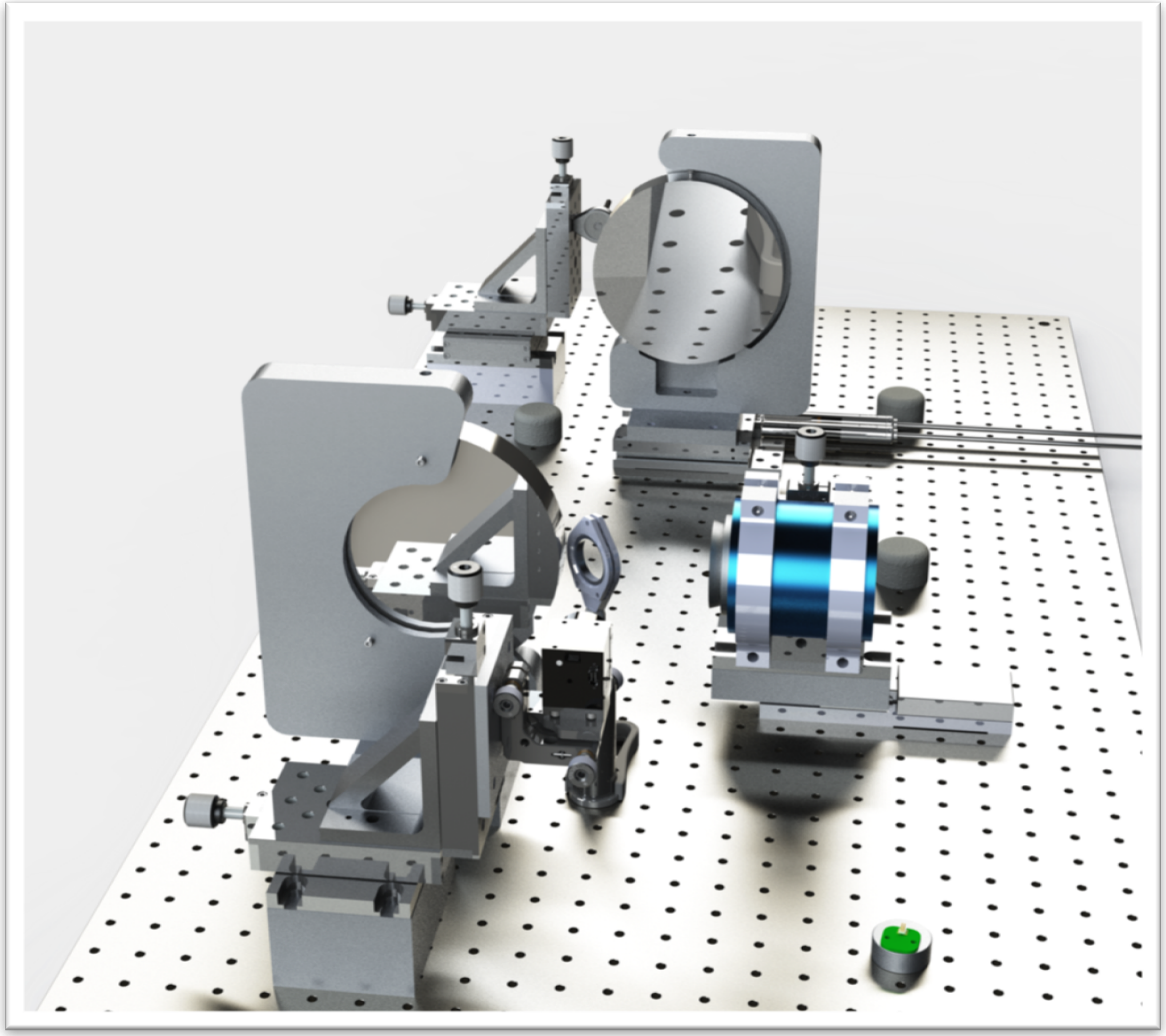
Apparatus for Wavefront Error Sensor Measurement:
Manufacturing Status Review

February 7, 2018

Authors: Robert Belter, Ali Colic, Jake Crouse, Lucas Droste, Diego Gomes, Ankit Hriday, Owen Lyke, Brandon Noirot, Owen Shepherd, and Brandon Stetler



Customer: Eliot Young
Southwest Research Institute
&
NASA Glenn Research Center

1.0 – OVERVIEW

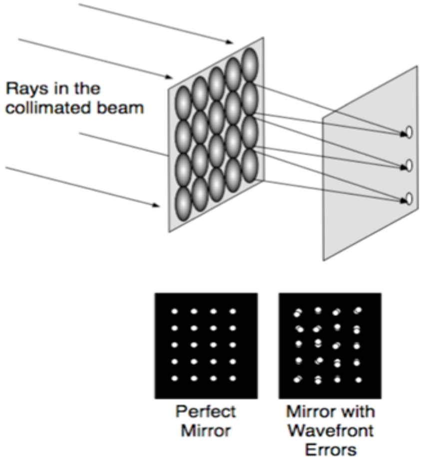
1.1 - Motivation

Project AWESoMe will characterize the performance of two wavefront detectors in order to determine which to use on an upcoming balloon optical payload.

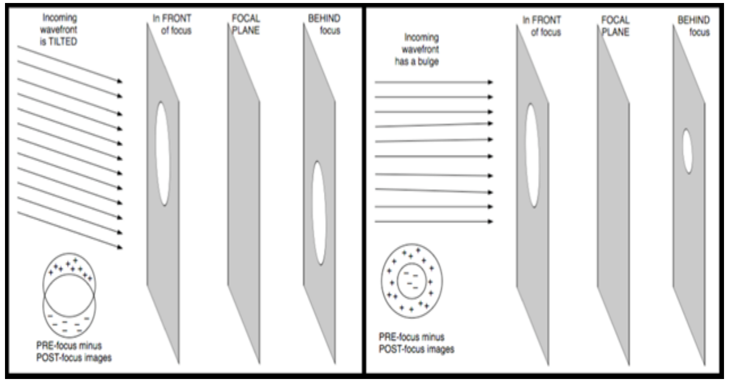
Potential benefits of RCWS:

- Simplicity in design - One CMOS vs. many microlenslets.
- Optics systems generally have a system for changing the focal length, can therefore use the main image detector.
- The RCWS method has the potential to perform equally or even better than the currently used methods on aerial platforms.
- Future missions could then choose SHA or RCWS systems based on performance data

Shack Hartmann Array

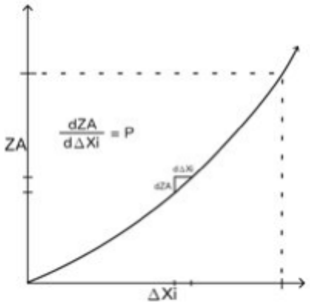


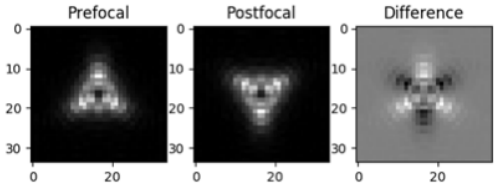
Roddier Curvature Wavefront Sensor



1.2 - Objectives

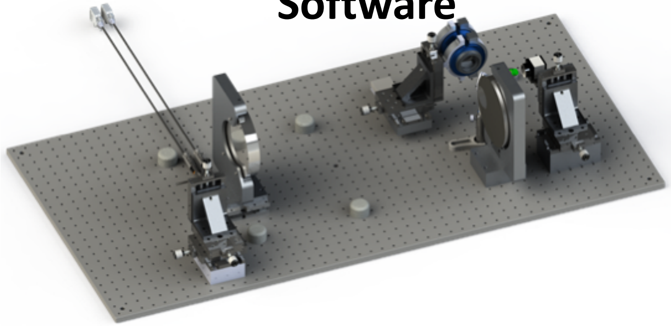
- Quantitatively compare the SHA and RCWS wavefront sensors as a function of source intensity
- Develop a prototype Roddier sensor to be used in the comparison
- Design and build a test platform that facilitates data collection with required precision and accuracy
- Develop forward-predictive models to drive the design and validate results
- Present preliminary results

