Weather Resistant Autonomous Imaging for Tracking HEOs

Final Oral Review

Sponsor

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Advisor

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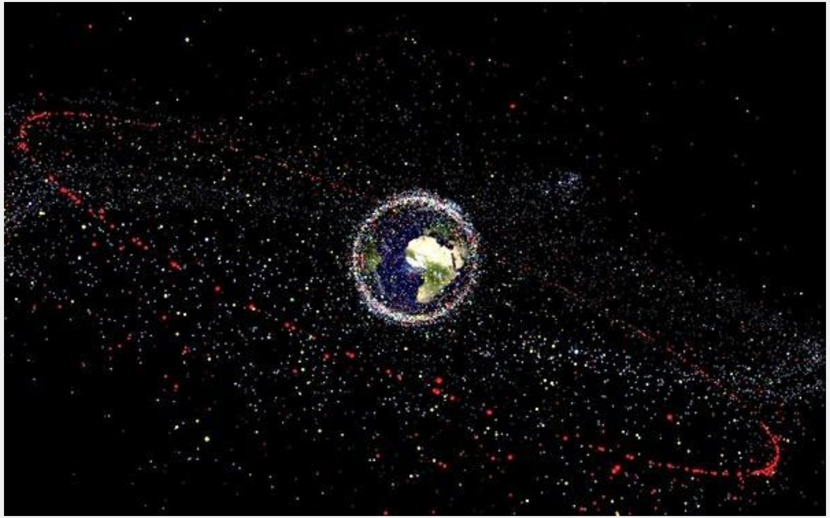
Project Purpose and Objectives

The Problem

- High Risk
  - Collision could be catastrophic for GPS, weather, national security, science, etc.
  - ~20,000/750,000 objects greater than 1 cm currently tracked
  - Launch costs continue to decrease
  - 2nd largest risk
- Current SSA systems:
  - Low Volume
    - Just over 20 in total
  - High Load
    - 80,000 observations per day
  - Expensive
    - Cost upwards of $100,000 each
  - Highly capable



Courtesy ESA

The Solution

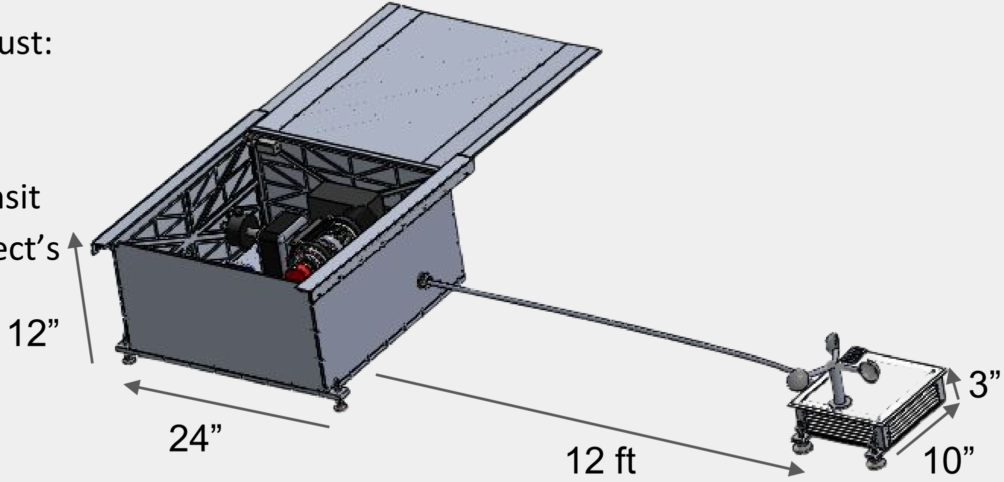
Weather **R**esistant **A**utonomous **I**maging for **T**racking **H**EOs

Mission Statement:

WRAITH's mission aims to demonstrate the feasibility of a low cost, autonomous, deployable space situational awareness system.

WRAITH is a Space Situational Awareness System that must:

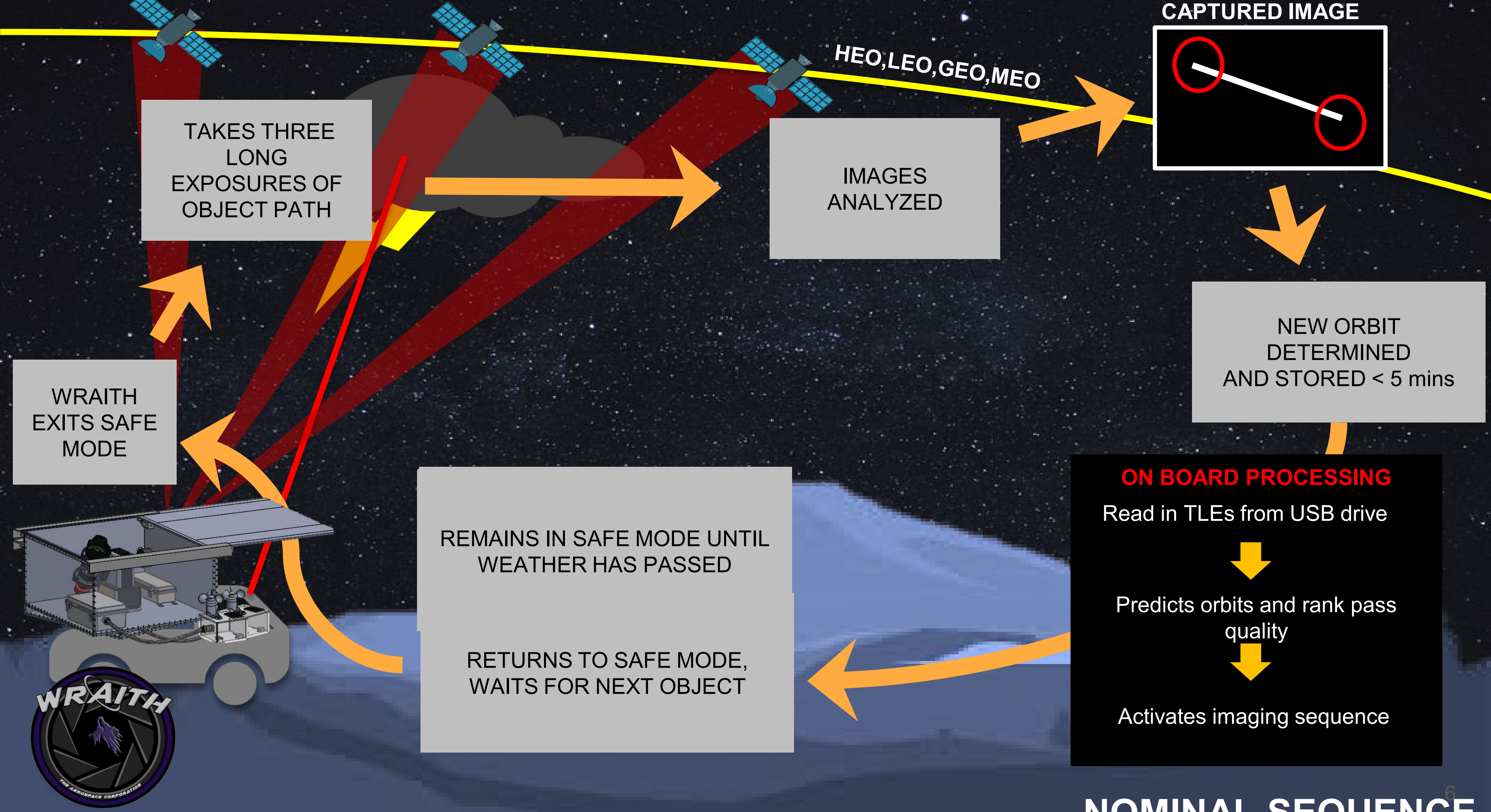
- Predict the orbit of a space object using a TLE
- Point a camera at an orbiting space object
- Capture 3 images throughout a space object's transit
- Generate and return an estimate of the space object's orbit
- Be capable of a 12 hour overnight deployment
- Do all of this autonomously



Levels of Success

	Level 1	Level 2	Level 3
Scheduler	Once Per Night	Runs Multiple Times	Adaptable to Missed Targets
Automation	Must be Monitored	Human Calibration	No human input after setup
Weather Detection	<95%	<99%	>99%
Weather Protection	Protects Against Rain	All Precipitation, Wind	Protects Against All Weather Types

