OSPRE
Spring Final Review

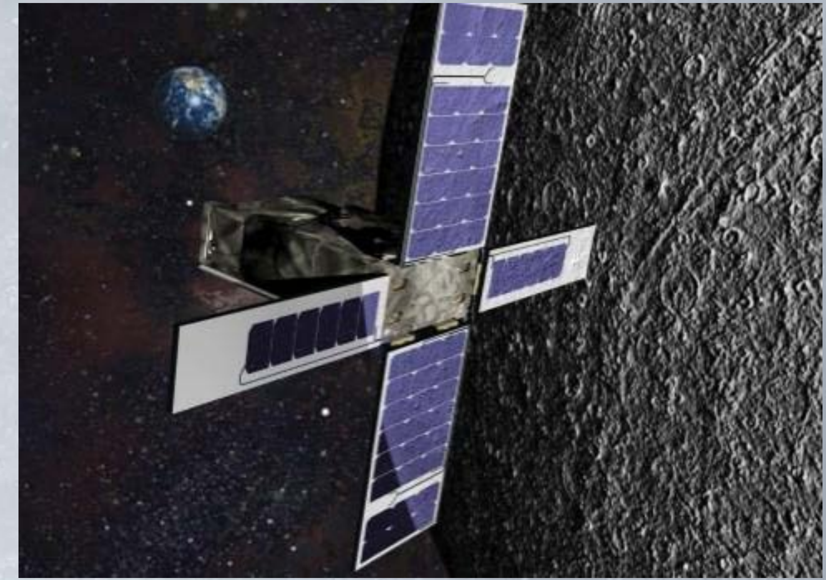
Project Purpose and Objectives

Motivation

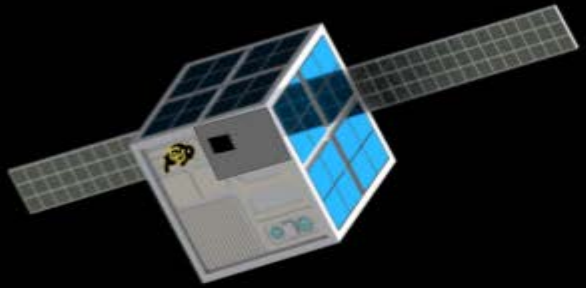
- CubeSat technology enables **low-cost** missions in a **small package**
  - As of now, mostly restricted to Low Earth Orbit
  - NASA’s CubeQuest Challenge employs CubeSats on a **lunar flyby**
- A CubeSat on a lunar flyby cannot use traditional methods for position and velocity determination
  - GPS will not work very far past geosynchronous orbit
  - Low-cost mission does not have resources for ground station ranging

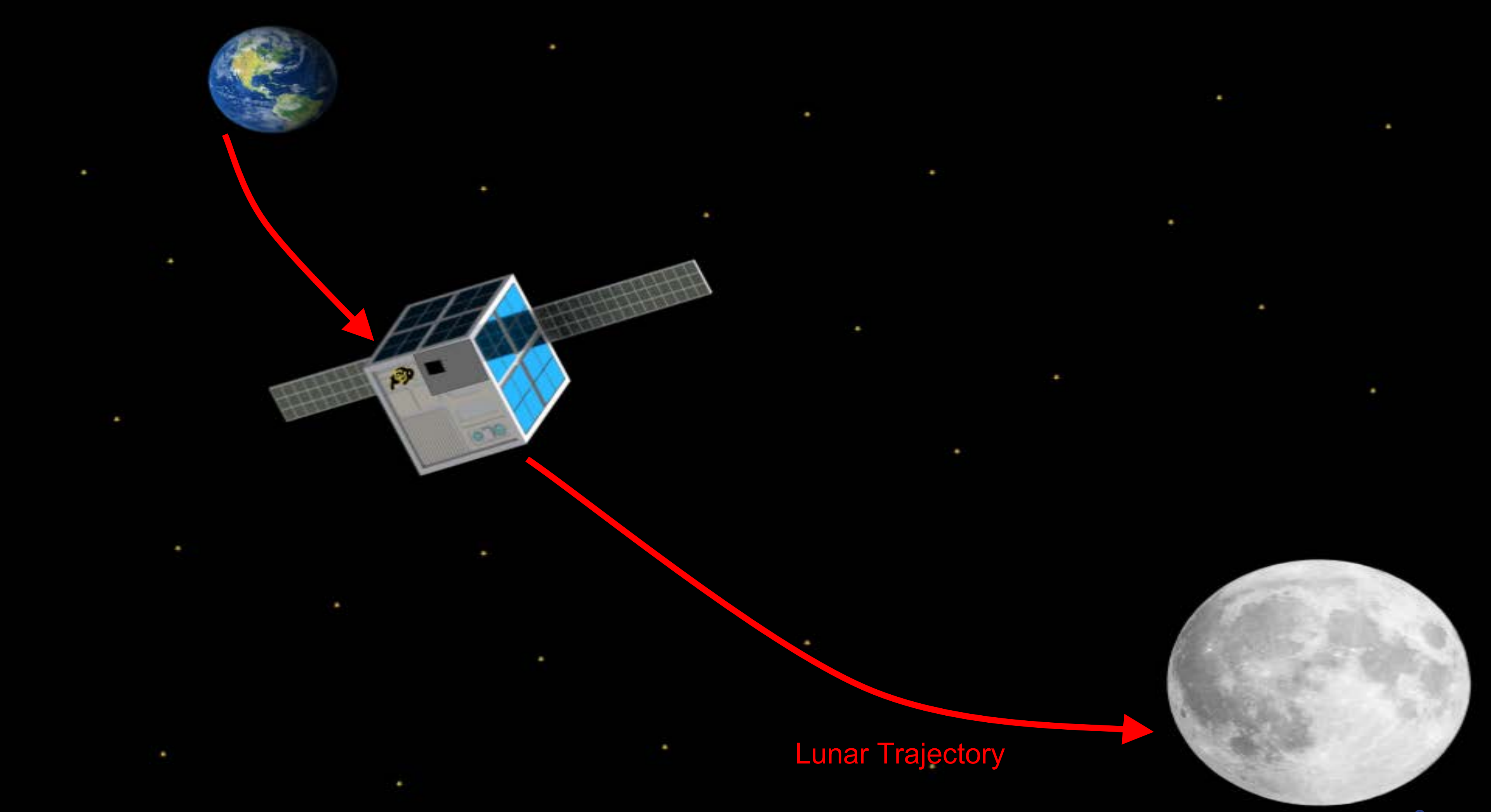
Project Purpose

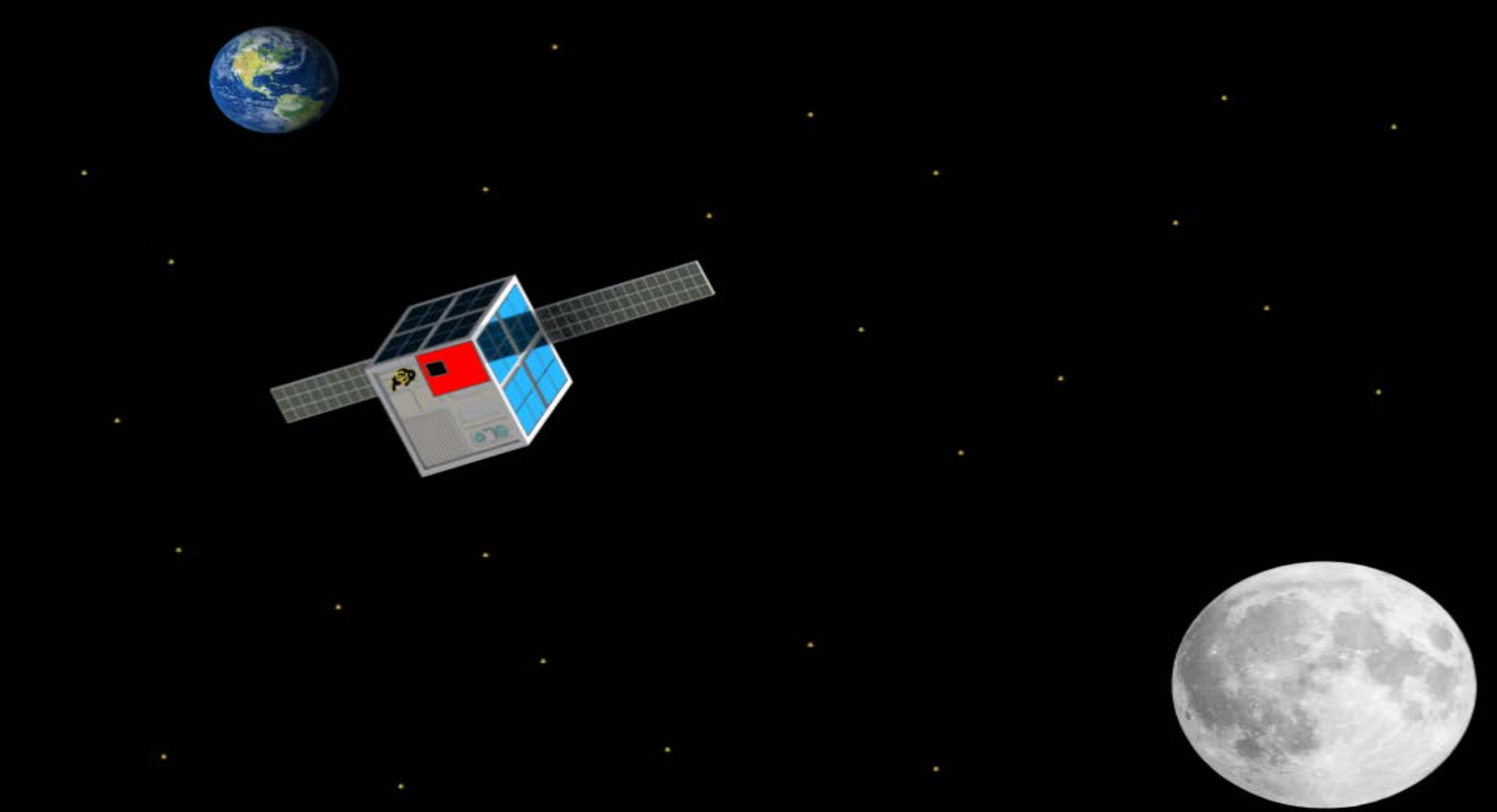
- OSPRE is a proof of concept to enable a low-cost CubeSat lunar flyby mission by implementing **optical relative navigation** to determine state vector and state vector error