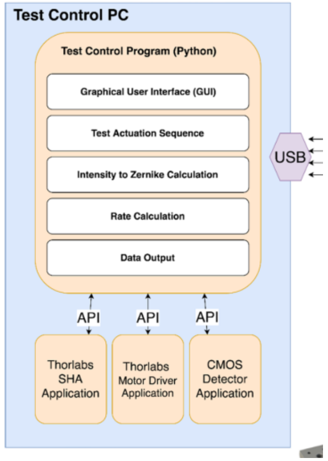




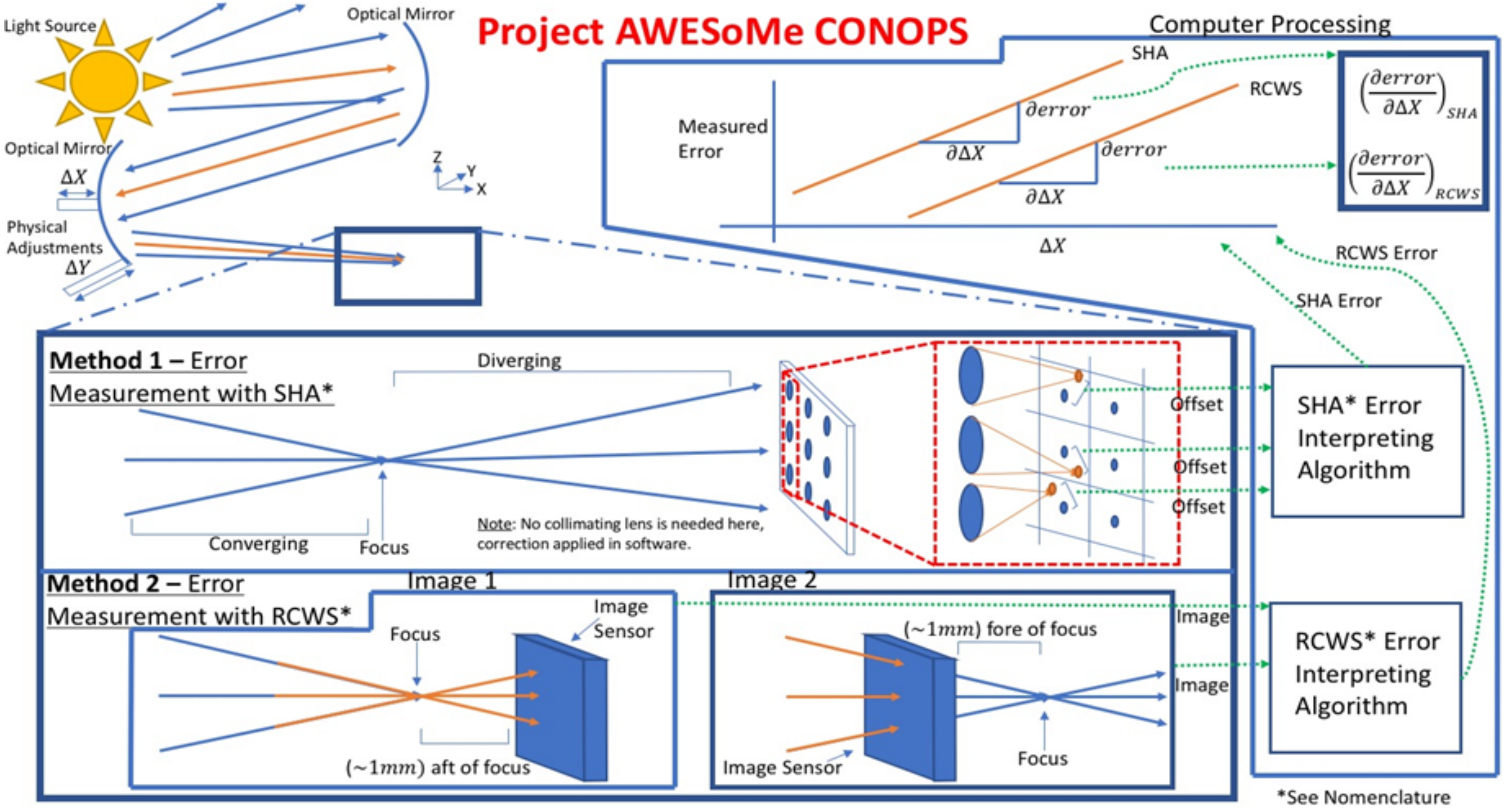
Rate Comparison

Testbed and Software

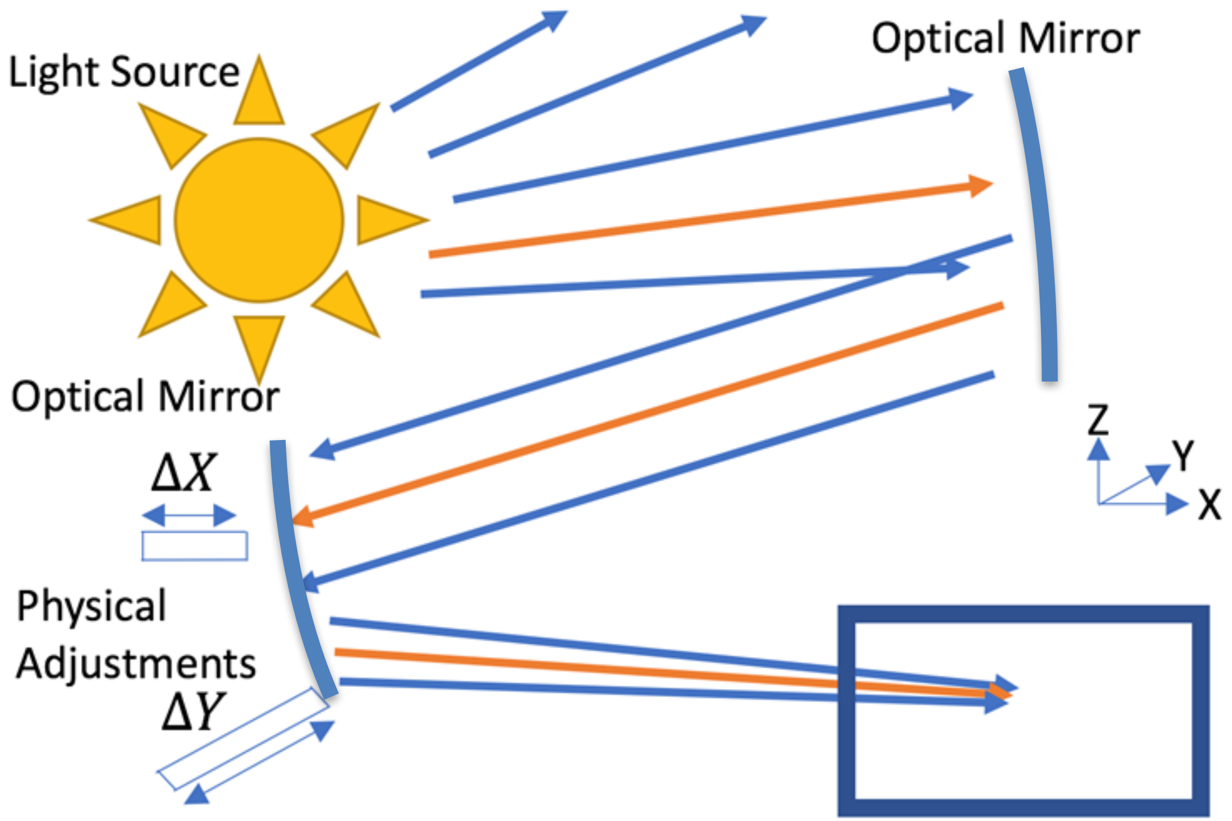




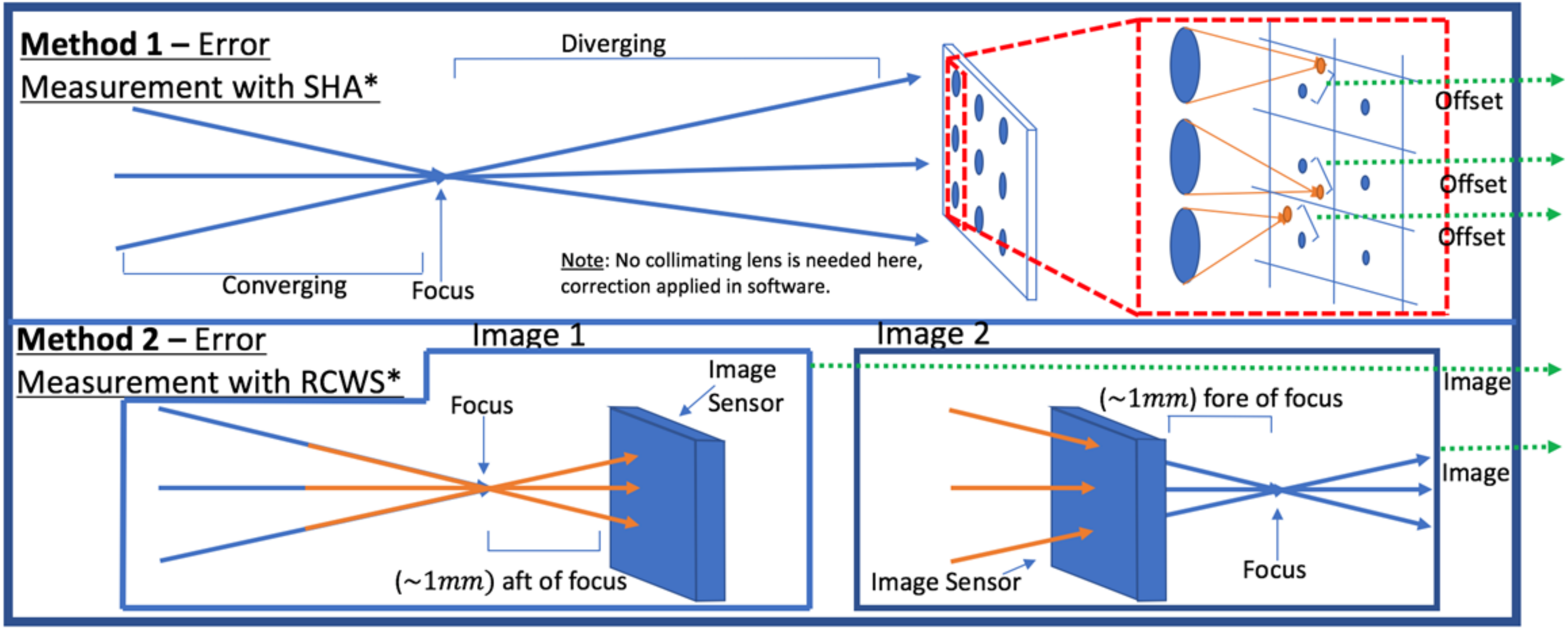
1.3 - CONOPS


Project AWESoMe CONOPS
Light Source
Optical Mirror
Optical Mirror
ΔX
Physical Adjustments
ΔY
Z
Y
X
Computer Processing
SHA
RCWS
Measured Error
∂error
∂ΔX
∂error
∂ΔX
ΔX
$\left(\frac{\partial error}{\partial \Delta X}\right)_{SHA}$
$\left(\frac{\partial error}{\partial \Delta X}\right)_{RCWS}$
RCWS Error
SHA Error
Method 1 – Error Measurement with SHA*
Diverging
Converging
Focus
Note: No collimating lens is needed here, correction applied in software.
Offset
Offset
Offset
SHA* Error Interpreting Algorithm
Method 2 – Error Measurement with RCWS*
Image 1
Image 2
Focus
Image Sensor
(~1mm) aft of focus
(~1mm) fore of focus
Image Sensor
Focus
Image
Image
RCWS* Error Interpreting Algorithm
*See Nomenclature

