University of Colorado Boulder

CCAR

Visual In-situ Sensing for Inertial Orbits of Nanosats
TRR

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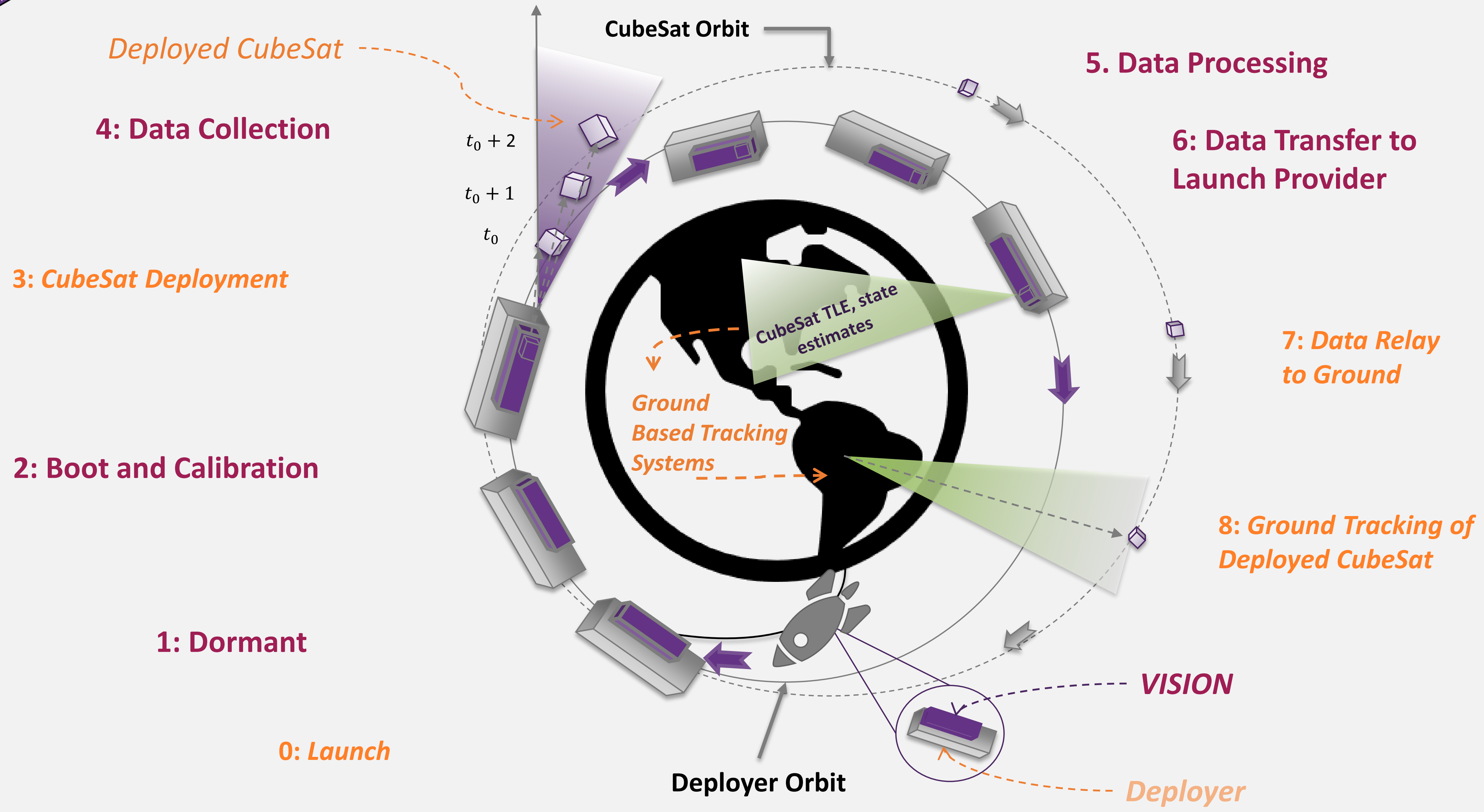
Objectives

VISION is a working prototype device that will monitor CubeSats from a launch provider as they deploy. VISION will deliver timely Two-Line Elements which will reduce the time between deployment and identification and eliminate ambiguity amongst CubeSats.

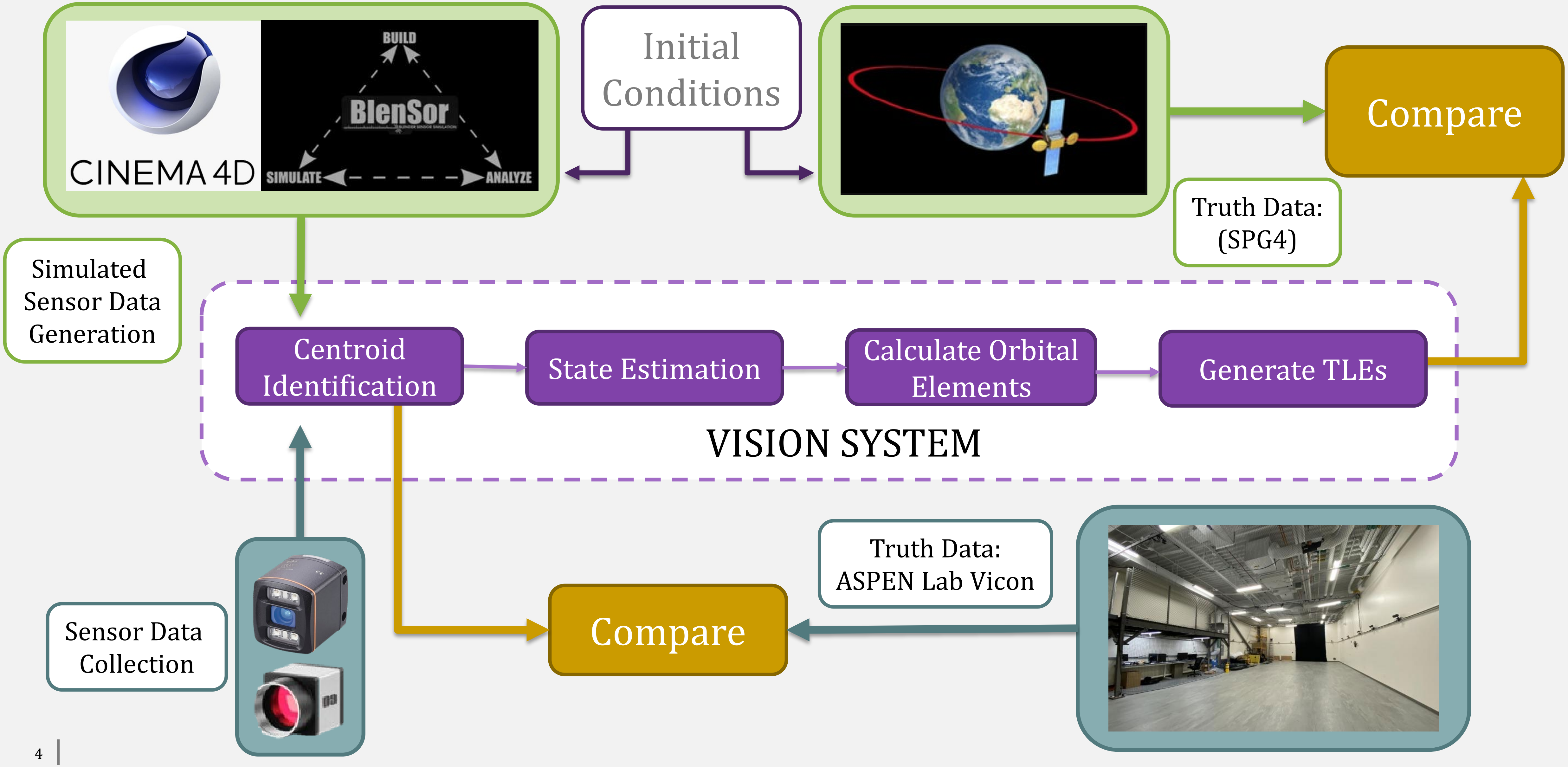
Mission Statement:

Project VISION will improve Space Situational Awareness (SSA) by developing an in-situ, autonomous prototype that tracks and estimates individual CubeSat trajectories during deployment.