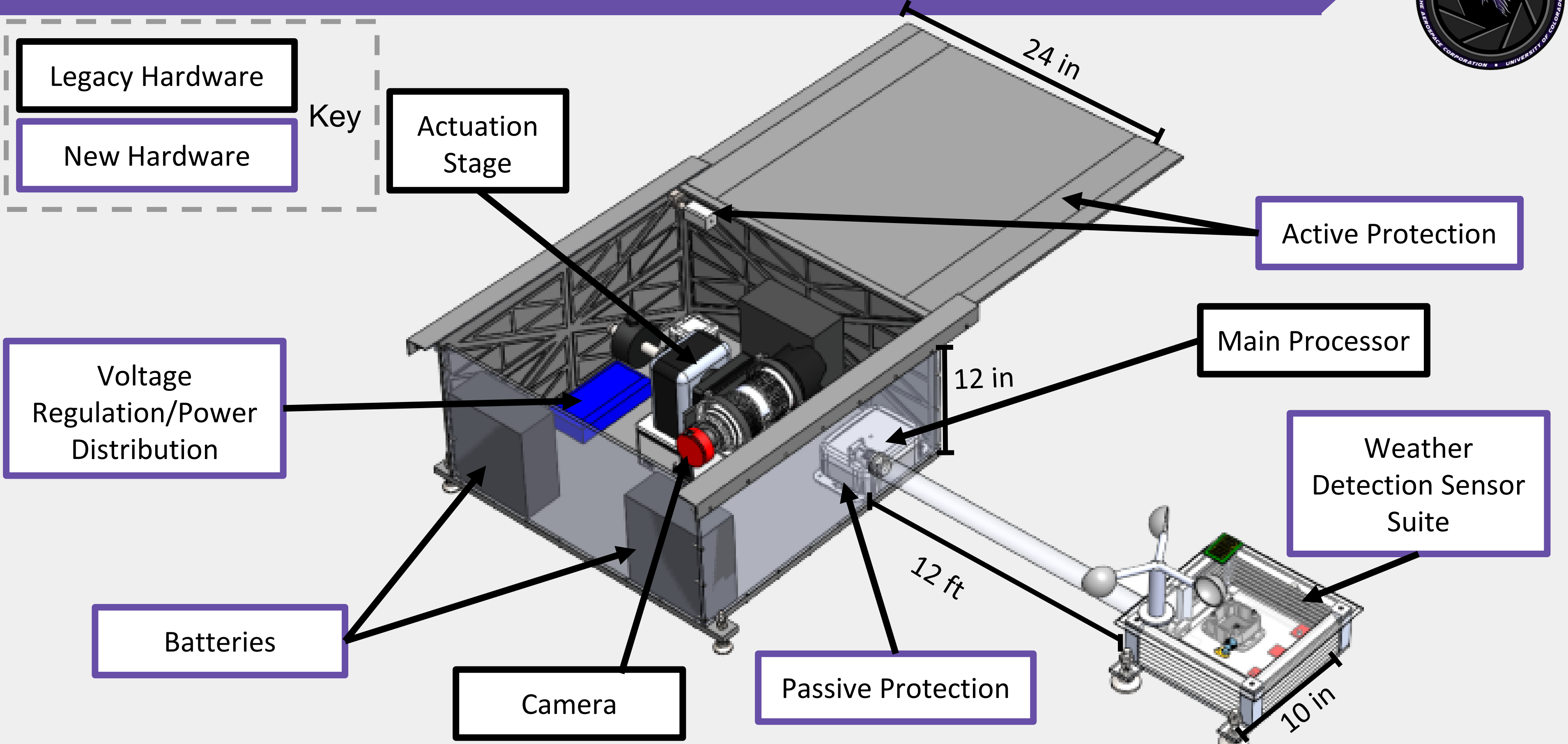
Accomplished	In progress as of shutdown



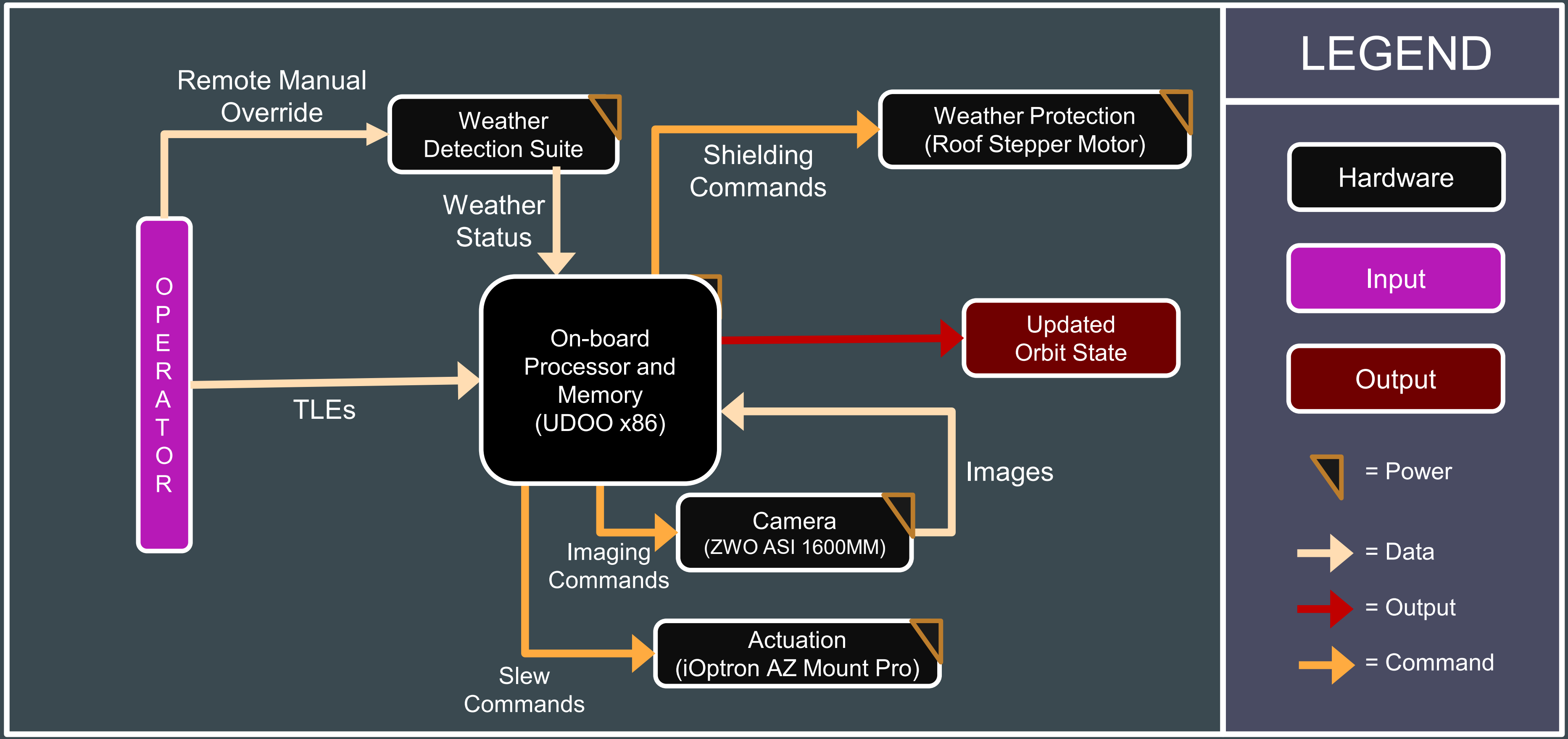
NOMINAL SEQUENCE

Design Description

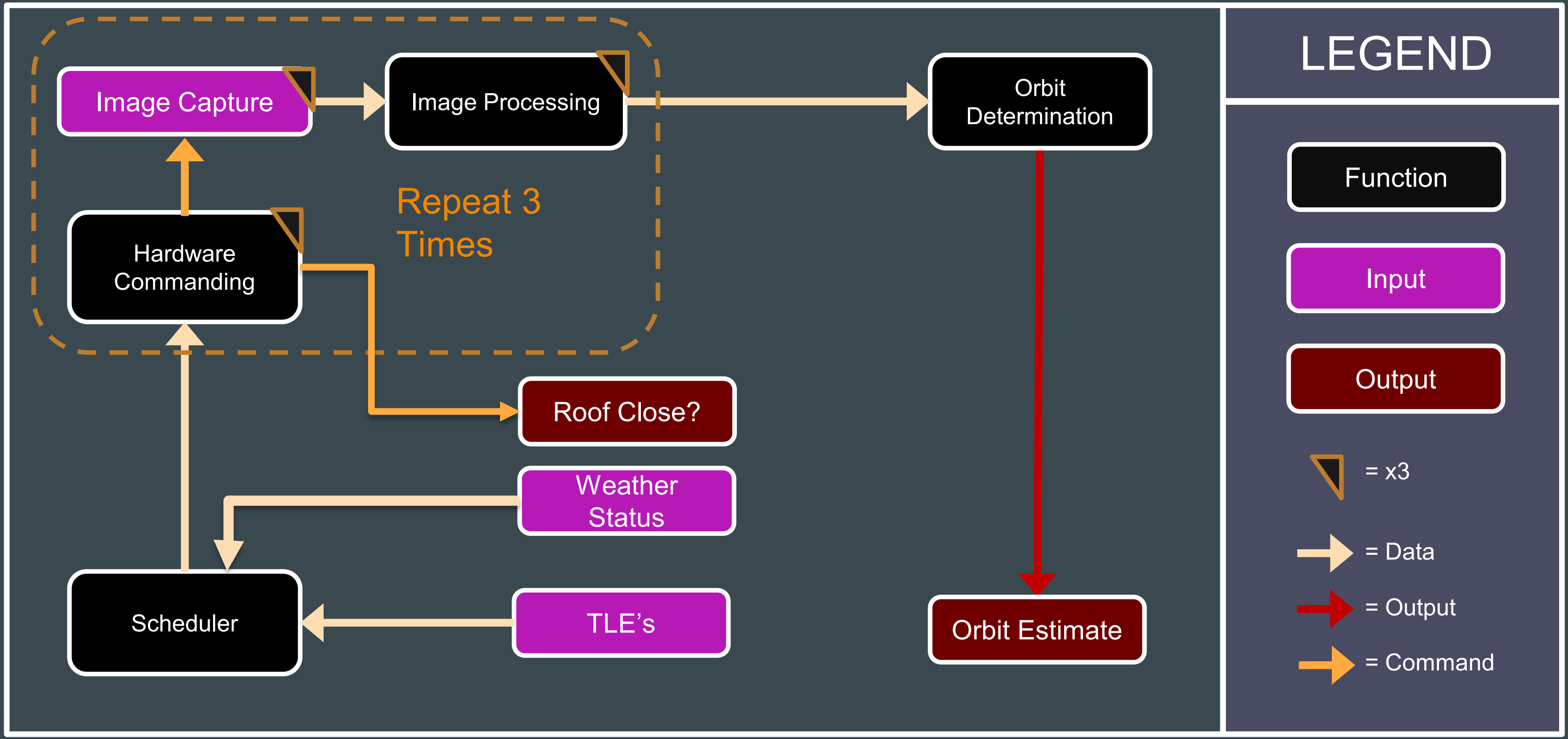
Baseline Design Hardware Overview



Functional Block Diagram



Software Functional Block Diagram



Critical Project Elements Review

Active Weather Protection

Weather Detection

Software / Hardware Integration

Automation

Test Overview

Test Progress

LEGEND

Completed Test | In Progress Test | Scheduled Test | Discussed - ★

Software

- ★ iOptron Calibration Test – FR 1 & FR 4
- ★ iOptron Slew Speed – FR 1 & FR 4
- Home Accuracy Test – FR 3
- Real Image Processing Test – FR 5
- ★ Partial System Test – FR 1, 4, 6

Hardware

- ★ Lid Actuation Versatility Test – FR 3
- Water Proof Test – Main Unit – FR 3
- Water Proof Test – COTS Boxes – FR 3
- Batteries – FR 2
- GPS Testing – FR 1, 4

Environmental

- Sensor Baseline Functionality – FR 2 & FR 3
- Individual Sensor Validation & Characterization – FR 2 & FR 3
- Combined Sensor Validation & Characterization – FR 2 & FR 3
- Communication Testing – FR 2 & FR 3
- ★ Sensor Suite Testing – FR 2 & FR 3

Overall System Testing

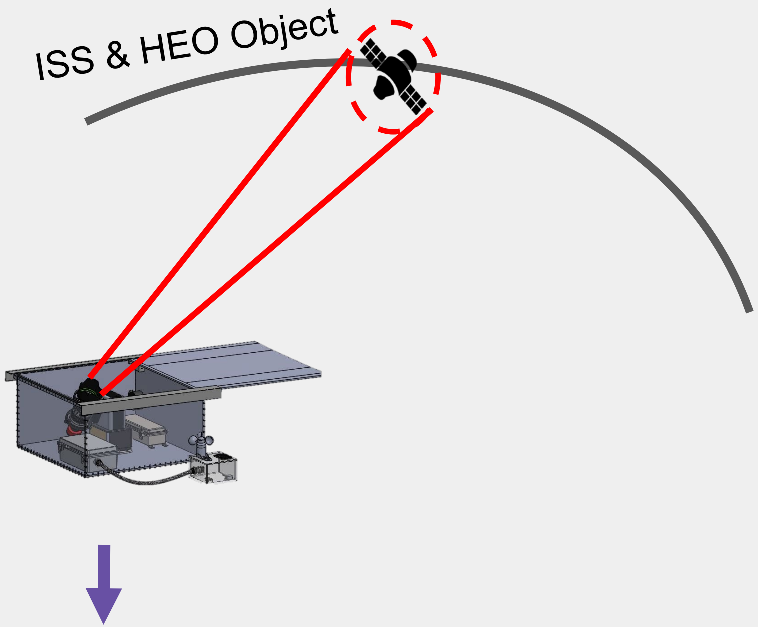
- ★ Full System Test – FR 1-7
- Long Duration Test – FR 1-7

Test Results

Full System

Final System Test

- **Goal: Show that WRAITH completes the project as designed by:**
  - **Detecting adverse weather**
  - **Protecting against adverse weather**
  - **Integrating GHOST's systems**
  - **Operating autonomously**
- **Materials: WRAITH enclosure, stage mount, camera, batteries, main processor, weather station**
- **Requirements Verified:** All
- Test Results: **Not Completed**



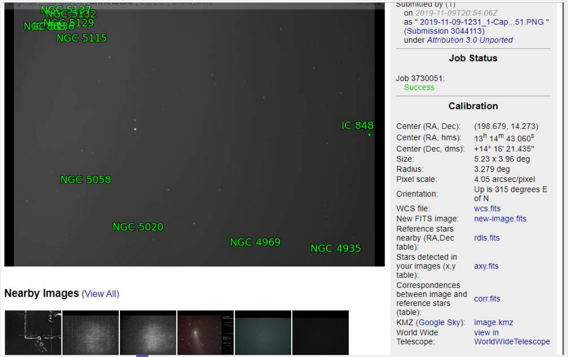
Output: Updated orbital elements of target object, system timing information, system accuracy, weather detection reports

Final System Test – Expected Results

Input:
```
1 25544U 98067A   20110.73034753 -.00014135  00000-0 -24642-3 0  9993
2 25544  51.6433 277.7944 0002012 165.2380 294.1637 15.49280247222958
```

Scheduler & Hardware Commanding

Image Processing

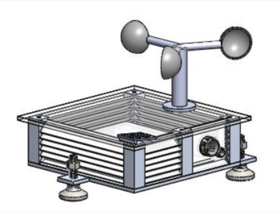


Orbit Determination

Updated TLE:
```
1 25544U 98067A   20110.33777738  .01441528  00000-0  23369-1 0  9998
2 25544  51.6449 279.7367 0002617 178.6717 249.7633 15.49465314222894
```