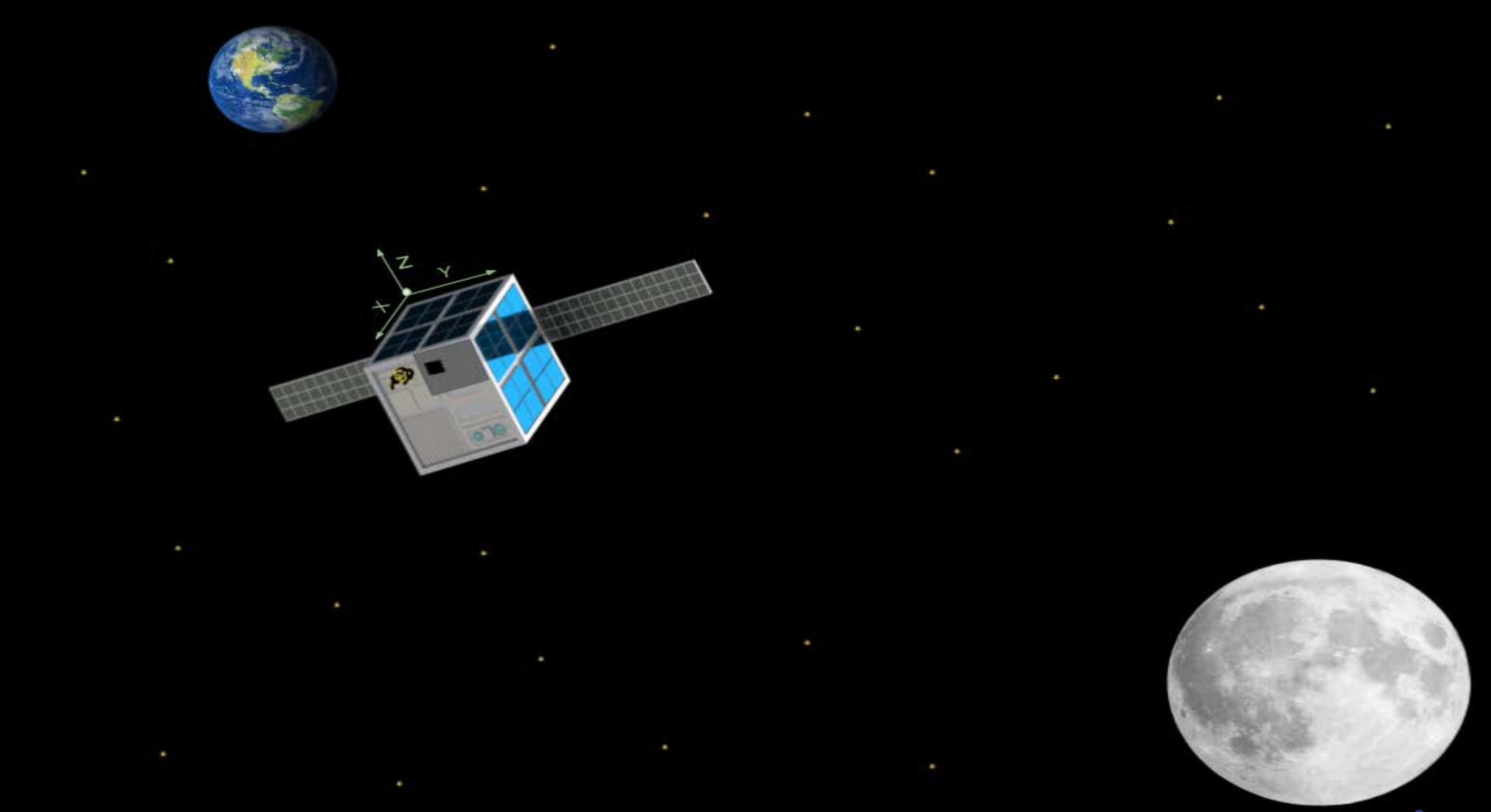


OSPRE Mission CONOPS




Lunar Trajectory

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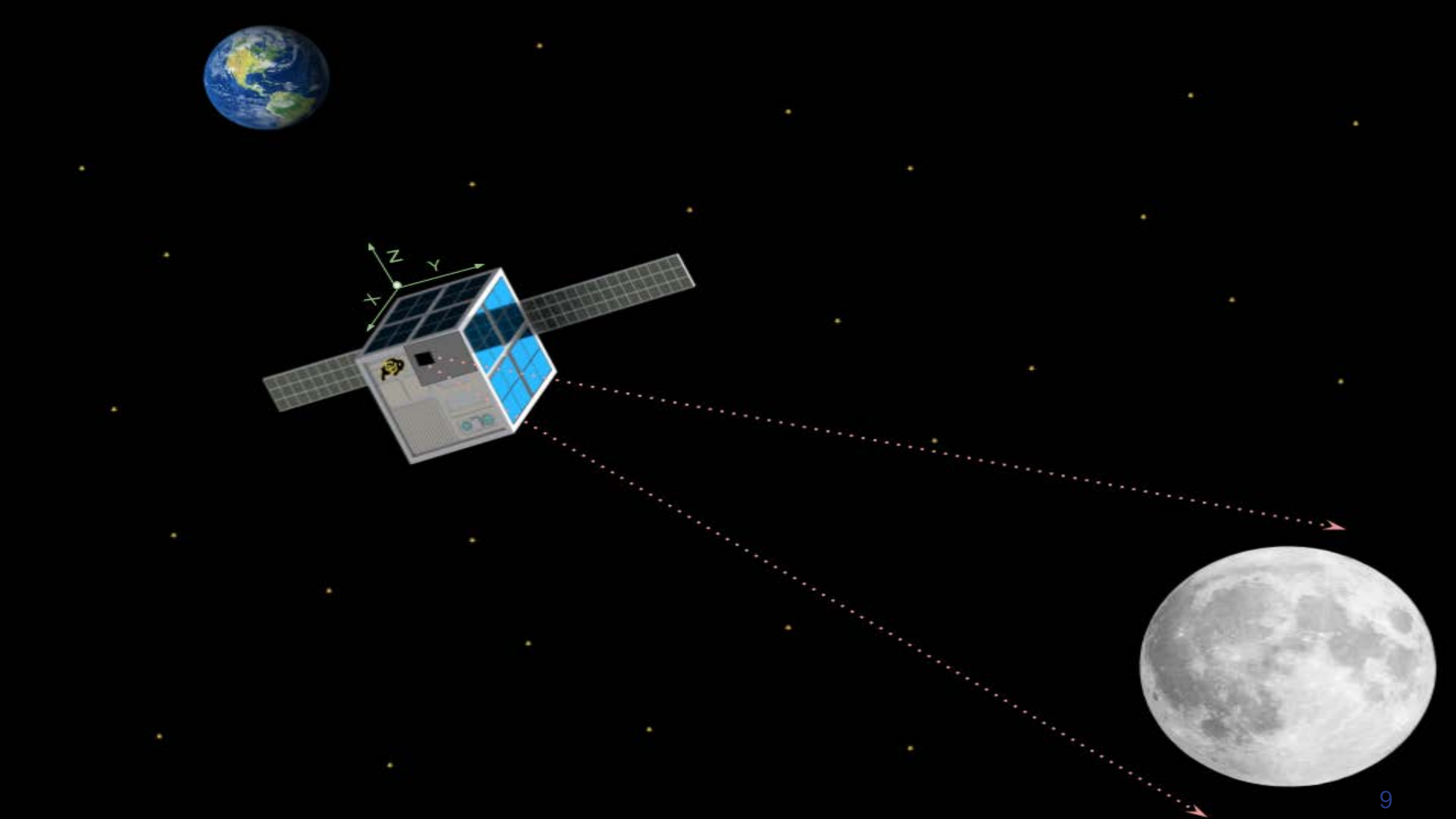
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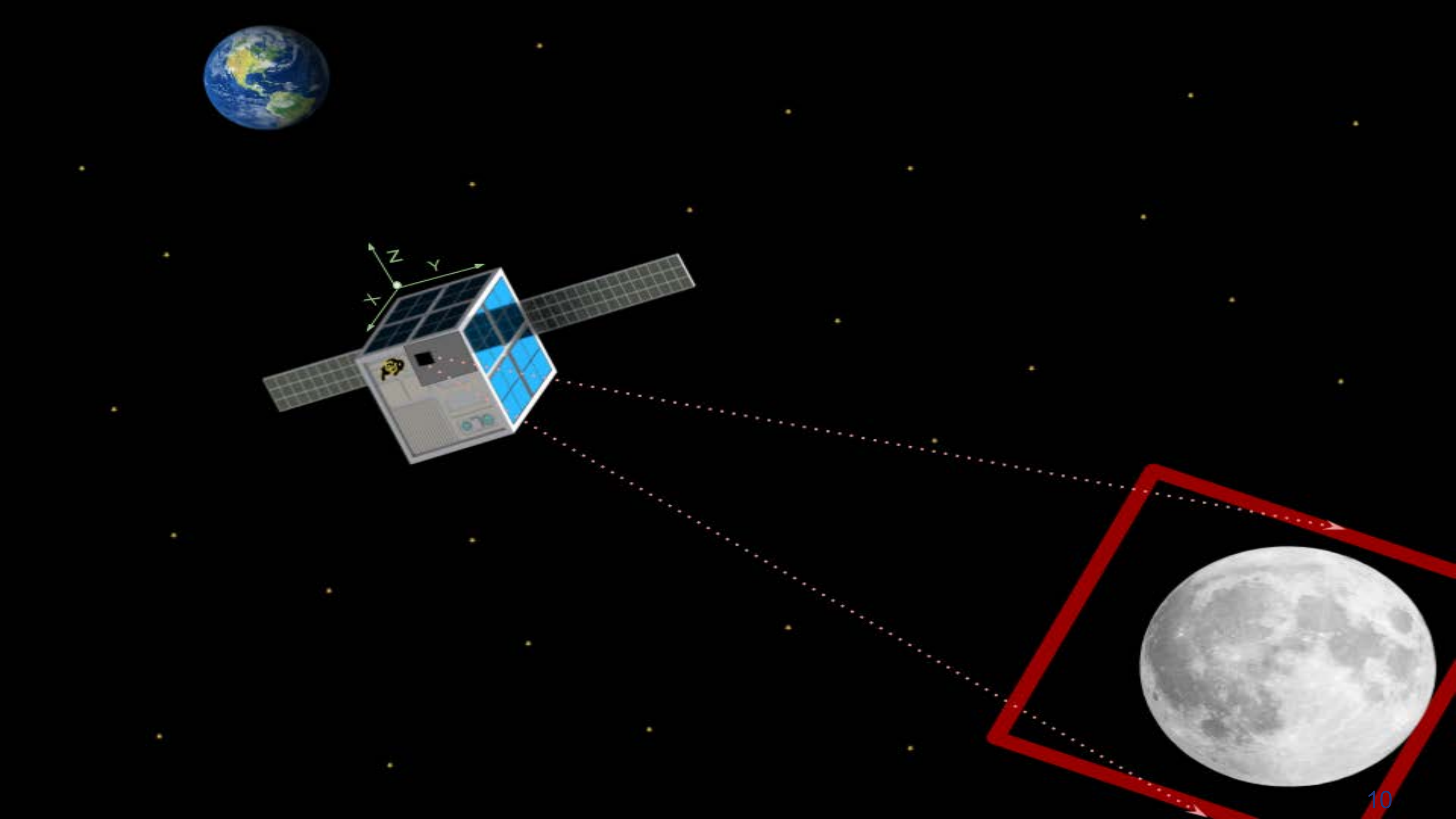
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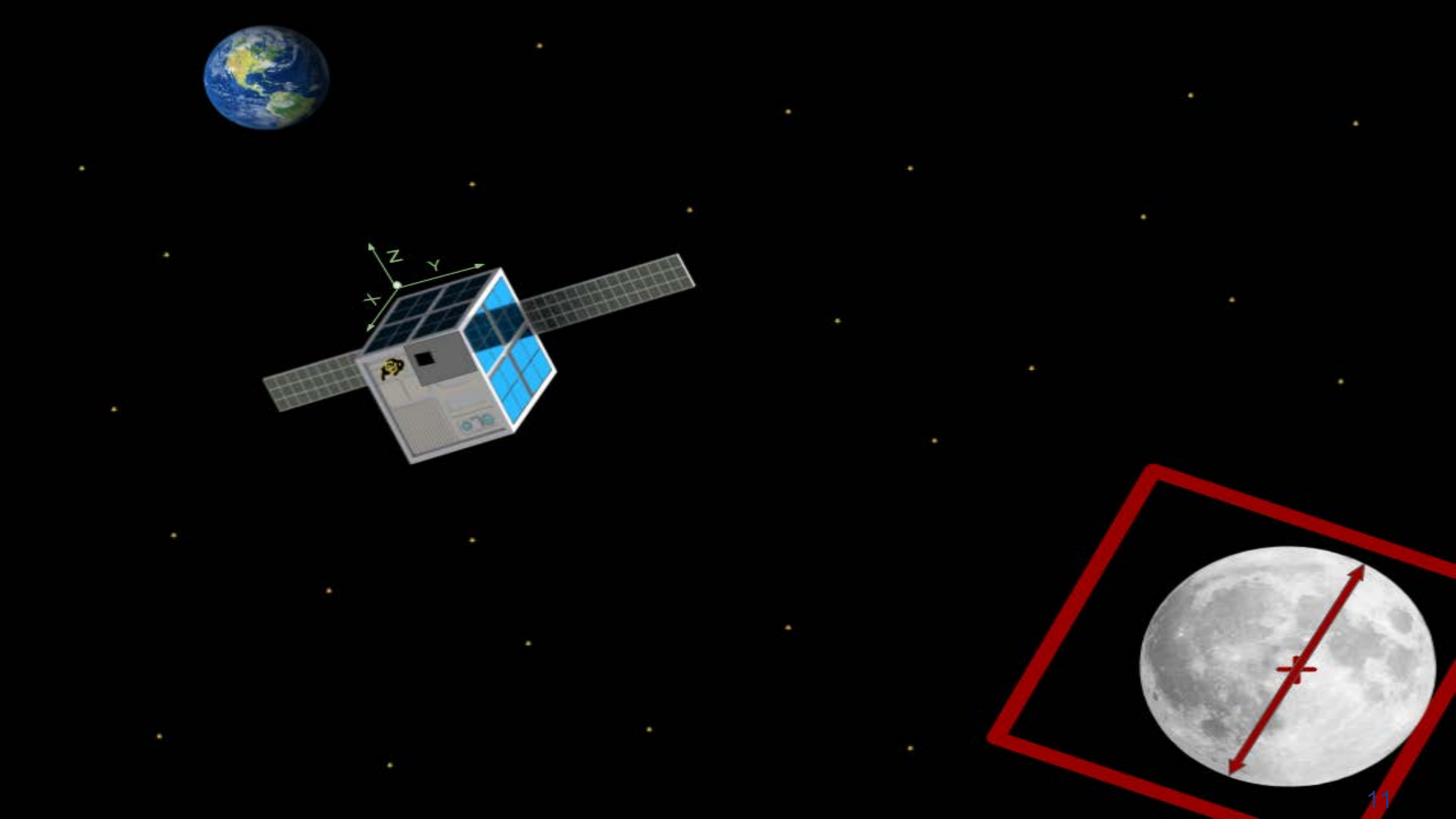
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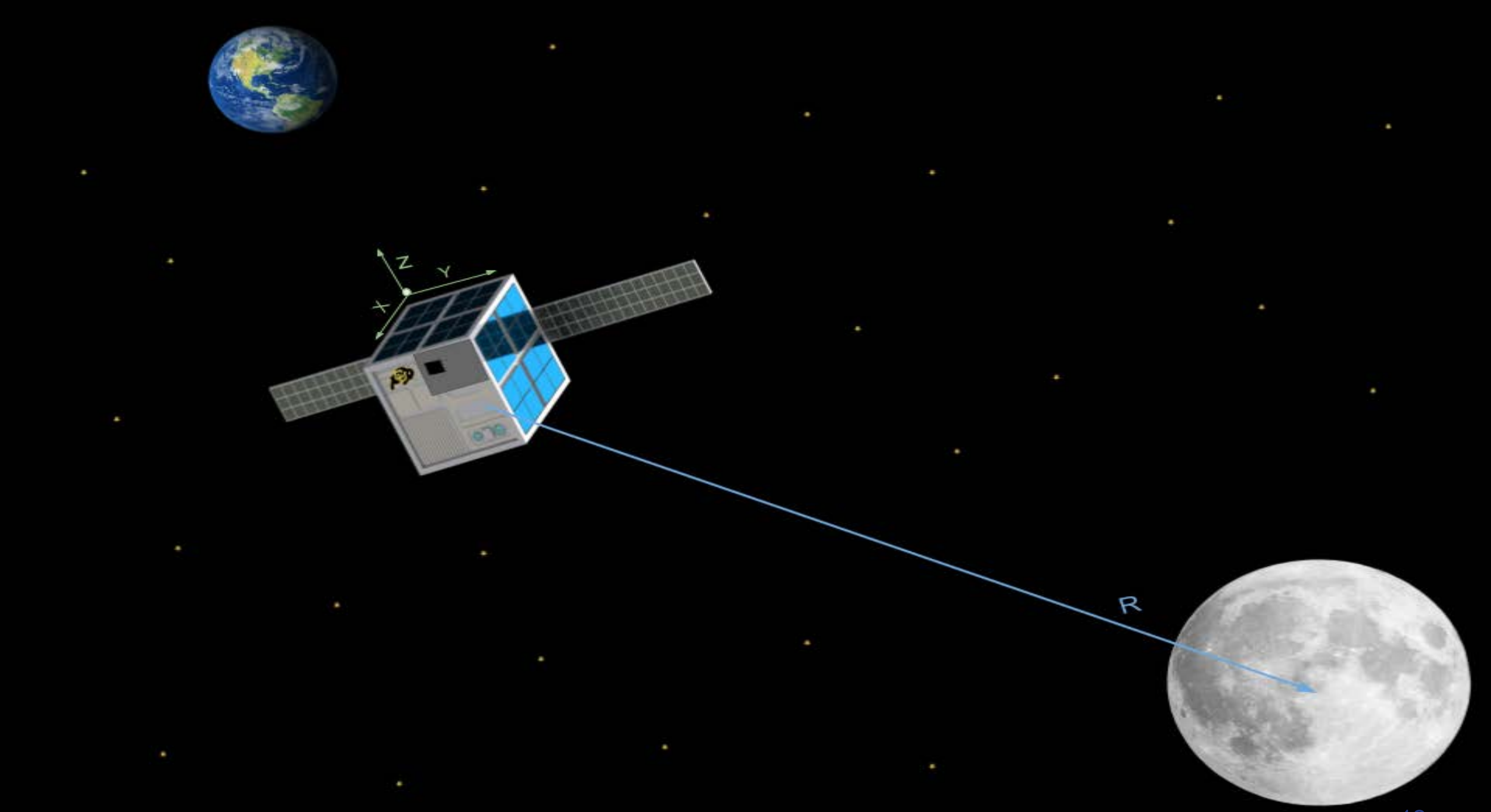
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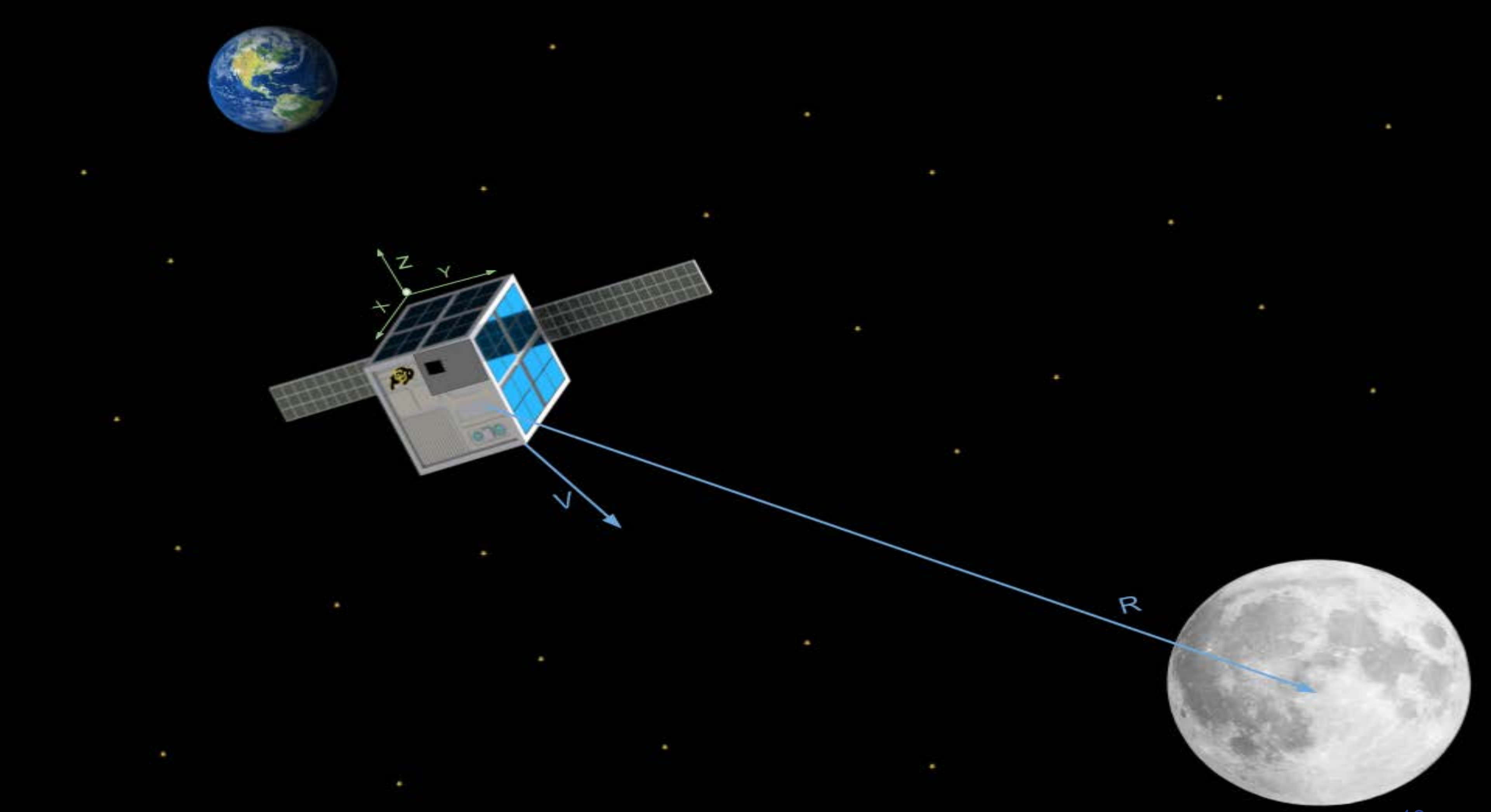
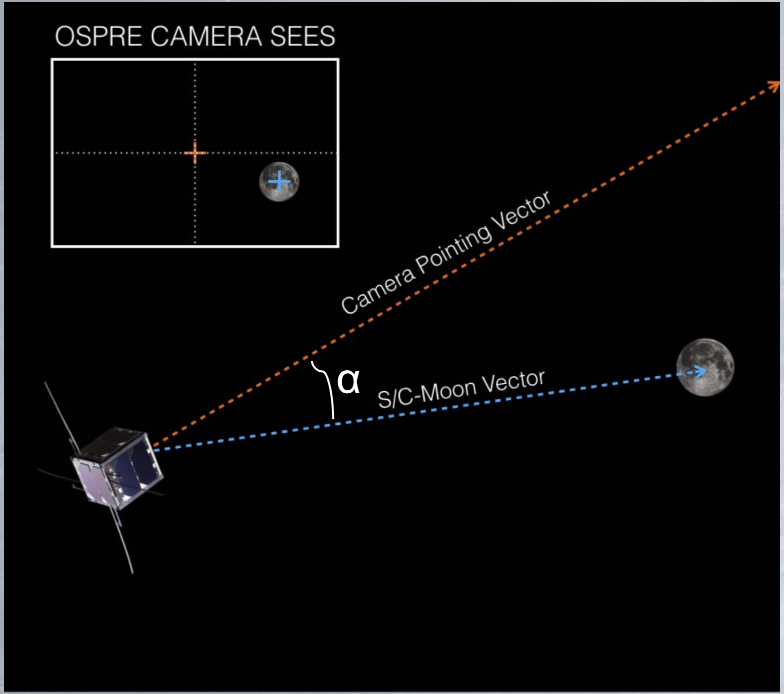
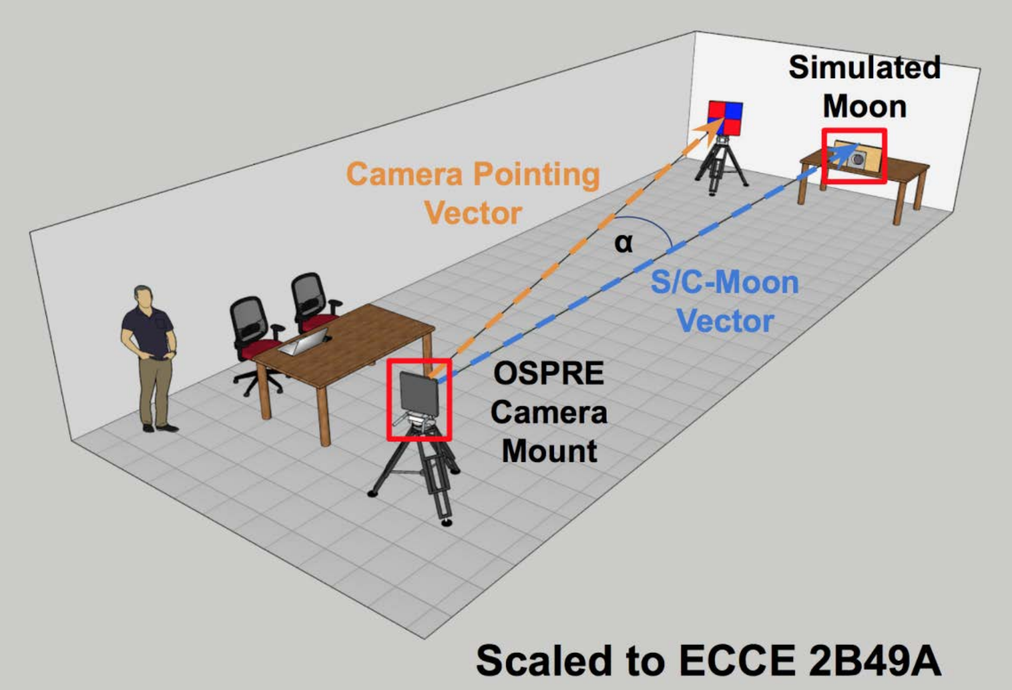