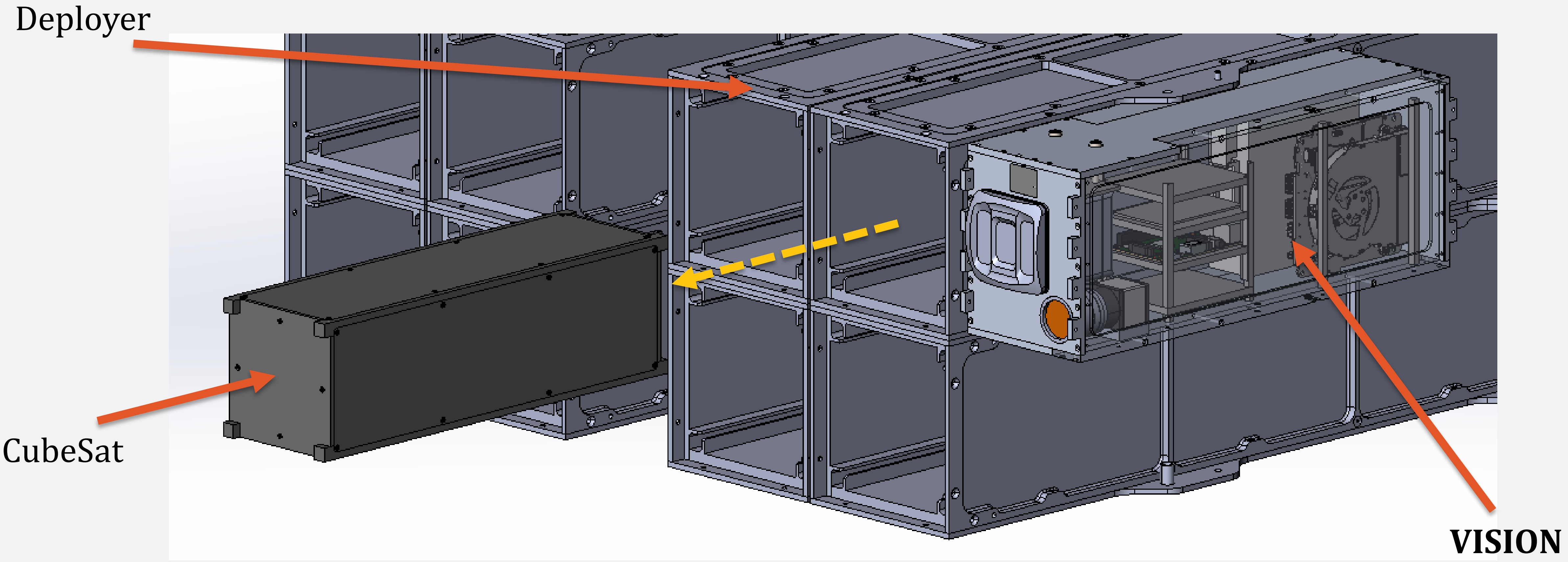
Concept of Operation: Mission Overview



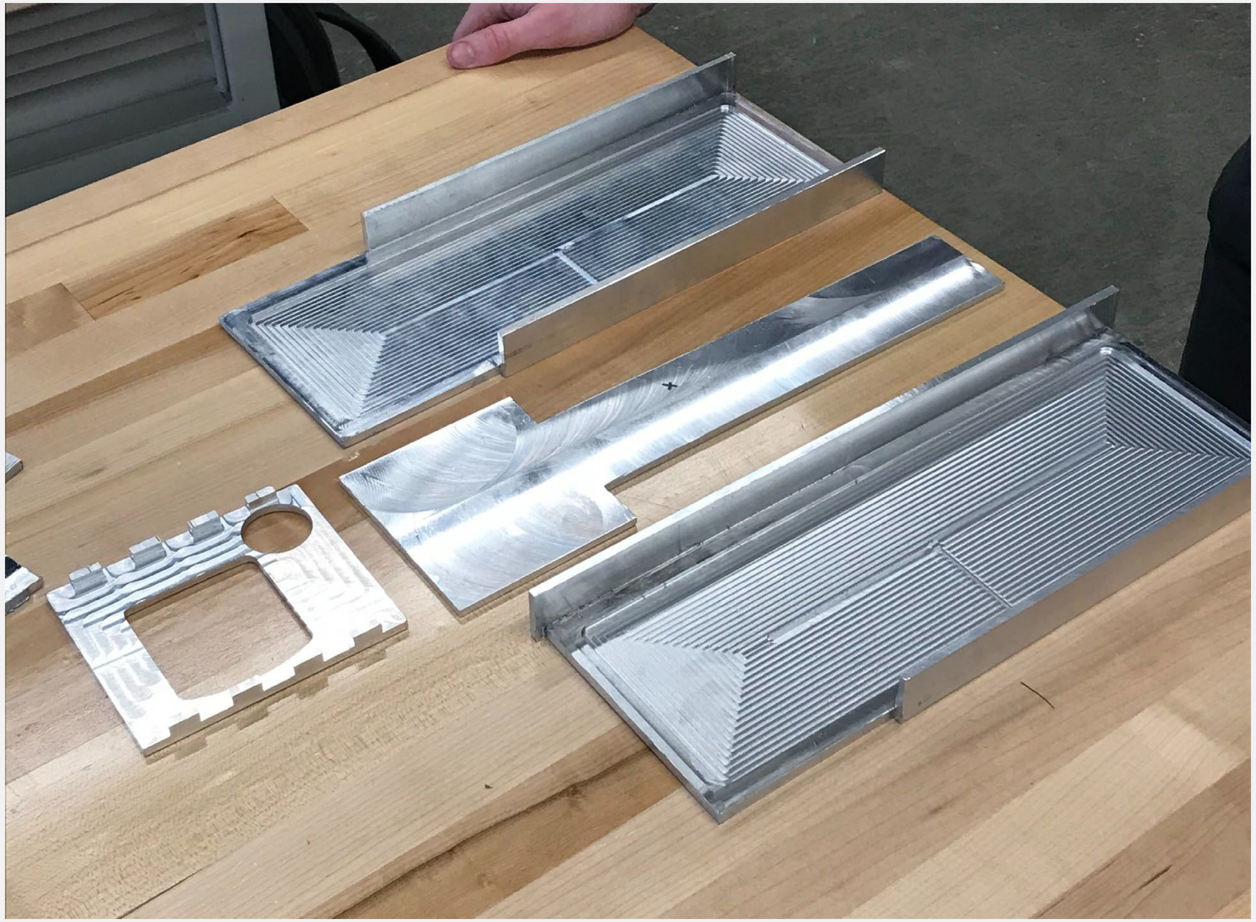
VISION Team CONOPS



Structural Overview



Structural Overview

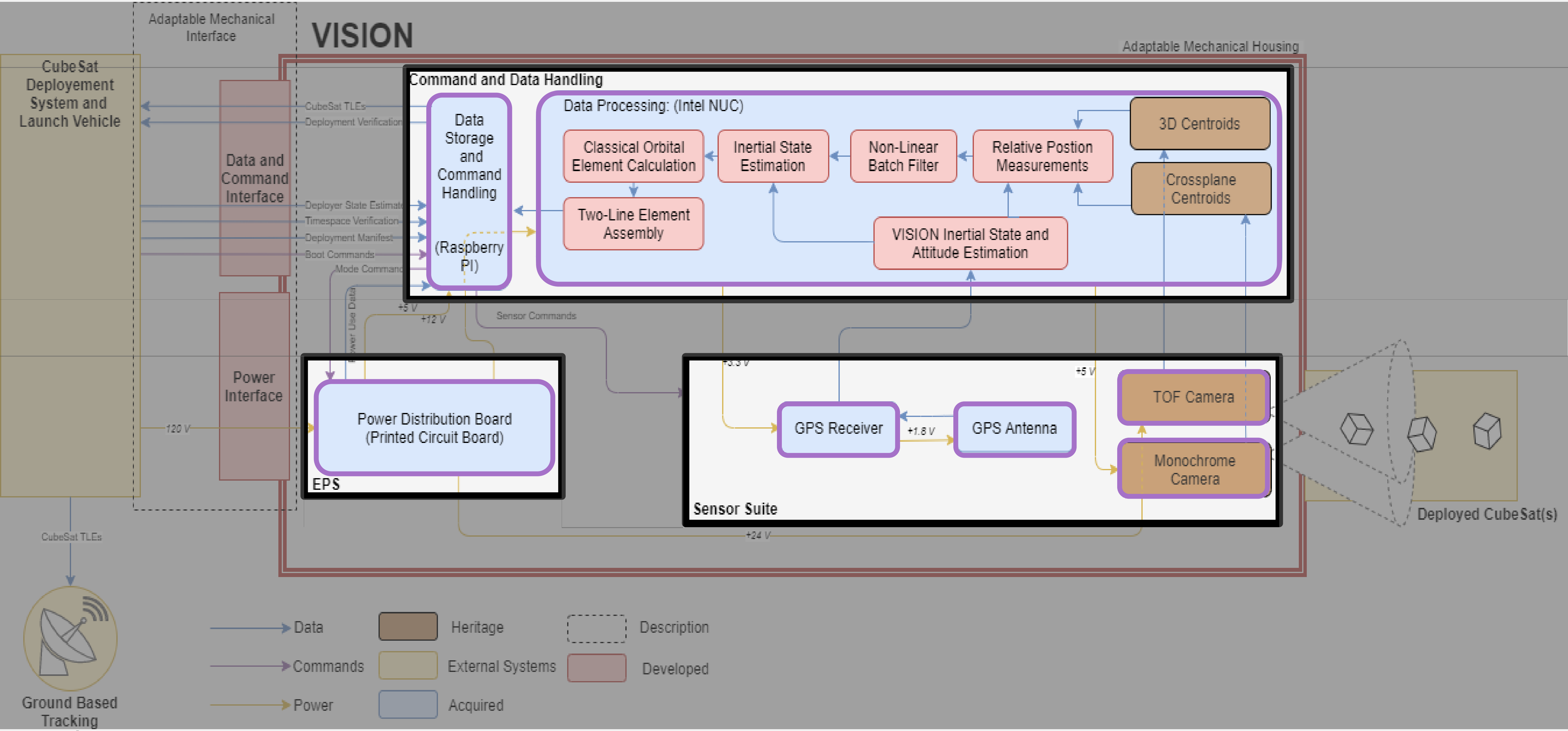


Critical Project Elements

Critical Project Elements

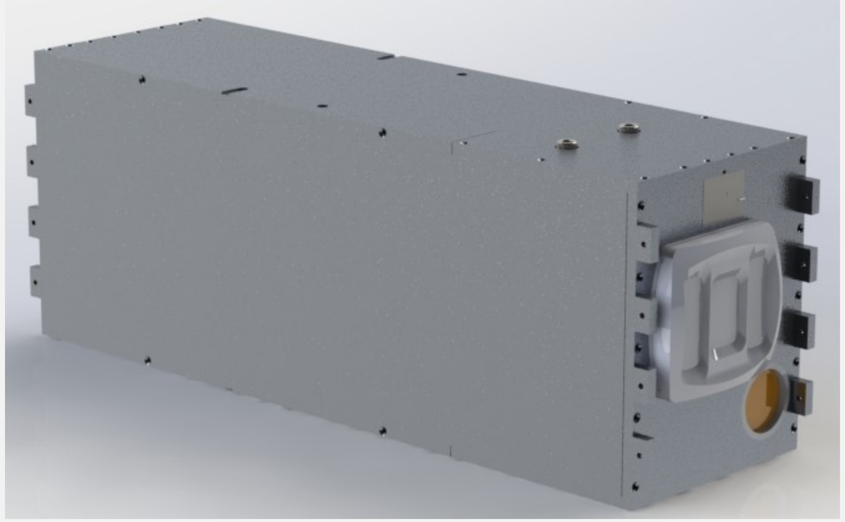
- **Software Simulation**
  - Simulate sensor data inputs in relevant environment
- **Sensor Data Collection**
  - Automated data collection of sensors: TOF, Monochrome, GPS
- **Data Processing**
  - Determine centroid positions and filter relative velocities
- **TLE Estimation**
  - Deliverable to enable integration with existing SSA solutions

Functional Block Diagram



Changes from VANTAGE (2018/19 Senior Project)