Deployment Time

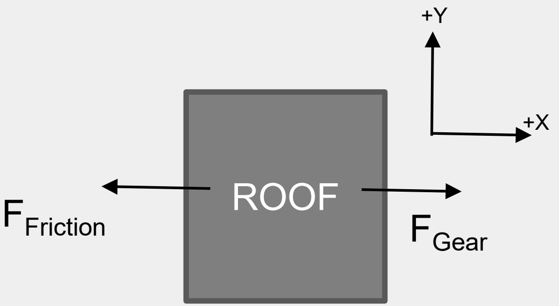
If Adverse Weather Detected

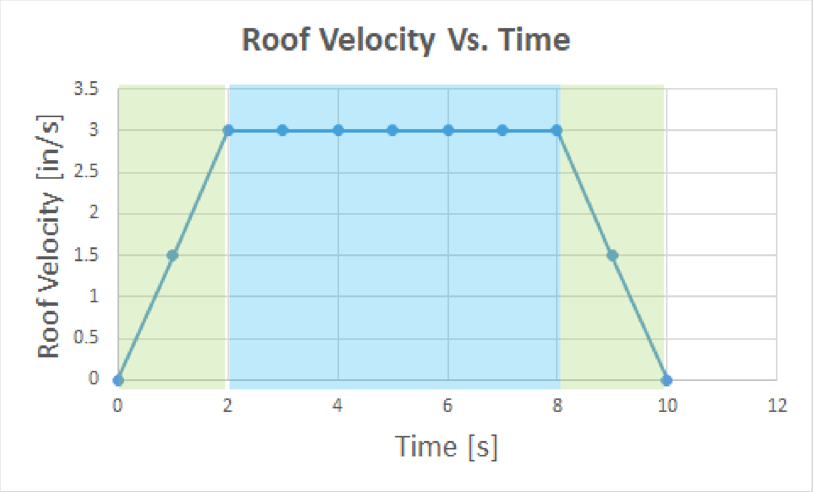


Expected Output:
```
1222000,Last Close:1221000,cell:0,WindSpeed:1.5,Lightning Distance:255,
Rain:2452,Humidity:93.05,Pressure:84458,IR:29.05
```

Weather Protection

Roof Actuation - Stepper Motor Model





Constant Acceleration

Constant Velocity

Motor Specification Model

$\Sigma F_x = m a_x$

$F_{Friction} = N \mu_{static}$

$F_{Friction} = N \mu$

$a = \alpha R$

$T = I \alpha$

$T_{required} = 146$ [oz in]

Gear Rate Model

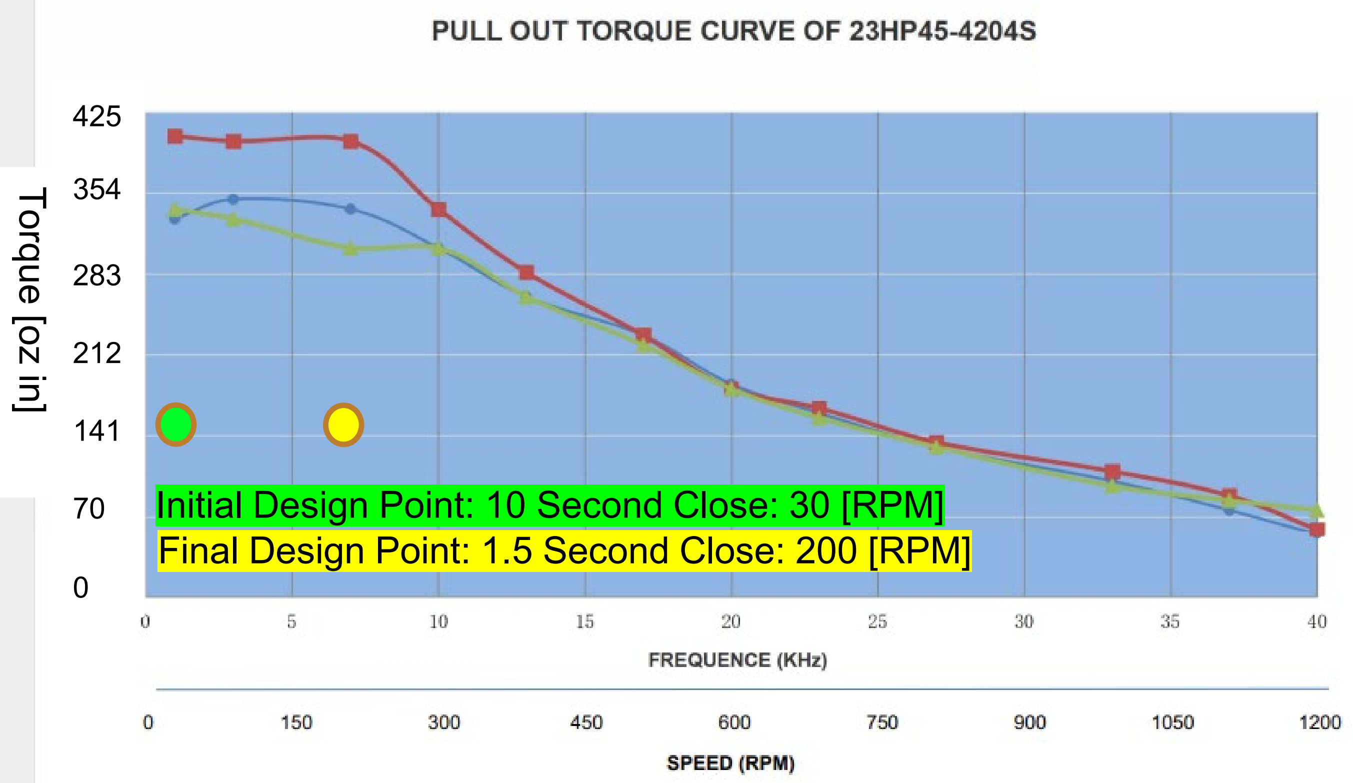
24 Teeth/Revolution

5 Teeth/Inch

24 Inches of Travel

10 Second Close: 30 [RPM]

Roof Actuation - Stepper Motor Model



Roof Actuation - Stepper Motor Model

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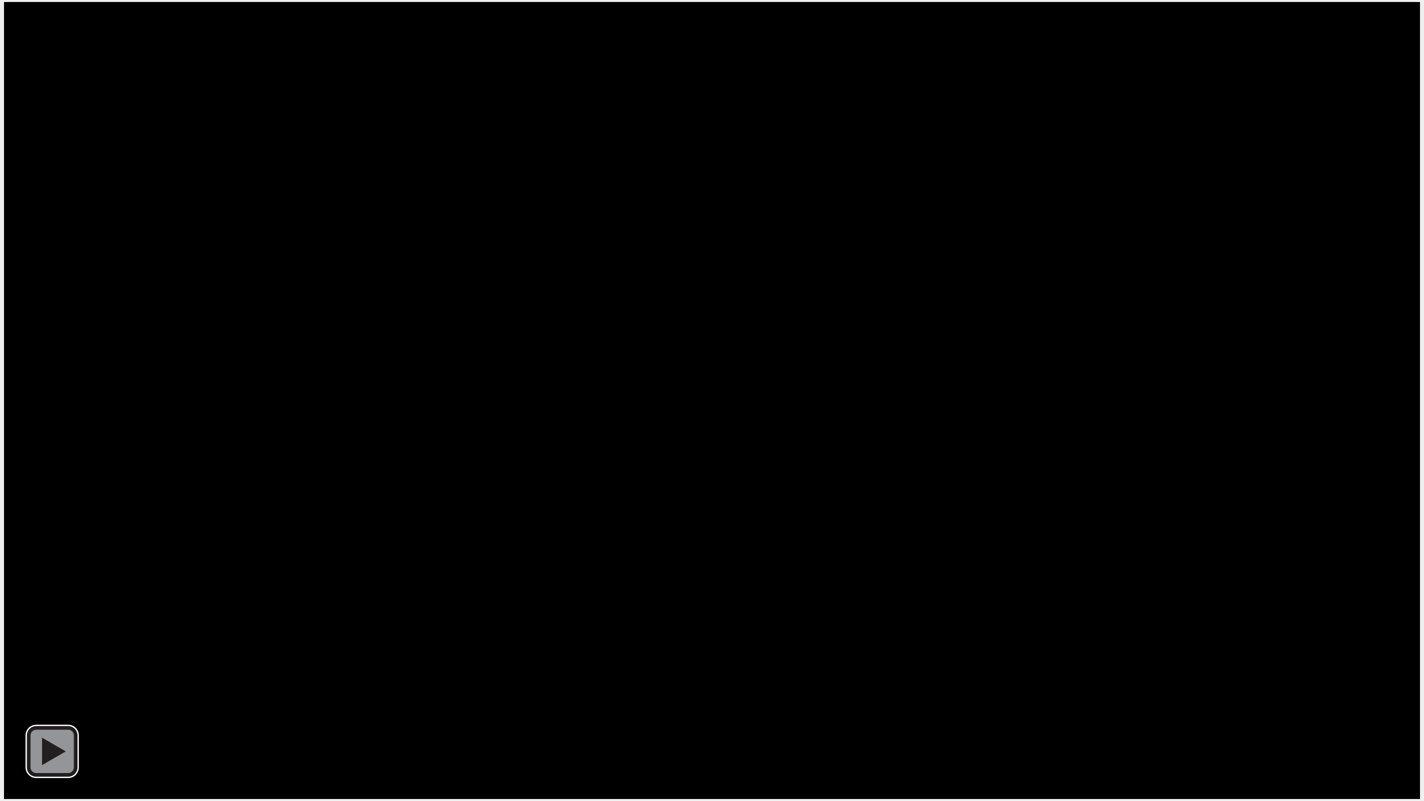


Roof Actuation Test - Overview

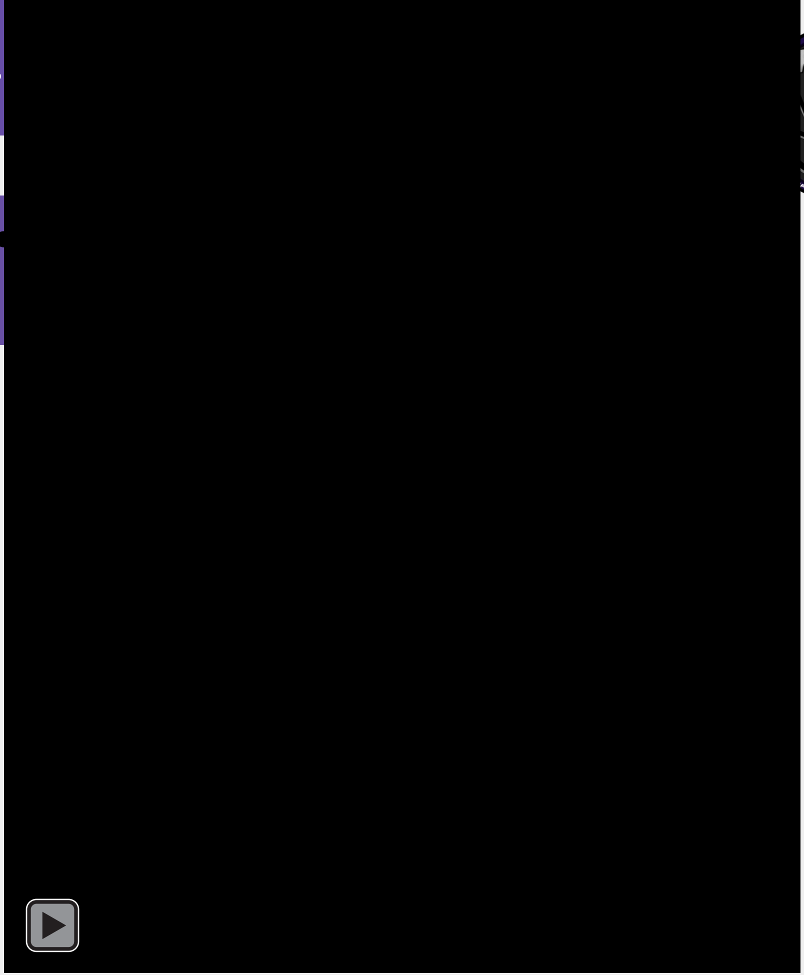
- **Testing Goal:** Verify operation of roof motor and gear system through onboard controls
- **Motivation:** Ensure timely and reliable actuation of WRAITH's roof
- **Materials:** Assembled WRAITH enclosure, UDOO, motor controller & roof motor
- **Requirements Verified:** FR 3, DR 3.1
- **Risks Reduced:** Timely roof actuation protects against quickly developing precipitation

- **Initial Testing:** 125 [oz in] motor actuated roof at 1 [in/sec] reliably

- **Next Steps:** Test full length actuation with new motor but same parameters [425 oz in limit]

Roof Actuation Longevity Test -

- **Testing Goal:** Verify operation of roof motor and gear system through onboard controls
- **Motivation:** Ensure long term reliability for actuation of WRAITH's roof
- **Materials:** Assembled WRAITH enclosure, UDOO, motor controller & roof motor
- **Requirements Verified:** FR 3, DR 3.1
- **Risks Reduced:** Timely roof actuation protects against quickly developing precipitation