Z
Y
X
V
R

Mission Analog

MISSION ENVIRONMENT



TEST ENVIRONMENT



Functional Requirements

INPUTS FROM SPACECRAFT
Spacecraft attitude quaternion
Moon ephemeris
Time
Sun ephemeris
Sun angle
Angular velocity

OUTPUTS TO SPACECRAFT
Position to within 1000 km
Velocity to within 250 m/s
Position uncertainty
Velocity uncertainty
Solution validation
Earth-spacecraft-moon angle
Health and Status

Exchange of information every **two minutes**

Levels of Success

	Level 1	Level 2	Level 3
Data Processing	OSPRE shall output a state vector for full Moon and Earth disks and shall gather data for no longer than an hour at a time.	OSPRE shall estimate the error of the state vector.	OSPRE shall provide the state vector error within an accuracy of 1000km and 250m/s and shall function for all Moon and Earth phases.
Electrical	OSPRE shall operate nominally provided 3.3V, 5V, or 12V electrical power, and interface with the ZedBoard and image sensor(s) using SPI, I^2C, or Cameralink.	OSPRE shall have a peak current of no more than 500mA and maximum power draw of no greater than 3W.	The system shall provide voltage sense and current sense telemetry.
Structural	OSPRE's mass shall not exceed 0.8kg.	OSPRE's dimensions shall not exceed 5cm x 5cm x 1cm.	-
Testing	OSPRE's testing shall include testing the accuracy of the algorithm. OSPRE shall create a software test capable of quantifying the navigation software's error.	OSPRE's testing shall include a physical simulation. OSPRE shall create an Earth-Moon testbed that quantifies the error of the navigation hardware.	OSPRE's testing shall incorporate hardware and software testing simultaneously. The system shall compute the state vector autonomously in a test environment.

Levels of Success

Level	Description	Completed	Notes
1	Spacecraft Interface Requirements	Yes	
2	Required accuracy and error determination	Yes	
3	Complete Autonomy	No	• Not a requirement, but needs to be autonomous to function on a spacecraft • Failed to develop SPI software and camera drivers in allotted time

Design Description

Critical Project Elements

<u>Solution Accuracy:</u>

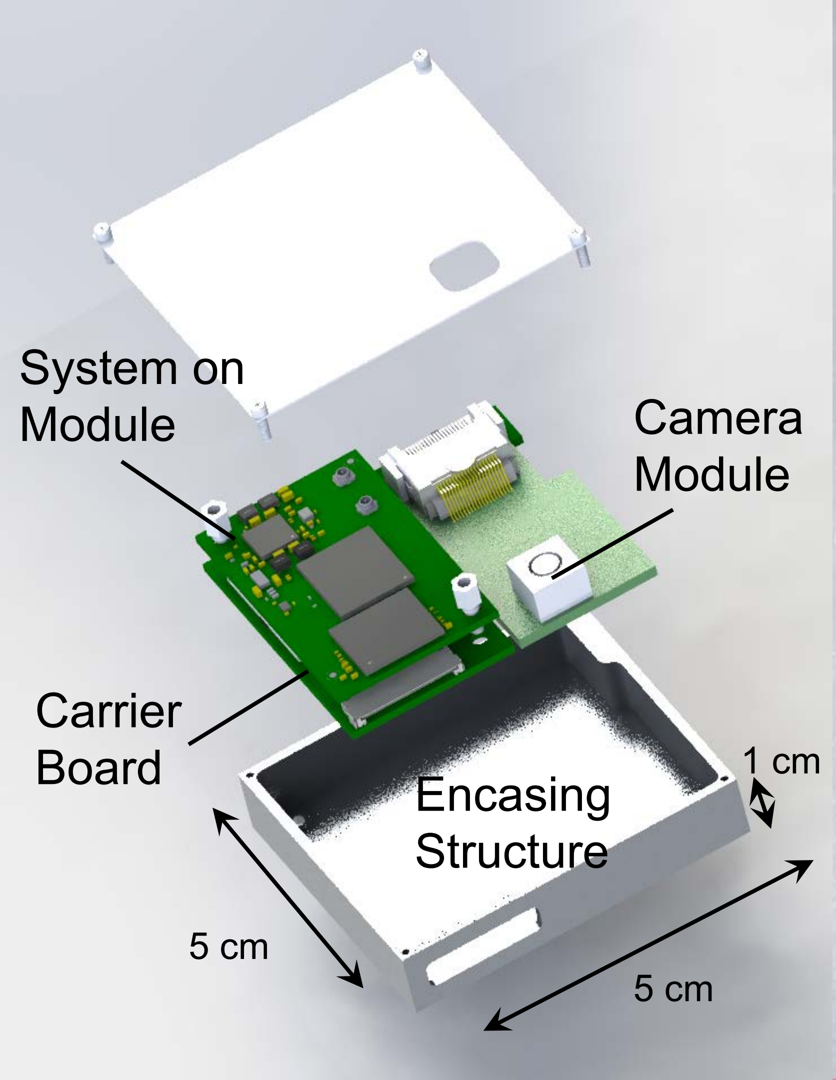
- State vector must be determined to within required accuracy - 1,000km position, 250m/s velocity
  - Camera resolution, Image processing, Navigation algorithms