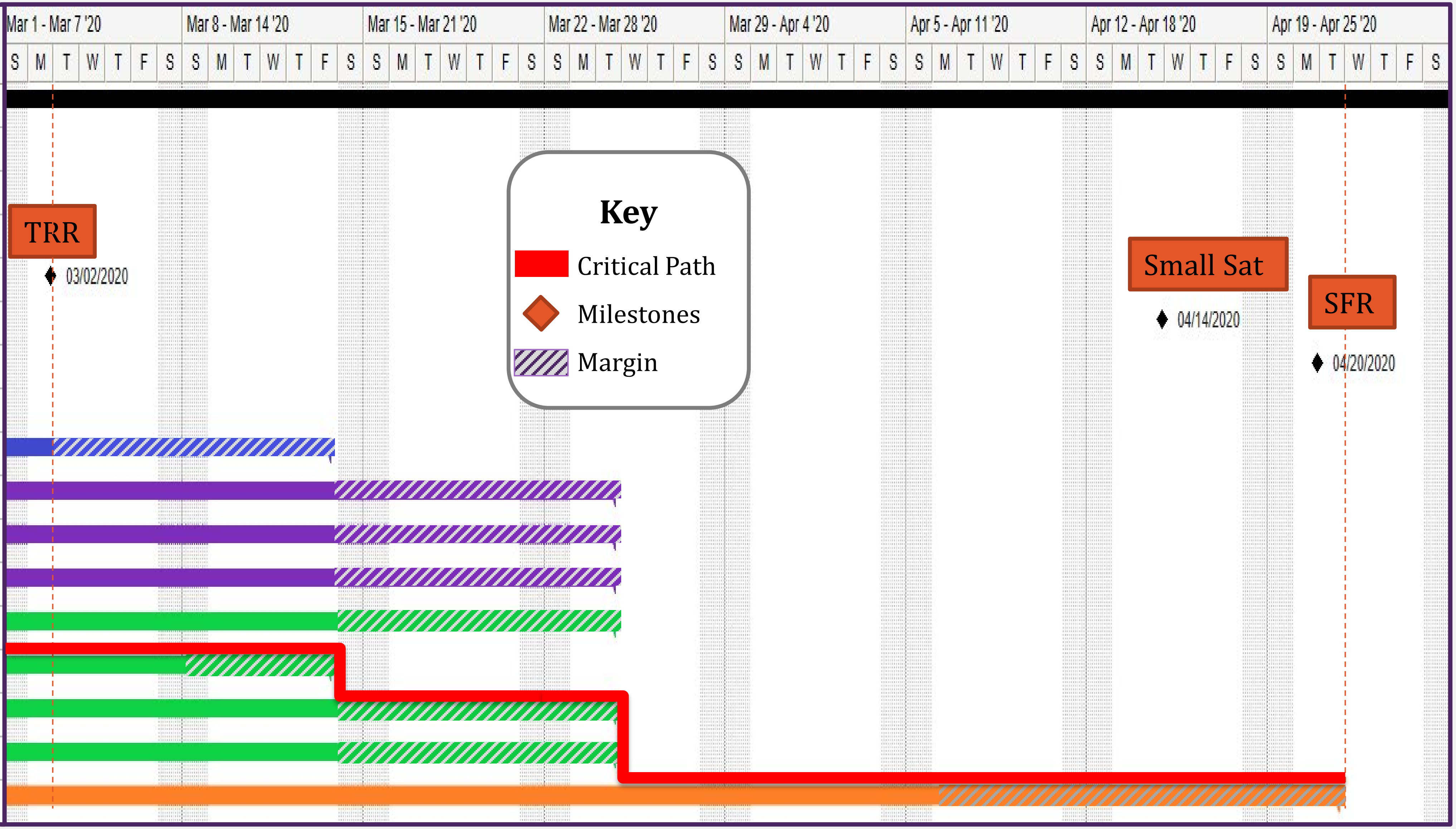
- Integration of Subsystems
  - **Single** power source
  - **PCB:** Soldered-in components
  - Raspberry Pi used to **power/control**
  - Fully **autonomous** system
- State Estimation Software → TLEs
  - **Implemented nonlinear batch filter**
- New Structure/Chassis
  - **Reduced** size by **45%**
  - **Complete** design rework
  - New **external** mounting mechanism
- Simulation
  - **Non-linear** CubeSat trajectories
- Integrated GPS
  - **Attitude** determination
- Testing
  - Centroid detection
  - Vibrational/Shock **testing of chassis**
    - Advanced TRL



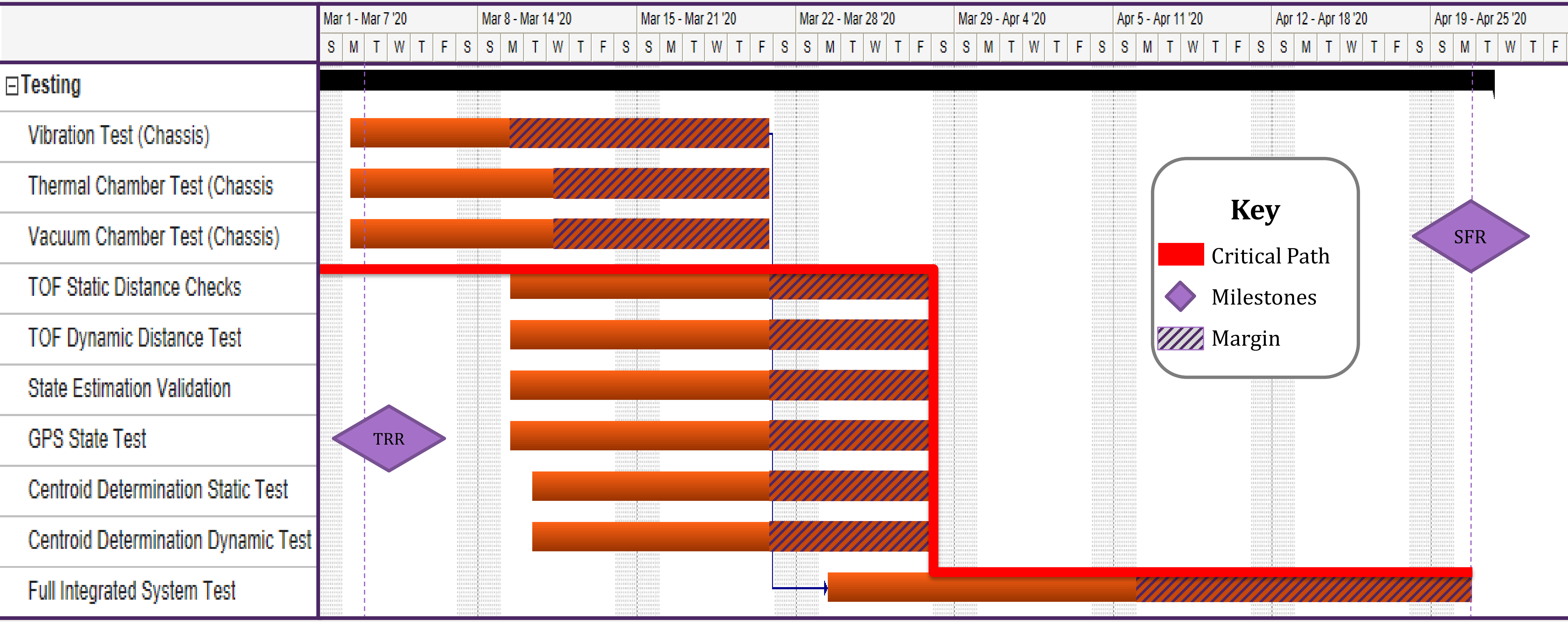
Schedule

Project Schedule - Overview

Task	%
⊟ Project Logistics	67%
Receive Parts	100%
MSR Due	100%
AIAA Abstract Deadline	100%
TRR Due	100%
Small Sat Due for Conference	0%
SFR Due	0%
PFR Due	0%
⊞ Manufacturing	86%
⊟ Integration	77%
⊞ Hardware (Sensors)	73%
⊞ Electronics	81%
⊟ Software	90%
⊞ Simulations	95%
⊞ Post Processing	81%
⊞ State Estimation	93%
⊞ Testing	17%

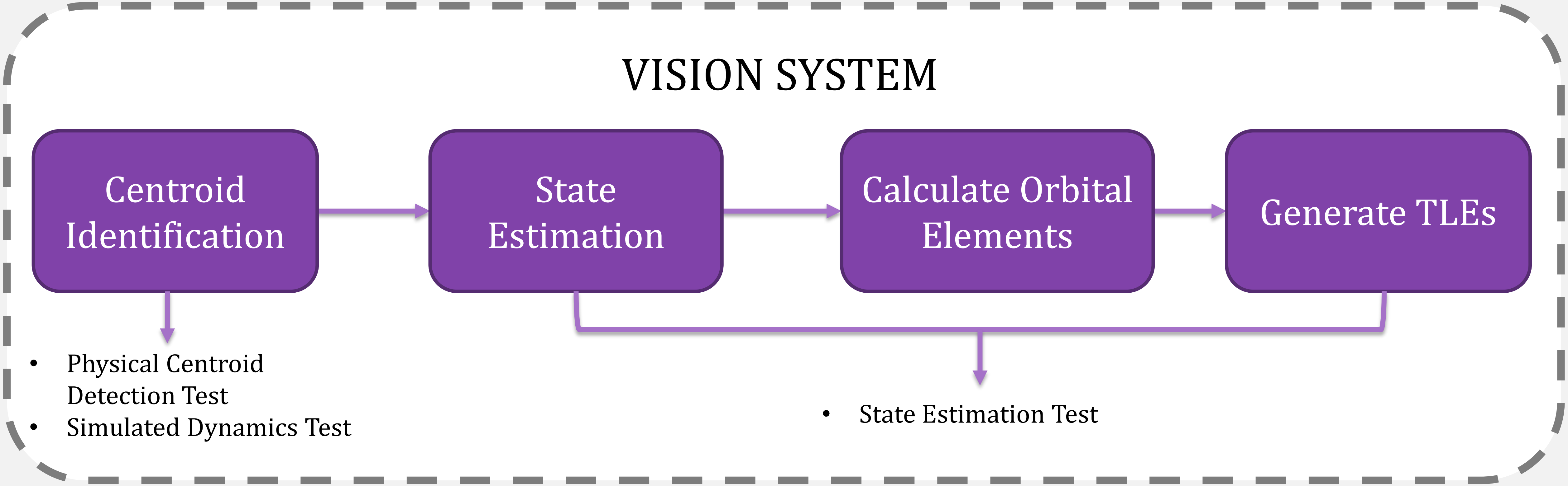


Project Schedule – Testing



Testing

VISION Team CONOPS



Full System Test

Physical Centroid Detection Test Overview

- **Centroid detection** is extremely important in VISION's state estimation process
- The Physical Centroid Detection test will validate VISION's ability to **differentiate between** up to 6 CubeSats and **estimate centroids** for each CubeSat.