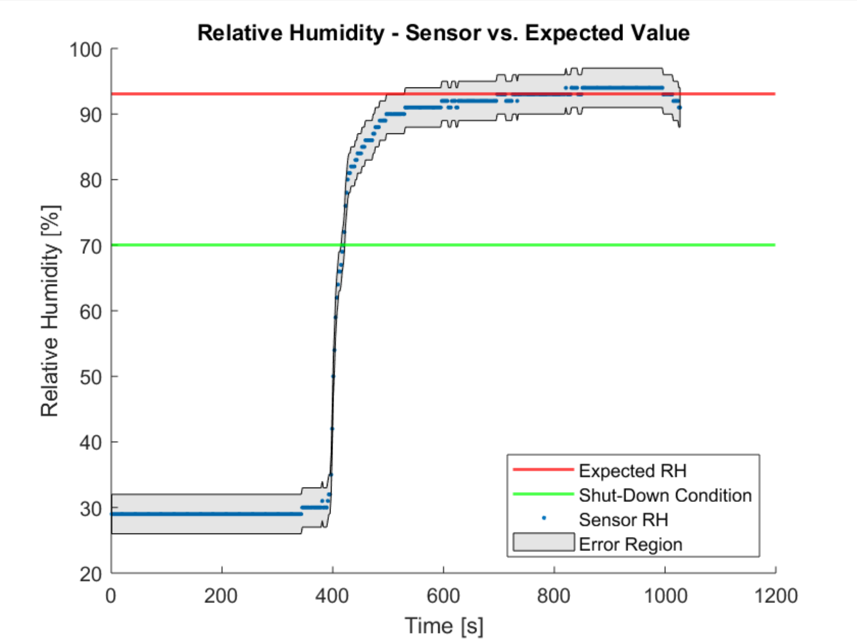


Weather Detection

Completed Environmental Sensor Tests

All sensors have been **tested individually** and compared to known data provided by NWS

All sensors (except the anemometer) have been **tested together** with the completed environmental code



Satisfies Functional Requirement 7 since sensors reach equilibrium in less than 30 minutes

Weather Detection Logic

Single Sensor Safe Mode Trigger:

Lightning detected at any distance

OR

Precipitation detected

OR

Wind speeds detected > 8 m/s

1 Hz

Multiple Sensor Safe Mode Trigger:

Pressure drops by > 3 mb

AND

RH detected above 70%

AND

IR temperature higher than 10°C

Remote Operator Safe Mode Trigger:

Shutdown command received over cellular

Environmental System Tests – Planned

FR 3: Autonomously protect itself from adverse weather

What's our confidence in the Environmental System detecting Adverse Weather (AW)?

Adverse Weather Detection Test:

1. Verify various sensor outputs by comparison with the NWS
2. Integrate the sensor suite and trigger condition code
3. Statistically compare weather suite output with qualitative observations

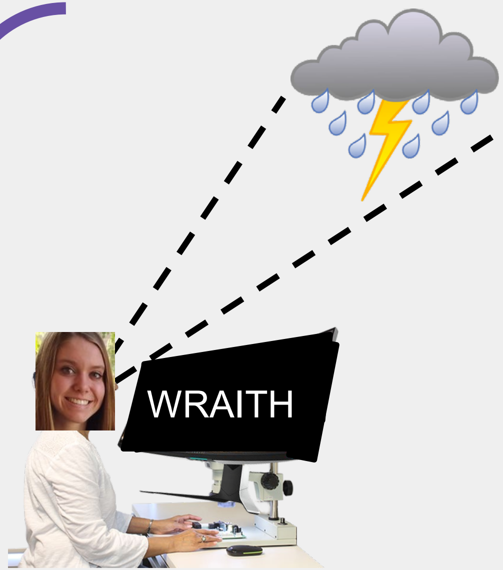
Detected AW ÷ Observed AW ≥ 95%

Materials: Laptop, WRAITH Weather Suite, Project Notebook, Pen/Pencil

Location: Outdoor Clearing

Testing Goal: 95% confidence in the WRAITH Weather Suite

Environmental Systems Test – Incomplete



Record Qualitative Observations
[Including Time of Observation]

↓

Pull System Data from Time of Observation
[System is Running during Observations]

↓

Run System Data through Trigger Conditions
[Output to Be Compared with Qualitative Good/Bad]

x 100

Matching the **Trigger Condition** output to the **Qualitative Observation** output will yield a **positive result**. With **95 out of 100** results positive, the weather detection model will be **validated**.

Environmental System Tests – Results

- **Test Results:** **Never Completed**
- **Expected Results:** Successful detection of adverse conditions
- **Data to Be collected:**
  - -System Timing Response to Adverse Conditions
  - -Potential Instances of Coding Loop failure
  - -Quantitative Measurements for Conditions
  - -Qualitative Assessments of Conditions
- **Models to Be Verified :**
  - -Ability to detect Adverse Weather to 95% confidence

System State is compared to operator's observations

System operations and conditions are analyzed to ensure 95% of time confidence in weather detection to minimize fatal risks to system

Expected Test Progression and Results

Observed Weather Conditions:

Detected Weather Conditions:

- RH: 100%
- IR Thermometer: 29°F
- Precipitation Sensor: 2452 (out of 4096)
- Anemometer: 1.5 m/s
- Lightning Detector: None
- Barometer: Steady 845 mb

Expected Output:

```
1222000,Last Close:1221000,cell:0,WindSpeed:1.5,Lightning Distance:255,Rain:2452,Humidity:93.05,Pressure:84458,IR:29.05
```

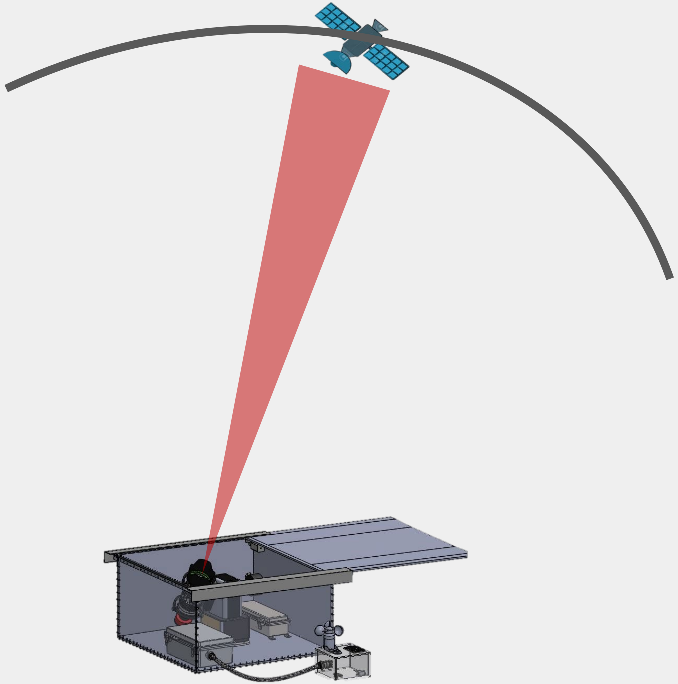
This is a MATCH!

We expected matches **95%** of the time.

Software

Partial System Test – Overview

- **Testing Goal:** Test the following systems ability to run in unison:
  - -Pass scheduler
  - -Hardware Scheduler
  - -Hardware Commanding
- **Materials:** Processor, Camera, Stage Actuator, Main Box
- **Requirements Verified:** FR 1, 4, 6



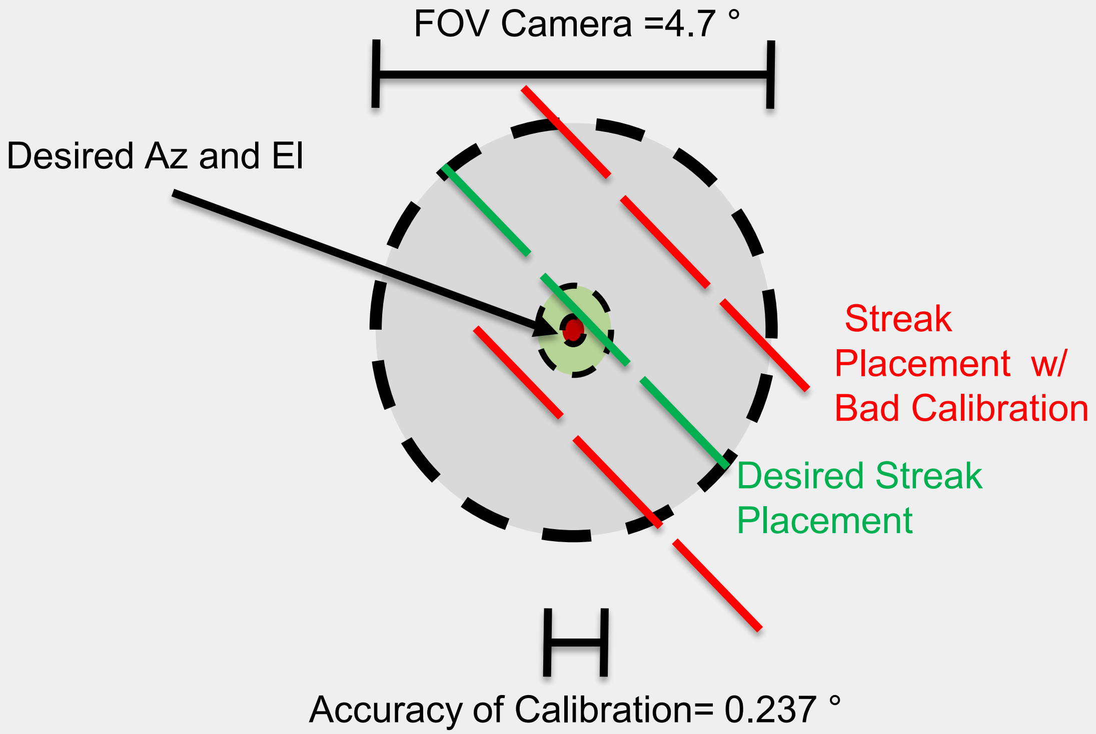
Partial System Test - Results

- **Test Results: Not Completed**
- **Expected Results:** Successful imaging and orbit solution of multiple objects
- **Data to Be collected:**
  - -Timing Data
  - -Component Integration
- **Models to Be Verified :** Worst case scenario of 6 object/hr processor timing model practicality

```
Jobstore default:
    Az_El_slew (trigger: date[2020-05-08 00:01:00 MDT], next run at: 2020-05-08 00:01:00 MDT)
    start_stop_sidereal (trigger: date[2020-05-08 00:01:29 MDT], next run at: 2020-05-08 00:01:29 MDT)
    Dark_Image (trigger: date[2020-05-08 00:01:30 MDT], next run at: 2020-05-08 00:01:30 MDT)
    streak_capture (trigger: date[2020-05-08 00:02:00 MDT], next run at: 2020-05-08 00:02:00 MDT)
    streak_capture (trigger: date[2020-05-08 00:02:06 MDT], next run at: 2020-05-08 00:02:06 MDT)
    streak_capture (trigger: date[2020-05-08 00:02:12 MDT], next run at: 2020-05-08 00:02:12 MDT)
    Slew_Home (trigger: date[2020-05-08 00:02:12 MDT], next run at: 2020-05-08 00:02:12 MDT)
```