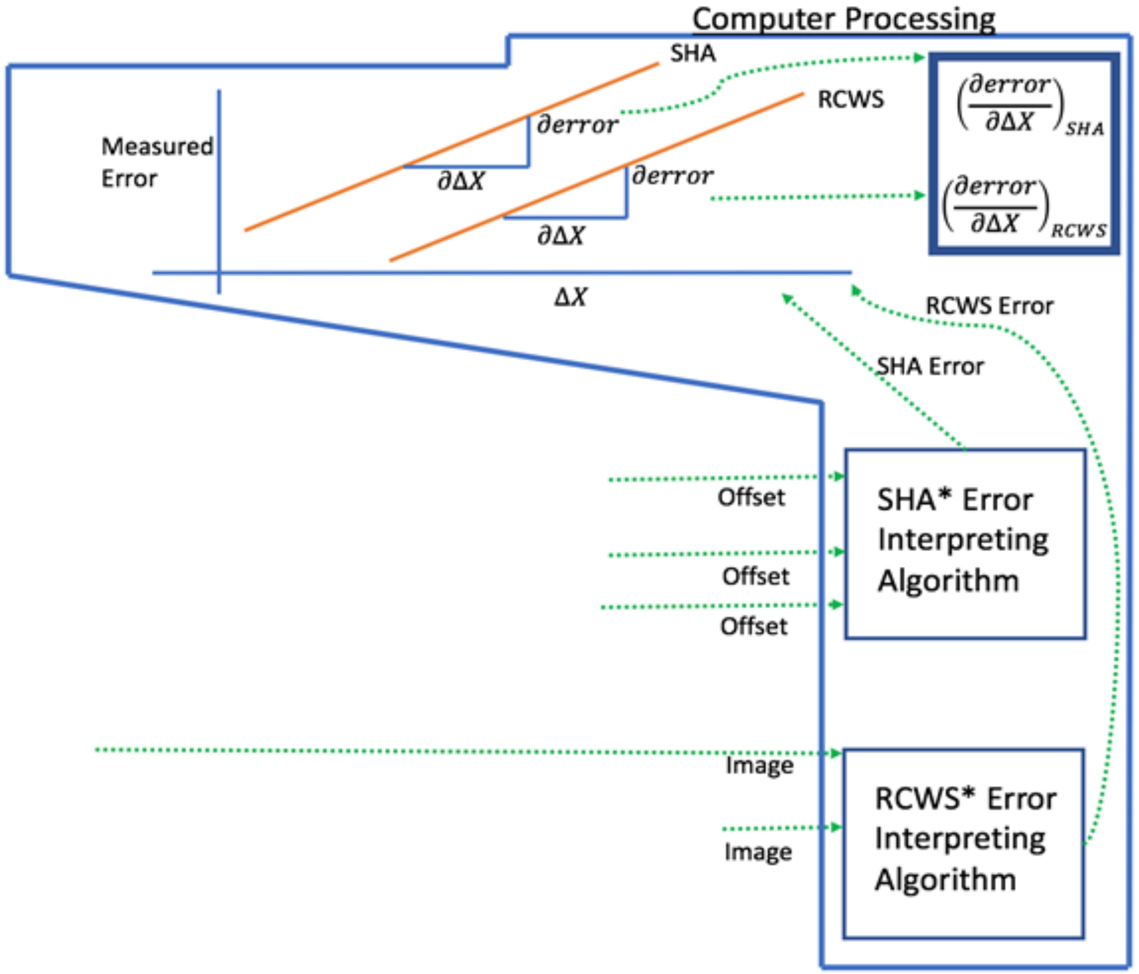
1.3.1 – CONOPS Part 1



1.3.2 – CONOPS Part 2

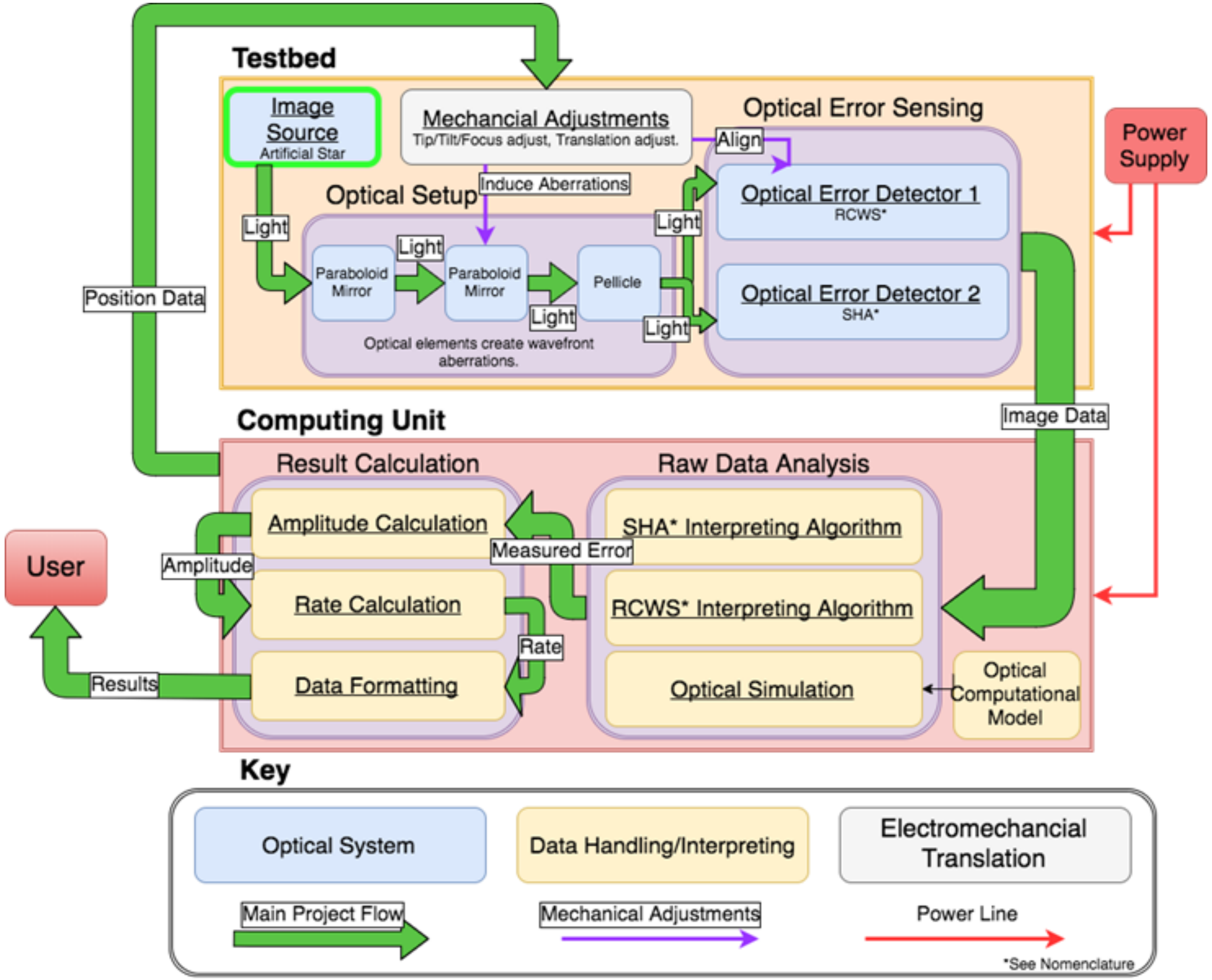


1.3.3 – CONOPS Part 3

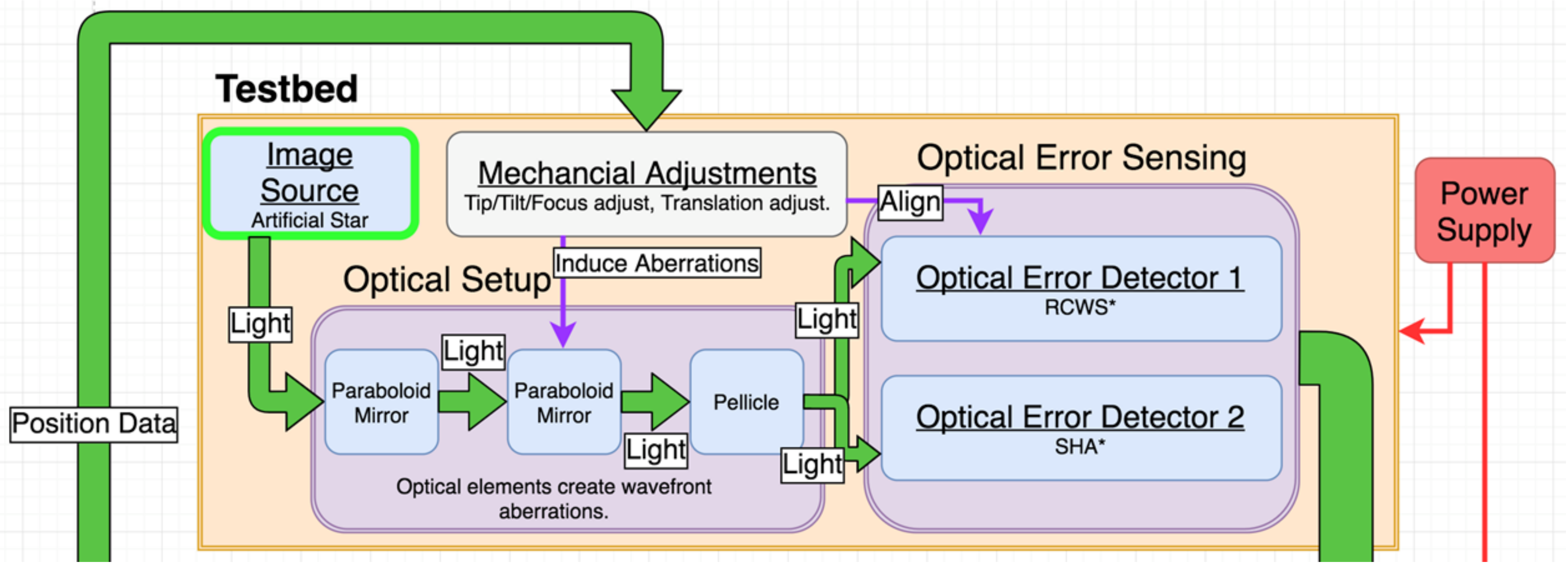


*See Nomenclature

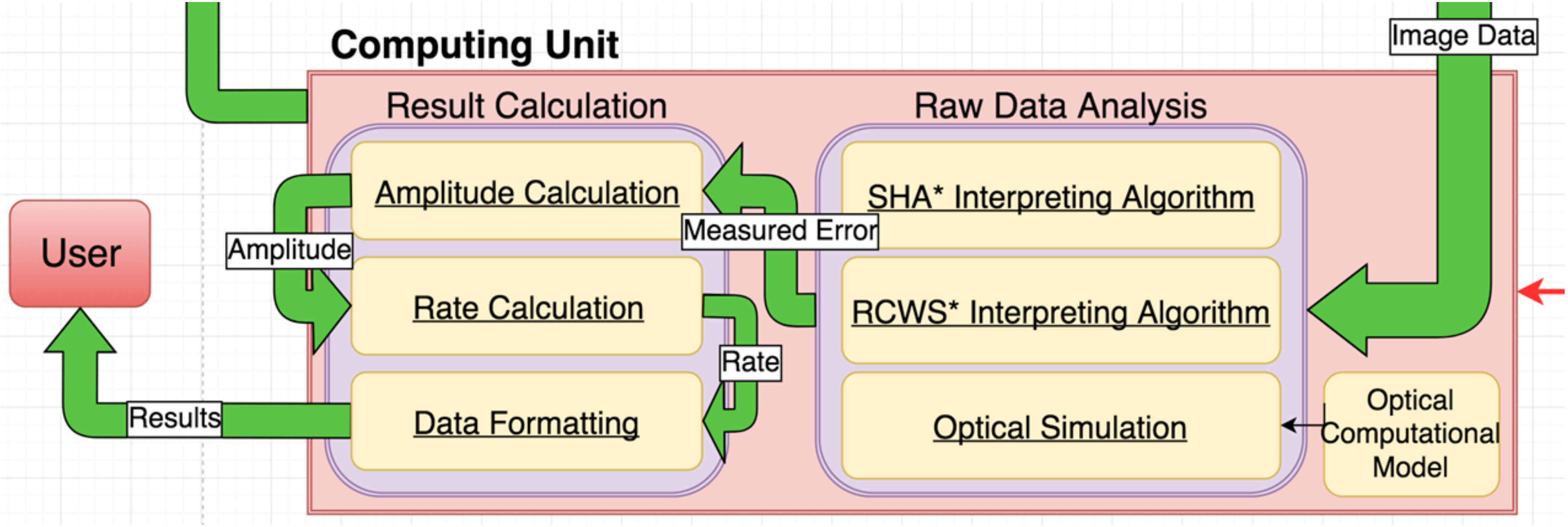
1.4 – Functional Block Diagram (FBD)



1.4.1 – FBD Part 1



1.4.2 – FBD Part 2



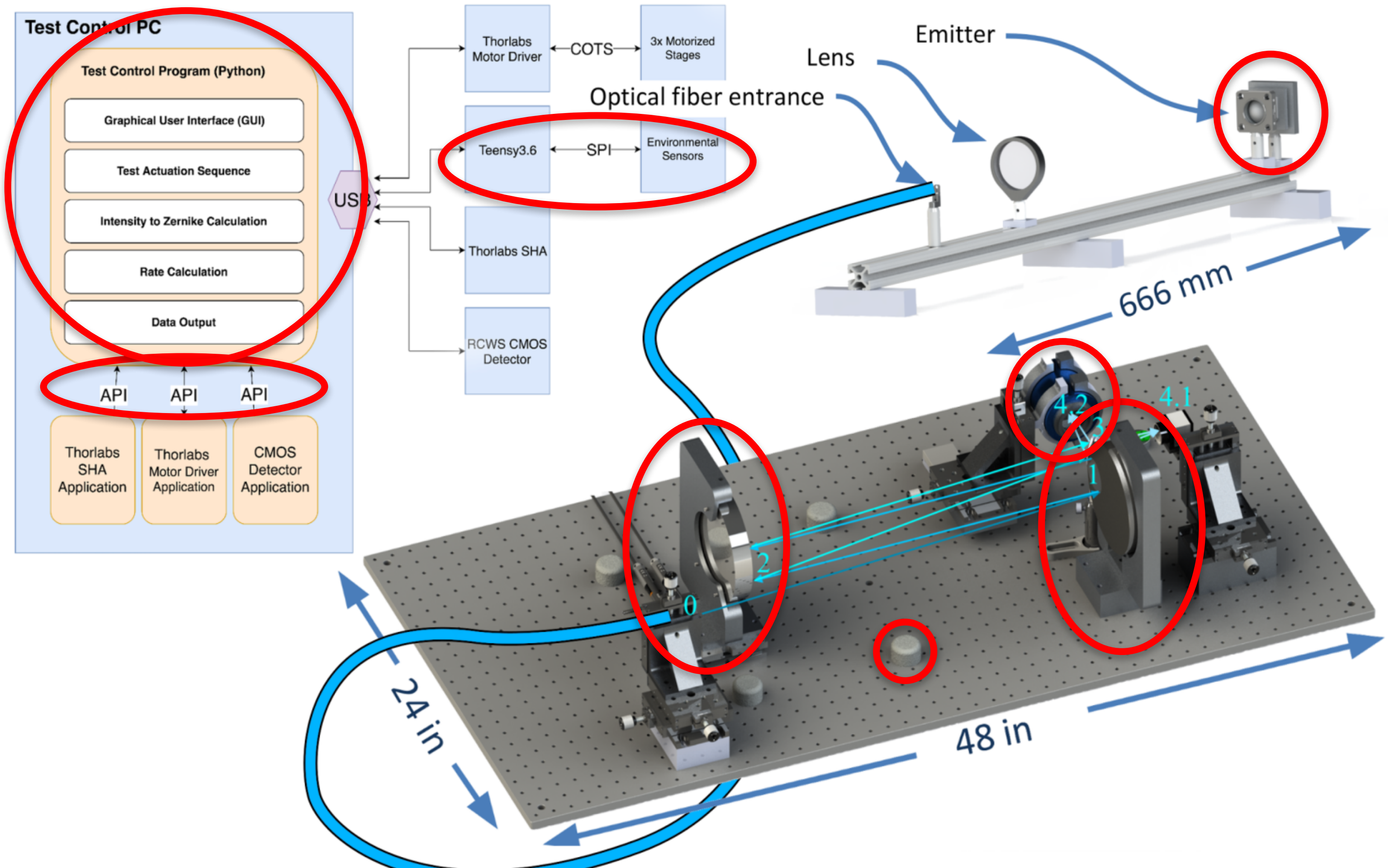
1.5 – Baseline Design

Element	Purpose
Image Source	Provide known conditioned state at the input to the system
Optical System	Introduce wavefront error and focus image to sensors
Shack-Hartmann Array	Test Article #1
Roddier Curvature Wavefront Sensor	Test Article #2
Testbed	Align, isolate, and protect optical components
Environmental Sensor System	Track environmental changes
RCWS Algorithm	Compute RCWS Zernike amplitudes from RCWS data
Test Control Software	Automate test procedure and perform data handling

Changes since CDR:

- Alignment stages are purchased rather than manufactured due to required precision
- Range of defocus distances for RCWS significantly reduced because of results from predicted images
- Shroud designed to reduce stray light and air movement in the optical path

1.5.1 – Baseline Design



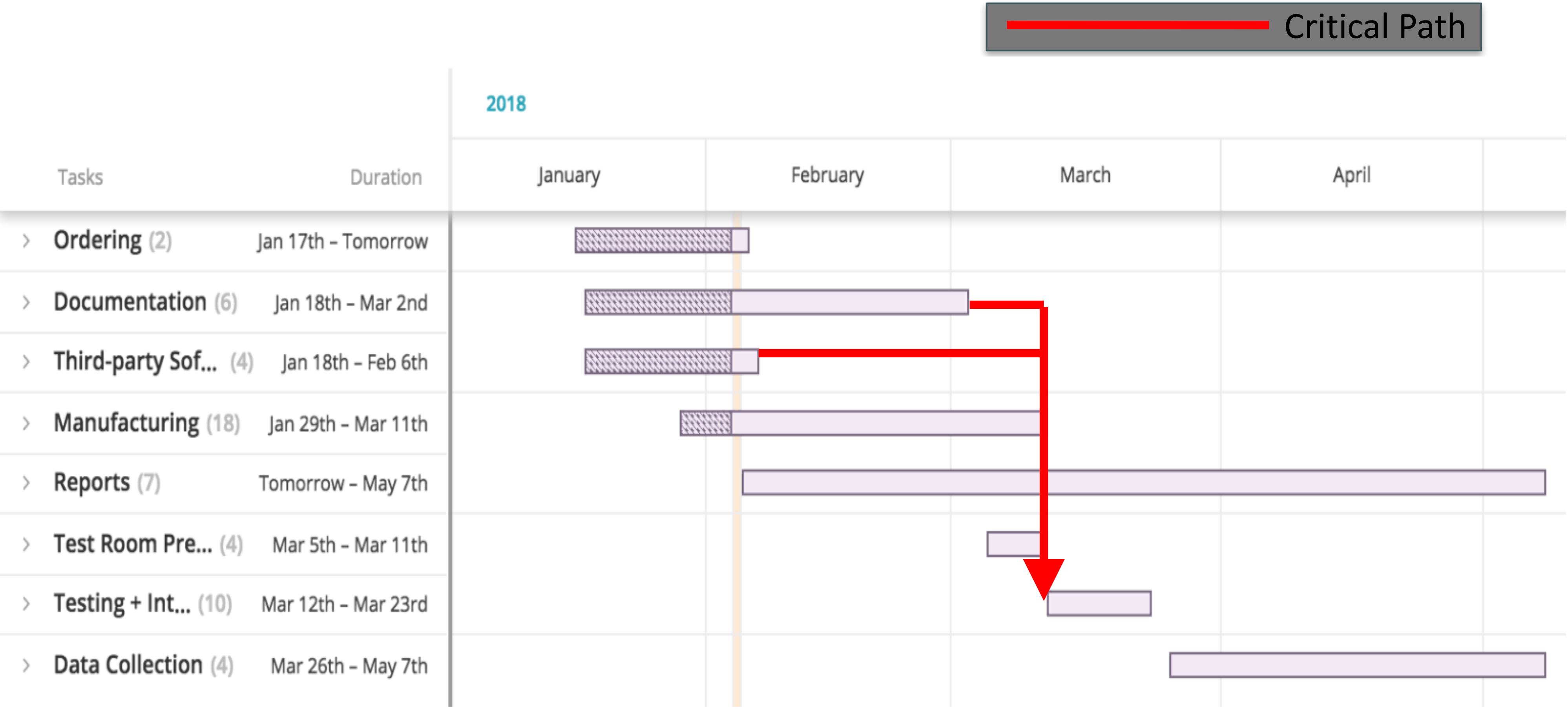
1.6 – Critical Manufacturing Elements

Region	CPE	Description of CPE Criteria
Documentation	Test Procedure	Ensures testing is complete and proceeds smoothly
	Equipment Handling Procedure	Avoid costly mistakes and damage to equipment
	Data Format Specification	Drives software development and integration
Software	Wavefront Reconstruction	Meets requirement to develop RCWS system
	Manual Control	Minimum success of project
	Test Control	Allows for much larger data set
	Teensy Program	Meets environmental sensing requirements
Hardware	Light Enclosure	Reduces lght and air movement effects on results
	Image Source	Provides the test image
	Mirror Mounts	Complicated part to manufacture, must hold mirrors
	Environmental HW	Meets environmental sensing requirements