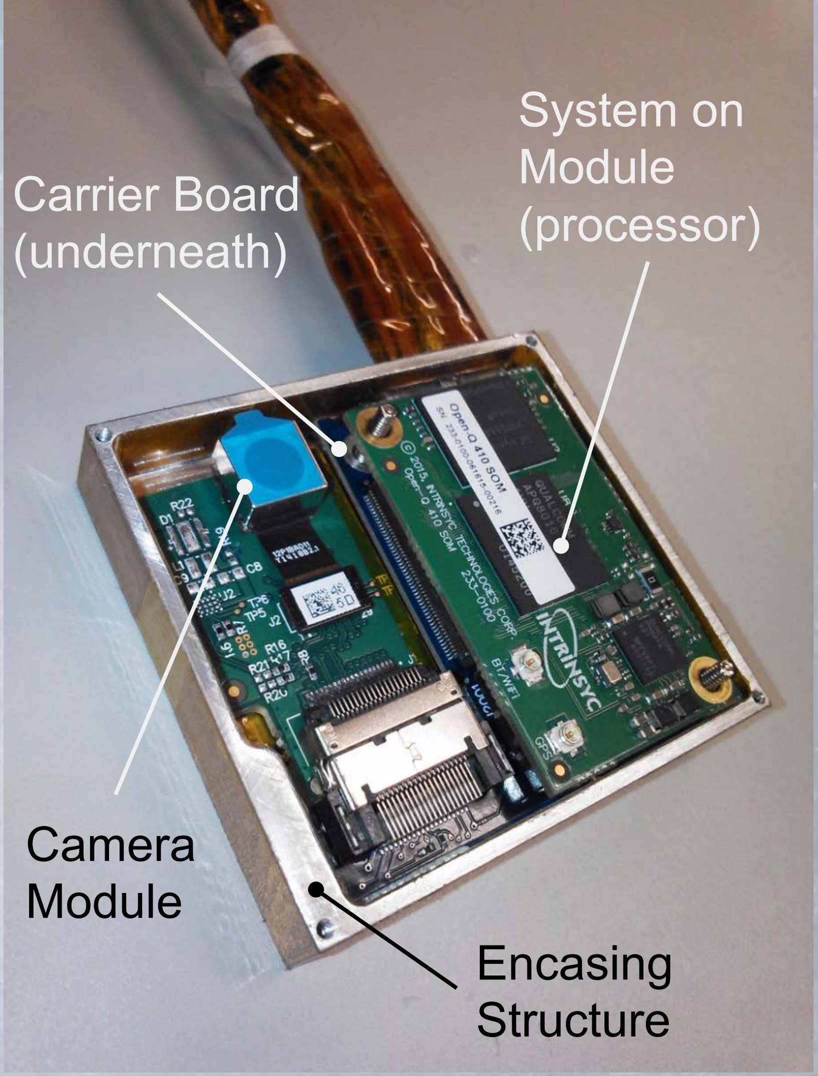
<u>Testing Accuracy:</u>

- Solution accuracy must be verified in testing
  - <100km test-attributed position error
- Scaling of the Earth-Moon system
  - Measurement of distance between camera and target, measurement of the location of the center of the target

<u>SWAP:</u>

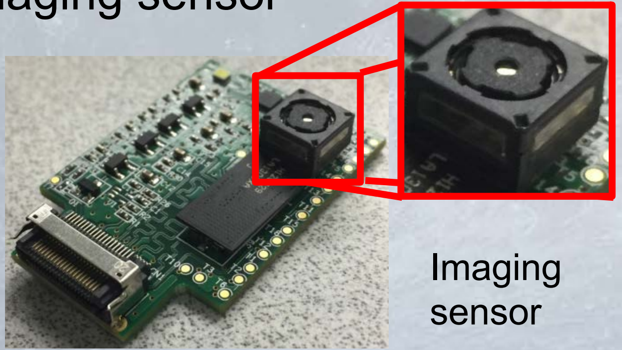
- Size, Weight, And Power requirements must be met
  - Component size, component power draw, component weight


System on Module
Camera Module
Carrier Board
Encasing Structure
1 cm
5 cm
5 cm


System on Module (processor)
Carrier Board (underneath)
Camera Module
Encasing Structure

Imaging Sensor

- 13 MP Sony Imaging sensor chosen for high pixel number and low volume
- Camera drivers not supported
- Testing done with Nexus cellular device containing identical imaging sensor

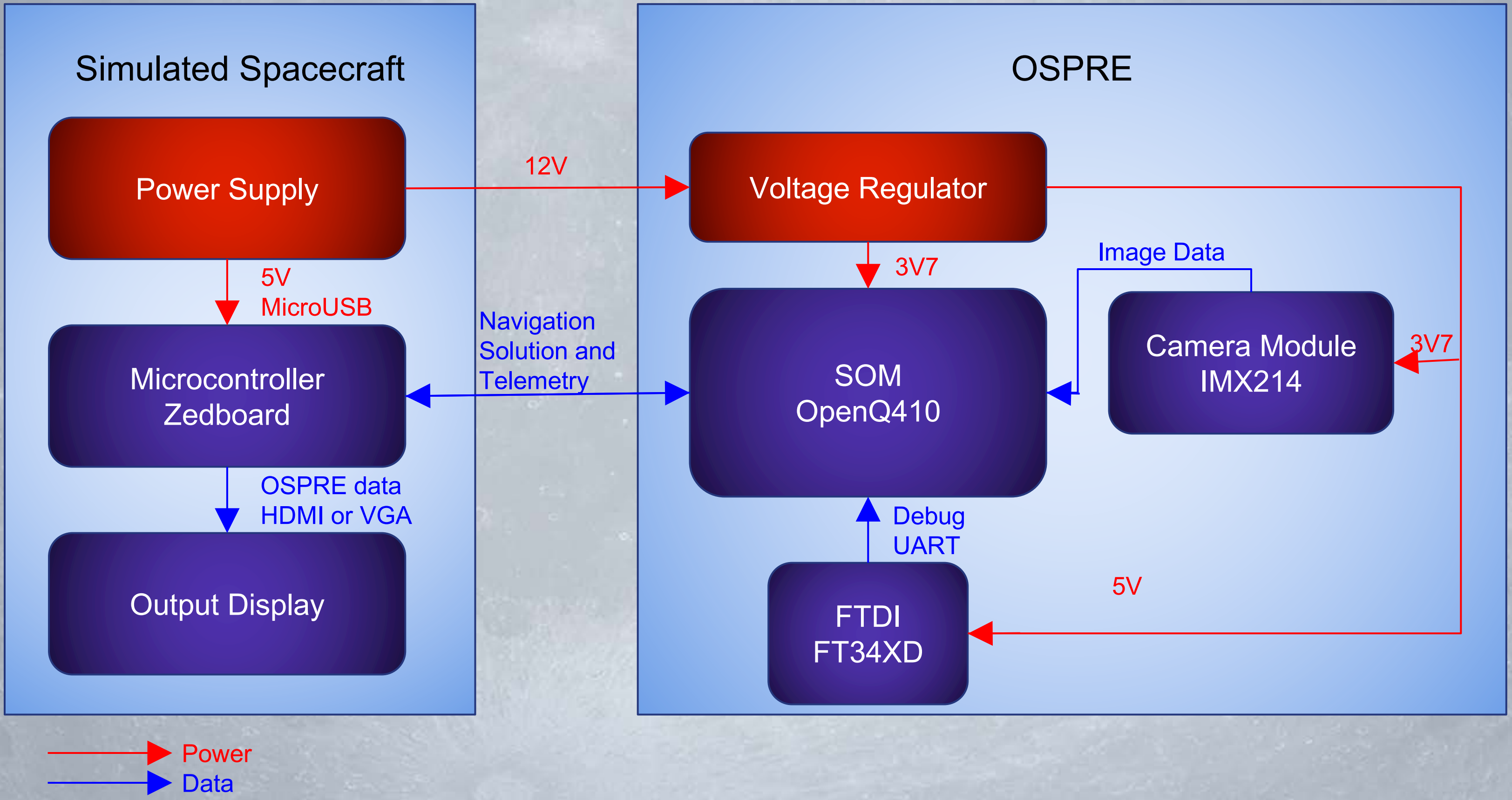


Imaging sensor

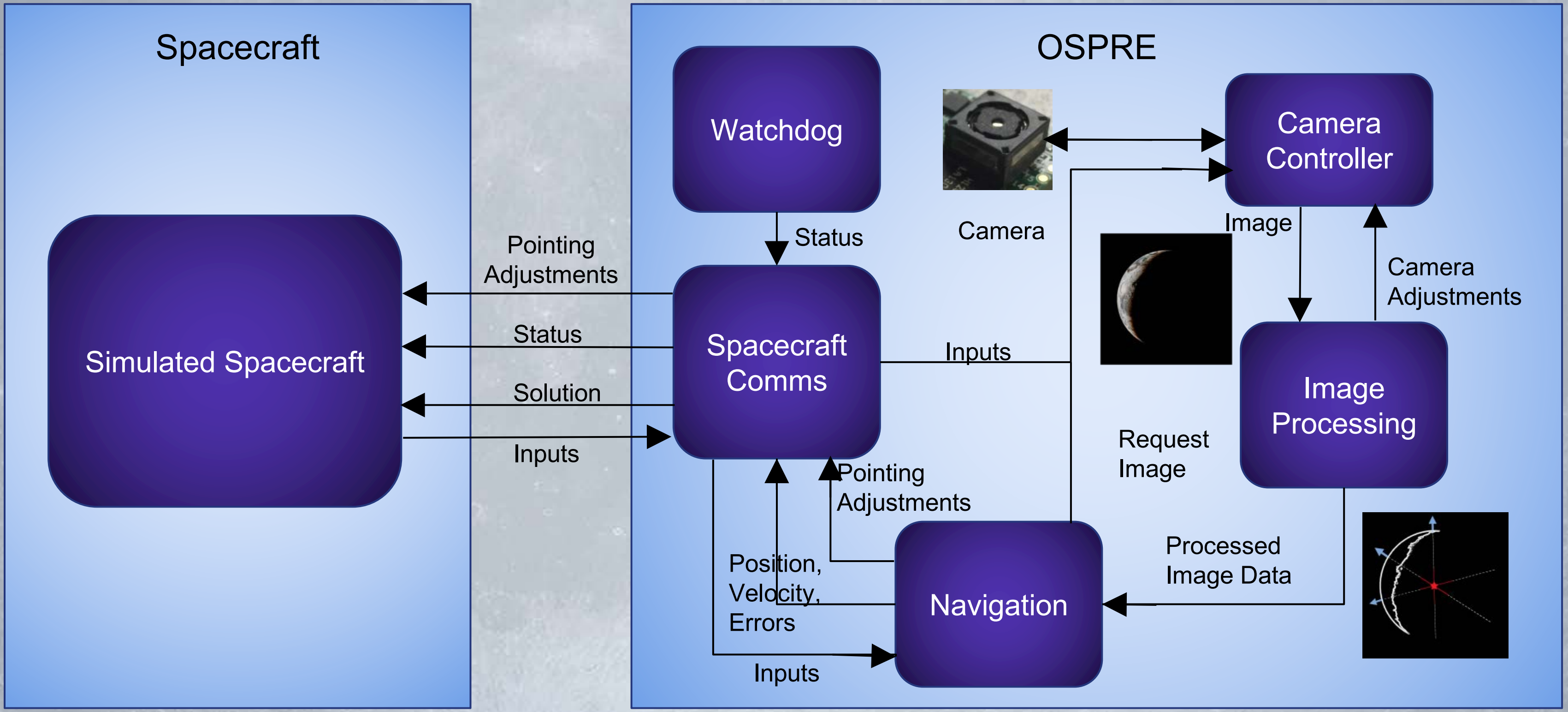
Cellular Device

"Google Nexus 6, Motorola, XT1100, 32GB, 5.9", Unlocked, LTE, Android 7.0 Nougat."Amazon. Amazon.com, Inc, n.d. Web.