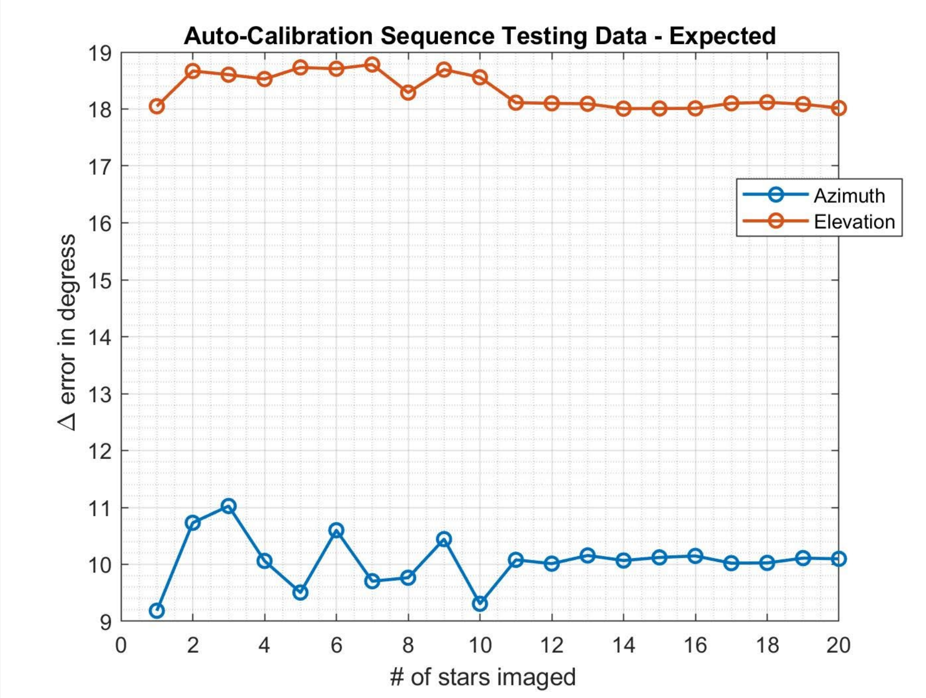
Stage Auto-Calibration Test – Overview

- **Testing Goal:** Quantify the number of calibration points needed in order to ensure streaks will pass within 5% of camera FOV center
- **Motivation:** Maximize the number of streaks capture per image opportunity
- **Materials:** stage, camera, calibration python script
- **Requirements Verified:** FR 4, DR 4.1
- **Risks Reduced:** Missing objects due to a ground system inaccuracy



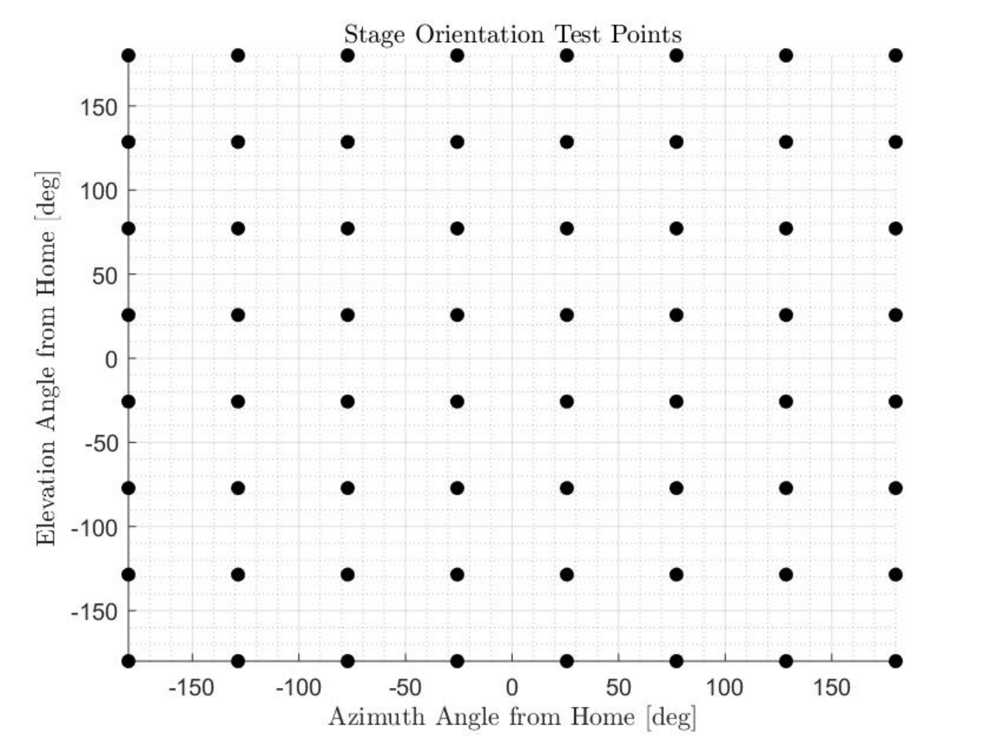
Stage Auto-Calibration Test – Results

- **Testing Results: Not Completed**
- **What the Data Would be Used for:**
  - Tuning the calibration
- **Model Verified:** Ability to match manufacture human-needed 3-star calibration of **0.237 °**



Stage Slewing Test – Expected Results

- **Goal:** Characterize time for stage to slew home from all possible orientations
- **Motivation:** Allows for fastest possible shutdown sequence without roof hitting stage
- **Materials:** Stage, Stopwatch, Bash Script
- **Requirements Verified:** FR 3, DR 4.2 (Autonomous weather protection, acceptable slew speed)
- **Risks Reduced:** Collision between stage or camera and roof, Roof remaining open too long in inclement weather



Full System Timing Test

- **Testing Goal:** Characterize processing time across full system and some individual subsystems
- **Motivation:** Image as many objects as possible without overlapping sequences
- **Materials:** The 'datetime' function in python, completed WRAITH unit
- **Requirements Verified:** FR 5 (At least 6 objects per hour)
- **Risks Reduced:** Overlapping imaging sequence reduces chance of either object's orbit being determined

```
from datetime import datetime
startTime = datetime.now()

# Test: 3 to 30 objects

print(datetime.now() - startTime)
```

Slew sta	6
Auto g	6
Take i	6
Total	
Path 2	
Image	6
Orbit	6
Total	

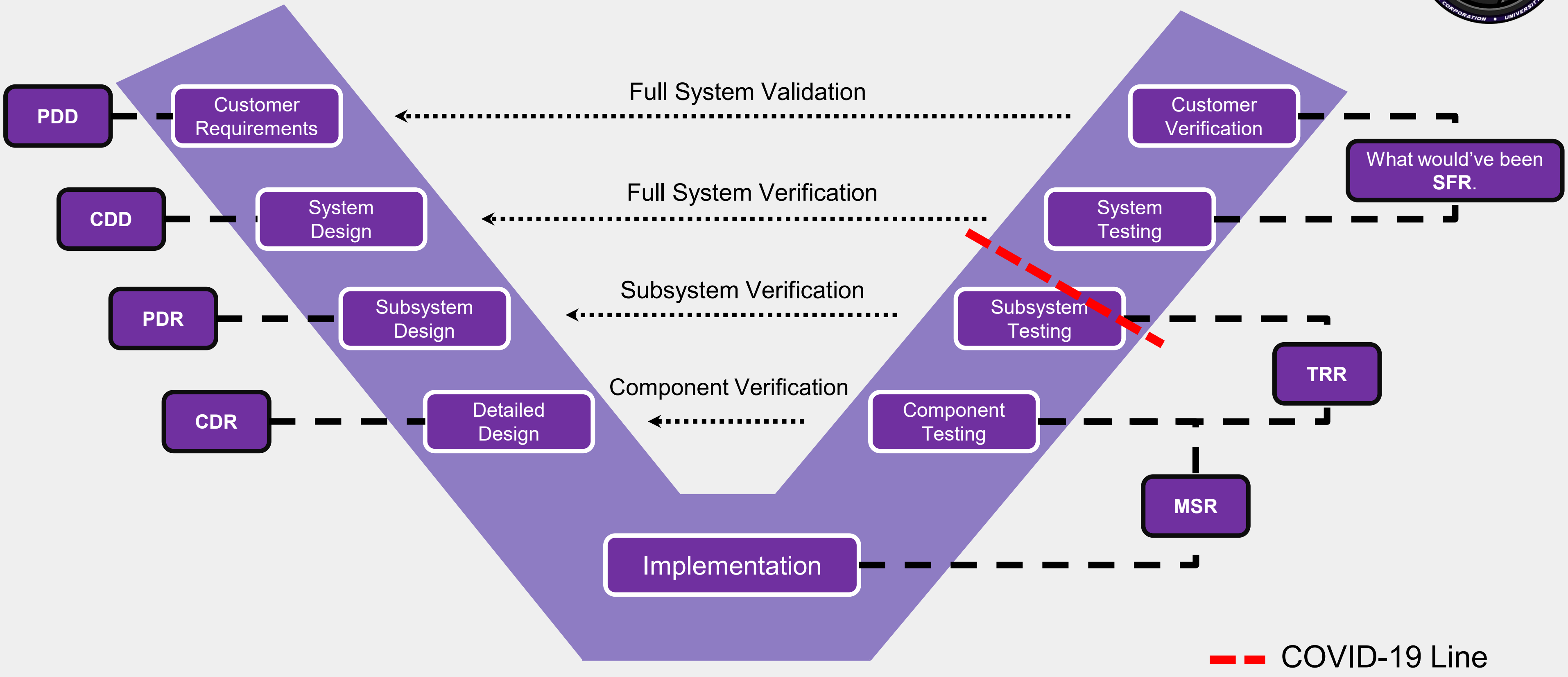
Path 1
- Individual imaging functions
- Scheduler to HW Interface
- Roof open/close
- Mount slewing time

Path 2
- Image Processing
- Astrometry Solver
- Orbit Determination

Full System End to End

Systems Engineering

Systems Engineering Approach



Requirements Development

Customer Given **Threshold** and **Objective Requirements**

GHOST Legacy Hardware, Software, and Mission

Functional Requirements

1. Scheduling visibility windows and locations
2. Function autonomously for 12 hours
3. Enter and Exit Safe Mode
4. Autonomous Pointing
5. Objects magnitude of light 10 or less and image processing in 10 seconds
6. 5 minutes to create and save updated orbit estimates
7. Deployable/Deconstructed in 30 minutes

Design Requirements

1. Palletized and contained within 70cm by 70cm by 70cm cube
2. Any system component mass < 45.35kg
3. Setup and takedown in accordance to *WRAITH System Operation Manual*

Key Trades

Weather Detection

- Sensor Suite
- Radar
- Sensor Suite & Radar

Study Result: **Sensor Suite**

Scheduler

- Passive Scheduler
- Active/Live Scheduler
- Active/Live Traveling Salesman

Study Result:

Active/Live Scheduler

Weather Protection

- Moon Roof Box
- Lateral Garage
- Canvas Convertible
- Concentric Segmented Dome
- Sliding Canopy

Study Result: **Moon Roof Box**

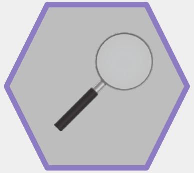
Major Issues & Challenges

Actuation Stage Breaking

Originally a focus, yet slated at a high risk due to recoverability, **Single Point Failures** had to be readdressed so to ensure designs and implementation were peer reviewed.

UDOO Arduino Interfacing

Issue with integrating the stepper motor for the rack and pinion roof actuation. Turned an assumed simple task into an increased already high risk of **active weather protection failure**.



Legacy Hardware and Software Constraints

Taking on legacy HW & SW yielded challenge in unforeseen inherited errors or constraints. Forced team to redesign certain aspects like the stage pointing methods during implementation. **Increased multiple risk areas**.