2.1 – Schedule Overview
2.2 – Manufacturing Plan
2.3 – Testing Plan

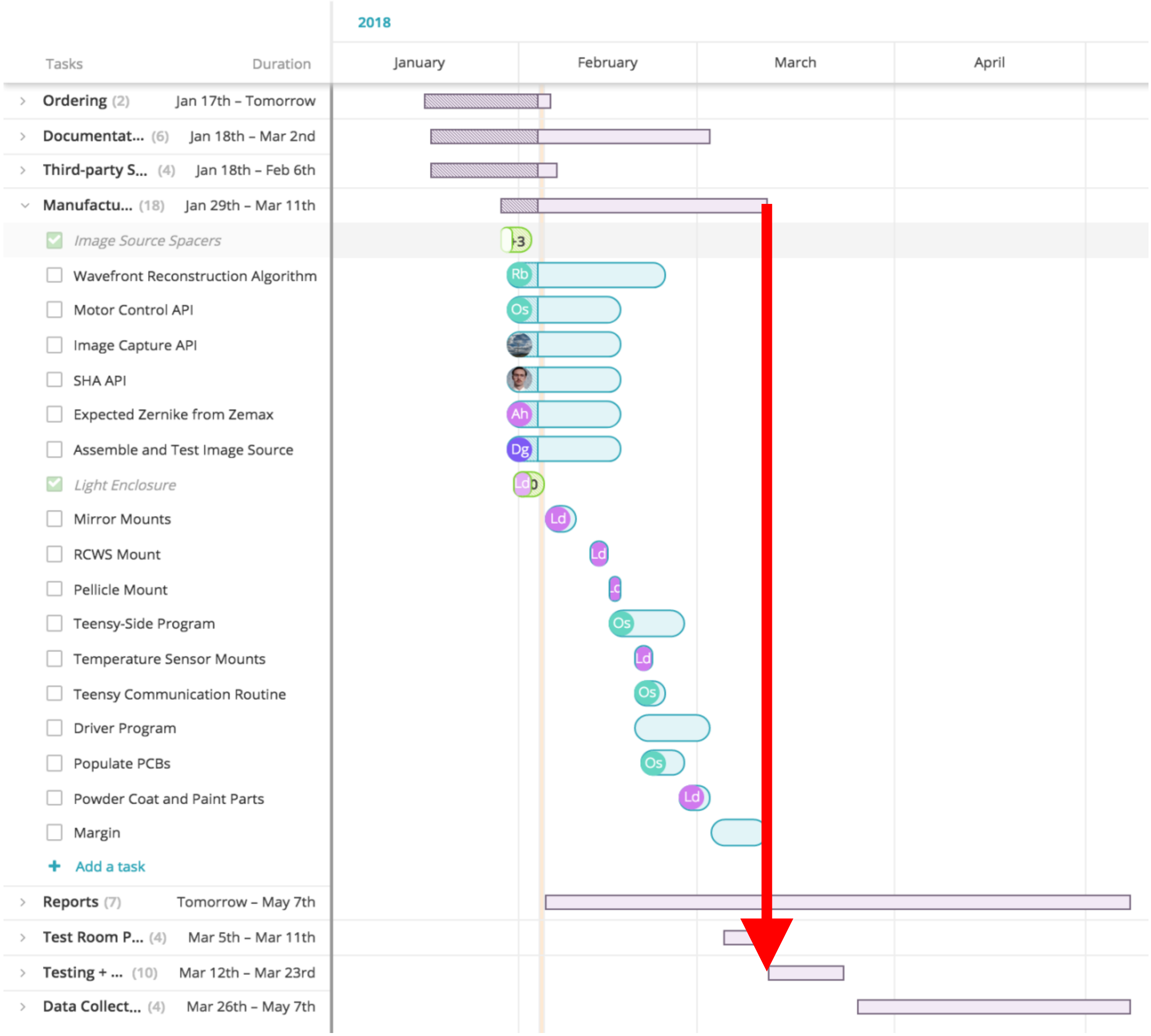
2.0 – SCHEDULE

2.1 – Schedule Overview



Integration and testing as well as the final experiment cannot proceed without manufacturing and documentation complete.

2.2 – Manufacturing Plan

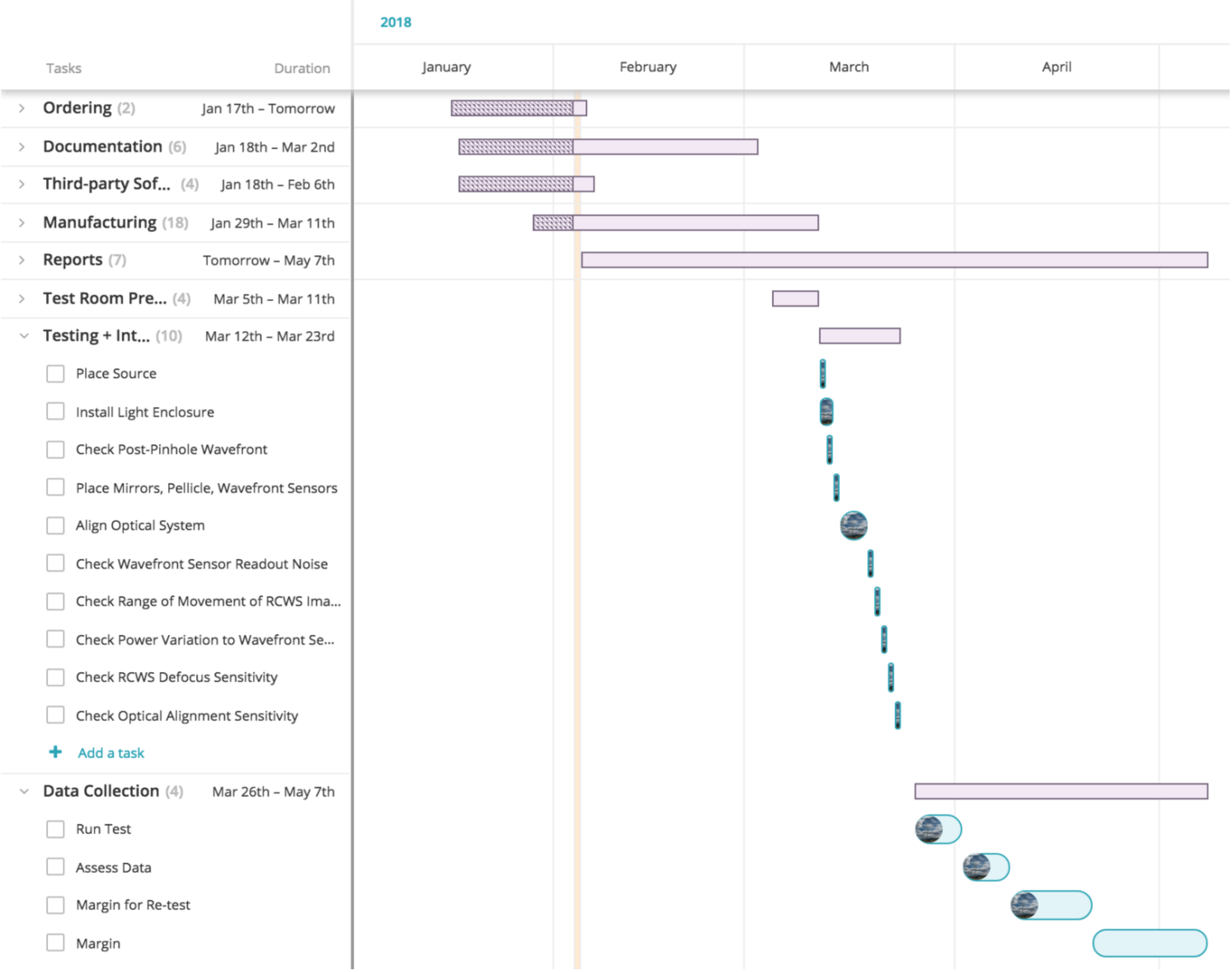


March 2nd : Manufacturing complete.

Hardware and software development occurs independently.

Feb 19th : Independent software aspects combined into main driver

2.3 – Testing Plan



March 12^{th} : Integration and characterization on optical table.

March 26^{th} : Experiment begins.

April 2^{nd} : Need for re-test evaluated from data

April 9^{th} : Margin for re-test and data analysis.

April 20^{th} : Additional margin for course requirements

3.1 – Documentation

3.2 – Software

3.3 – Hardware

3.0 – MANUFACTURING

3.1.1 – Equipment Handling Procedures

3.1.2 – Testing Procedures

3.1.3 – Data Format Standardization

3.1 – DOCUMENTATION

3.1.1 – Equipment Handling Procedures

Component Handling Guidelines:

- Details procedures to be used when transporting/installing each component
- General guidelines for handling, storing, and cleaning optical components
- Specific details for working in the SwRI lab

Component Location Schedule and Checklist Document:

- Tracks when and where components are moved between CU and SwRI
- Eliminates resource conflicts
- Team member sign off sheet for each critical step of transport, installation, and testing

Drafts of both items complete, to be finalized by ***Feb. 16th*** for integration

3.1.2 – Testing Procedures

A preliminary *Experimental Procedure* has been created. Describes the generalized flow of the experimental process to help direct the development of the interfaces and automation.

- Detailed experimental procedure stepping any user through the experimental process
  - Dependent on user-computer interface, which is still under development.

- Verification and Validation testing procedures
  - Detailing step-by-step processes for each of the verification and validation tests (six tests).
  - Not necessarily automated.

Test procedures shall be completed by ***March 5th***

3.1.3 – Date Format Standardization

A specification of data formats is necessary to unify individual SW development and manage resulting data for post-processing.

The specification is finalized, allowing software development to continue and integrate smoothly.

Message format:

0xA0	0xA1	RT	SN	{PL}	SH	SL	MH	ML	CS	0x0D	0x0A

Temperature Sensor Payload:

Temperature High Byte	Temperature Low Byte

Accelerometer Payload:

Acc. Axis 1 H	Acc. Axis 1 L	Acc. Axis 2 H	Acc. Axis 2 L	Acc. Axis 3 H	Acc. Axis 3 L

Name

- EXAMPLE_EXPERIMENT
  - 2018_02_03_13_48_41_STATE1
  - 2018_02_03_13_50_55_STATE2
  - 2018_02_03_13_52_13_STATE3
  - 2018_02_03_13_54_32_STATE4
    - data_RCWS
      - img_RCWS_aft.png
      - img_RCWS_fore.png
      - zernikes_RCWS.csv
    - data_SHA
      - img_SHA_aft.png
      - img_SHA_fore.png
      - spt_SHA_aft.png
      - spt_SHA_fore.png
      - wft_SHA_aft.png
      - wft_SHA_fore.png
      - zernikes_SHA.csv
    - env_data_raw.txt
    - state_parameters.csv
    - zernikes_model.csv
  - experiment_schedule.csv

3.2.1 – Wavefront Reconstruction
3.2.2 – Manual Control
3.2.3 – Test Control
3.2.4 – Teensy Program

3.2 – SOFTWARE

3.2.1 – Wavefront Reconstruction

$$\frac{I_1(\vec{r}) - I_2(-\vec{r})}{I_1(\vec{r}) + I_2(\vec{r})} = \frac{f(f-l)}{2l}\left[\nabla^2 z(\vec{u}) - \frac{\partial}{\partial u} z(\vec{u})\delta_c\right]_{u = f\vec{r}/l}$$

Wavefront reconstruction is a critical portion of the RCWS package. The mathematical solution and software implementation may be the limiting factor in RCWS performance.

Current Issues:

- Few solutions are published for reference
- Some examples such as Large Synoptic Survey Telescope code appear to be specialized, and with limited documentation
- The team's lack of optics experience is limiting the efficacy in evaluating the problem, specifically as to whether or not Airy disk patterns will mask the required structures

3.2.1 – Wavefront Reconstruction

Next Steps:

- Blob detection software can be used to determine first 6 Zernike modes, already implemented for modes 1-4.
- A sub-team is dedicated to studying the mathematical concepts in order to understand and solve the Poisson equation.

Expect to spend February and 2 weeks of March to solve this.

Fortunately, this problem is isolated, thus, does not hinder progress in the rest of the project. However, the wavefront reconstruction is critical for a fair evaluation of the performance of the RCWS.

3.2.2 – Manual Control

The experiment can be completed without automated test control as long as the provided software for various hardware items works. This has been **verified** for:

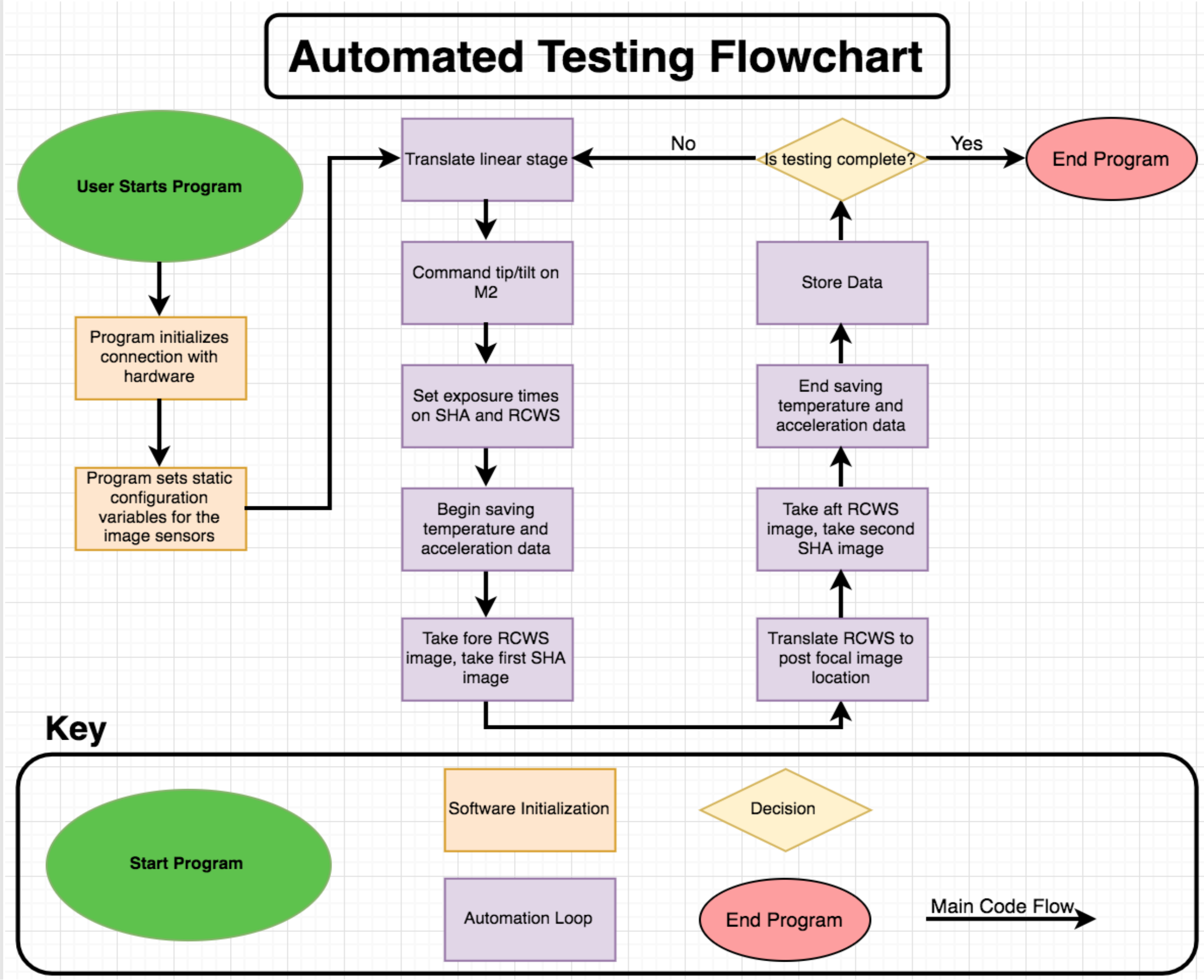
- ThorLabs WFS150-7AR with the ThorLabs-provided software
- QHY174-M and the ASI120MM detectors using COTS software
- ThorLabs motorized optical stages utilizing the ThorLabs-provided software

Proves that all required data can be collected manually. Test control software will allow for faster execution and increased reliability of results.