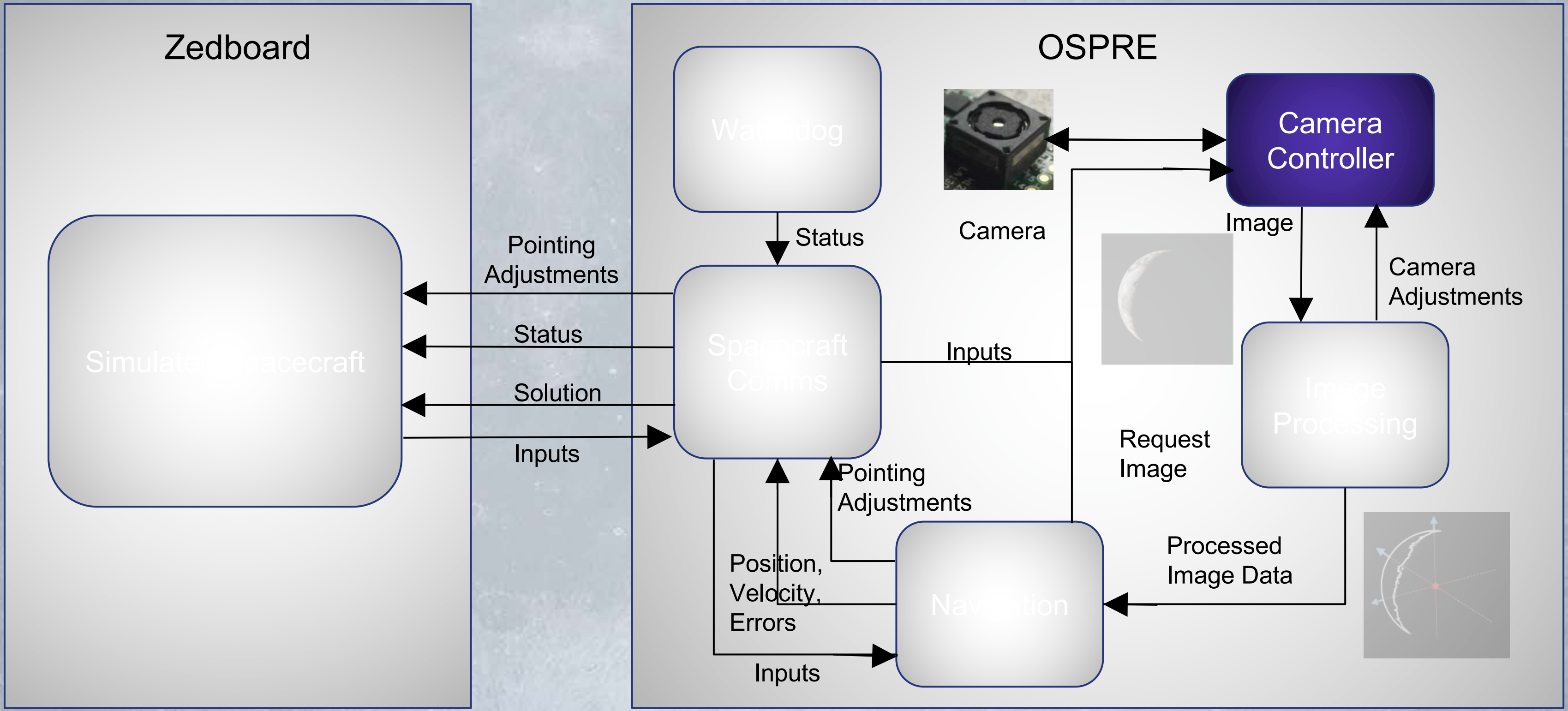
Hardware Functional Block Diagram



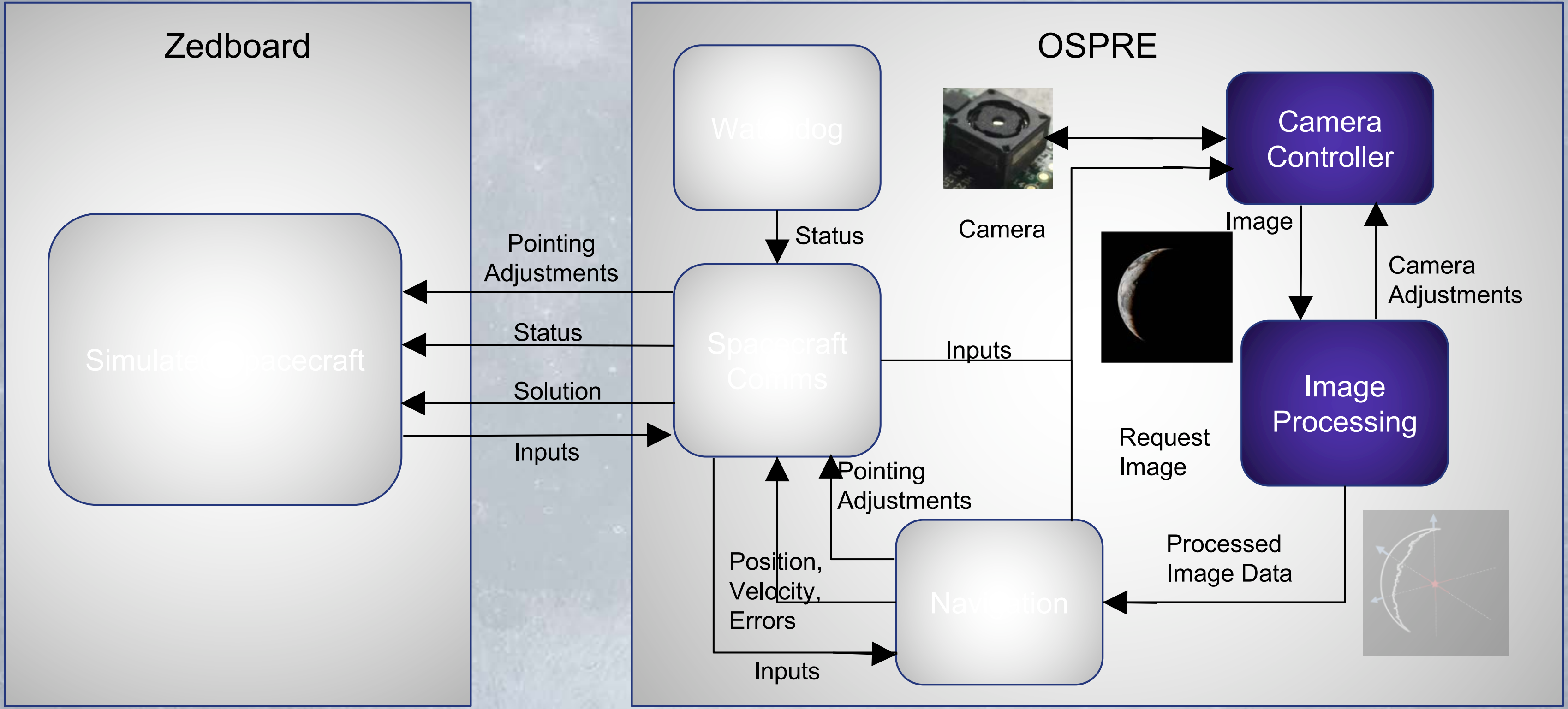
Software Functional Block Diagram



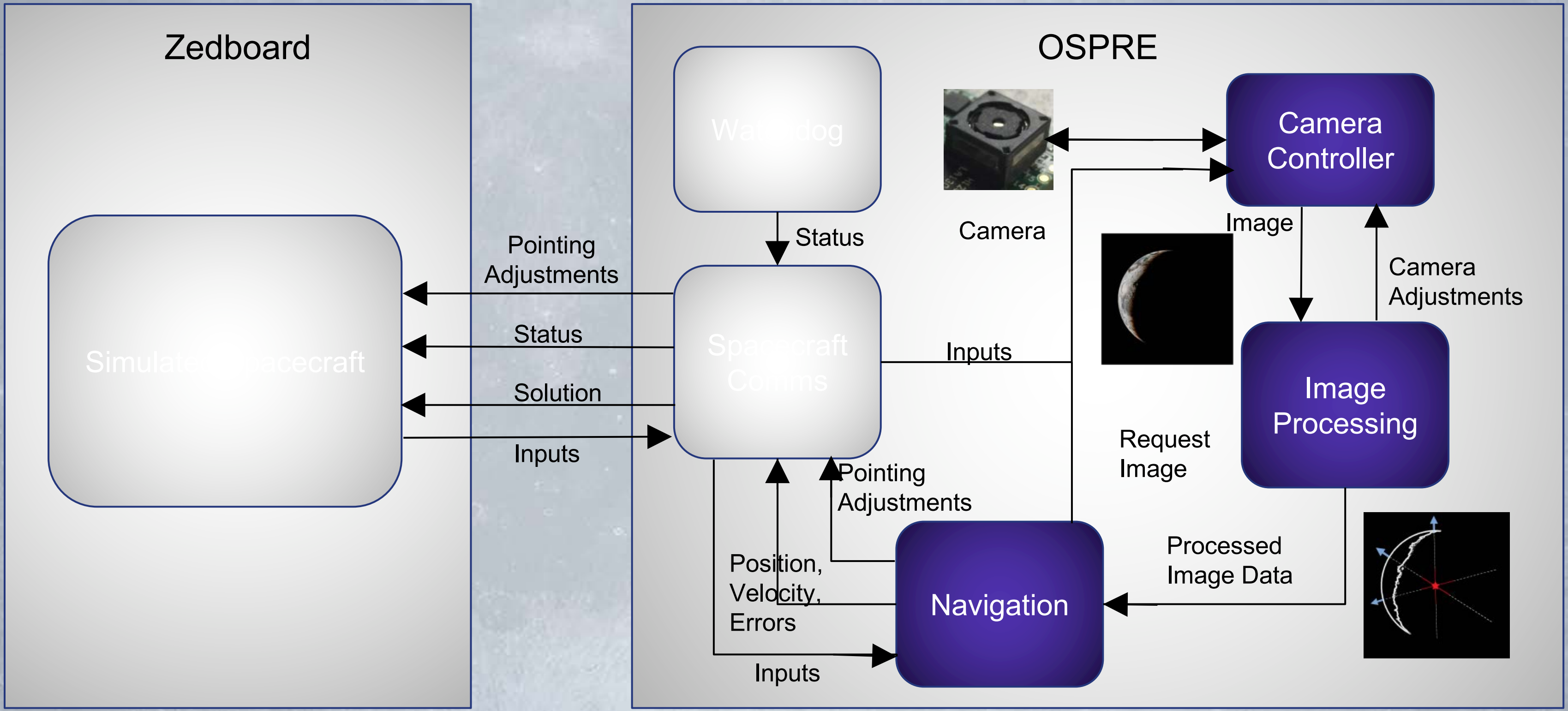
Software Functional Block Diagram



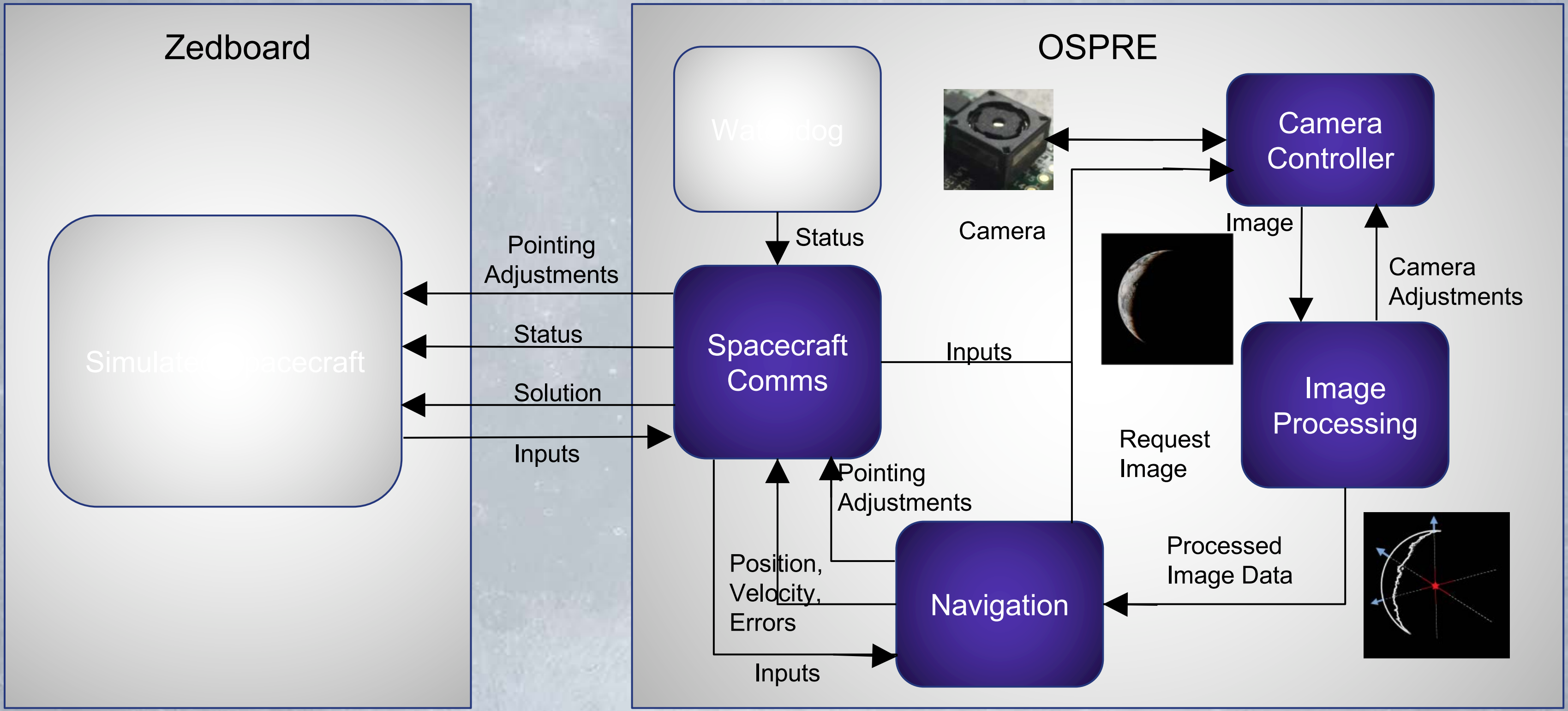
Software Functional Block Diagram



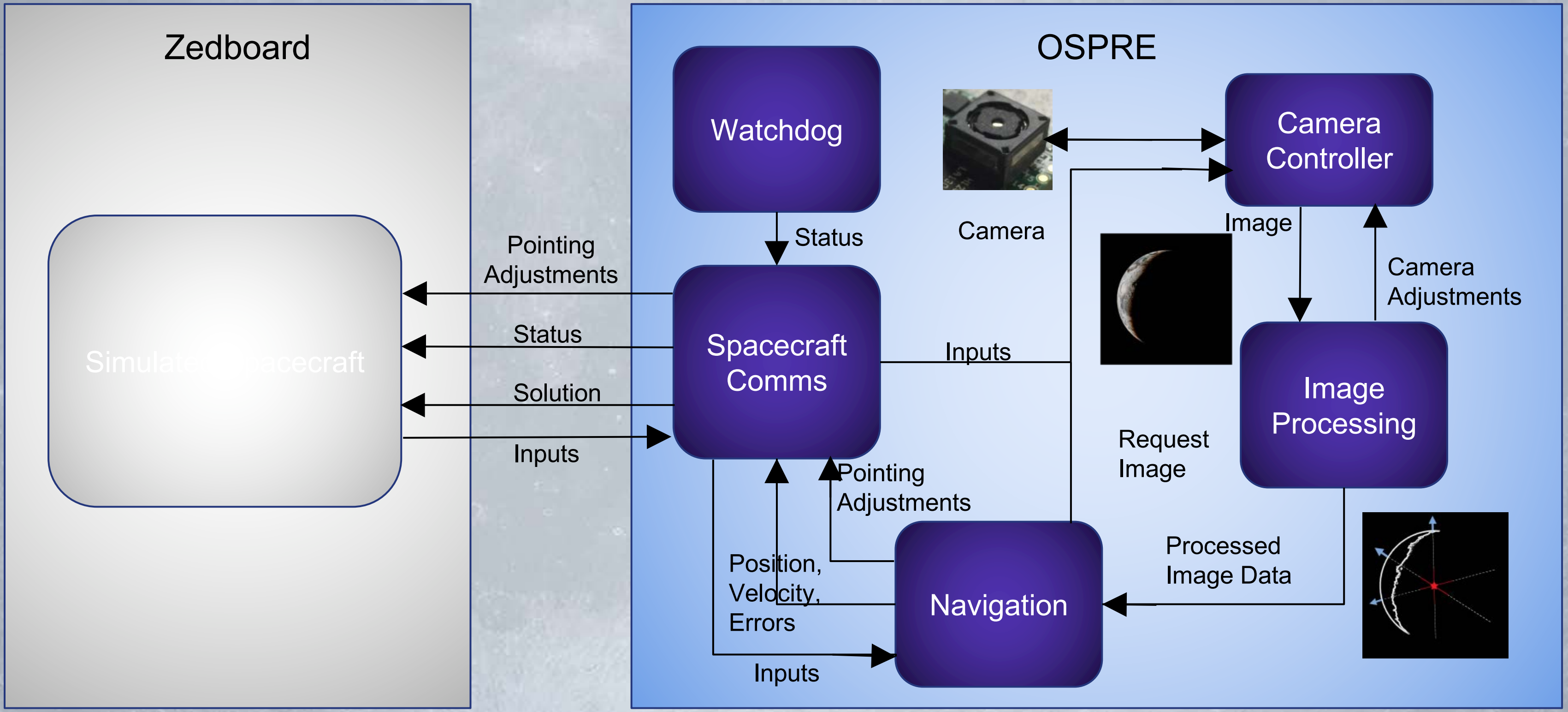
Software Functional Block Diagram



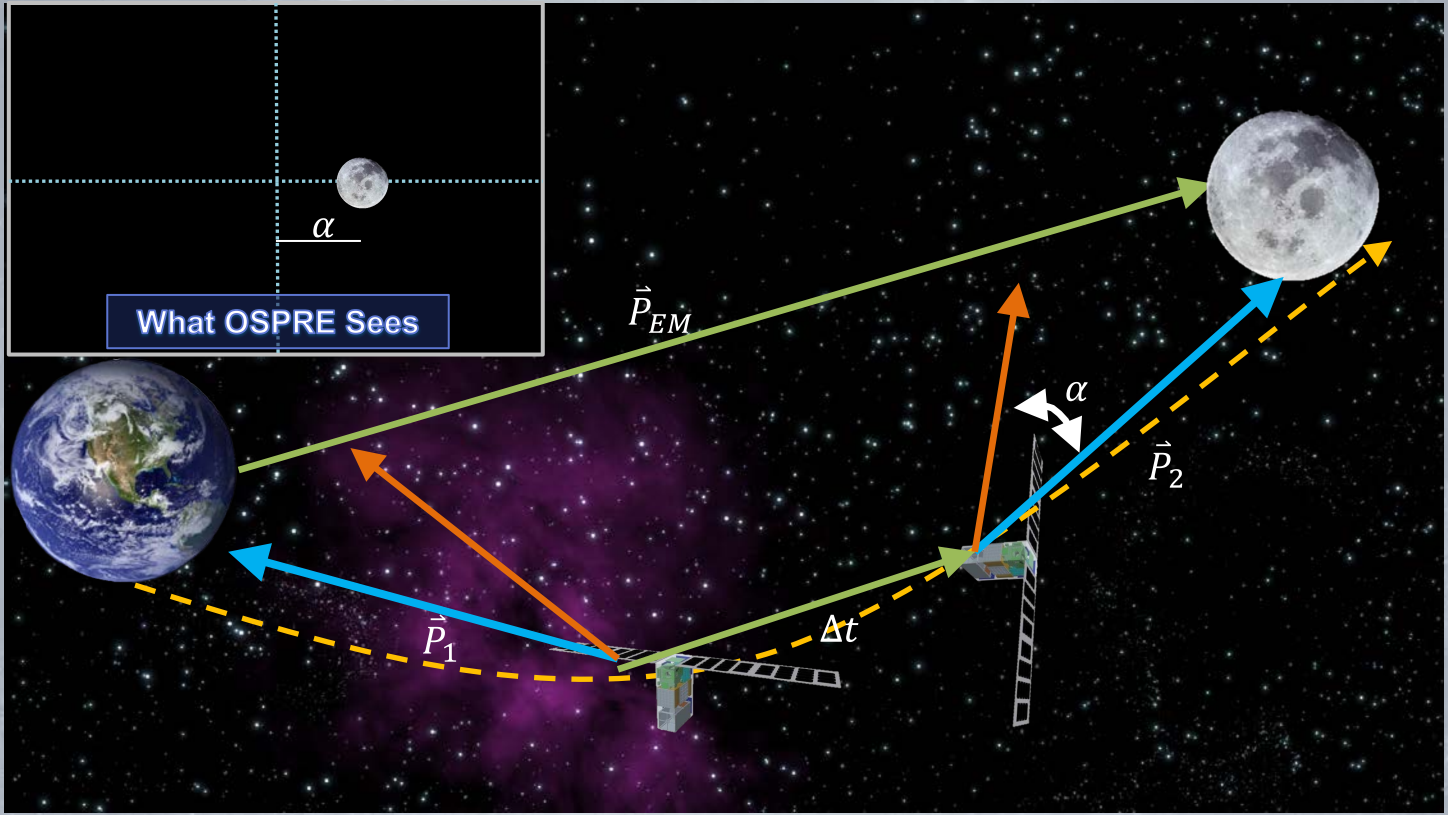
Software Functional Block Diagram



Software Functional Block Diagram

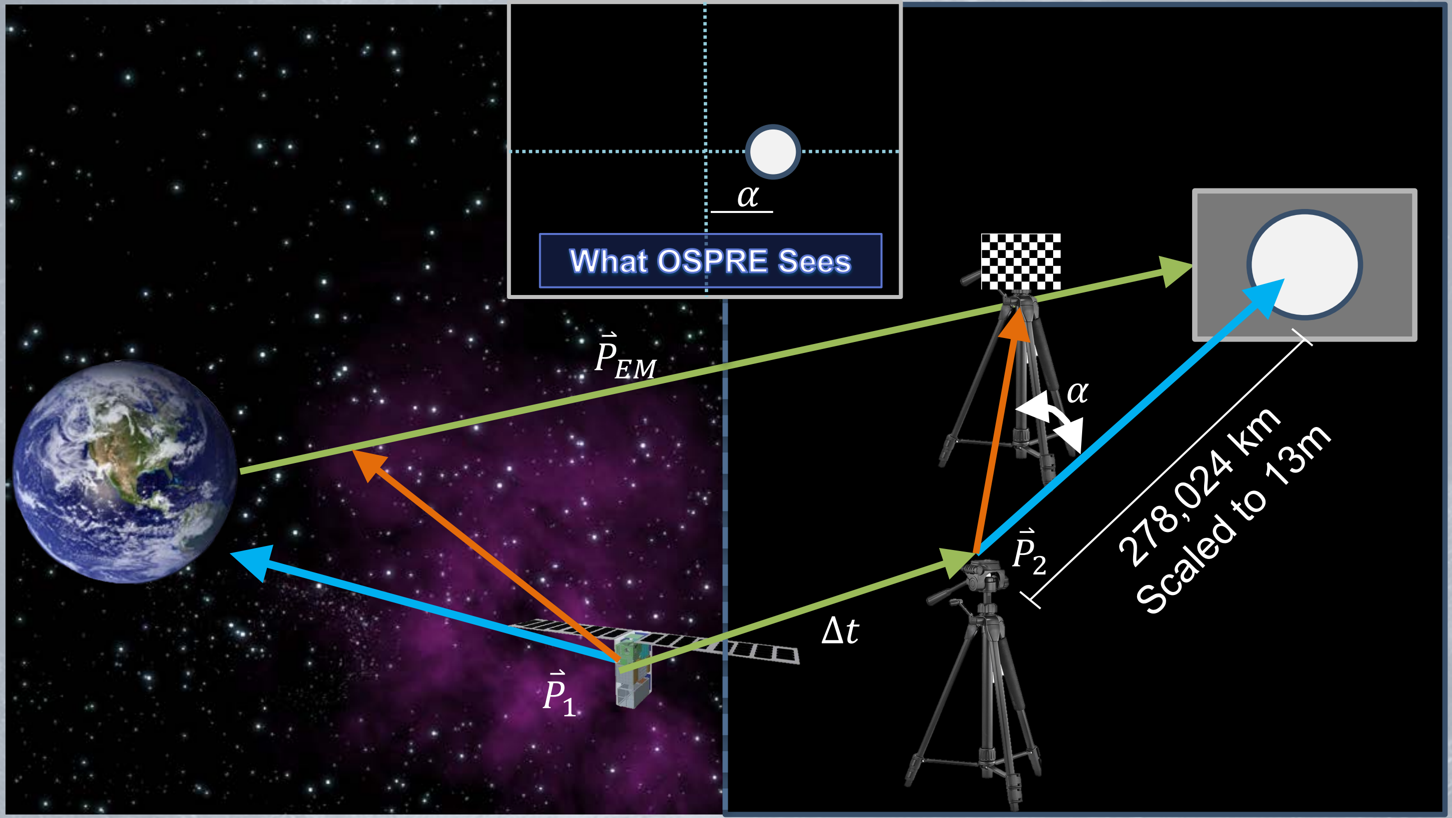


Total OSPRE C Code Developed - 10,764 Lines of Code



What OSPRE Sees
α
$\vec{P}_{EM}$
α
$\vec{P}_2$
$\vec{P}_1$
Δt

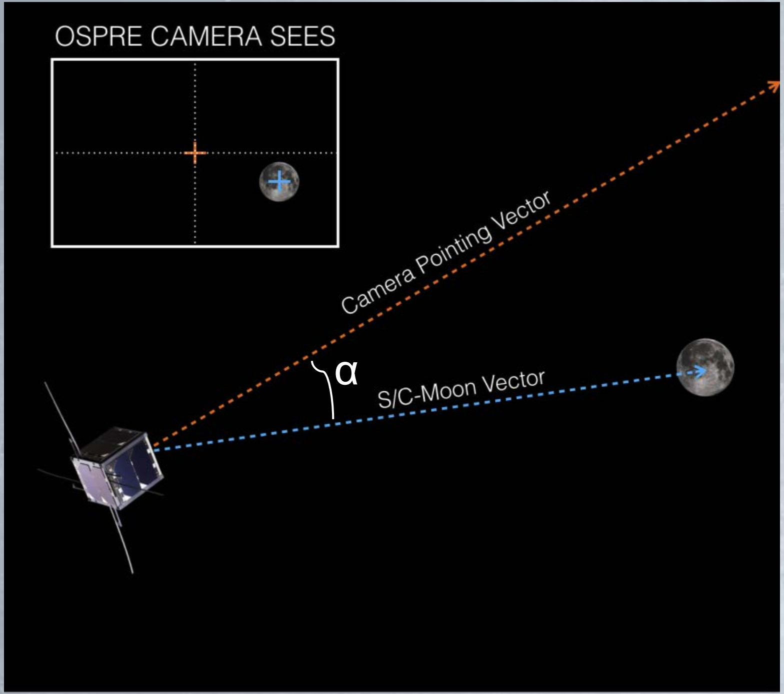
Simulated   Test Environment



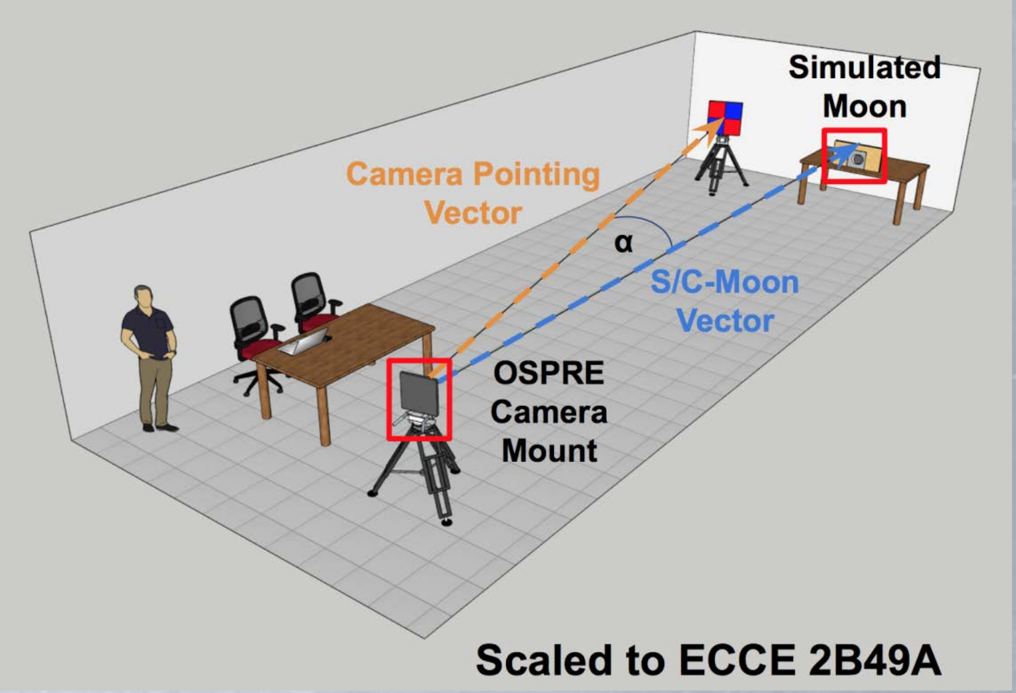
Test Overview

Performance Testing
Test Setup

MISSION ENVIRONMENT

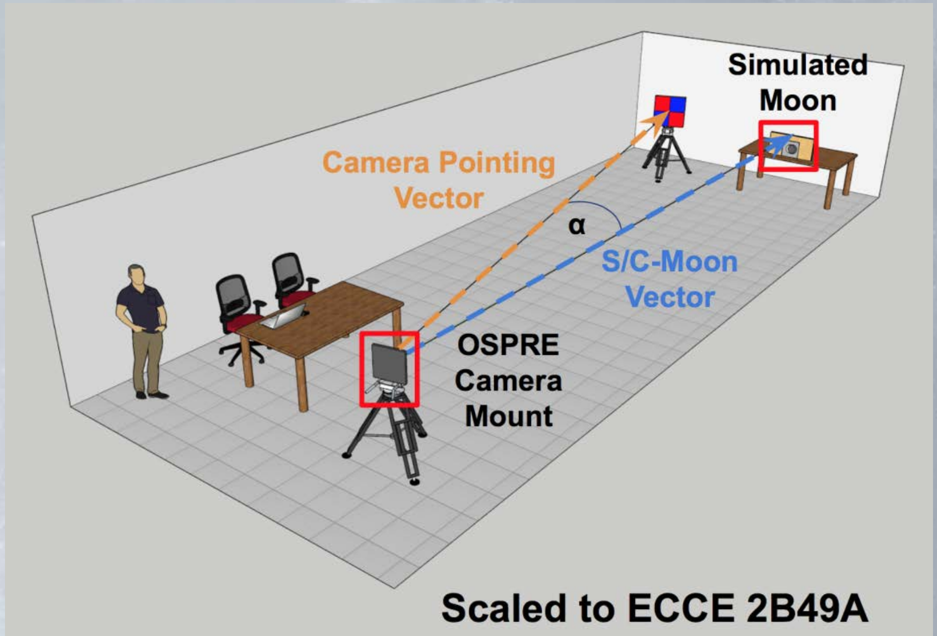


TEST ENVIRONMENT



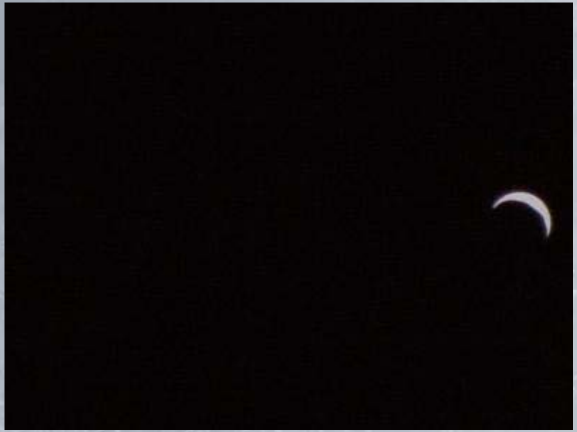
Solution Generation

- Measure test setup to determine:
  - S/C-Moon Vector
  - α_{meas}