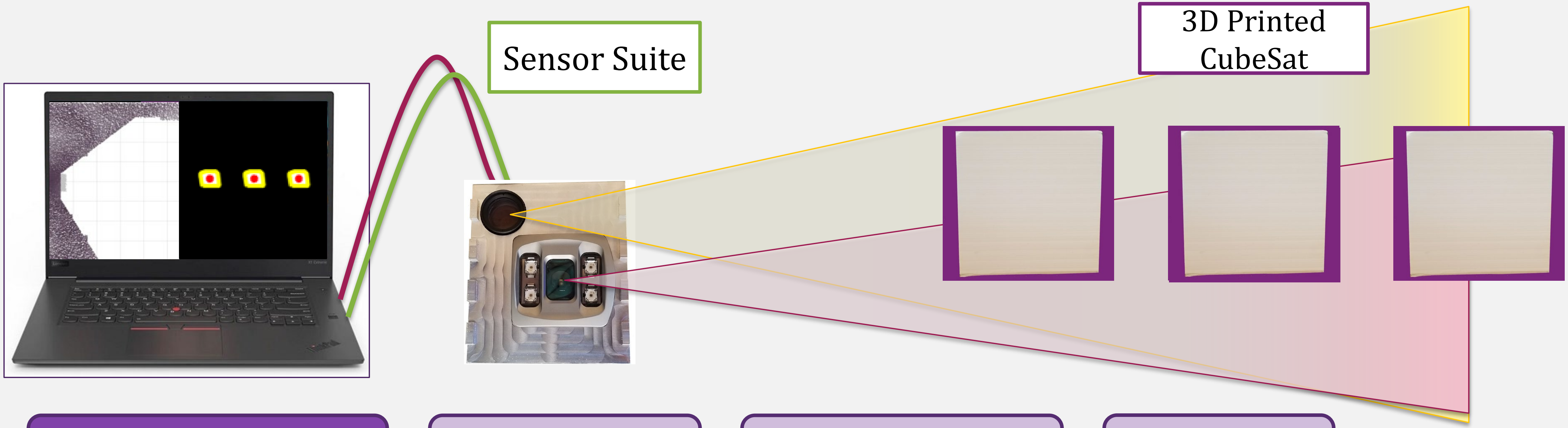
Req.	Description
DR-1.1	VISION shall characterize and differentiate up to 6 CubeSats of 1U and up to 3U sized CubeSats.
DR-1.2	VISION shall estimate the centroid of each CubeSat of 1U up to 3U size

Centroid Identification → State Estimation → Calc Orbital Elements → Generate TLEs

Centroid Detection Test Overview

Single Body Static Test
- Randomly orient CubeSat
- Determine centroid

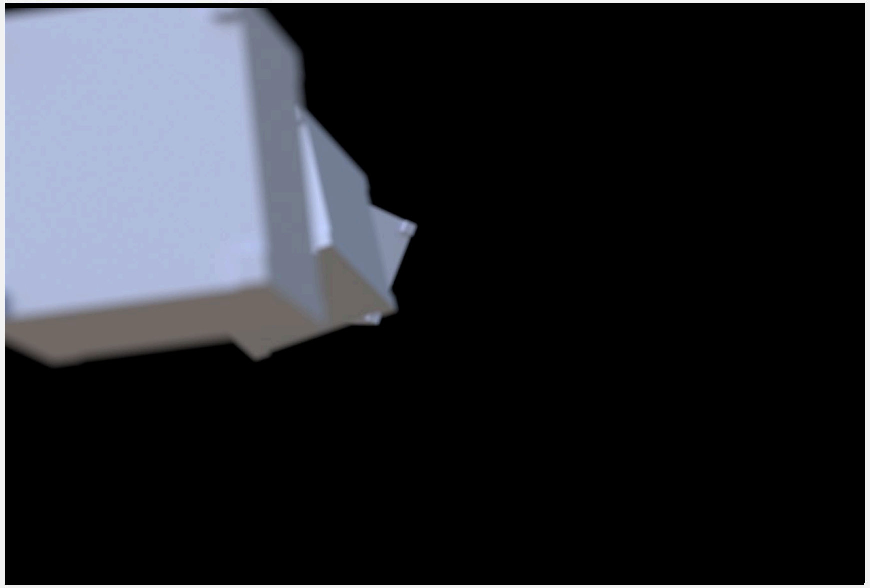
Multi-Body Static Test
- Orient mock CubeSats Collect data
- Determine centroid of each CubeSat
- Determine system centroid



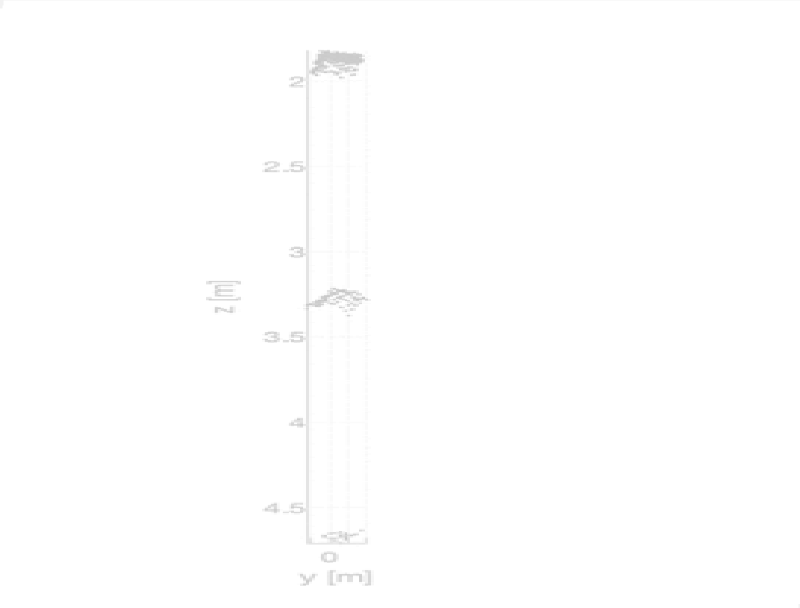
Centroid Identification → State Estimation → Calc Orbital Elements → Generate TLEs

Simulated Dynamics Test Overview

Req.	Description
DR-1.1	VISION shall characterize and **differentiate** up to 6 CubeSats of 1U and up to 3U sized CubeSats.
DR-1.2	VISION shall estimate the **centroid** of each CubeSat of 1U up to 3U size
DR-2.1	VISION shall **collect data** of each CubeSat while the CubeSats can be differentiated by more than 1 pixel between frames.



Cinema 4D



BlenSor

Centroid Determination → State Estimation

Centroid Identification → State Estimation → Calc Orbital Elements → Generate TLEs

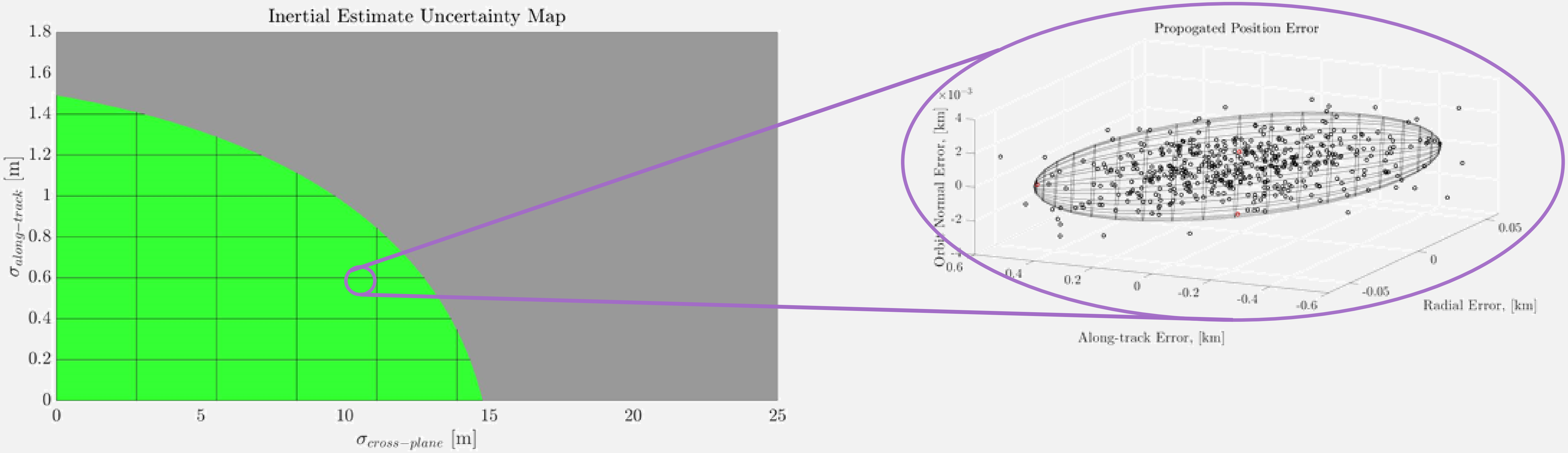
State Estimation: Pre-Testing Status

	Development Status	Level of Validation	Integration Testing Readiness
Rotation into Orbit Frame	Complete	Unit Testing	Ready
State Estimation (Batch Filter)	Complete	Unit Testing	Tune using test data
Rotation into Inertial Frame	Complete	Unit Testing	Ready
Estimation of Classical Orbital Elements	Complete	Unit Testing	Ready
TLE Assembly	In - Progress	N/A	Not Ready

Centroid Identification → **State Estimation** → **Calc Orbital Elements** → Generate TLEs

State Estimation: Requirements Review

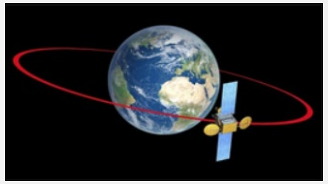
Req.	Summary
DR-2.2	VISION shall **estimate the inertial position** of each CubeSat such that the STD conforms to the Inertial Position Uncertainty Map.
DR-2.6	VISION shall produce **Two-Line Elements** that can be **propagated** using the **SPG4** propagation tool.