Key Takeaways

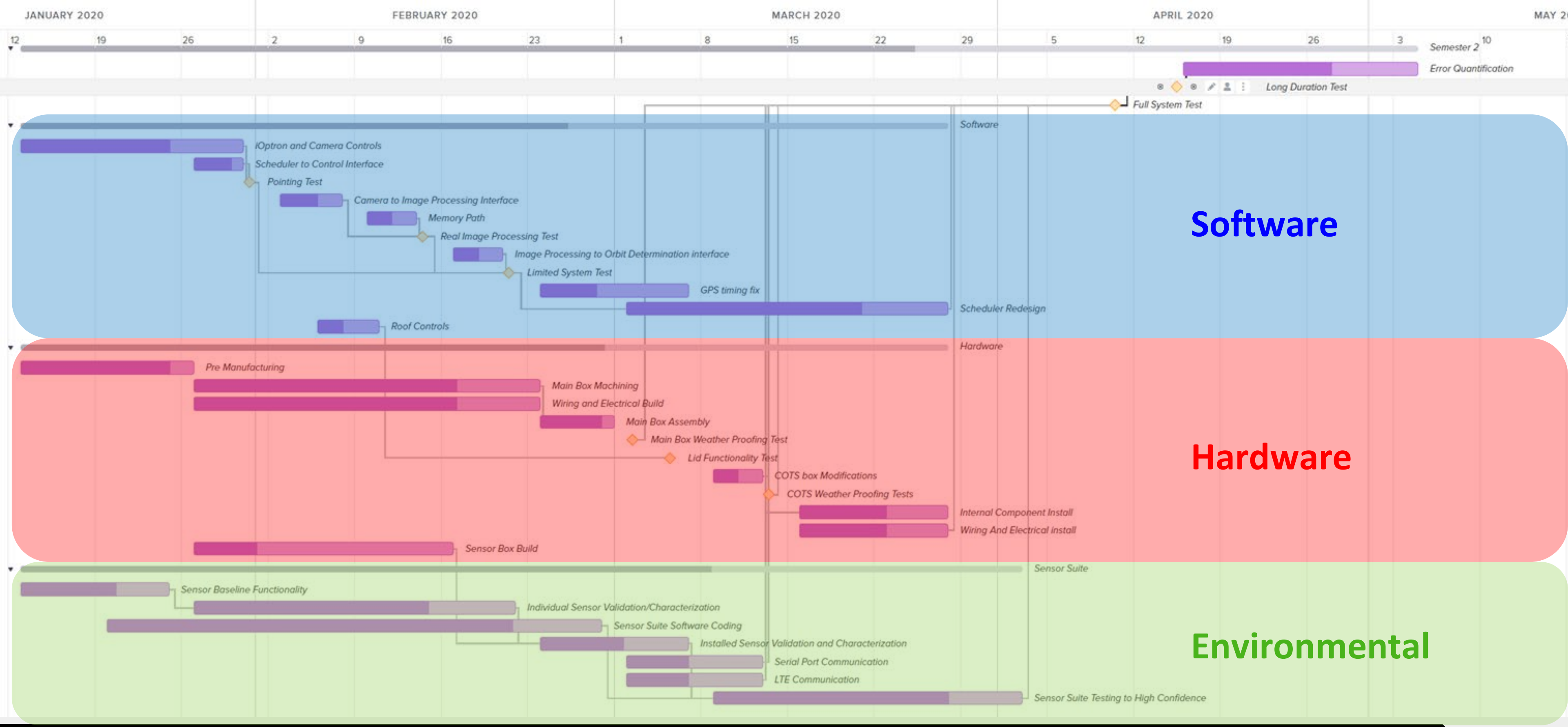
Legacy projects require complete understanding of previous work to mitigate implementation risk and allow for better requirements creation.

Operate closer to line between too constrained and implementation free in requirements development.

Utilize all budget for buying down integration/interfacing struggles. Past functionality can be maintained without the same past hardware.

Project Management

Strategy


JANUARY 2020
FEBRUARY 2020
MARCH 2020
APRIL 2020
MAY 2
12 19 26 2 9 16 23 1 8 15 22 29 5 12 19 26 3 10
Semester 2
Error Quantification
Long Duration Test
Full System Test
Software
iOptron and Camera Controls
Scheduler to Control Interface
Pointing Test
Camera to Image Processing Interface
Memory Path
Real Image Processing Test
Image Processing to Orbit Determination interface
Limited System Test
GPS timing fix
Scheduler Redesign
Roof Controls
Hardware
Pre Manufacturing
Main Box Machining
Wiring and Electrical Build
Main Box Assembly
Main Box Weather Proofing Test
Lid Functionality Test
COTS box Modifications
COTS Weather Proofing Tests
Internal Component Install
Wiring And Electrical install
Sensor Box Build
Sensor Suite
Sensor Baseline Functionality
Individual Sensor Validation/Characterization
Sensor Suite Software Coding
Installed Sensor Validation and Characterization
Serial Port Communication
LTE Communication
Sensor Suite Testing to High Confidence
Software
Hardware
Environmental

Objectives

	Integrate First	Rule of 2's	Single Path
Reasoning	• GHOST • Working product first	• Single point failure	• GHOST • Quick Progress tracking
Result	Mostly Successful • Very Near Working	Moderate Success • Too strict → Got lax • Lost hardware	Mostly Successful • 3 paths • Difficult to get everyone
Lessons Learned	• Difficult to communicate	• Not always possible • Difficult to enforce • Not always needed	• Mostly a good idea • Things don't always run so smoothly
If there was a next time	• Continue to integrate early	• Guideline of 2's • Checklists	• Single Phases

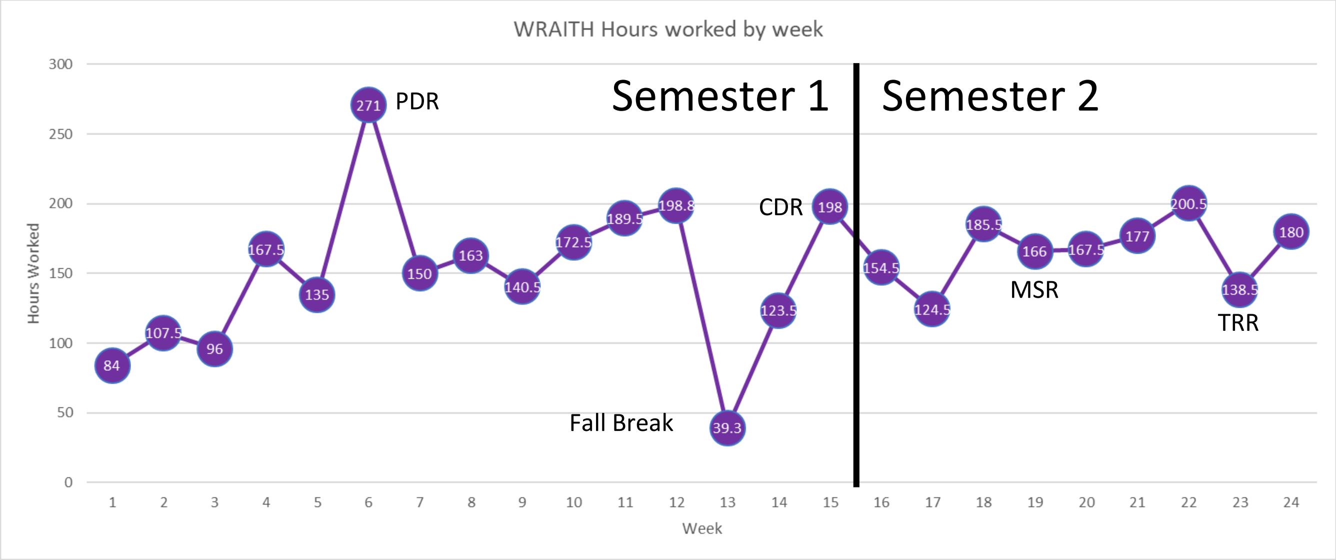
How Much Would We Have Cost

Assumptions:

- Entry level salary of $65,000 (2080 hours of work)
- Overhead rate of 200%
- Materials included

Figures

- 31.25 $/hr Salary
- 93.75 $/hr with overhead
- 3730 hours completed
- ~$355,000 w/ materials



Hypothetical

- Average 155 hrs/week
- 4973 hours (using avg)
- ~$471,000 w/ materials

Budget Comparison

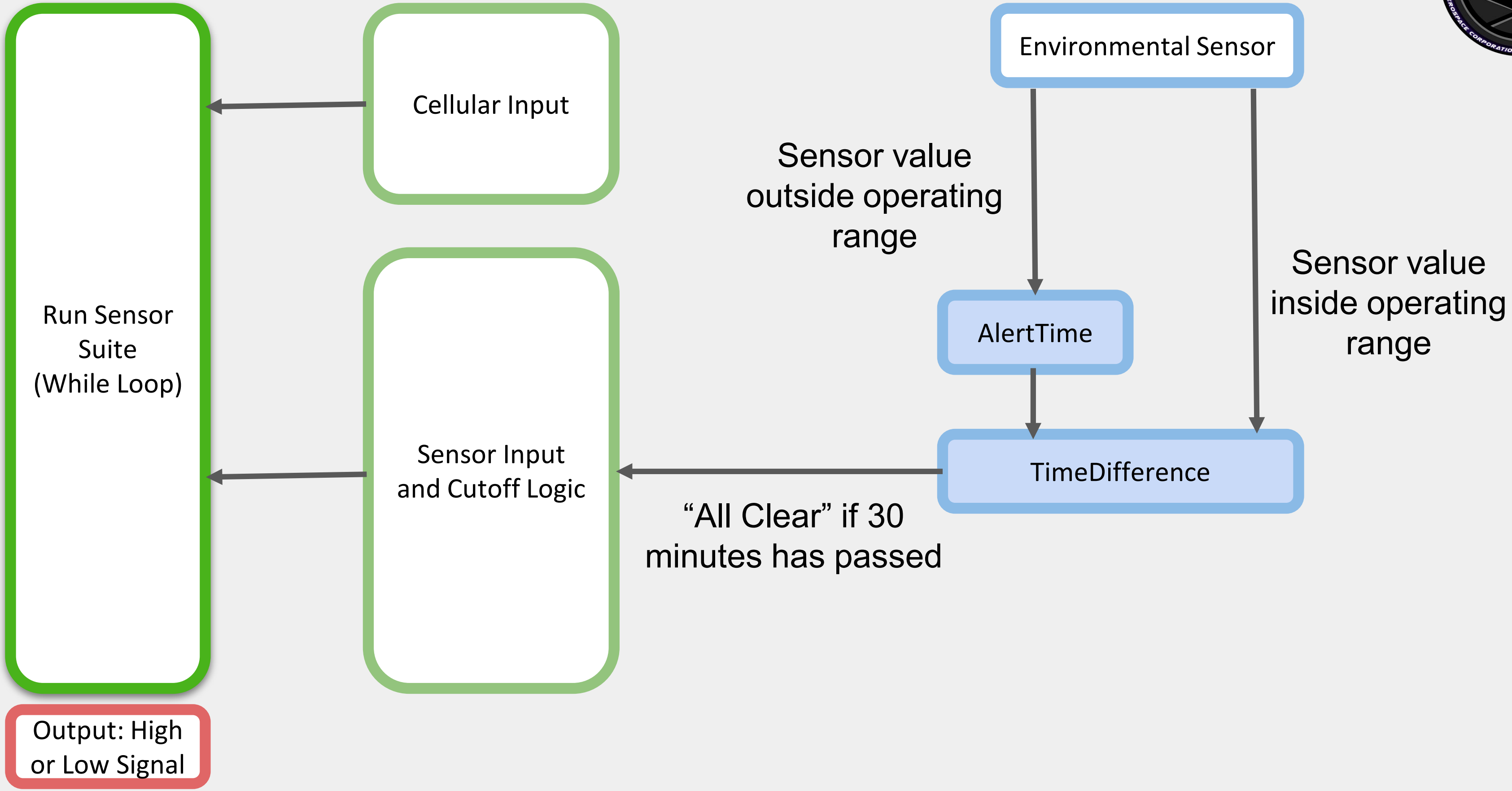
CDR Budget				
Subsystem	**Cost**	**Budget**	**Individual Margin**	**Project Margin**
Active Protection	$ 862.67	$ 1,200.00	28%	-
Passive Protection	$ 92.56	$ 300.00	69%	-
Power Systems	$ 521.80	$ 600.00	13%	-
Testing	$ 50.00	$ 100.00	50%	-
Weather Detection	$ 391.81	$ 500.00	22%	-
Miscellaneous	$ 13.55	$ 20.00	32%	-
WRAITH Total	**$ 1,932.39**	**$ 5,000.00**	**-**	**61%**
Reserve Funding	**$ 3,067.61**	**$ 2,280.00**	-	-

FOR Budget				
Subsystem	**Cost**	**Budget**	**Individual Margin**	**Project Margin**
Active Protection	$ 1,184.90	$ 1,200.00	1%	-
Passive Protection	$ 188.99	$ 300.00	37%	-
Power Systems	$ 715.32	$ 600.00	-19%	-
Testing	$ 246.94	$ 100.00	-147%	-
Weather Detection	$ 524.73	$ 500.00	-5%	-
Software	$ 177.92	$ -	-	-
To Be Purchase	$ -	$ -	-	-
Shipping	$ 134.20	$ -	-	-
WRAITH Total	**$ 3,173.00**	**$ 5,000.00**	**-**	**37%**
Reserve Funding	**$ 1,827.00**	**$ 2,300.00**	-	-

Questions?