- Test setup analysis shows setup introduces only **±190 km** of position uncertainty ~95% of the time
- Degree-per-pixel (°/pixel) value for the camera previously determined with Field-of-View Test

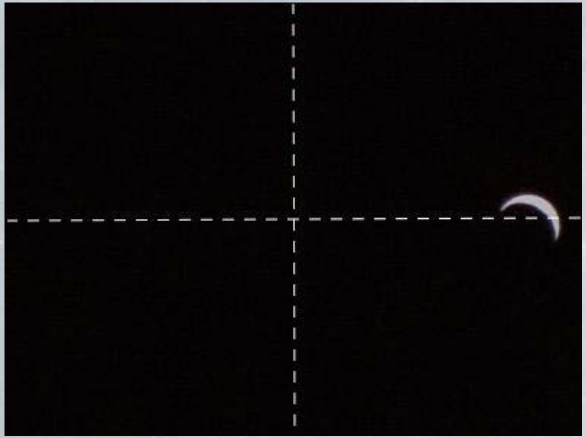


Solution Generation

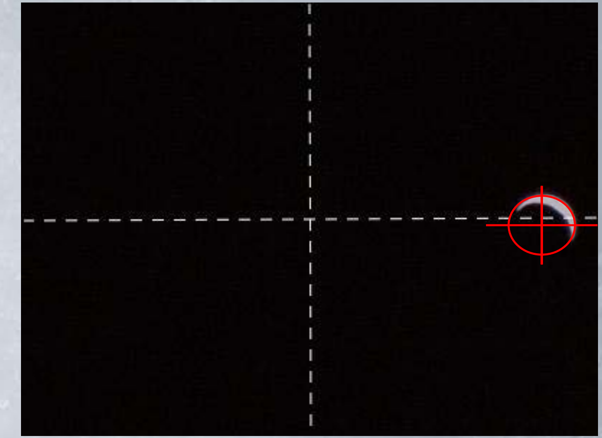
*Real images from test setup



Capture Test Image

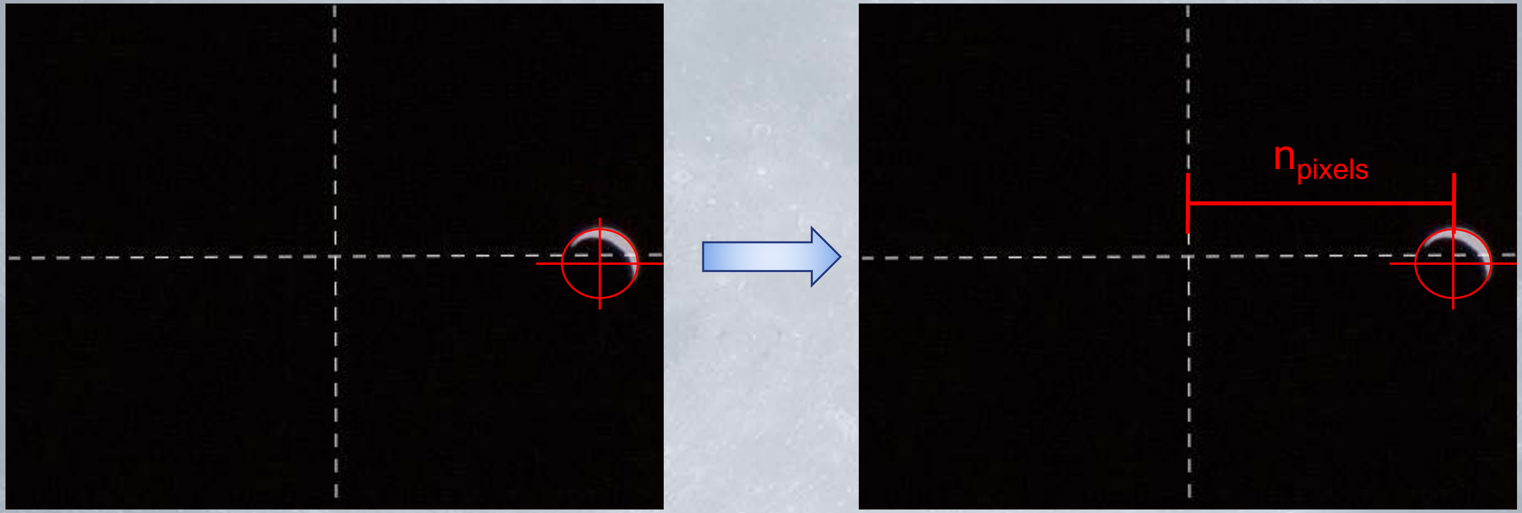


Known center of image



Identify center of body

Solution Generation



Measure number of pixels (n_{pixels}) between center of body and center of image

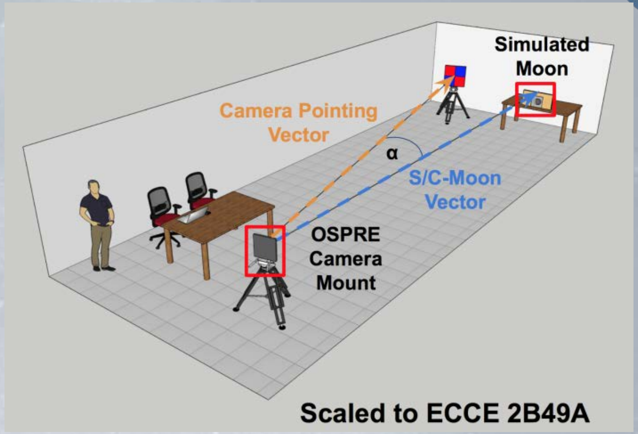
Solution Generation

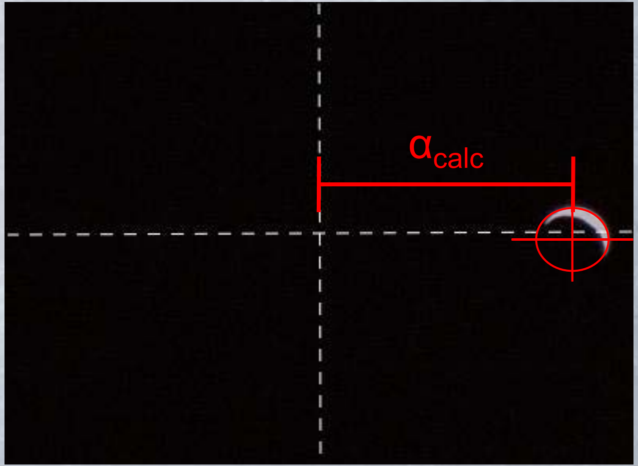
- Compute the angle α by dividing the number of pixels by the camera's degree-per-pixel value:

$$\alpha_{calc} = n_{pixels}(°/\text{pixel})$$

- Compare α_{meas} to α_{calc} to verify the accuracy of the test setup

- α_{calc} is used by navigation algorithms (along with the spacecraft quaternion) to compute a position vector





Test Results

SWAP Testing

Requirements Verification Matrix

Req ID	Requirement	Verification Method	Value	Pass/Fail