3.2.3 – Test Control

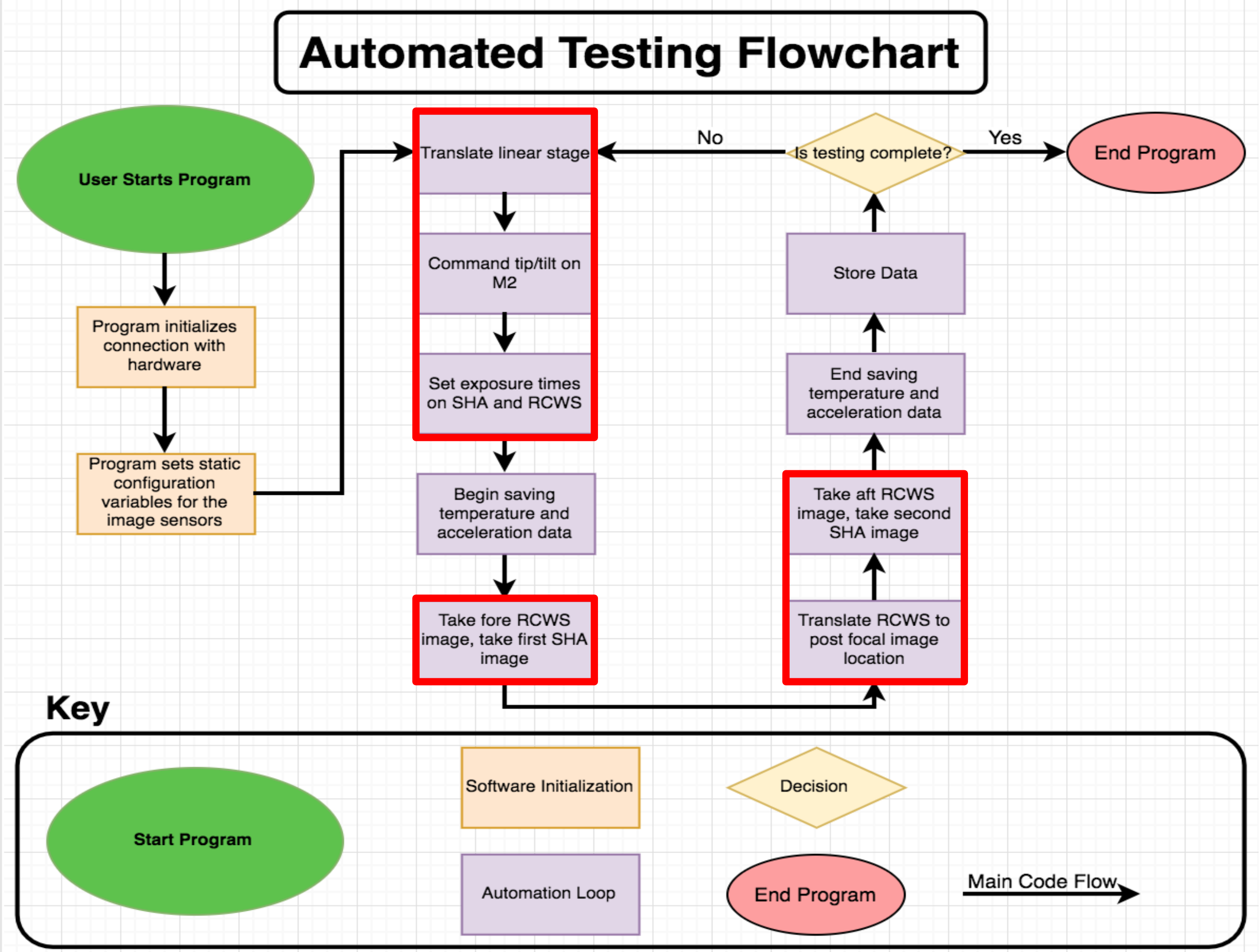
The test control software is designed to automate the collection of 500+ data points. Information determined at each system state includes:

- SHA wavefront measurement
- RCWS fore and aft-focus images
- Environmental sensor data
- Predicted wavefront and images



3.2.3.1 – Automation APIs

Outlined boxes are where programs with APIs will be utilized for automation.



3.2.3.1 – Automation API Status

Purpose: The automatic image capture software is to simplify the collection of many iterations of data through computer control of both the image sensors and motorized stages because we have limited time in the optics lab to test.

Current State: Currently becoming familiar with first- and third-party drivers for the image sensors and motorized stages, as these will be the primary method of interfacing with the hardware and will allow for automation of testing.

Next Step: Experimentation with driver functions and creation of rudimentary control programs to validate the functionality on the test hardware.

Biggest Challenge: Debugging the initial problems with utilizing the OS-specific drivers, as there seems to be a very specific set of steps to connect to the hardware.

Automatic Image Capture Progress

CMOS Image Capture Automation: The manufacturer of the CMOS image sensors don't directly provide drivers, so we are reliant on 3rd party drivers to automate the image capture and exposure time.

15%

SHA Image Sensor Automation: The SHA is from ThorLabs, so they provide drivers to support user-developed applications, along with explanations of the provided functions, which will aid development.

20%

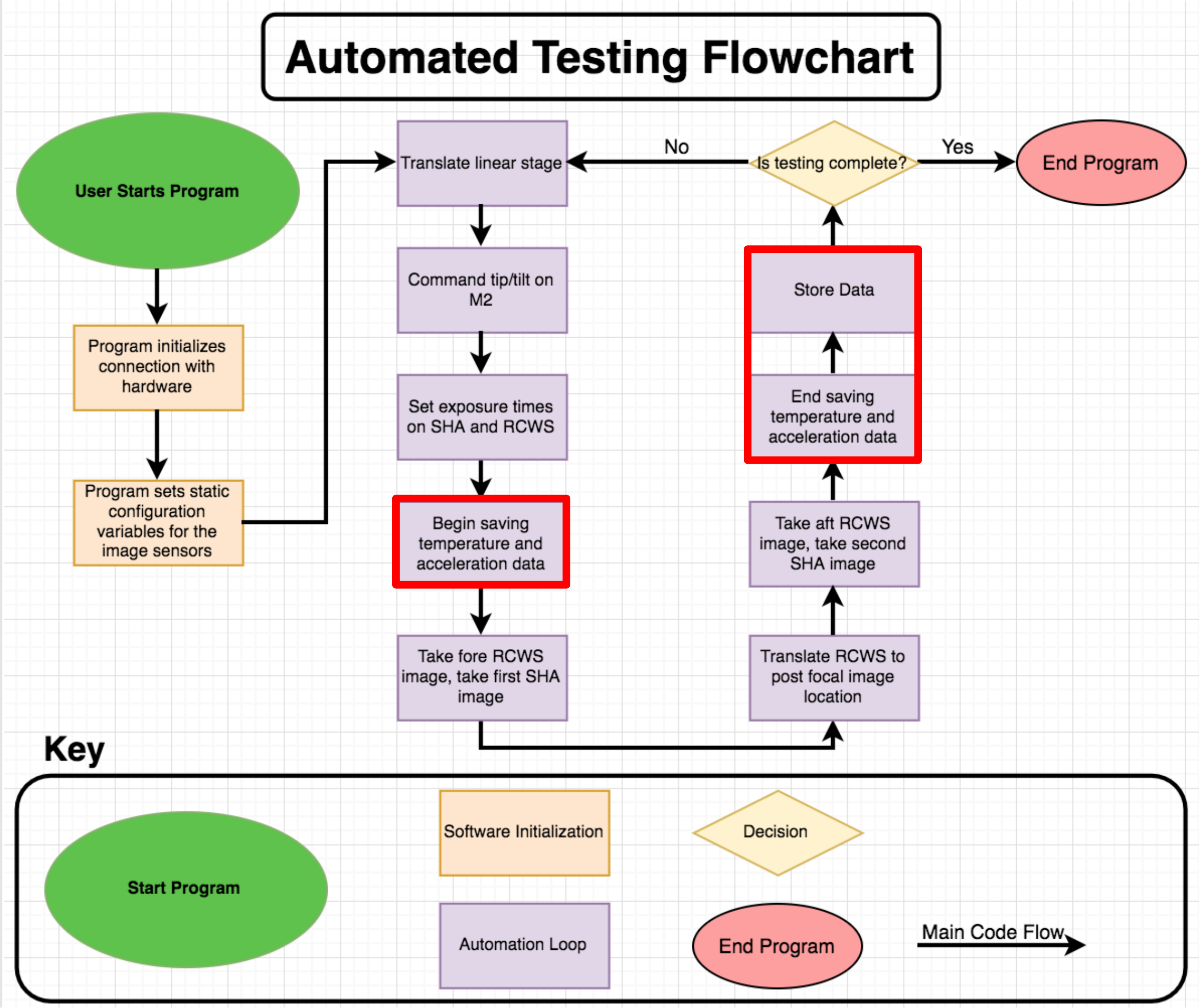
Motorized Stage Automation: The motorized stages are also from ThorLabs which come with their own 1st party drivers. This aids with end-user application development.

20%

Estimated Time Remaining: **50 hours**, based on the amount of hardware which needs to be automated.

3.2.3.2 – Environmental Sensor Data

Outlined boxes display where the environmental sensor data requires programming.



3.2.3.2 – Environmental Sensor Data Status

Purpose: This software needs to be written in order to transmit the environmental sensor data from the Teensy to the test computer over serial.

Current State: Currently specified data format in which the data will be transmitted for storage (proof of concept was completed last semester).

Next Step: Create an emulator which generates dummy data in the correct format in order to validate data storage so we can move on to writing the sensor-reading code.

Biggest Challenge: Implementing data streaming at the same time as other control functions.

Teensy Communication Software

Teensy Communication: We proved last semester that we could stream data to a computer from the Teensy over serial, as well as sample the environmental sensors at the acceptable rates.

33%

Estimated Time Remaining: **10 hours**, since the group members already have experience with Teensy serial communication and reading sensors.

3.2.3.3 – ZEMAX Automation

Purpose: The optical model in Zemax will be polled for each system state to determine expected wavefront shape. This will validate the results of the wavefront sensors and further help determine accuracy of the RCWS method.

Current State: Python API into Zemax has verified key access and the access the optical path specification file.

Next Step: Programmatically change values in lens file, then save expected Zernike amplitudes to text file.

Biggest Challenge: Changing the desired data point in the lens file programmatically.

Zemax Expected Results

Zemax Model Automation: We have verified the connection between Zemax and Python, but still need to programmatically change the values in the Zemax model using Python.

20%

Estimated Time Remaining: **15 hours**, because communication between Python and Zemax has already been established, but still need to implement core functionality.

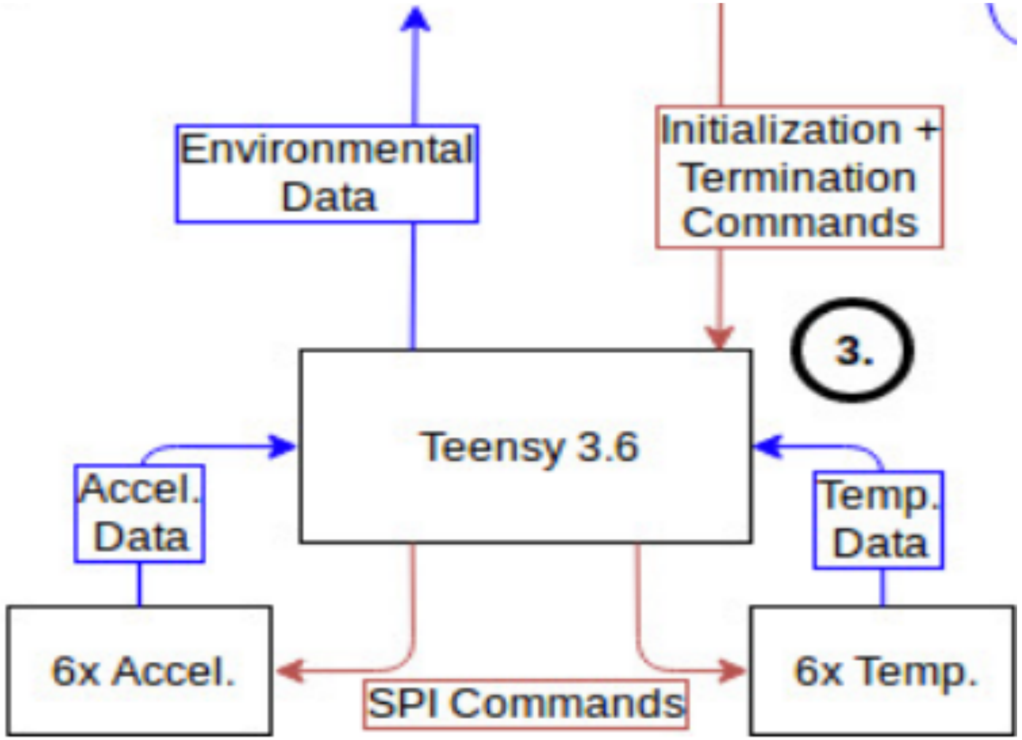
3.2.4 – Environmental Sensor Drivers

Programming Scope:

- Samples from 12 sensors at upwards of 1 kHz
- Data from 12 sensors is time-stamped and written to serial
- Central program handles PC-side serial monitoring / data collection and data storage.