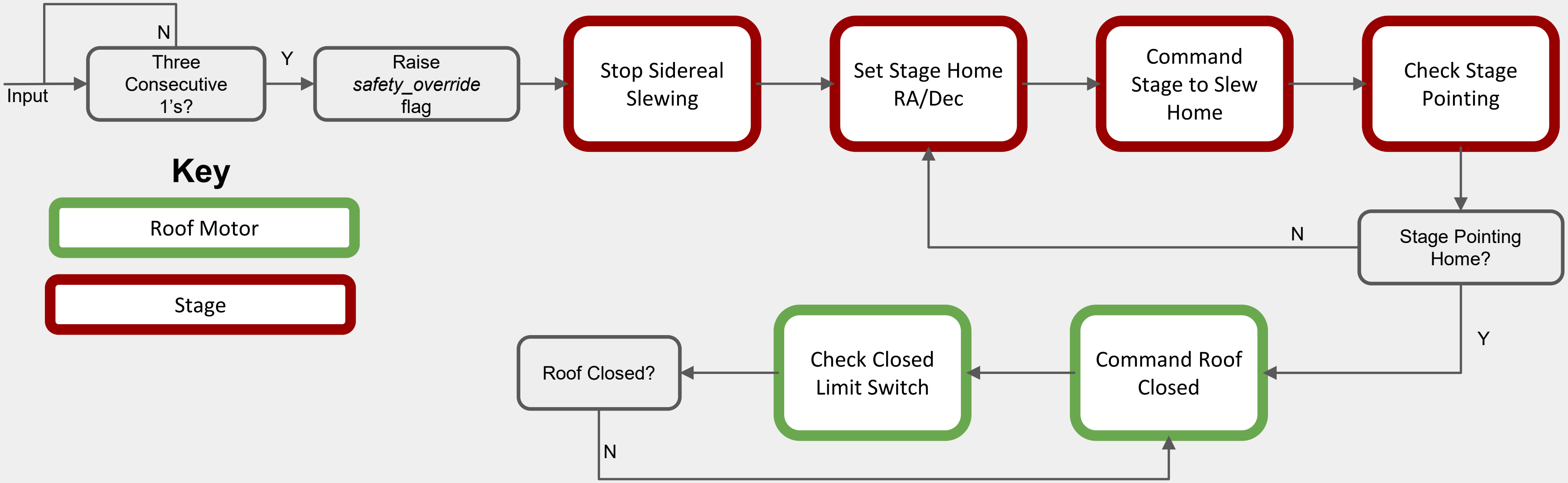
Backup Slides

Environmental Sensing Software Logic

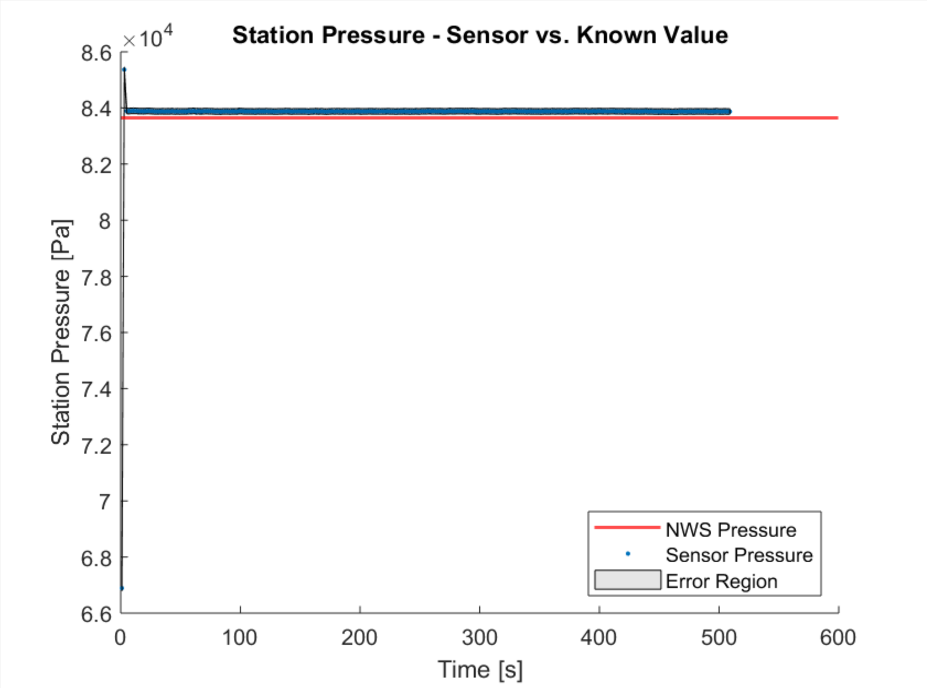


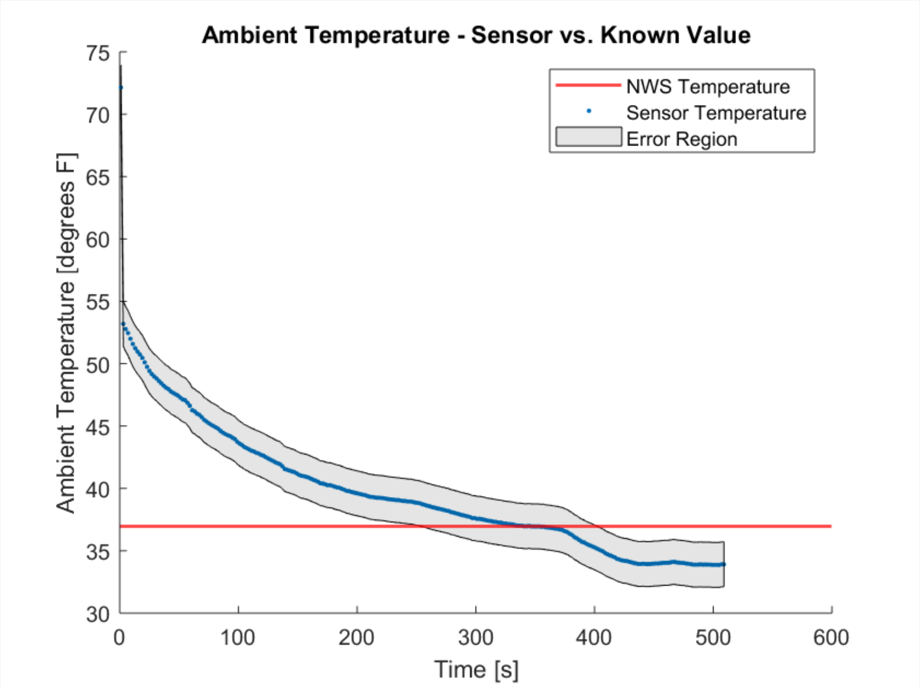
Safety Override

- **Input -** Constant weather status from environmental sensing suite (0 - safe   or   1 - unsafe)
- **Recovery**
  - Scheduler notified to reschedule
  - *Safety_override* flag lowered