DR 2.6	Total mass of less than or equal to 800g	Measured assembly	37 g	Pass
DR 2.7	Dimensions of 5 x 5 x 1 cm	Measured assembly	5 x 5 x 1 cm	Pass
DR 2.1.1	Operate on 3.3, 5, and/or 12VDC	Demonstrated with DC supply	12 V	Pass
DR 2.1.2	Peak Current NGT 500 mA	Measured during operation	170mA	Pass
DR 2.1.3	Peak Power NGT 3 W	P = V x I	2.04 W	Pass

Performance Testing

Requirements Verification Matrix

Req ID	Requirement	Verification Method	Value	Pass/Fail
DR1.5	OSPRE shall calculate the Earth, spacecraft, Moon angle.	Analyze Test Data	-	Pass
DR1.5	OSPRE shall output the computed state vector update and error.		Covariance Matrix	Pass
DR1.2	OSPRE shall achieve less than 1000 km of positional accuracy.		585.904 km (max)	Pass
DR1.3	OSPRE shall achieve less than 250 m/s of velocity accuracy.		9.105 m/s (max)	Pass

Performance Testing

Initial Results

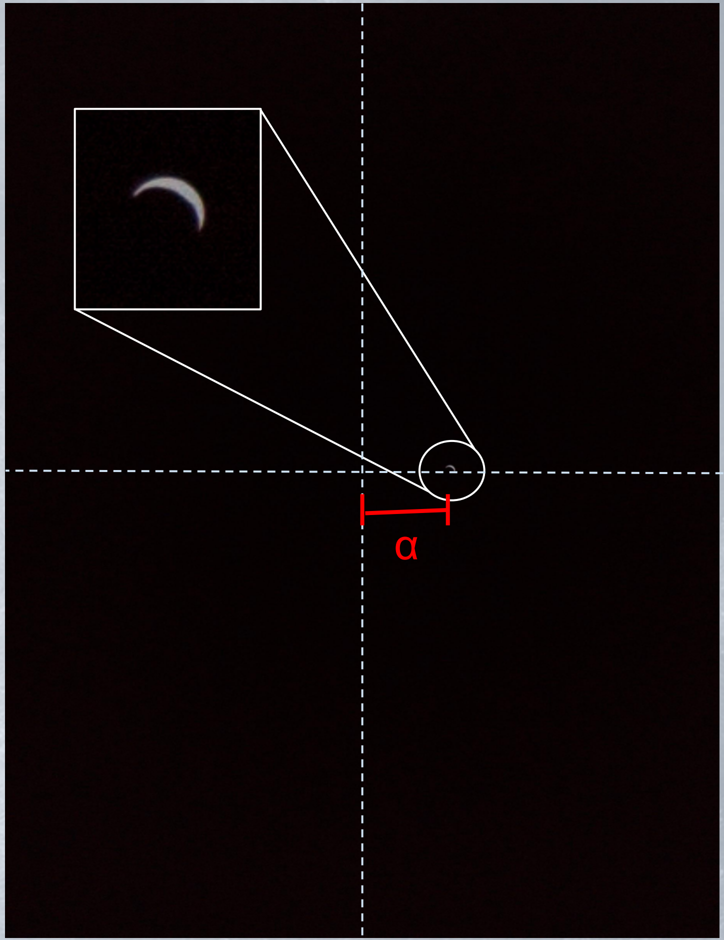
TEST ENVIRONMENT

$\alpha_{meas} = 6.4^o$

IMAGE PROCESSING

$\alpha_{calc} = 5.9^o$

-0.5º discrepancy
~30X greater than error model predicted (± 0.0156º)