State Estimation: Test Overview

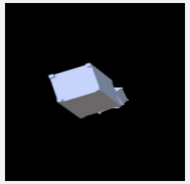
Test Procedure

Orbit Simulation



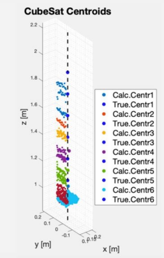
Truth Motion

C4D/Blensor



TOF Point Clouds

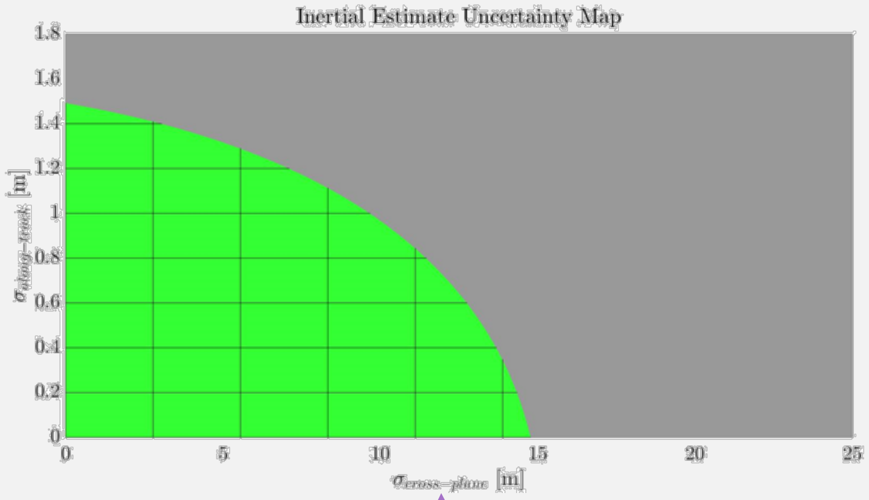
Centroid Determination



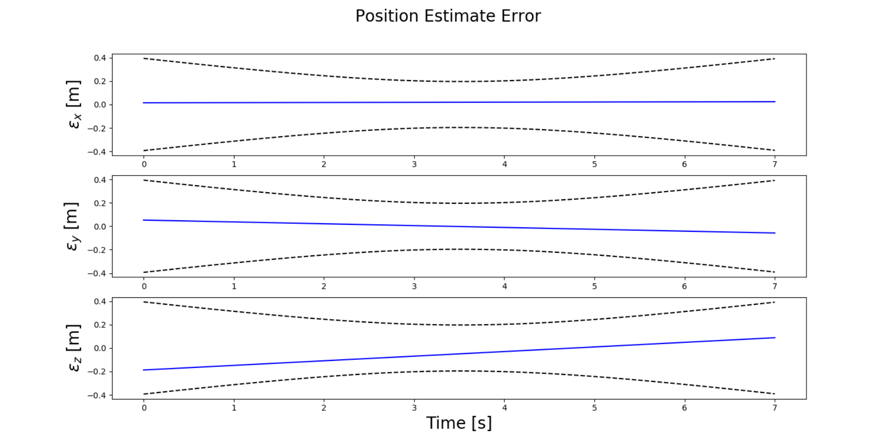
Centroids

State Estimation Algorithm

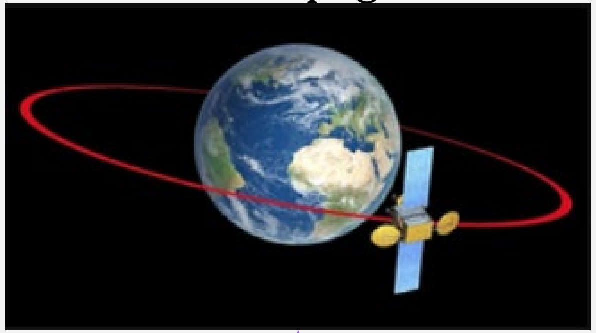
Verification and Validation



Estimates and Covariance (DR-2.2)



SPG4 Propagation



Two-Line Elements (DR-2.6)

01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
1		2	5	5	4	4	U		9	8	0	6	7	A				0	8	2	6	4	.	5	1	7	8	2	5	2	8
1		2					3		4		5			6				7		8											

Full System Test Overview

Purpose of Full System Test

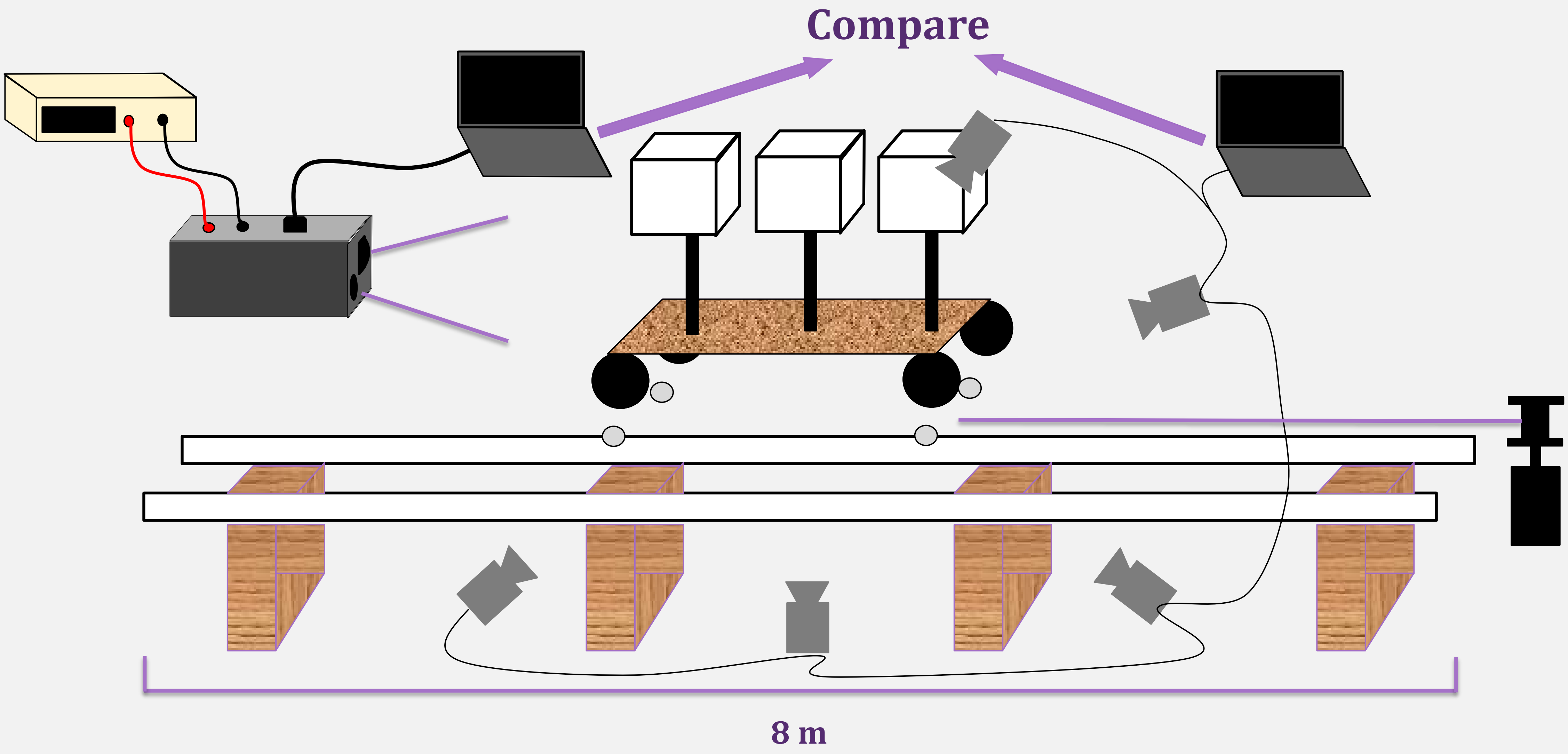
- Show **full integration** of system
- **Autonomous functionality** of entire system to provide TLE
- Test **accuracy** and **uncertainty profiles** of real sensors and state estimation software integration

Full System Test Overview

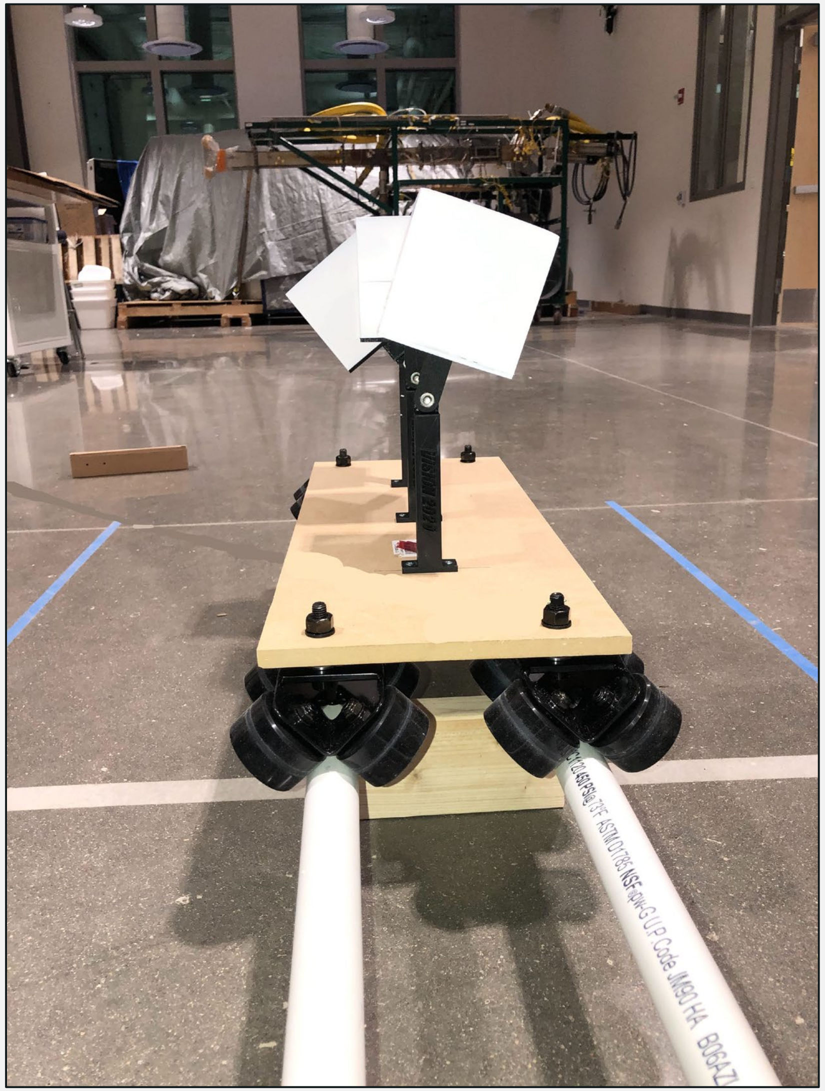
Req.	Description
DR-2.7	VISION shall calculate and package TLE estimates within 15 minutes of the end of the deployment sequence.
DR-3.1	VISION shall deliver a still image of each individual CubeSat in a deployment.
DR-4.1	The chassis envelope shall enclose all components, excluding protruding instrument sensors.
DR-4.4	The system shall store images, raw data, and estimates of one deployment cycle, onboard, for the duration of the data processing and downlink period.

