials with a basic LCD character display, which allows direct control. We may also consider making it software controlled via a program on a plugged-in computer. This gives more choice to the astronomer for how much continuous data they may want.

To ensure minimal optical power loss from reflection and absorption when the light is coupled and manipulated by the instrument. This is an important consideration given the low incident light intensity from astronomical sources. This can be accomplished by minimizing the amount of glass material that the light must travel through, such as lenses and beamsplitters. When a lens is used, an anti-reflective (AR) coating can be used to virtually eliminate Fresnel reflection losses. To ensure minimal losses, the optical power loss will be calculated for the optical design to ensure that sufficient power reaches the detectors.

2.3.3 Illustrations

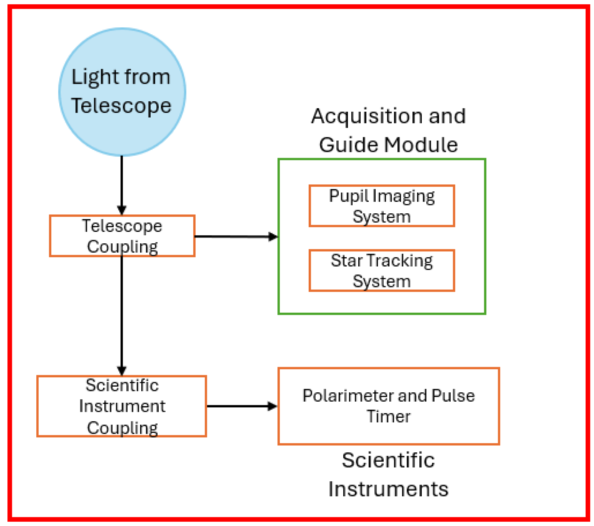

Figure 2.1 - (Left) Illustration of prototype (red) mounted onto a model of the Robinson Observatory telescope (black). (Right) Preliminary layout of individual optical system blocks within the prototype

2.3.4 Hardware Objectives

The physical structure of this device is separated into three components: power supply unit (PSU), printed circuit board (PCB), and the optics coupling and detection module. Within the power supply unit, we will house a battery which will supply power to printed circuit board and its peripherals. The design must meet our specification of supplementing the module with enough power for at least one hour before shutdown. In cases in which the module is low on battery, we will also include a 120V AC adapter within our design to charge the module. The module is intended to operate with the power from the adapter but can be disconnected if desired.

The printed circuit board will consist of the following components: Controls for adjusting sampling rate and start/stop of data collection. A separate potentiometer control for the half wave plate oscillation frequency will also be included allowing for the user to adjust the quality of the collected signal. MCU must have an ADC module which can sample at a rate of 1MSPS for our desired resolution. A Control board will host the necessary peripherals such as: buttons, knobs, and LCD needed for the previously mentioned functionalities. These control features will help us to collect an accurate sampling of data and allow for resolution adjustment if needed. We will have four distinct plane wave detectors in the optics module which would require approximately 780KB of data for all sensors to read for 50ms. The PCB will contain on-board memory storage of 4GB which will allow for approx. 5377.3, 50ms samples before needing to be cleared. A USB 3.0 port will be installed for first programing the MCU for proper functionality, and secondly allowing for data collection from an outside computer. The MCU will have input from the detectors which will be processed by the internal ADC to sample then save the incoming signal from each plane wave detector. Lasty, also in conjunction with the optics section we must include an oscillator which will send a signal to the half wave plate retarder. Our target output for the oscillator is 100 Hz sinewave anywhere from 5V to 25V depending on wave plate selected.

Attaching to the telescope mount itself will be the star tracking equipment, polarimeter and pulse timer, and the necessary coupling optics. Due to the rotation of the Earth, the telescope will need to be constantly adjusted to stay pointing at the target star. We will accomplish this by building a separate optical path from the scientific instruments, where the starlight is instead imaged onto a CCD. The image detected by this CCD will then be sent to the established telescope tracking and control software, which will make all necessary adjustments. This will be sufficient for the telescope to stay on target during our observations. The scientific instrumentation that we will be building is a linear stokes polarimeter that will simultaneously be used to measure pulse timing. This consists of a double wedged Wollaston prism, which will split the incoming light into two pairs of beams, where each pair has orthogonal polarizations. Each path will have its own linear polarizer at a unique angle. By using 0, 45, 90, and 135 angles for the four polarizers, we can determine the signal's stokes parameters by comparing the intensity readings from each detector. Changes in the total detected intensity will be used to find pulse timing. The variable half-wave plate is continuously cycled to filter out variations in polarization created by the instrumentation itself that would otherwise overwhelm the signal. Coupling optics will be needed to ensure that all light collected by the telescope can be received by the scientific instruments. The telescope in question is a 20" f/8.2 Ritchey-Chretien telescope, and our coupling optics will need to fit this system such that all light enters the system, while also not being overly large to allow extraneous signals in.