Status:

- Serial monitoring has been tested on the Teensy, PC
- SPI transfers have been tested, need to be scaled for 6 sensors
- Code mostly requires re-tooling, possible GUI addition at this point



Estimated Time Remaining: 8 hours for scaling existing code to 12 sensors and incorporating communication standards.

3.3.1 – Light Enclosure
3.3.2 – Image Source
3.3.3 – Mirror Mounts
3.3.4 – Environmental Sensors

3.3 – HARDWARE

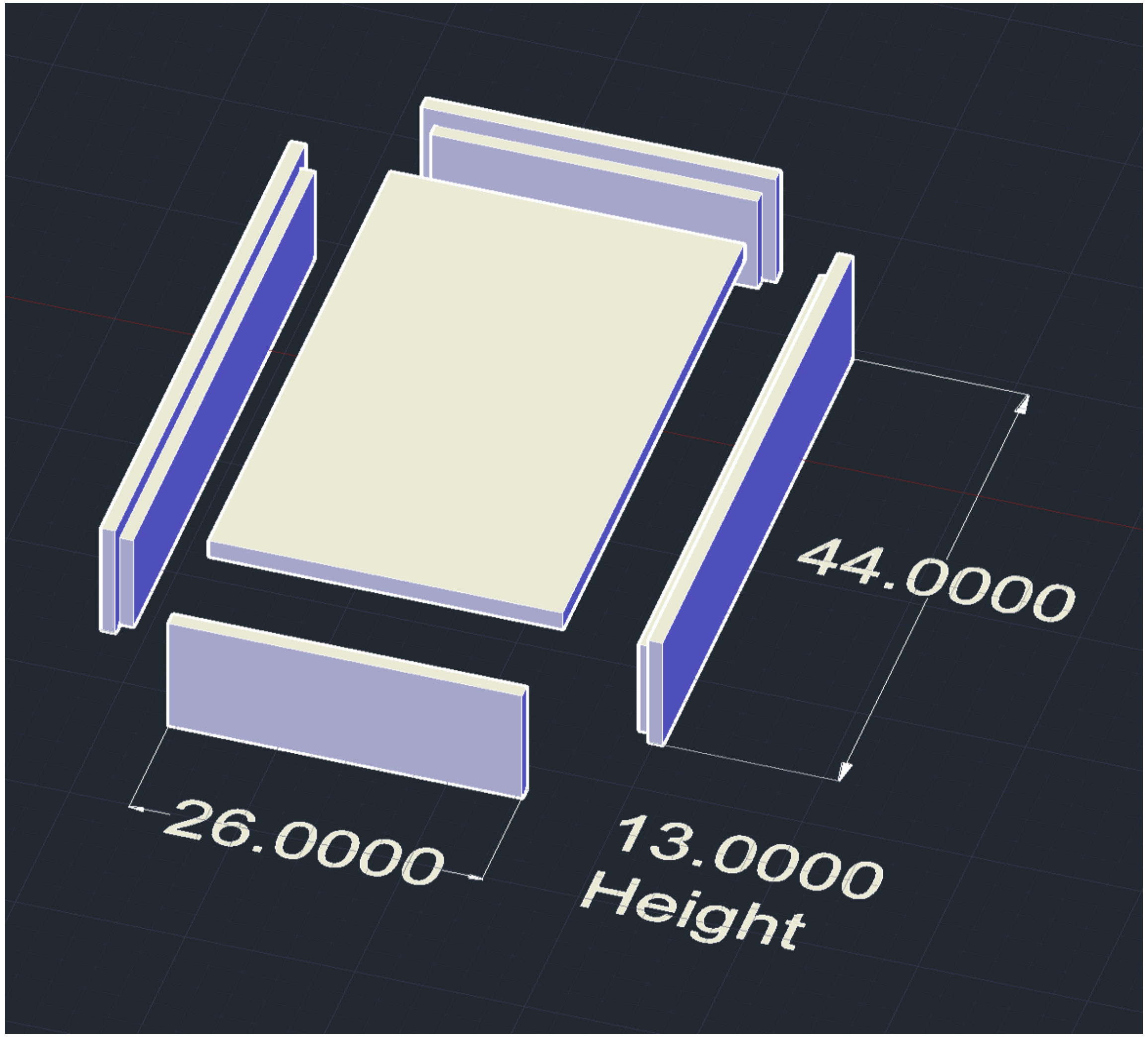
3.3.1 – Light Enclosure

<u>Purpose:</u> Reduces air movement and incident light

- Inside painted black to absorb reflected light
- Interlocking design blocks direct light entry
- Black fabric will cover silver optical table surface
- Minimal volume reduces air movement

<u>Status:</u>

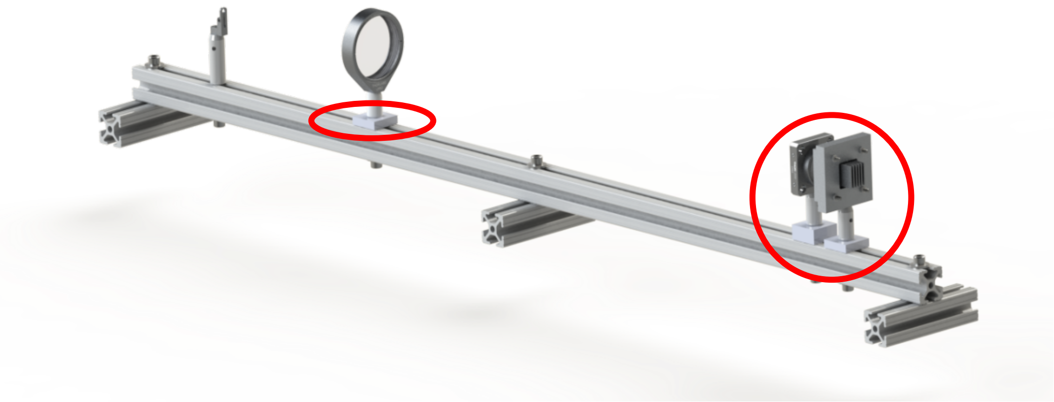
- Construction complete
- Still needs to have sealing ring installed on optical table

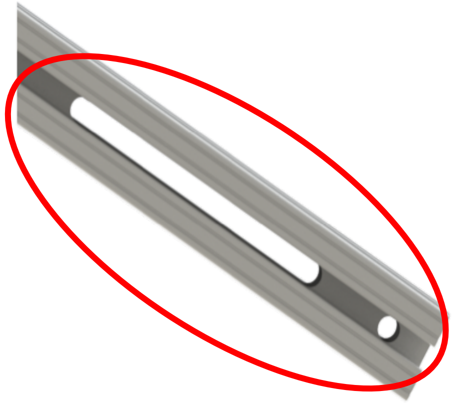


3.3.2 – Image Source

Purpose: Source directs light into optical fiber to be diffused before pinhole

Scope:
- Mechanical and electronic components to be purchased
- Components require minimal modification





Manufactured by team

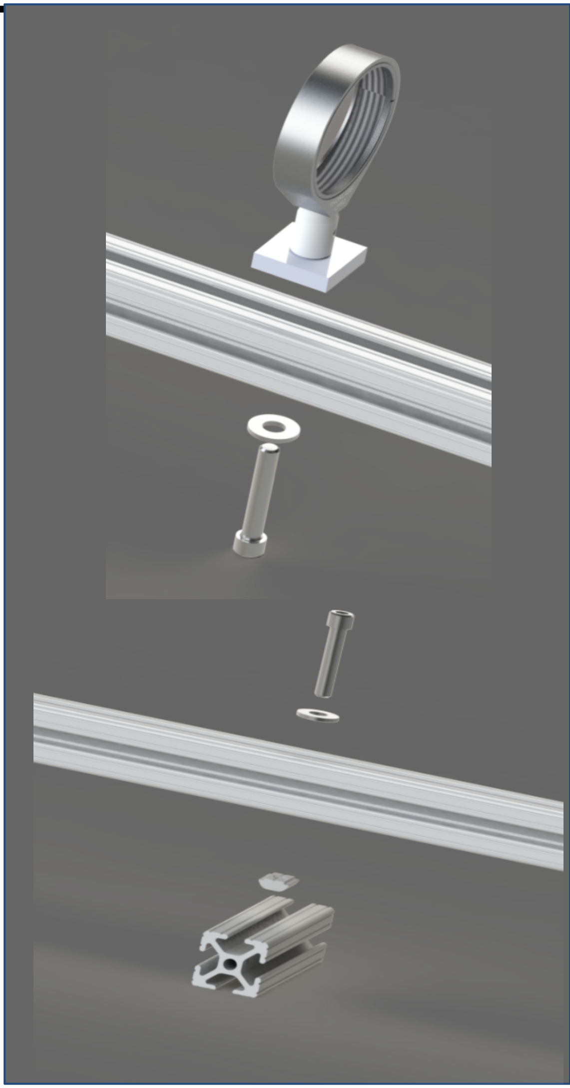
3.3.2 – Image Source

In Progress Components:

- Emitter electrical connections and mounts
- Soldering and simple mounting with PCB standoffs
- Testing individual components for out-of-box functionality
  - AC-DC converter works as expected (nominal 12V output)
  - DC-DC booster to be tested (variable voltage and current output)

Next Steps:

- Mechanical rail mounting system, ~3 hrs machining
- Emitter Mount, ~4 hours machining
- Alignment, ~3 hrs
- Secondary shroud, ~2 hrs



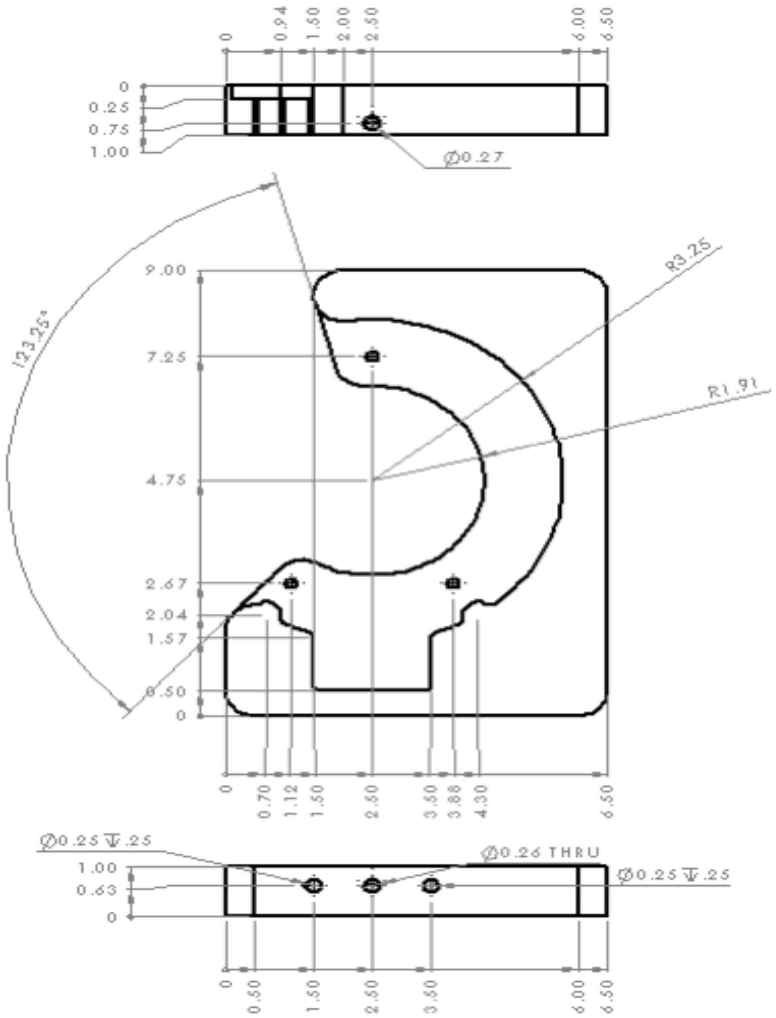
3.3.3 – Mirror Mounts

Unique notched design of mirror mounts allows for close spacing of beams per optical path specs.