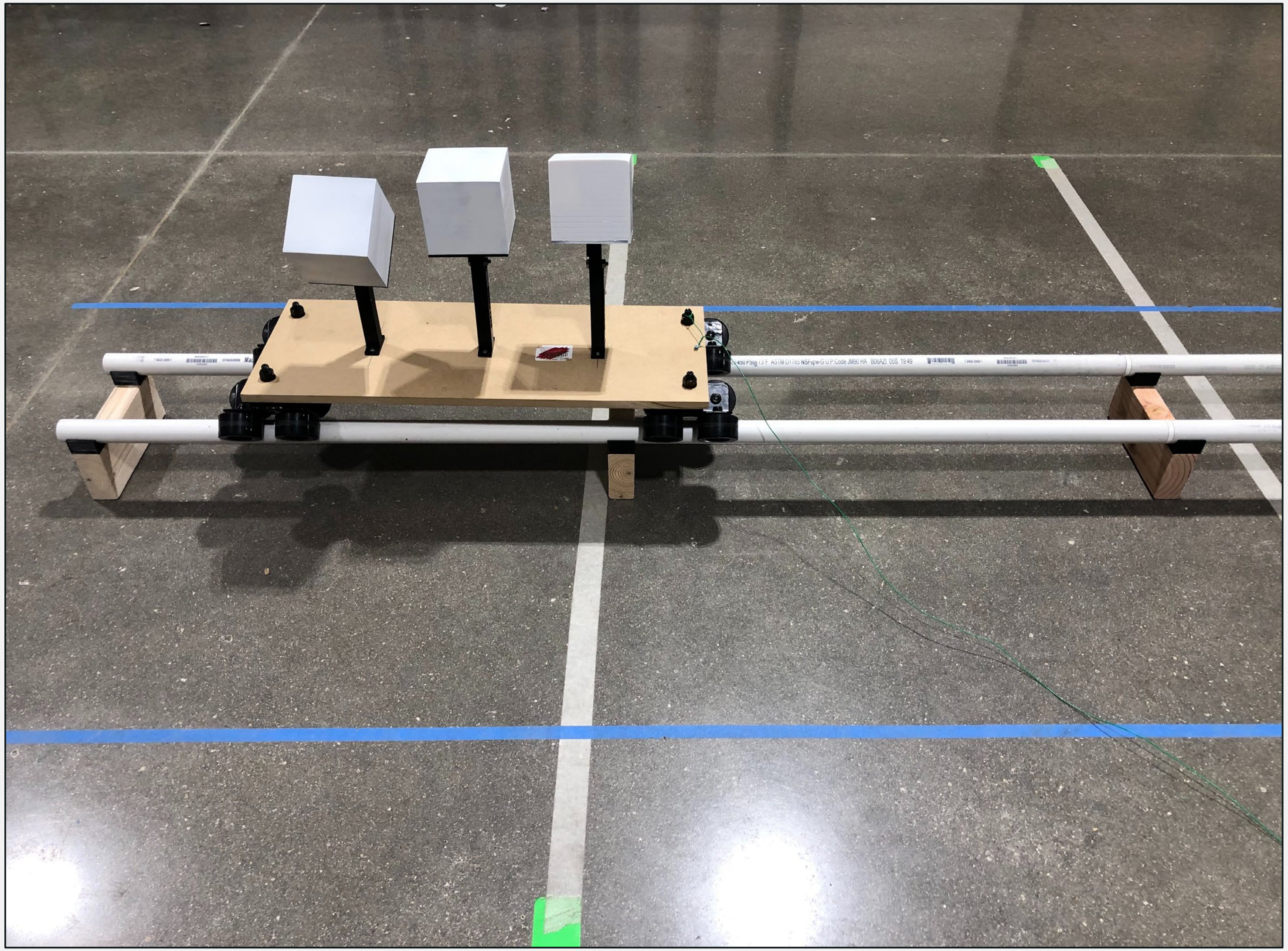
Full System Test Overview

Overview of Test:

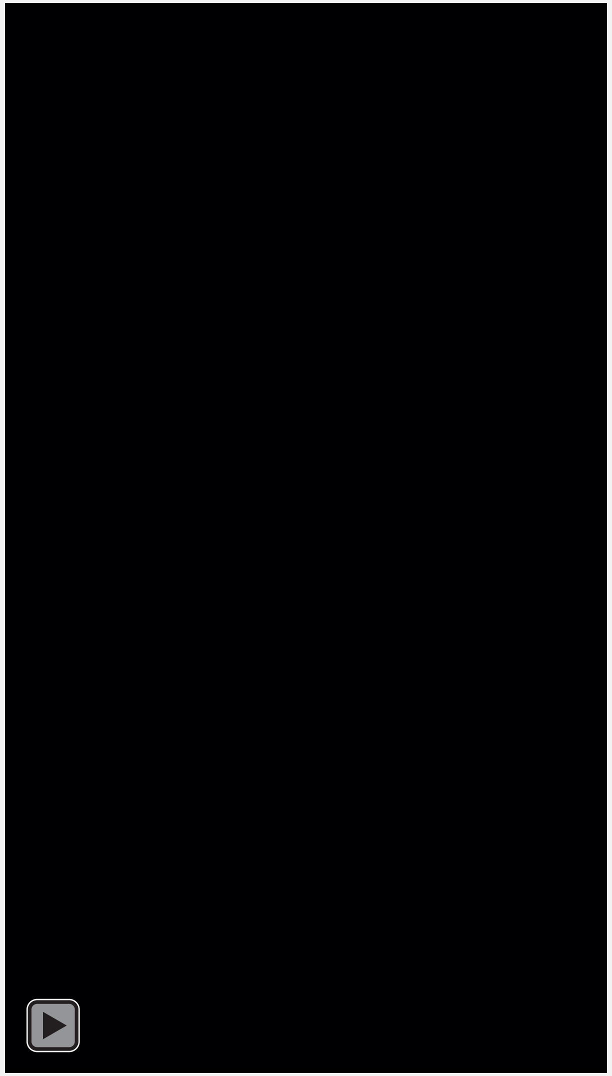


Full System Test Overview





Full System Test Overview



Budget

Budget

Spent to Date:

$2,303.08

System Hardware:

$1784.34

Test Hardware:

$518.74

Budget

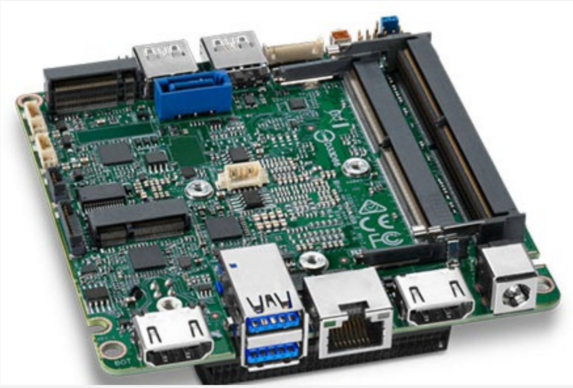
Budget Remaining:

$2,696.92

Plans for funds:

- Replace any component that fails

Intel NUC $641.84



TOF $1584.00

Questions?

Back-Up Slides

Structural Tests Overview

Req.	Description
DR-4.1	The chassis envelope shall enclose all components, excluding protruding instrument sensors.
DR-5.1	The chassis shall mechanically integrate with one deployment system, as defined in the Mechanical Interface Control Document (MICD).
DR-5.2	The system shall have a mass of less than 8 kg.
DR-5.3	The system shall have dimensions less than 6000 cm3.
DR-6.1	Chassis structure shall reach an advanced TRL certification, or equivalent.
DR-6.2	Chassis structure shall maintain structural integrity within a safety factor of 2.