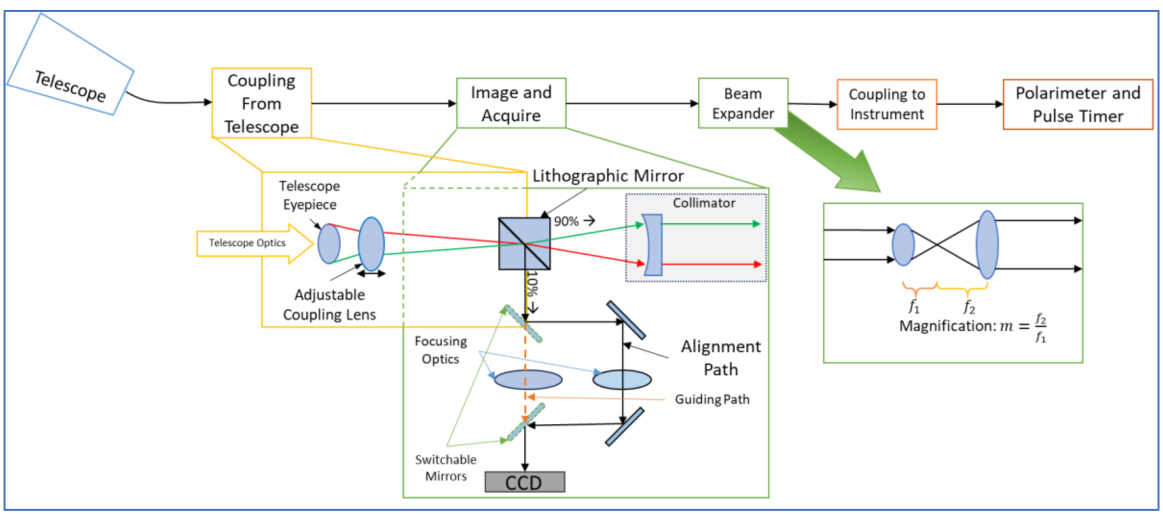

Figure 2.2 - Initial Optical Design for Coupling, Imaging, Collimation and Beam Expansion.

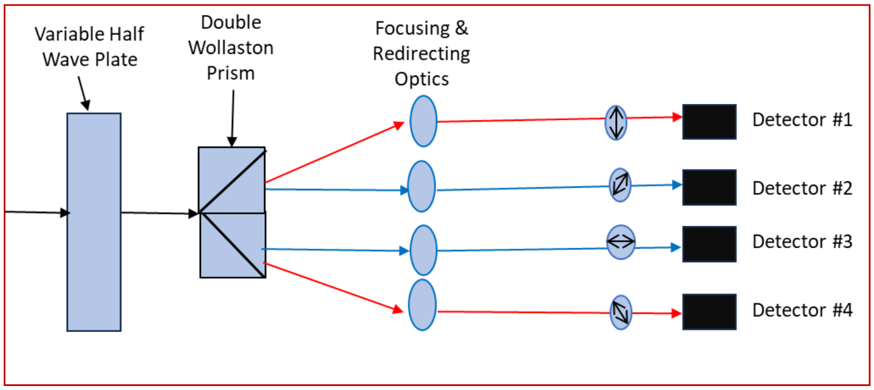

Figure 2.3 - Initial Optical Design for the Polarimeter.