- Stock has been ordered from online metals
- Expected machine time: ~16 hrs for 2 mounts

<u>Other mounts to manufacture:</u>

- Pellicle Mount: ~6 hrs
- CMOS Camera Mount: ~4 hrs



3.3.4 – Environmental Sensors

Parts Not Yet Acquired:

- Sensor Circuit Boards + Teensy Connector Board
- Temperature caps (manufactured)
- Adhesive Pads

Parts Acquired:

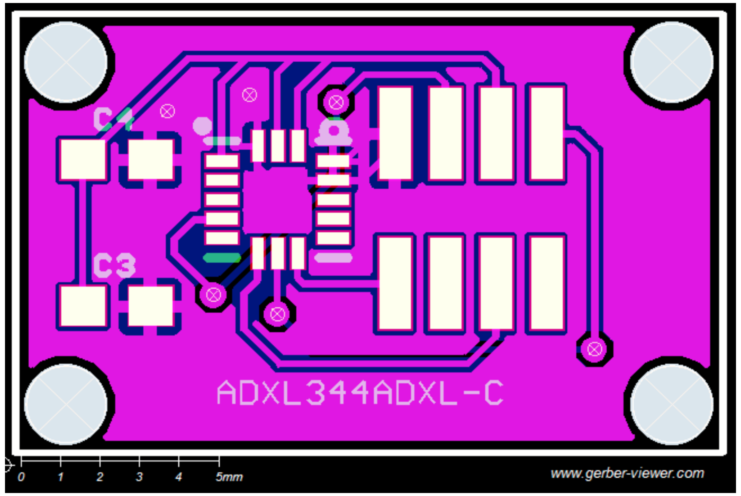
- ICs (OR gates, ADXL345, ADT7320)
- Connectors
- Capacitors
- Teensy

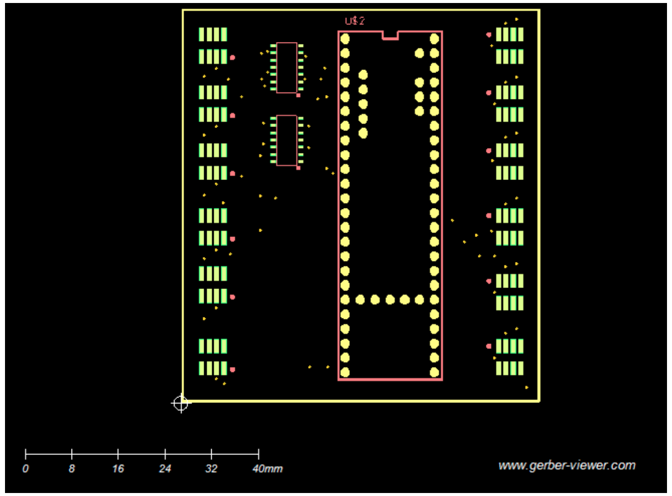
- The ICs, connectors, capacitors, and the Teensy will all be soldered to the designed PCBs
- Temperature caps are non-crucial, and will be 3D-printed for the temperature sensors
- Adhesive pads will be used for mounting the accelerometers

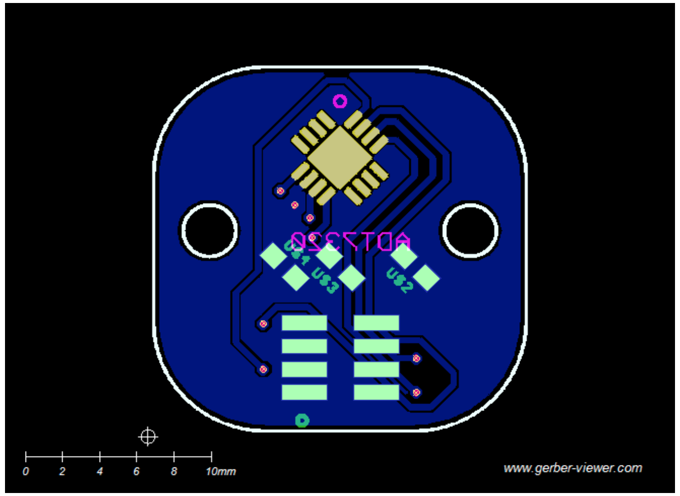
3.3.4 – Environmental Sensors

Circuit Board Status:

- Design completed / reviewed
- PCB order placed January 25th, expected February 5th
- Tasks remaining: populating PCBs, make cables for sensors
  - Estimate: 10-12 hours for soldering, error-checking







4.1 – Budget Overview

4.2 – Ordering Status

4.0 – BUDGET

4.1 – Budget Overview

	By Funding Source		
	Source/Sink	USD ($)	Percent of Total Funding
Funding	Class Budget	-5000	-38.46%
	EEF	-3000	-23.08%
	NASA Glenn	-5000	-38.46%
Expected Spending:	Class + EEF	$ 5,087.57	63.59%
	SwRI/NASA Glenn	$ 5,379.15	107.58%
Funds Spent	Class + EEF	$ 4,352.13	54.40%
	SwRI/NASA Glenn	$ 5,379.15	107.58%

Class + EEF Funding:

- 54.4% spent, 63.6% expected use

Equipment on Loan:

- ThorLabs Shack-Hartmann Array
- QHY174M detector
- ThorLabs motorized stages
- Lab space

AWESoMe Bill of Materials

Project ID	Name	Order Number	Ordered	Received	Purpose	Manufacturer	Manufacturer ID	Source	Source ID	Quantity	Cost Each ($)	Discount Each (%)	Subtotal ($)	Export Controlled Material?
Optical Path														
O-1	Parabolic Mirror	P2	6.18	1.19.18		Edmund Optics	32-069-533	Edmund Optics	32-069-533	2	675	0	1350	No
O-2	Pellicle Beamsplitter	P2	6.18	1.19.18		Edmund Optics	39-481	Edmund Optics	39-481	2	170	0	340	No
O-3	Clamp	P6	5.18	1.31.18	amping to table	ThorLabs	CF125	ThorLabs	CF125	1	8.95	0	8.95	
O-4	Post holder	P6	5.18	1.31.18	olding posts	ThorLabs	PH3E	ThorLabs	PH3E	1	24.99	0	24.99	
O-5	Post	P6	5.18	1.31.18	ost	ThorLabs	TR4	ThorLabs	TR4	1	5.87	0	5.87	
Optomechanics														
T-1	PY004Z8	S0	4.18	1.30.18	2 pitch and yaw atform	ThorLabs	PY004Z8	ThorLabs	PY004Z8	1	2113.44	-100	0	
T-2	PT1-Z8	S0	4.18	1.30.18	CWS translation age	ThorLabs	PT1-Z8	ThorLabs	PT1-Z8	1	840.48	-100	0	
T-3	KCH301	S0	4.28	1.30.18	ower supply for 3 otors	ThorLabs	KCH301	ThorLabs	KCH301	1	494.7	-100	0	
T-4	KDC101	S0	4.28		otor controller	ThorLabs	KDC101	ThorLabs	KDC101	3	638.52	-100	0	
T-5	PT1-B	P6	5.18	1.31.18	gnment traverse age	ThorLabs	PT1-B	ThorLabs	PT1-B	7	215.22	0	1506.54	
T-6	KM100 WFS	P6	5.18	1.31.18	HA tip/tilt	ThorLabs	KM100 WFS	ThorLabs	KM100 WFS	1	83.39	0	83.39	
T-7	PY003	P6	5.18	1.31.18	CWS tip/tilt	ThorLabs	PY003	ThorLabs	PY003	1	214.24	0	214.24	
Image Detectors														
D-1	ASI120MM-S		ve	Possession	MOS Detector	ZWS	ASI120S	Eliot	ASI120S	1	199	-100	0	
D-2	QHY 174M		ve	Possession	MOS Detector	QHY	QHY 174M	Eliot	QHY 174M	1	939	-100	0	
D-3	WFS150-7AR		ve	Possession	HA	ThorLabs	WFS150-7AR	Eliot	WFS150-7AR	1	4009	-100	0	
Image Source														
I-1	LH-XP-100W-6000k	P5	4.18	1.30.18	mitter	AMZNSPCL	LH-XP-100W-600	Amazon	LH-XP-100W-60	1	12.89	0	12.89	
I-2	LPV-100-12	P5	4.18	1.30.18	ower Supply	Mean Well	LPV-100-12	Amazon	LPV-100-12	1	25.2	0	25.2	
I-3	GREE U024V	P5	4.18	1.30.18	oost Converter	GREE	GREE U024V	Amazon	GREE U024V	1	11.69	0	11.69	
I-4	Heatsink		.18		eatsink	Advanced Thermal Slutions Inc.	ATS-54170W-C1-R(	DigiKey	ATS1247-ND	1	7.79	0	7.79	
I-5	LB1106-A	P6	5.18	1.31.18	convex lens	ThorLabs	LB1106-A	ThorLabs	LB1106-A	1	43.1	0	43.1	
I-6	P10H	P6	5.18	1.31.18	nhole	ThorLabs	P10H	ThorLabs	P10H	1	74.5	0	74.5	
I-7	FCM32	P6	5.18	1.31.18	ber Mount	ThorLabs	FCM32/M	ThorLabs	FCM32/M	2	22.64	0	45.28	
I-8	ACL25416U-A	P6	5.18	1.31.18	ondenser Lens	ThorLabs	ACL25416U-A	ThorLabs	ACL25416U-A	1	27.54	0	27.54	
I-9	LMR2	P6	5.18	1.31.18	ns mount	ThorLabs	LMR2	ThorLabs	LMR2	1	25.76	0	25.76	
I-10	SM1RRC	P6	5.18	1.31.18	aining ring	ThorLabs	SM1RRC	ThorLabs	SM1RRC	1	10.51	0	10.51	
I-11	CP02	P6	5.18	1.31.18	age Plate	ThorLabs	CP02	ThorLabs	CP02	1	16.4	0	16.4	
I-12	SM1L05	P6	5.18	1.31.18	ns tube	ThorLabs	SM1L05	ThorLabs	SM1L05	1	12.59	0	12.59	
I-13	TR1	P6	5.18	1.31.18	ost	Thorlabs	TR1V	Thorlabs	TR1V	2	4.74	0	9.48	
I-14	TR075	P6	5.18	1.31.18	ost	Thorlabs	TR075V	Thorlabs	TR075V	1	4.74	0	4.74	
I-15	TR1.5	P6	5.18	1.31.18	ost	Thorlabs	TR1.5V	Thorlabs	TR1.5V	1	4.97	0	4.97	
I-16	M105L02S-B	P6	5.18	1.31.18	ber optic cable	ThorLabs	M105L02S-B	ThorLabs	M105L02S-B	1	131.58	0	131.58	
I-17	LMR1	P6	5.18	1.31.18	nhole mount	ThorLabs	LMR1	ThorLabs	LMR1	1	15.23	0	15.23	
Environmental Sensors														
E-1	Teensy3.6	P3	6.18	1.23.18	crocontroller	PJRC	Teensy3.6	PJRC	Teensy3.6	1	29.25	0	29.25	
E-2	ADXL344ACCZ-RL7	P4	7.18	1.22.18	mperature sensor	Analog Devices Inc.	ADXL344ACCZ-RL7	Digikey	ADXL344ACCZ -RL7CT-ND	10	3.041	0	30.41	
E-3	ADT7320UCPZ-RL7CT	P4	7.18	1.22.18	celerometer	Analog Devices Inc.	ADT7320UCPZ-RL7	Digikey	ADT7320UCPZ-RI	10	6.934	0	69.34	
E-4	8 Pin Header M	P4	7.18	1.22.18	PI Sensor onnection	Amphenol	20021121-00008C4	DigiKey	609-3694-2-ND	30	0.609	0	18.27	
E-5	8 Pin Header F	P4	7.18	1.22.18	PI Sensor onnection	Amphenol	20021311-00008T4	DigiKey	609-3753-ND	30	0.596	0	17.88	
E-6	10k Resistors	P4	7.18	1.22.18	k resistors	Vishay Beyschlag	MCT06030C1002FF	DigiKey	MCT0603-10.0K-C	100	0.0596	0	5.96	
E-7	0.1uF cap	P4	7.18	1.22.18	1uF cap	Murata Electronics North America	GRM188R71C104K	DigiKey	490-1532-1-ND	100	0.0316	0	3.16	
E-8	Regulator	P4	7.18	1.22.18	3V Regulator	Exar Corporation	SPX1117M3-L-3-3/T	DigiKey	1016-1848-1-ND	10	0.378	0	3.78	
E-9	Male Header	P4	7.18	1.22.18	ale Header	Sullins Connector Solutions	PRPC040SAAN-RC	DigiKey	S1011EC-40-ND	10	0.592	0	5.92	
E-10	USB	P4	7.18	1.22.18	SB Cord	Qualtek	3025010-03	DigiKey	Q853-ND	2	2.51	0	5.02	
E-11	Cables	P4	7.18	1.22.18	ensor Cables	Tensility International Corp	30-00510	DigiKey	T1347-5-ND	1	9.99	0	9.99	
E-12	Solder Paste	P4	7.18	1.22.18	older Paste	Chip Quik Inc.	SMD291AX50T3	DigiKey	SMD291AX50T3-!	1	12.98	0	12.98	
E-13	OR gate		.18		R gate	Nexperia USA Inc.	74HC32D,652	DigiKey	1727-3786-ND	10	0.29	0	2.9	
Raw Materials / Miscellaneous														
R-1	N/A				tical table	N/A	SwRI	N/A	SwRI	1	100000	-100	0	No
R-2	PCB Manufacturing	P7	5.18		v. Sensor PCB	Seeed	N/A	SeeedStudio	N/A	1	14.7	0	14.7	No
R-3	Auluminum bar	P8	0.18		rror mounts	OnlineMetals	N/A	McMaster Carr	N/A	1	73.63	0	73.63	No
R-4	Aluminum rod		.18		mperature sensor ounts									
R-5	Powder coat		.18		R coating on ounts							0	0	No
R-6	Gloves		0.18		oves							0	0	No
R-7	Masks		0.18		asks							0	0	No
R-9	Foam	P10	0.18	1.30.18	nclosure	N/A	N/A	Home Depot	#207179253	2	18.98	0	37.96	No
R-10	Spray paint	P10	0.18	1.30.18	nclosure	N/A	N/A	Home Depot	#202097745	1	3.93	0	3.93	No
R-11	Spray adhesive	P10	0.18	1.30.18	nclosure	N/A	N/A	Home Depot	#100184611	1	5.77	0	5.77	No
Shipping														
S-1	P2 - Edmunds Order #1									1	10.99	0	10.99	
S-2	P3 - PJRC Order #1									1	3.11	0	3.11	
S-3	P4 - Digikey									1	8.99	0	8.99	
S-4	P5 - Amazon									1		0	0	
S-5	P6 - Thorlabs on P Card									1	14.97	0	14.97	
S-6	P8 - OnlineMetals									1	22.59	0	22.59	

4.2 – Ordering Status

Planned:

- All planned items have been ordered

Pending:

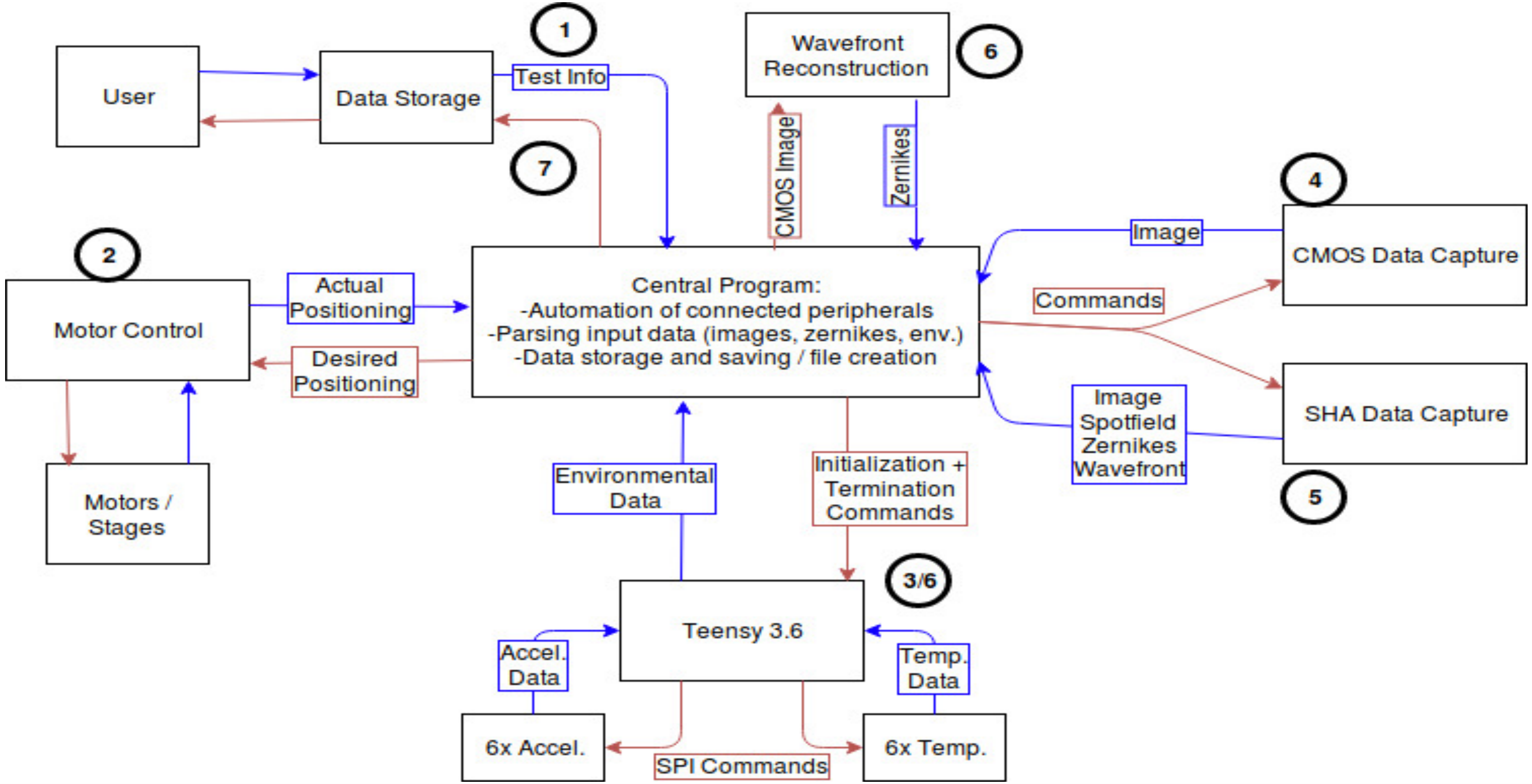
- ThorLabs KDC101 Motor Controller (1 of 3)
- Gloves
- Masks
- LED heatsink
- OR gates
- Aluminum rod
- Fasteners
- Powdercoat

All other components have been received. Lead times not expected for any of above items.

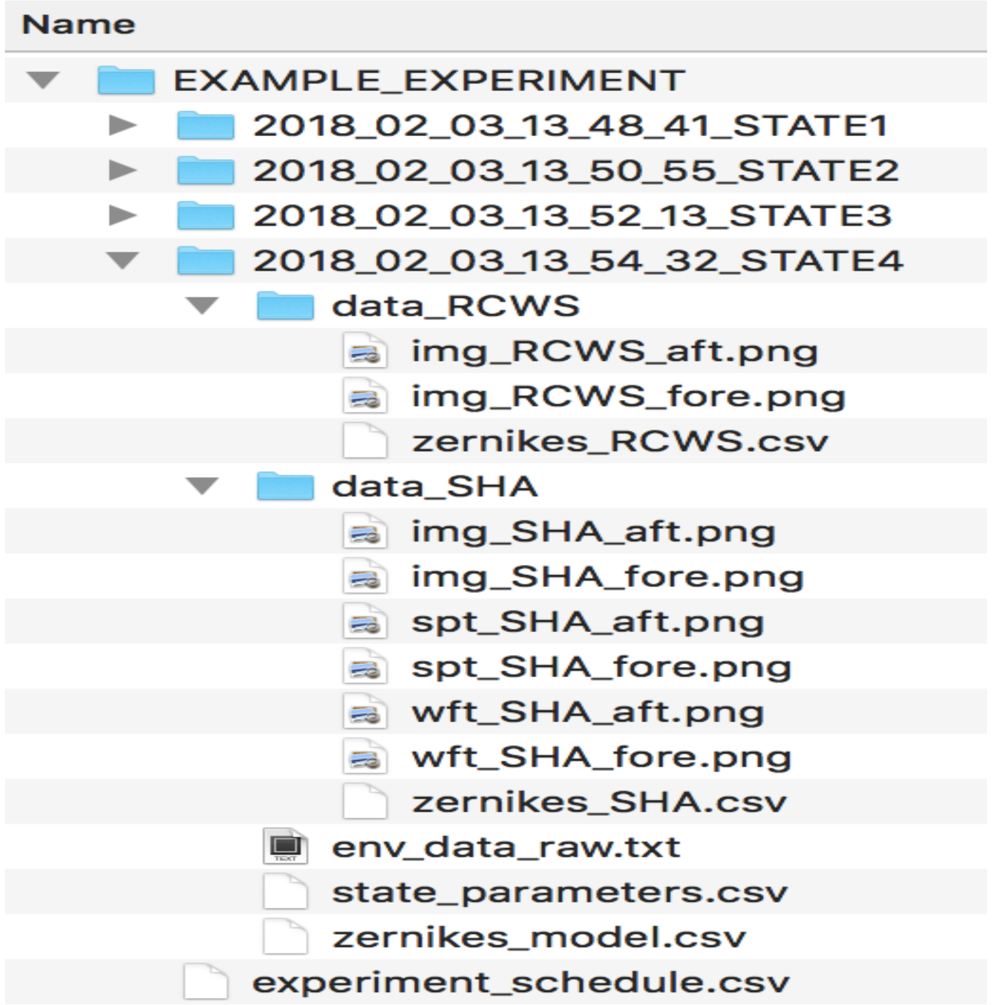
QUESTIONS?

BACKUP SLIDES

Test Control FBD

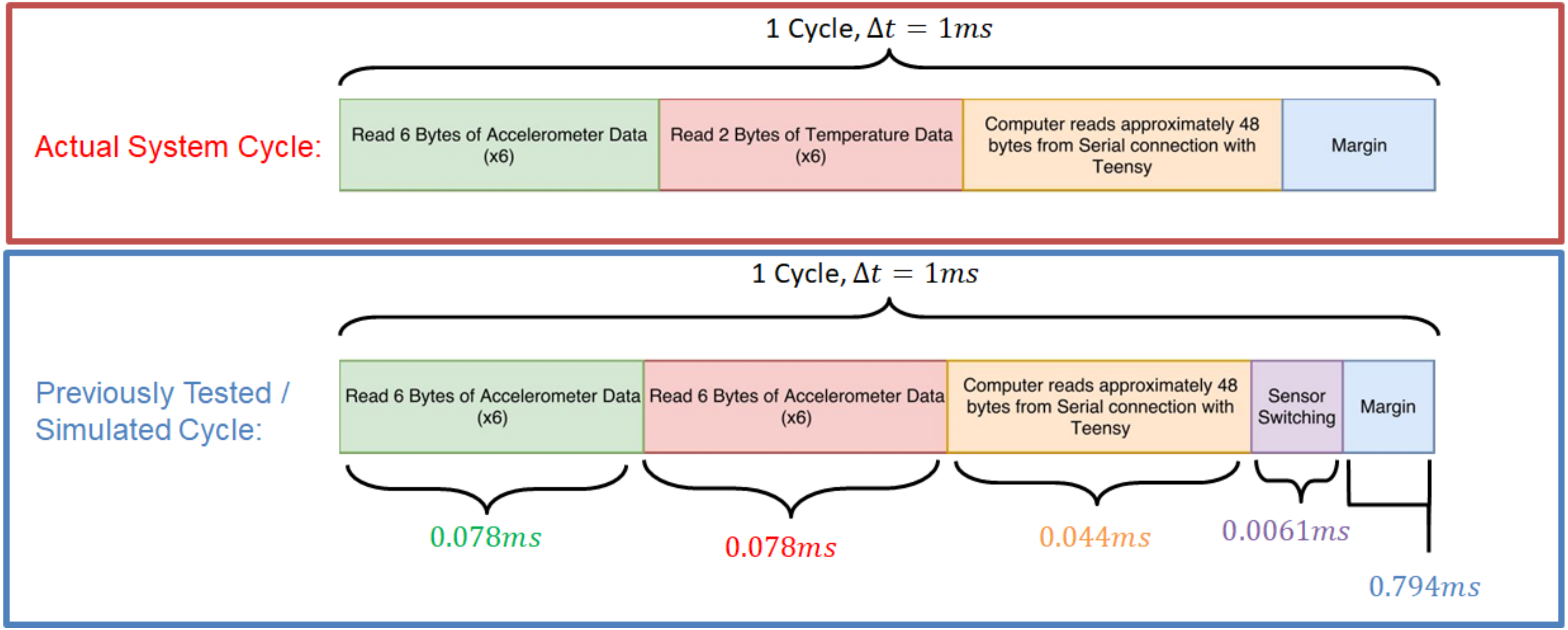


Data Standardization Document



1. User specifies a “schedule” of states to test
2. Test control program reads the test specification and creates timestamped sub-folders for each state of the system.
3. Each sub-folder can stand alone with required state information, raw data from sensors, predicted results, and reconstructed wavefronts.

Environmental Sensors – Timing Diagram

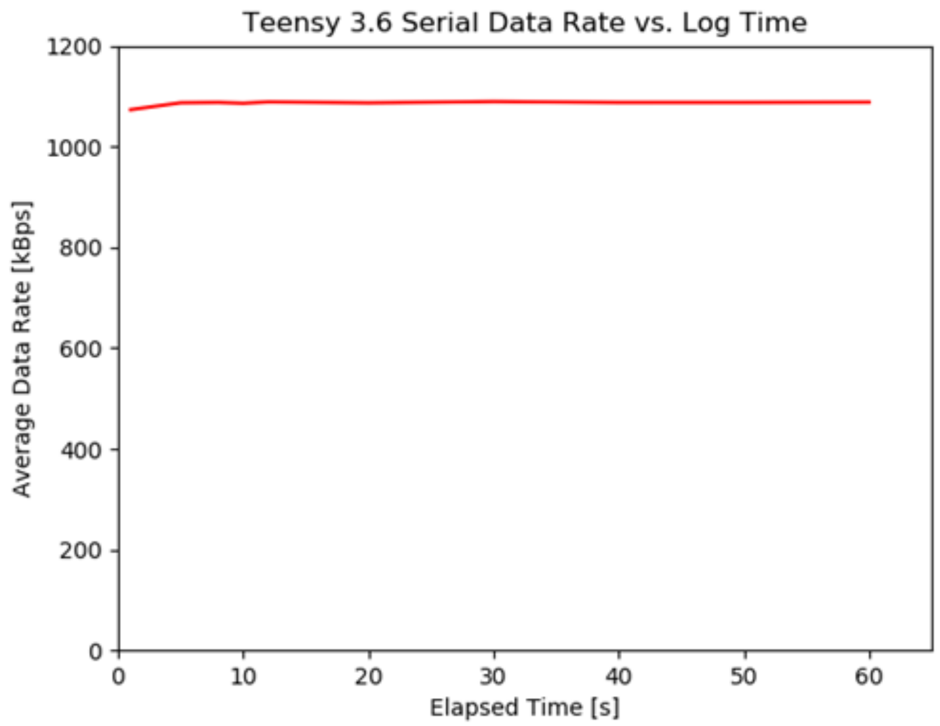


Environmental Sensors – Data Rate Testing

- Serial Read Data Rates were constructed using Python with pyserial, Windows 10, and a Teensy 3.6.
- For Data checking, the Teensy had been set to count from 0 to 99 endlessly while streaming the data over serial. The data was detected to have zero errors.
- Tests were run with varying time intervals of 1, 5, 8, 10, 12, 20, 30, 40, 50, and 60s

Serial Testing Results			
Average Data Rate: [kBps]	Total Number of Bytes Sent	Total Time Taken: [s]	Tests Conducted:
1086.041	256754500	236.066	10

Generic SPI Device Testing Results			
Average Switching Time [μs]	Average 48-bit Read Time [μs]	Total Number of Switches and Reads	Tests Conducted
0.5104	12.976	465572	10



- SPI testing was completed with two generic accelerometers, testing read time and the time required to switch between sensors

Environmental Sensors – Sensor Characteristics

- **Component Choices:**
  - Microcontroller: Teensy 3.6
  - PC Interface : Serial USB connection
  - Accelerometer: ADXL 344
  - Temperature Sensor: ADT7320
  - Overall Schematic

ADXL344 Requirements and Performance				
	Sampling Rate	SPI Data Rate	Resolution	Filtering?
Requirement:	1 kHz	0.55 MHz	NA	Yes
ADXL-344 Performance	3.2 kHz (Maximum)	5 MHz ($\approx$ 5 $Mbps$)	$\pm 3.9mg$	Yes

ADT7320 Requirements and Performance					
	Sampling Rate	SPI Data Rate	Resolution 16 bit (13 bit) [°C]	Accuracy [°C]	Filtering?
Requirement:	1 Hz	0.55 MHz	$\pm$0.15	$\pm$0.5	No
ADT7320	4 Hz (Maximum)	5MHz ($\approx 5Mbps$)	$\pm$0.0078 ($\pm$0.0625)	$\pm$0.31	No

Wavefront Reconstruction

$$\frac{I_1(\vec{r}) - I_2(-\vec{r})}{I_1(\vec{r}) + I_2(\vec{r})} = \frac{f(f-l)}{2l}\left[\nabla^2 z(\vec{u}) - \frac{\partial}{\partial u} z(\vec{u})\delta_c\right]_{u = f\vec{r}/l}$$

This is the data collected by the test setup

The wavefront (z) is the structure of interest that should be solved for.

- This expression leaves out terms due to diffraction because of assumptions made in the original paper
- To obtain a general solution this relationship would need to be re-derived including the diffraction terms
- At that point a forward-model would exist, but a simple solution for z is not guaranteed.
- A numerical solution could likely be found, however the work required exceeds the capabilities of the team