Requirement Justification:

- VISION System must be compact, and accessible (CubeSat Restrictions)
- VISION is aware of the intended environment (TRL must improve)
- Interface Control Documents are integral to setting a baseline for integration with customer/deployer
- Structure is a Non-Critical component, but essential to robustness
- 3 Structural Tests:
  - Physical Inspection
  - Vibe
  - Thermal & Vacuum

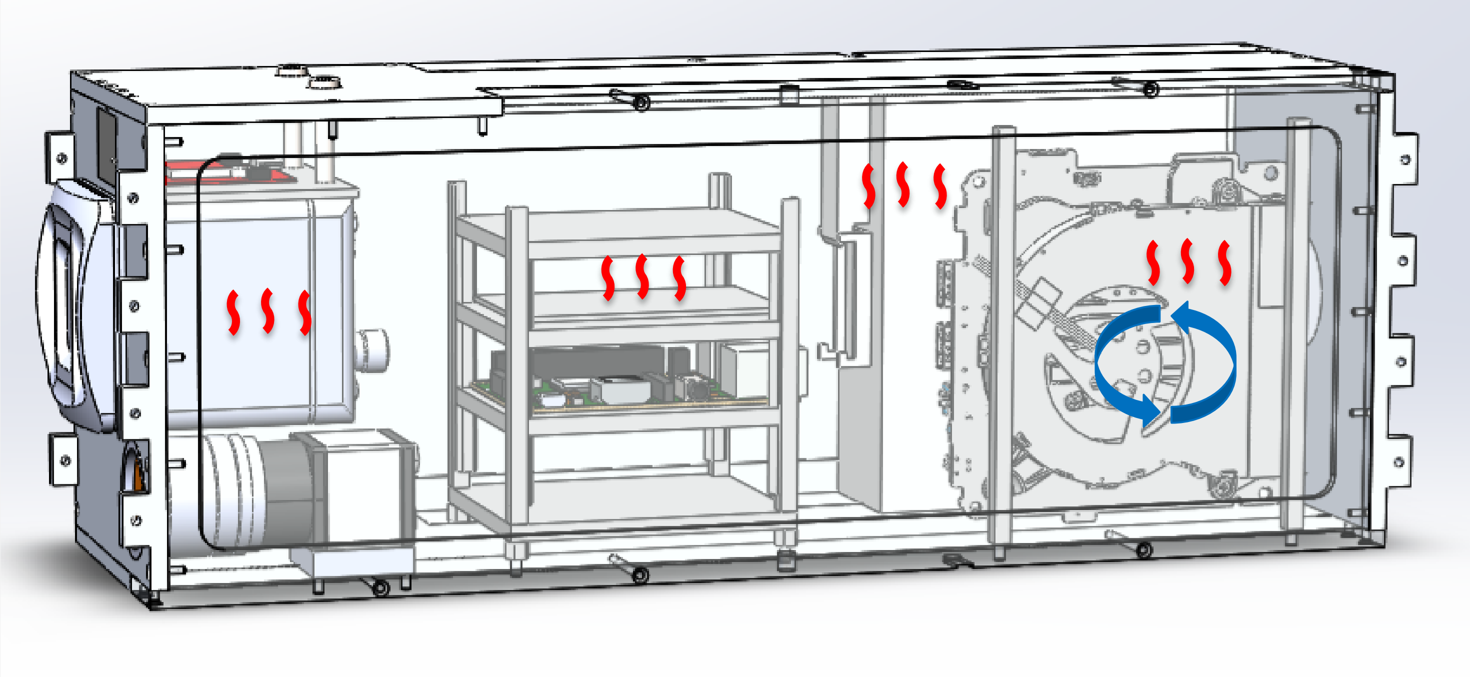
Structural Tests Overview

Component	Status
Chassis	3 Faces Completed, anticipated completion on March 1st
Mechanical Interface Control Document	50% Written, anticipated completion of March 5th
Electrical Components	Purchased/Tested, anticipated integration date of March 2nd
Vibe Test Fixtures	Test Confirmed, CAD drawings finished, anticipated milling date of March 7th

Test	Date of Completion
Physical Integration Inspection	March 1st
Vibe Test	March 19th *
Thermal Chamber Testing	March 11th
Vacuum Chamber Testing	March 11th

*Insert Evidence Photos

Full System Test (Thermal Considerations)



Components	Max Power Consumption
ToF camera	40W
Raspberry Pi	5W
Intel NUC	65W
Monochrome Camera	5W
GPS Receiver	1W
GPS Antenna	0.2W
DC/DC Converter (~90% eff)	**Expected Heat Draw**
124-24 V	12W
24-12 V	25W
24-5 V	25W
Expected Q_{in}	**178.2W**

Chassis Properties:

- $A_{total} \approx 2000\ cm^2$
- $t_{max} = 0.5\ cm$
- $k_{al(6061)} = 167\ [W/m{\cdot}C°]$

$$q_{in} = \frac{k}{t} \cdot A \cdot dT$$

$$dT = \frac{q_{in} \cdot t}{k \cdot A} \approx 1°C/min\ *$$

*Assuming all HW emits 50% max power as heat and converters operate at a lower efficiency.

Electrical Subsystem Test Overview

Test	Status	Validation
Electrical Power System Test (PCB mockup test)	Completed **Results:** The system booted up with simulated power supply.	DR. 4.2 & DR. 4.3
Boot up Test	Completed **Results:** The NUC was booted up by the student's laptop controlling raspberry pi remotely.	DR. 5.4
Data and Command Interface Test	**Planned** **Expected Results:** The student's laptop shall be able to send commands to raspberry pi to wake up the NUC and receive data from NUC via raspberry pi.	DR. 5.4

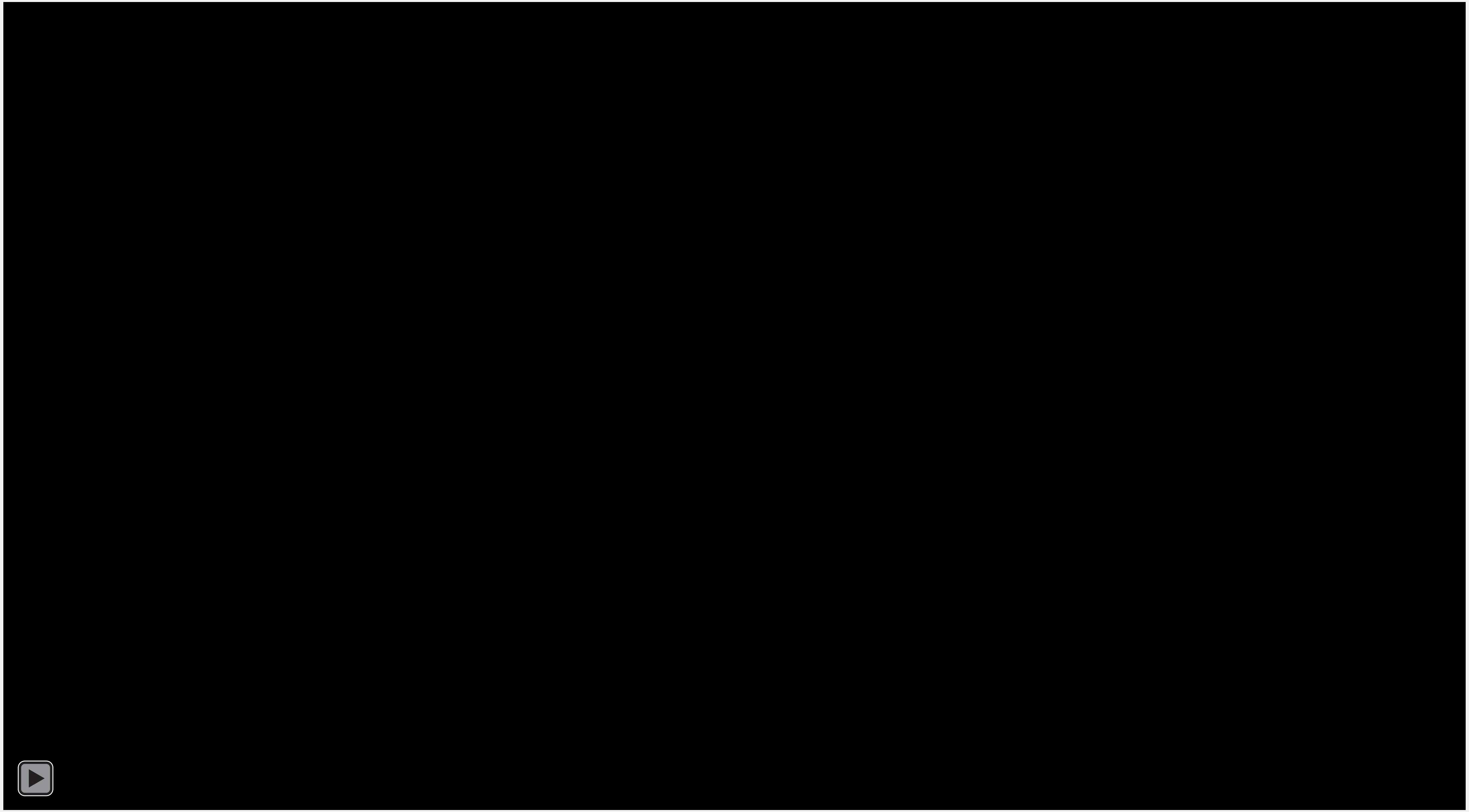
Electrical Subsystem Test Overview

Req. ID	Description
DR-5.4	The electrical power distribution subsystem shall interface with a PC. Note: This interface will simulate all data and power communications between a potential deployment system.
DR-4.2	The system shall operate with no more than 120 VDC, 3 Vpp ripple voltage, and 5 A.
DR-4.3	The system shall draw no more than 520 Watts.

Justification:

- The personal PC shall be able to boot up the whole system and receive estimates autonomously
- The system shall be able to operate with simulated power from the deployer

Back up – Electrical PCB Mockup Test

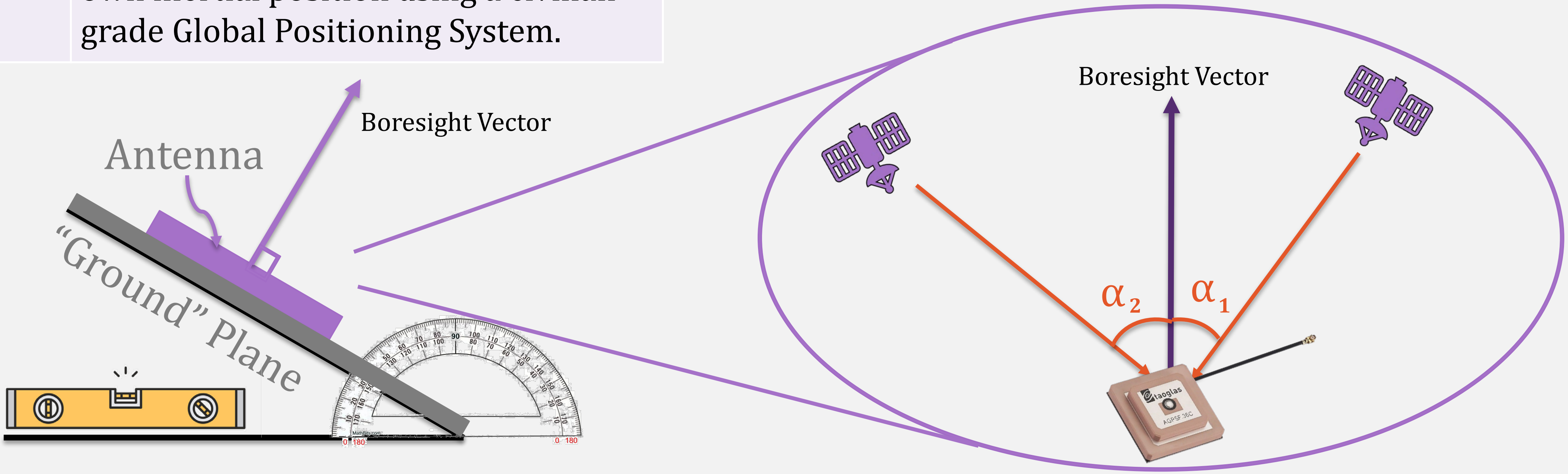


GPS Subsystem Test Overview

Req.	Description
DR-2.3	The VISION system shall measure its own single axis inertial attitude using a civilian grade Global Positioning System.
DR-2.4	The VISION system shall measure its own inertial position using a civilian grade Global Positioning System.