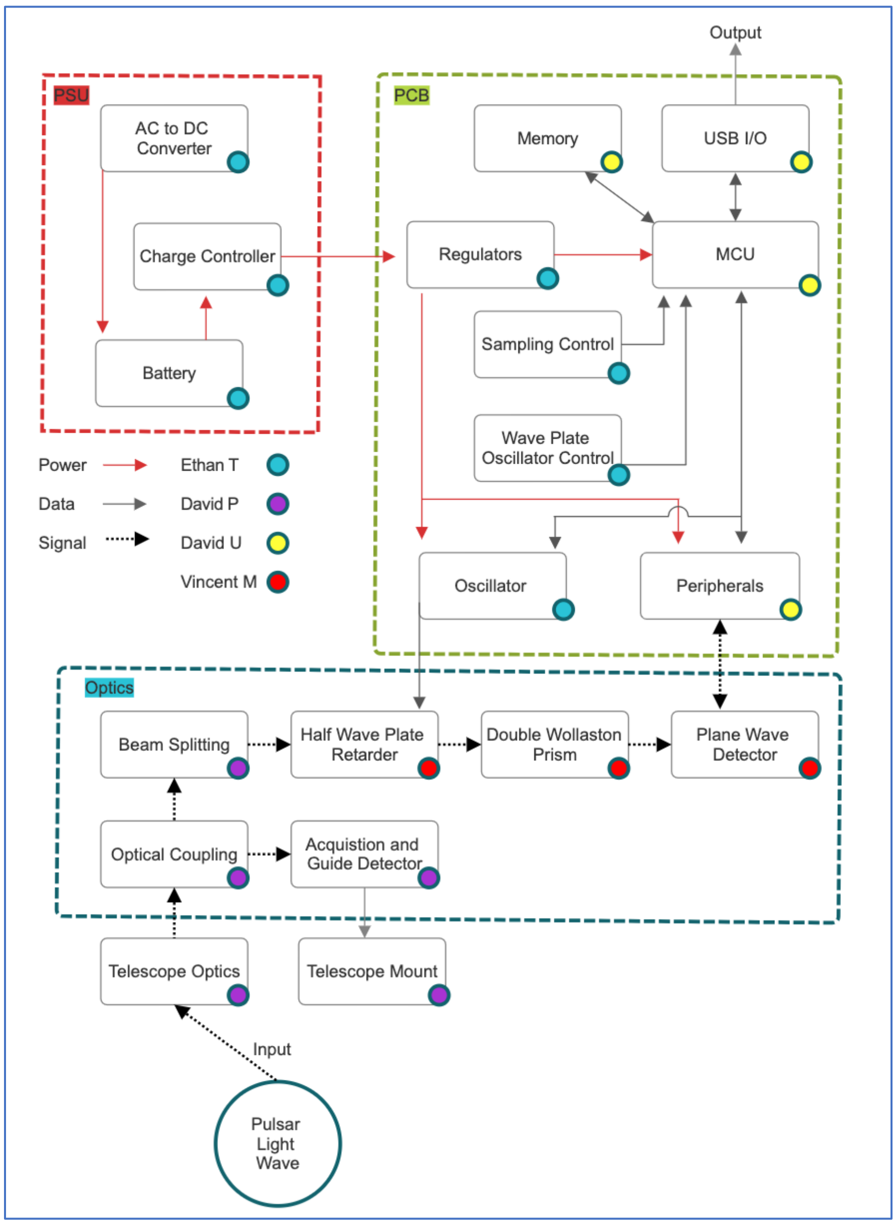

Figure 2.4 - HW diagram, broken down into 3 components: power supply (PSU), PCB, and Optics.

2.3.5 Software Objectives

On the software side, we will be acquiring the sensor data and processing it. The acquisition will be from 4 detectors, which require conversion from an analog signal to a digital signal. The digital signal can then be stored in a cache until sampling is complete, where it can be formatted and stored more permanently. We plan on formatting the data as a '.FITS,' which stands for Flexible Image Transport System, which is a common file type used by astronomers.

To get the pulse time, we first find the intensity of the light by combining the intensities from two orthogonal detectors, such as the ones at 0° and 90°. This finds the 1st Stokes' parameter and is used to scale the other parameters. With the intensity, the signal should be oscillating sinusoidally, and so we find the pulse time by measuring the difference between two maxima. The maxima can be found either by enumeration through the data, or by using calculus (derivatives) to find them. The general flow is shown in figure 2.5 (left).

For finding the polarization, we find the other two Stokes' parameters. The 1st parameter I is the intensity and is used to scale the Q and U parameters. The Q parameter is found by taking the difference of the squares between 0° and 90°. To account for unpolarized light, the 3rd parameter U is found by taking the difference of squares between 45° and 135°. The general flow chart is shown in figure 2.5 (right) below.