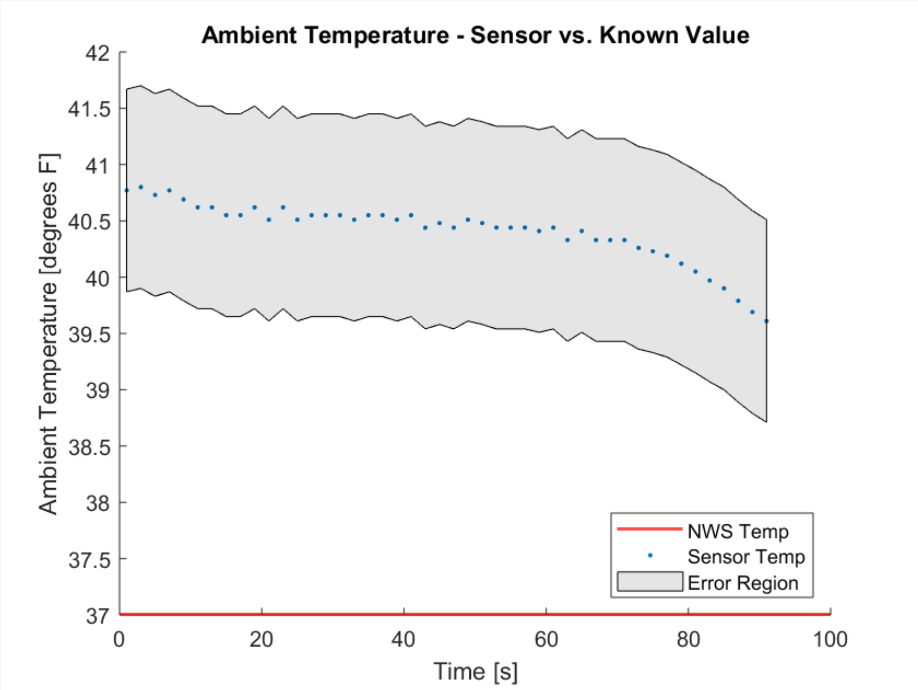


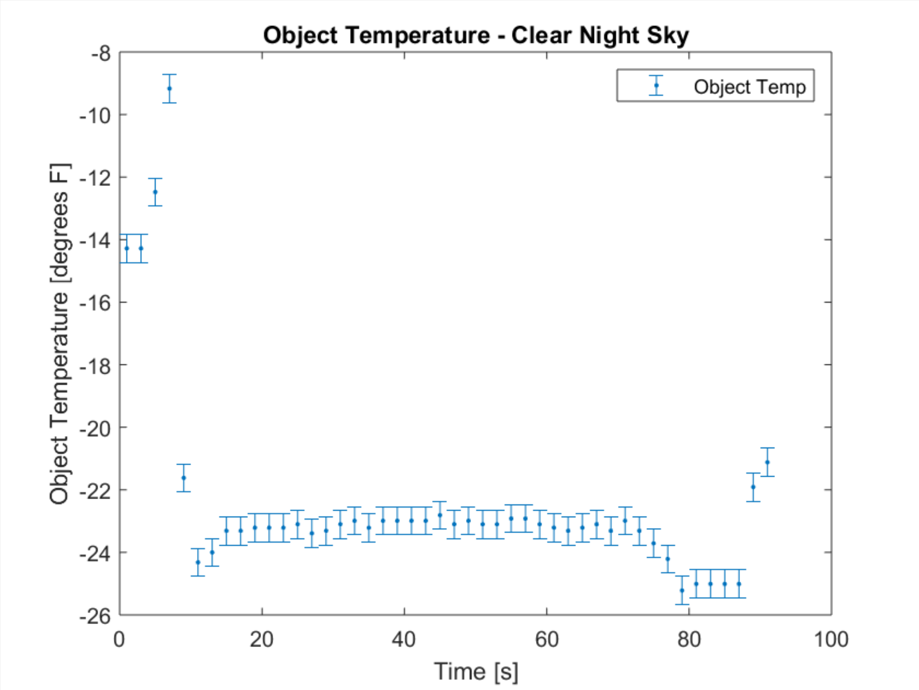
Pressure and Temperature Testing Data



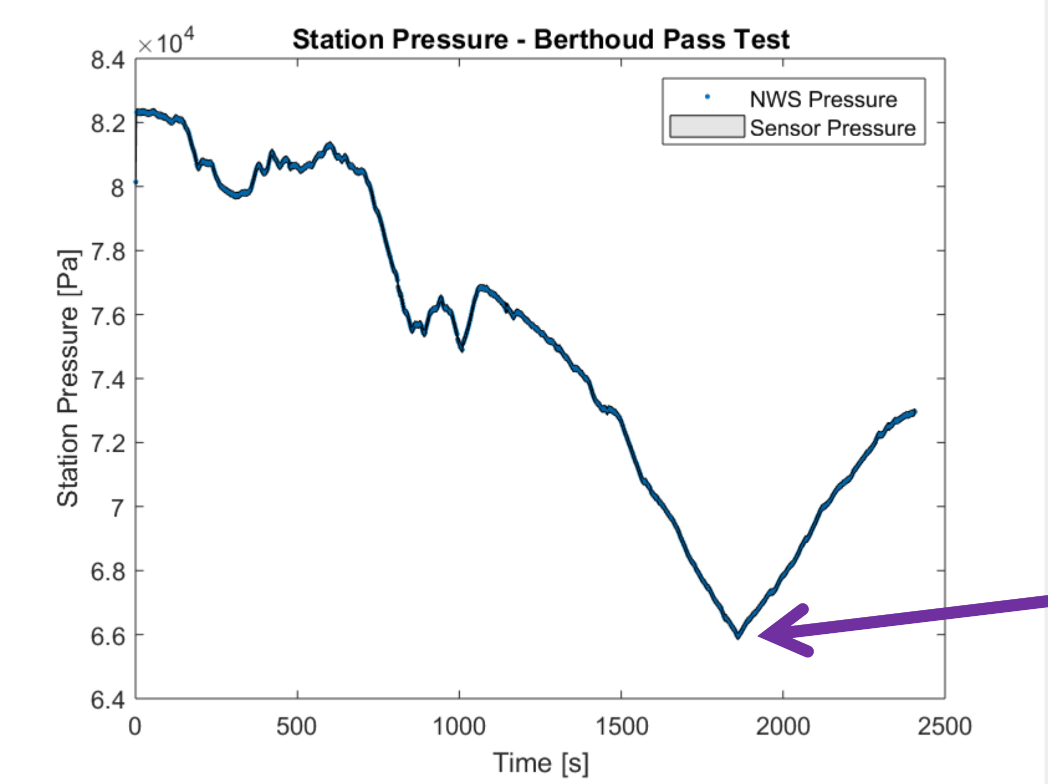


IR Thermometer Testing Data





Berthoud Pass Test: Pressure Data

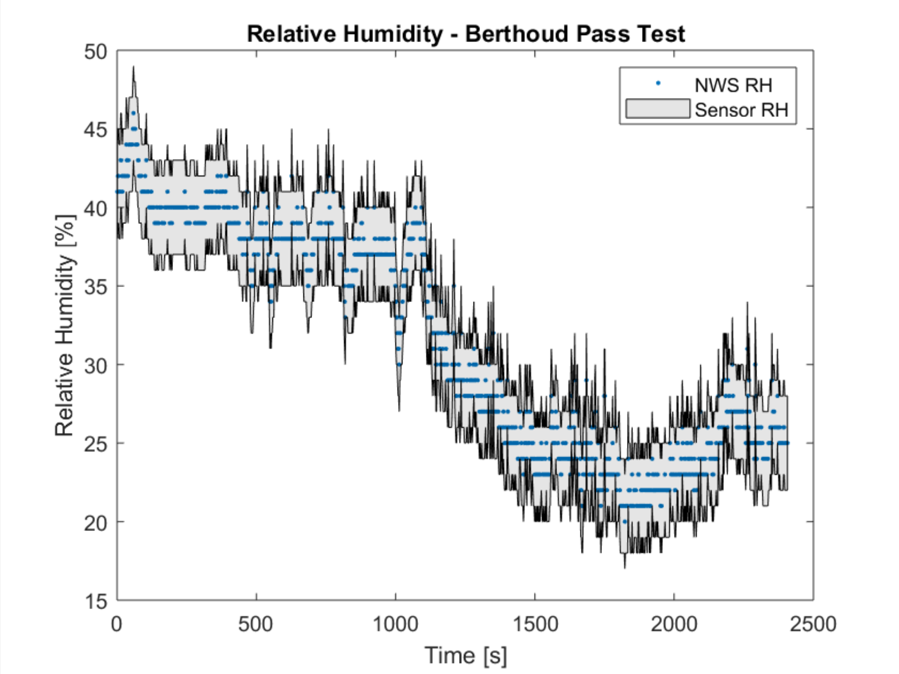


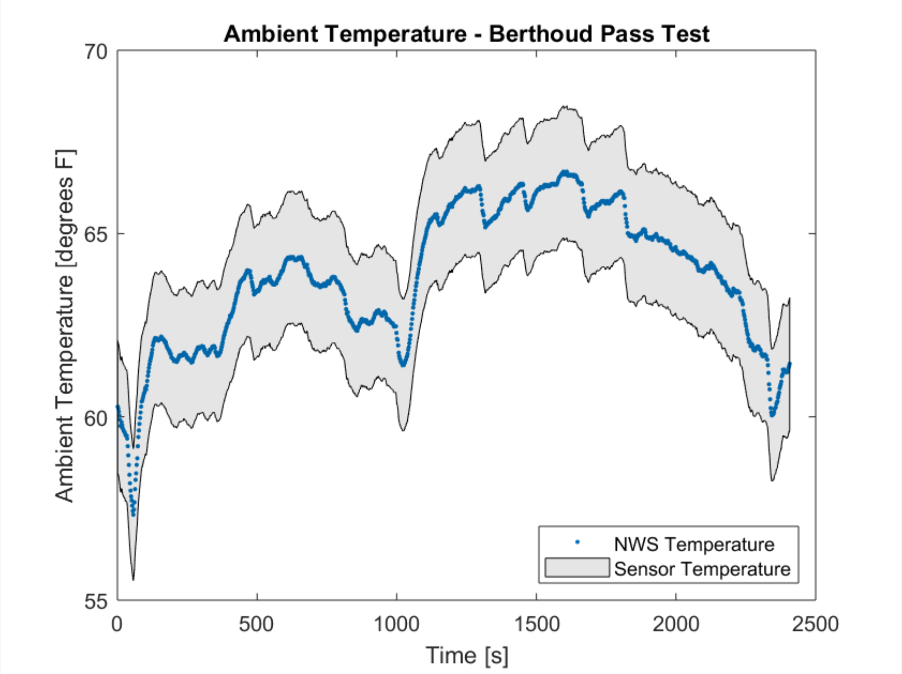
The atmospheric breakout board (barometer and relative humidity) was driven up Berhoud Pass to track the steadily changing pressures as well as record the low pressures at the top (about 12,000ft)

Top of Berthoud Pass = Lowest Recorded Pressure

Berthoud Pass Test: RH and Temp Data

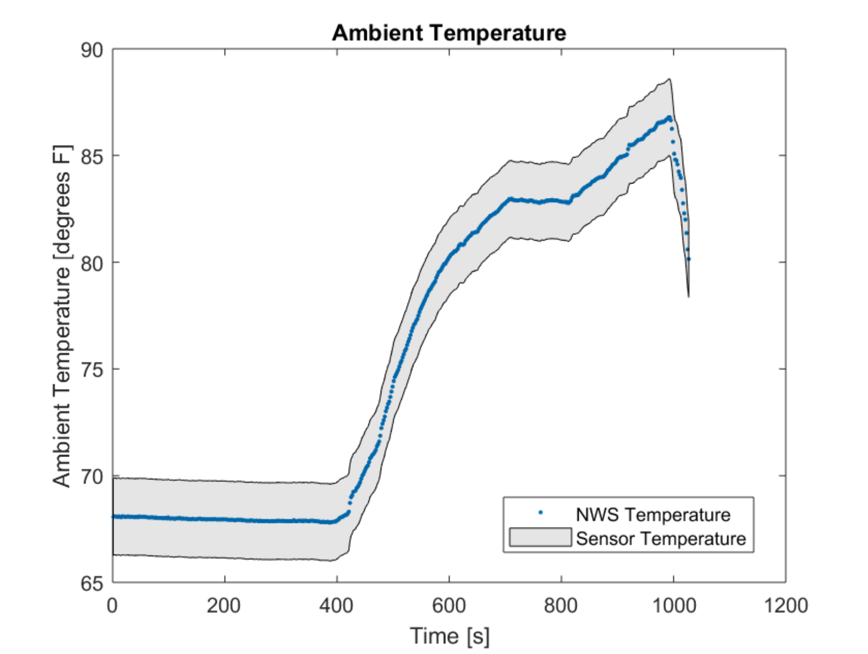
Inversely Related RH and Temperature



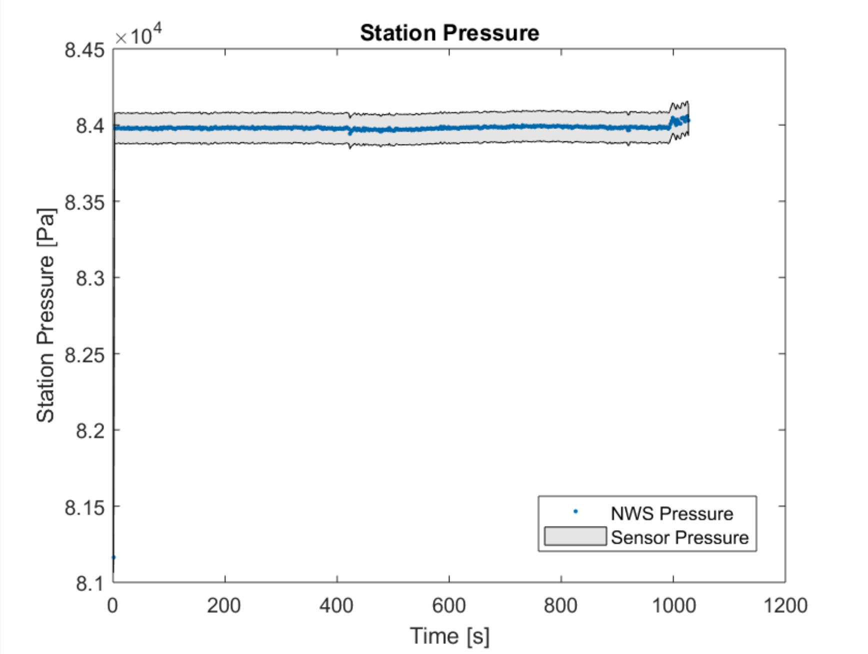


Additional Shower Test Data

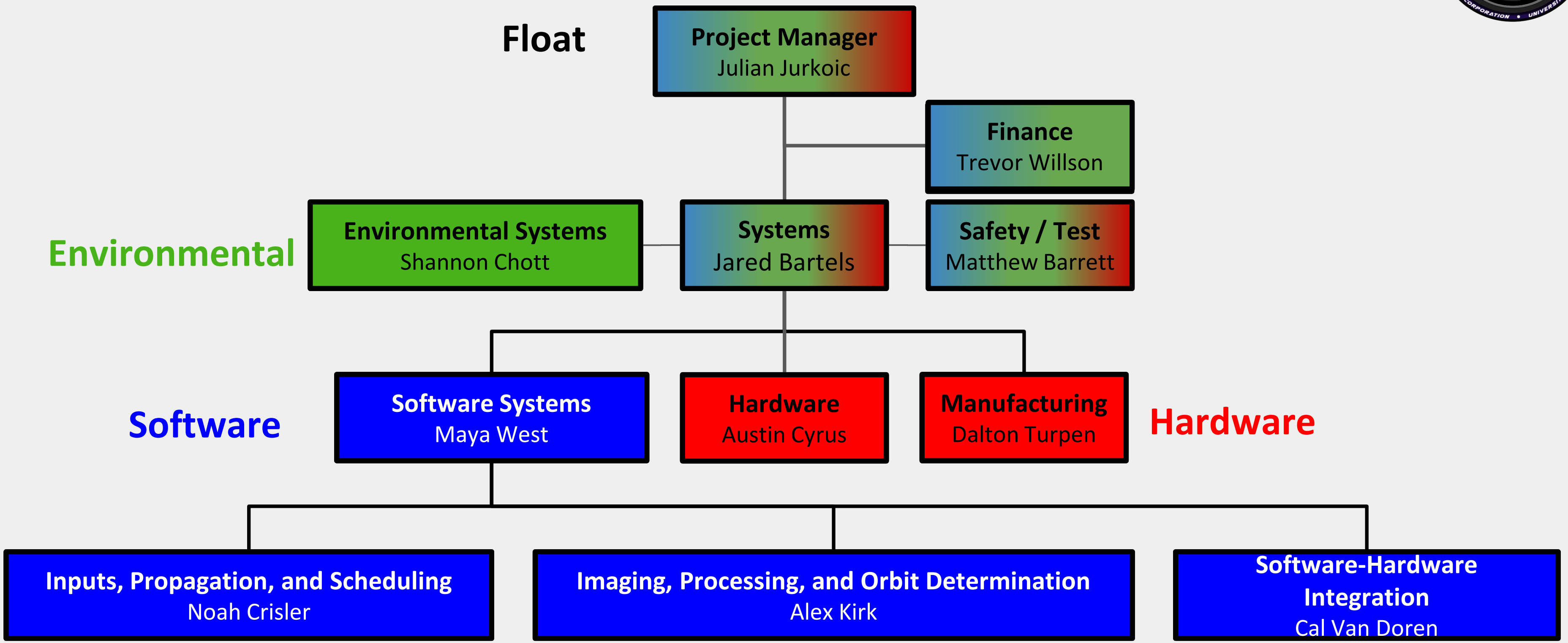
Fluctuating Temperature as Expected



Constant Pressure as Expected



Strategy


Float
Project Manager
Julian Jurkoic
Finance
Trevor Willson
Environmental
Environmental Systems
Shannon Chott
Systems
Jared Bartels
Safety / Test
Matthew Barrett
Software
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Dalton Turpen
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Inputs, Propagation, and Scheduling
Noah Crisler
Imaging, Processing, and Orbit Determination
Alex Kirk
Software-Hardware Integration
Cal Van Doren