Justification:

- Must know pointing of cameras
- Testing **capability** to provide attitude and position



Verifications

Requirement	Simplified	Structural/ Vibe	Electrical Subsystem	GPS Sub-System	Physical Centroid Detection	Simulated Environment	Orbital Simulation	Full System
DR-1.1	Differentiate CubeSats				x	x		
DR-1.2	Centroid Identification					x		x
DR-1.3	Identification by Manifest					x		
DR-2.1	Deployment Period					x		
DR-2.2	Estimation Accuracy						x	x
DR-2.3	GPS Single-Axis Attitude			x				
DR-2.4	GPS Position			x				
DR-2.7	15 Minute Estimates						x	x
DR-3.1	Proof of Deployment Image							x
DR-4.1	All Components Contained in Chassis	x						
DR-4.2	Voltage/Current Limitations		x					
DR-4.3	Power Limitations		x					
DR-4.4	Store Data Onboard							x
DR-5.1	MICD w/ Deployment System	x						
DR-5.2	Mass <8kg	x						
DR-5.3	Dimensions <6000cm^3	x						
DR-5.4	Communicate with PC		x					
DR-5.5	Comply with EMI/EMC Regulations		x*					
DR-6.1	Advance TRL Certification	x						
DR-6.2	Structural FOS of 2	x						
DR-6.3	Component Equivalency		x					

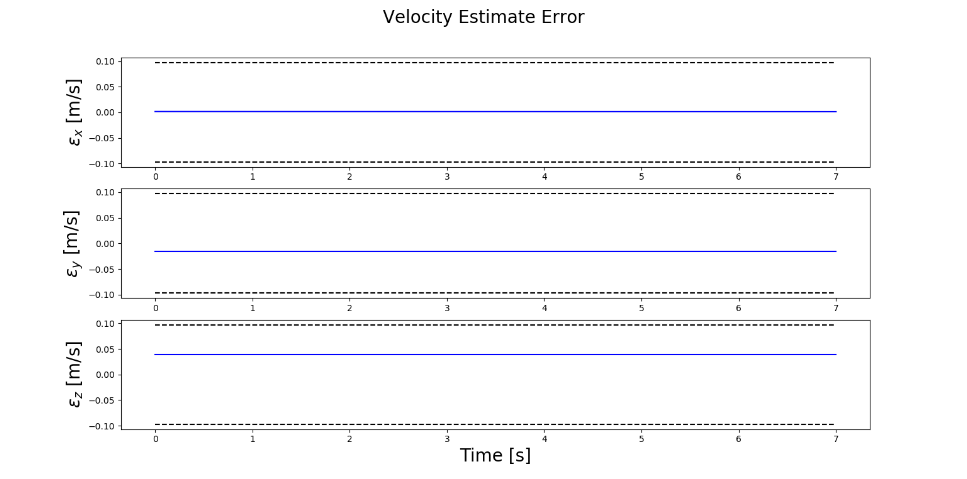
State Estimation Back-up: Batch Filter Performance

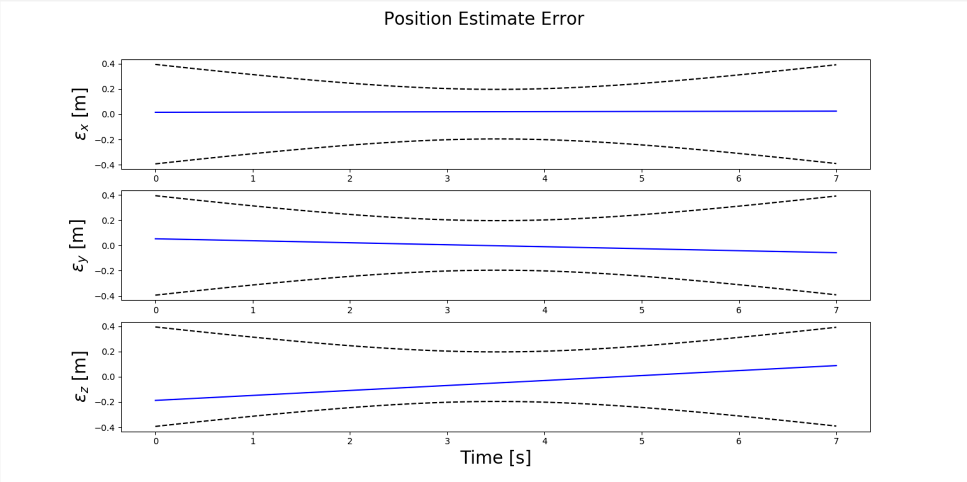
Scenario:

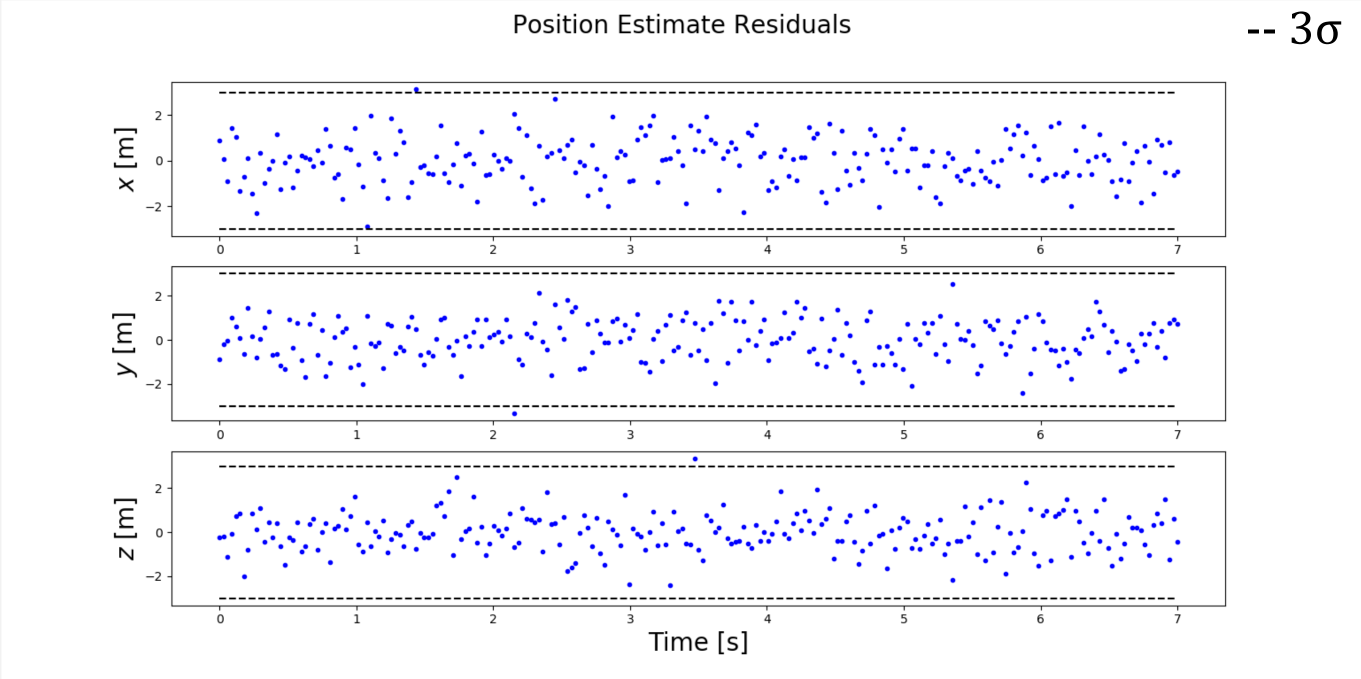
1. 1. Keplerian orbits
2. 2. Deployer ECC=0.1
3. 2. Measurement σ = 1 [m]
4. 3. 250 measurements over ~ 6 [s]

Performance:

1. Run Time: 3.32 [s]
2. Outer Batch Iterations: 2
3. Batch Convergence: 1.639e-16
4. Min Position 3σ ~ 20 cm
5. Max Position 3σ ~ 40 cm







-- 3σ

Schedule (Backup)

Task	%
⊞ Project Logistics	67%
⊟ Manufacturing	86%
Left / Right	95%
Front Face & Rear Panel	75%
⊟ Integration	77%
⊟ Hardware (Sensors)	73%
TOF Spec Verification	85%
Confirm Code for TOF	85%
GPS Calibration	50%
Confirm Code for GPS	50%
Integrate Sensors with NUC	50%
⊟ Electronics	81%
Integrate NUC with Sensors	25%
Integrate NUC with Post Processing Code	25%
⊟ Software	90%
⊟ Simulations	95%
Process Automation w/ processing	80%
⊟ Post Processing	81%
Integrate Post Processing Code with TOF	65%
Integrate Post Processing Code with Monochrome	75%
Integrate with NUC	25%
⊟ State Estimation	93%
format_satellite() development and unit tests	90%
format_deployer() development and unit tests	95%
Batch Filter V & V	85%
get_tle()	85%
Integrate with NUC	0%
⊞ Testing	17%