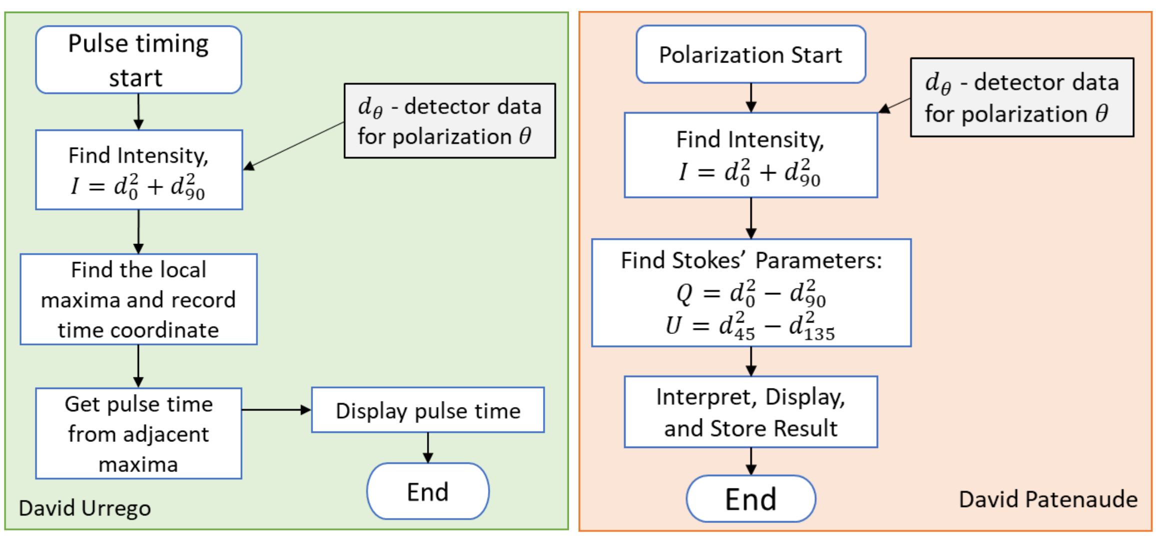

Figure 2.5 – (left) Flowchart for finding pulse time. (right) Flowchart for finding the polarization.

Additional programming of the microcontroller is also required. This is mainly for control flow. The control flow section of the flow chart below shows a design that displays systematic data processing and user interaction. It begins with the user pressing a yes/no button that will trigger a reaction of events, the system's first response is to catch the voltage level from the potentiometer. Each voltage range will have a respective frequency it corresponds to, a start message will be displayed alongside the frequency on the LCD screen. This way the user is always aware of the system's status. The system then generates a signal frequency directed at the wave plate which is crucial for data collection and polarization quality. Once the signal is output a 50 ms runtime sample is collected. During this period, the system samples and holds buffer data, then saves it to the main memory, efficiently capturing and storing data to maintain integrity and accuracy. From here, the control flow branches into two parallel paths: one where the system ensures sufficient memory space and organization for incoming data through memory allocation, and another where it stops sampling and displays a session termination message on the LCD, informing the user. This structured approach optimizes data handling and memory management while enhancing user experience by providing real-time updates.

In the data management portion of the flowchart, the process begins with memory allocation, a critical step ensuring that sufficient space is set aside for subsequent operations. From memory allocation, the flow branches into two paths. The first path involves assigning address space for detectors 1 through 4, with each detector receiving 1 GB of memory. The second path involves tagging the sampling session, which requires 200 KB of memory. These two branches converge into a single step: USB transfer out. This final step involves transferring the allocated data, both the detector address spaces and the sampling session tag, out via USB. This structured flow ensures efficient memory use and smooth data transfer, keeping the system organized and making it easier to analyze and store data later.

The USB transfer leads to the data processing section of the flowchart. The first block in this section is the software package, which splits into two paths. The first path combines the intensity data from single plane wave detectors with its pair, locates data maxima and timestamps, and then calculates the delta between two maxima to determine pulse time. The second path calculates the Stokes parameters from the plane wave detector and uses these parameters to display a graph along with the corresponding polarization. Both paths converge at the final block, which displays the processed data on the monitor, ensuring comprehensive data processing and visualization.

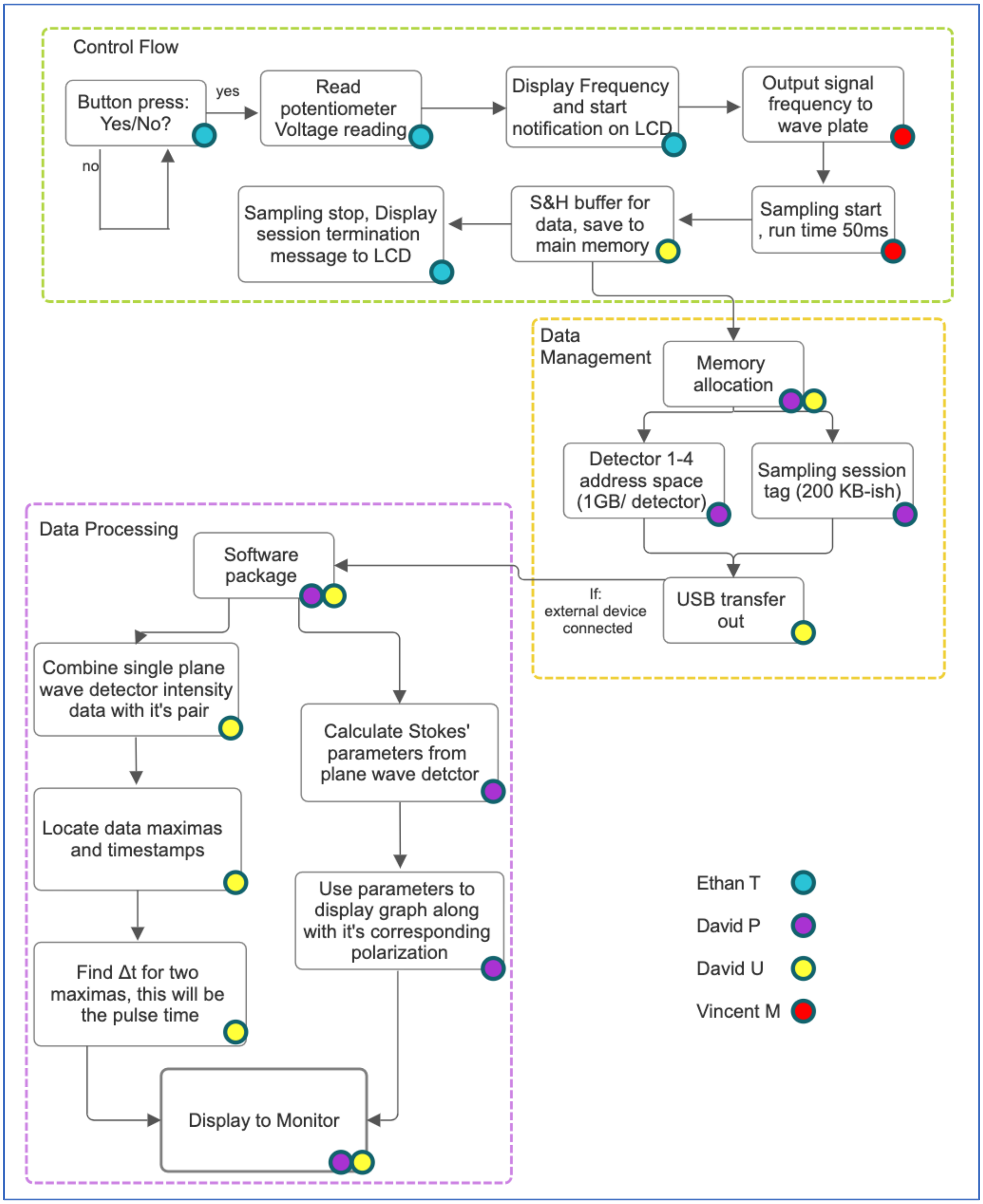

Figure 2.6 - Overall Software flow, including control flow, data management, and data processing.

2.4 Required Specifications

On account of the previous objectives and constraints, Table 2.1 provides the functional specifications.

Table 2.1 – Specifications for Design

Description	Specification	Justification
1. Angular Resolution for Polarization	0.1% Max. Error	Maximum allowable error
2. Sample Rate, ADC Module	1 MHz, 1 MSPS	Enables us to detect signals at 1µs temporal resolution
3. Optical Power Sensitivity	10 fW	The signals we intend to measure are weak
4. Sample Duration/Time	50 ms	Allows for capture of full pulsar pulse
5. On-board memory	4 GB	
6. Instrument Size	6”x9”x11”	Instrumentation must fit onto the available telescope slot.
7. Half Wave Plate Retarder Oscillation	0 –100 Hz	Determines quality of input signal

2.5 House of Quality

Figure 2.7 - House of quality, showing customer requirements and engineering specifications.

2.6 Budget and Financing

Our funding for this project is provided by Dr. Stephen Eikenberry through his Astrophotonics Laboratory. Dr. Eikenberry is a professor at the University of Central Florida, College of Optics and Photonics. Dr. Eikenberry is funding this project in order to further his astrophysics research. The instrument we are going to build will allow him and any other interested scientists access to astronomical data that has never been collected before.

Dr. Eikenberry is also providing our group with access to laboratory and observatory facilities for testing purposes. The telescope at the University of Central Florida's Robinson Observatory is where we will do much of our later stage testing and ultimately the final product integration for our project.

Table 2.2 – Preliminary Budget

Part	Quantity	Unit Cost	Total Estimated Cost
Single Photon Avalanche Photodetectors	4	$1000	$4000
Variable Half Wave Retarder	1	$100	$100
Guide Camera	1	$400	$400
Wedged Double Wollaston Prism	1	$1200	$1200
Polarizers	4	$300	$1200
Mirror/Lens Optics	10	$40	$400
Housing	1	$100	$100
PCB Printing	1	$100	$100
Power Supply	1	$100	$100
RP2040	1	$1	$1
TOTAL	**-**	**-**	**$8000**

2.7 Milestones

To make sure we are able to come up with a quality project and be able to deliver it in a timely manner, we have come up with key goals and milestones. Our main goals include defining clear objectives and requirements. Dr. Eikenberry is funding this project to further his astrophysics research. The significant PCB design and implementation, along with the 120-page documentation that will accompany our product. At the start of the project, we'll focus on setting clear goals, figuring out what we need, and understanding any limitations. We'll create a detailed plan that outlines when tasks should be completed by creating a Gantt chart with weekly deliverables that we discuss in biweekly meetings. Coming up with a budget given the specifications of our components needed will be essential.

Additionally, we'll conduct initial studies to ensure our ideas are realistic and aligned with our desired outcomes.

Next, we will select and acquire the major components, ensuring we have most, if not all, of the essential materials early in the project. During this period, we will test each major part using breadboards or development boards to verify their functionality and compatibility. This will lead to creating a detailed overall schematic design, which will be the basis for our PCB layout design.

Throughout the project, we will demonstrate our progress weekly during our twice-a-week meetings. These meetings will serve as checkpoints to ensure we are on track and to address any issues promptly so problems throughout our semester don't get a chance to build up. Additionally, we must produce a certain number of pages per week as deliverables to keep the project documentation on track and meet the 120-page final report requirement.

After the design phase, we will move on to the fabrication phase, where custom parts, optical components, and mechanical assemblies will be made according to our specifications. Following this, we will assemble all components into a working prototype. This phase will include careful alignment and calibration procedures to ensure our tool works correctly.

Midway through the project, we will conduct a midterm demonstration to get feedback and make necessary adjustments. This step is crucial for identifying any issues early and ensuring we stay on track. As we approach the final stages, we will focus on thorough testing to ensure all parts of the project meet our design specifications and performance criteria.

The final phase will involve completing all required documentation, including the final report, which must follow specific formatting and content guidelines. We will prepare for the final review and live demonstration by thoroughly rehearsing and ensuring all team members are ready to present their contributions effectively. Finally, we will participate in the Senior Design Showcase presentation, where we will demonstrate our fully functional prototype to faculty reviewers and other stakeholders. By following these goals and milestones, we aim to ensure the project's success and alignment with desired outcomes, ultimately leading to a successful demonstration of our prototype.

Declaration

Declaration: We hereby declare that we have not copied or used a Large Language Model (LLM) for the purposes of writing this proposal.

Appendices

Appendix A – References

[1] Jeremy Bailey, Daniel V. Cotton, Lucyna Kedziora-Chudczer, A high-precision polarimeter for small telescopes, Monthly Notices of the Royal Astronomical Society, Volume 465, Issue 2, February 2017, Pages 1601–1607, https://doi.org/10.1093/mnras/stw2886

[2] "Polarimeter Systems with High Dynamic Range." ThorLabs. www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=1564 Accessed 28 May 2024

[3] Paulo C. Cortes et al. "Interferometric Mapping of Magnetic Fields: The ALMA View of the Massive Star-Forming Clump W43-MM1" Volume 825, Issue 1, June 2016 INTERFEROMETRIC MAPPING OF MAGNETIC FIELDS: THE ALMA VIEW OF THE MASSIVE STAR-FORMING CLUMP W43-MM1 - IOPscience

Appendix B – Copyright Permissions (if applicable)

Appendix C – Color-Coded Contributions

Color Coded Contributions:

David Patenaude (SW Charts) Vincent Miller (Prototype Illustration) David Urrego Ethan Tomczak (HW, SW, and HoQ)