Performance Testing
Diagnosis

Using a regression analysis three primary suspects were identified

TEST SETUP → Re-setup, measure, and collect data

MATHEMATICAL ERROR → Re-evaluate Computations

OPTICS → Test for Optical Distortion

Performance Testing
Field of View & Distortion Testing

22 Segments to Quantify Distortion

Portrait & Landscape Orientations Tested

12 Photos Taken at 2 Different Focus Lengths

*performed in the Senior Projects Lab

Performance Testing
Distortion Testing Results

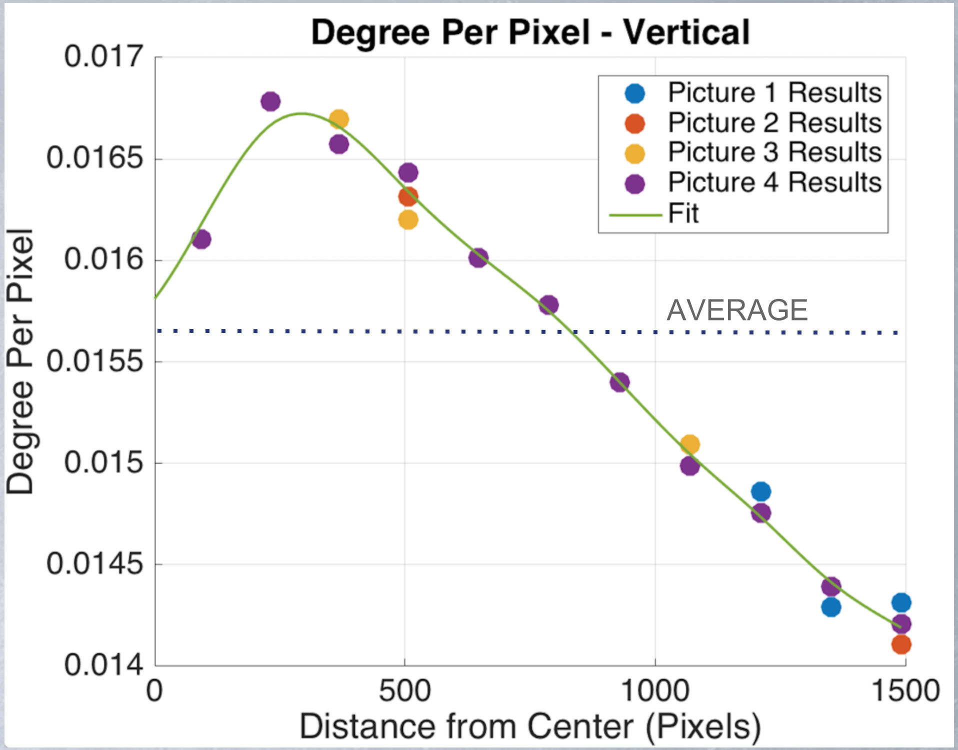
Spline fit utilized to create a trend in horizontal and vertical dimensions of sensor

Used curves to create sensor-wide distortion curve

RESULT

α_{ERROR} = - 0.012º

$\alpha_{TEST\ PREDICTION}$ = ± 0.0156º



Moon Phase Definitions

Full Moon

Small Crescent Moon

Half Moon

Tilted Crescent Moon

*Real images from test setup

Performance Testing

Results

- 4 different moon phases
- 40 images for each phase

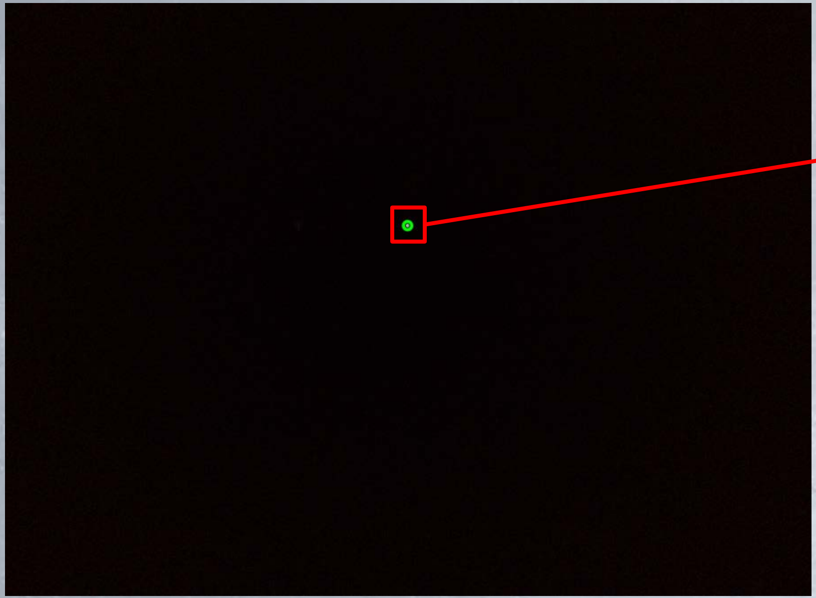
Actual test image, 4192 x 3104

Where’s the Moon?

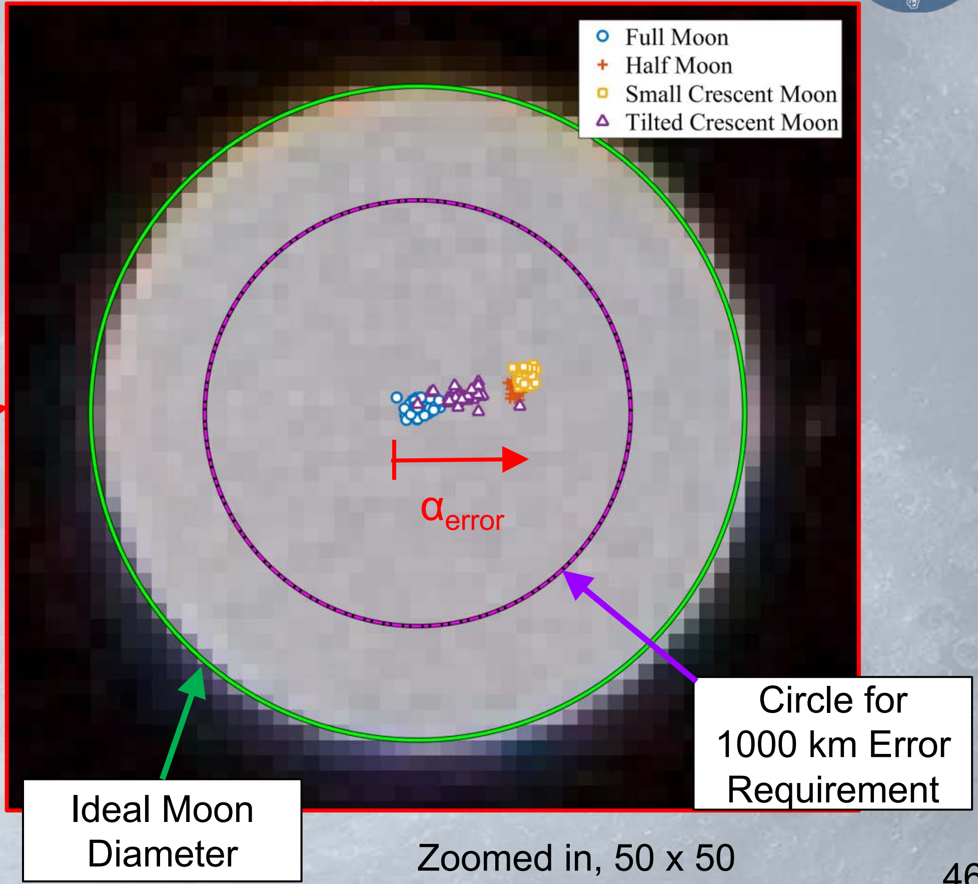
Performance Testing

Results

- 4 different moon phases
- 40 images for each phase



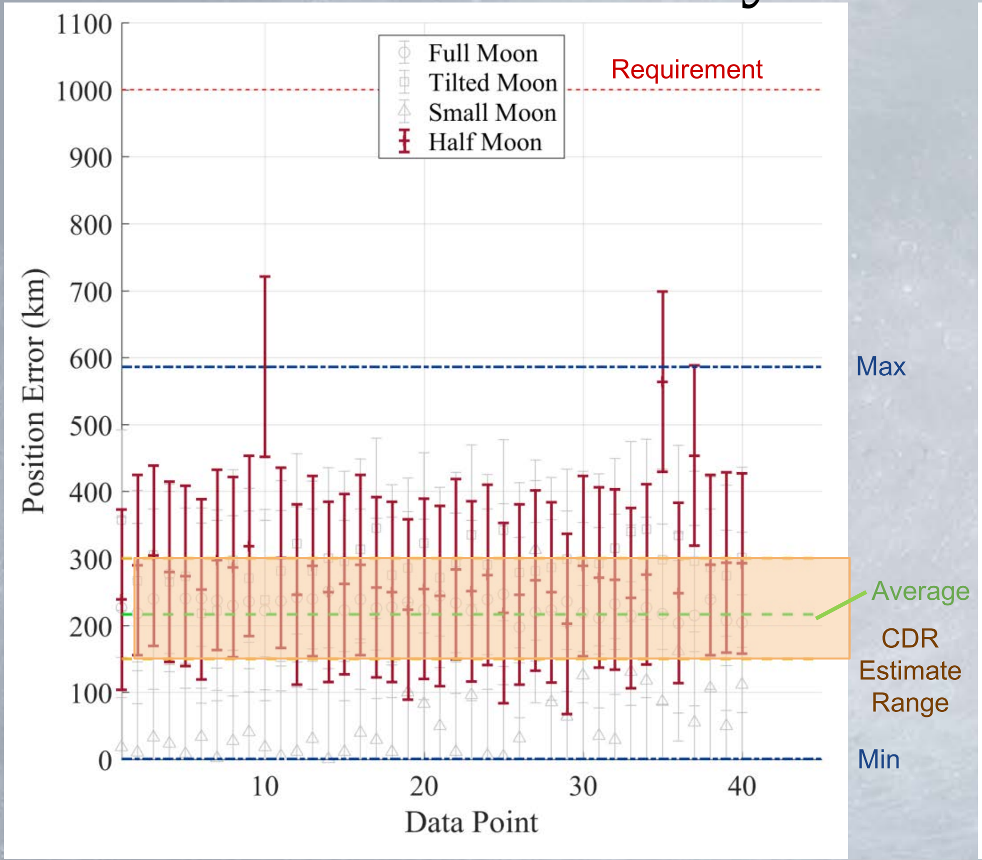
Actual test image, 4192 x 3104

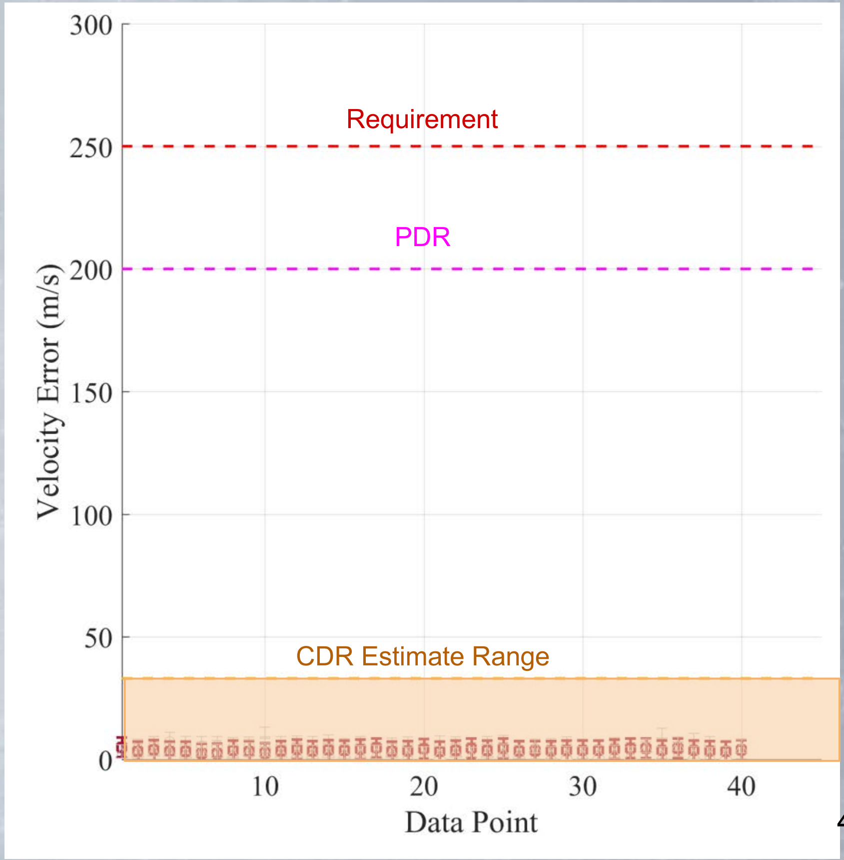


Zoomed in, 50 x 50

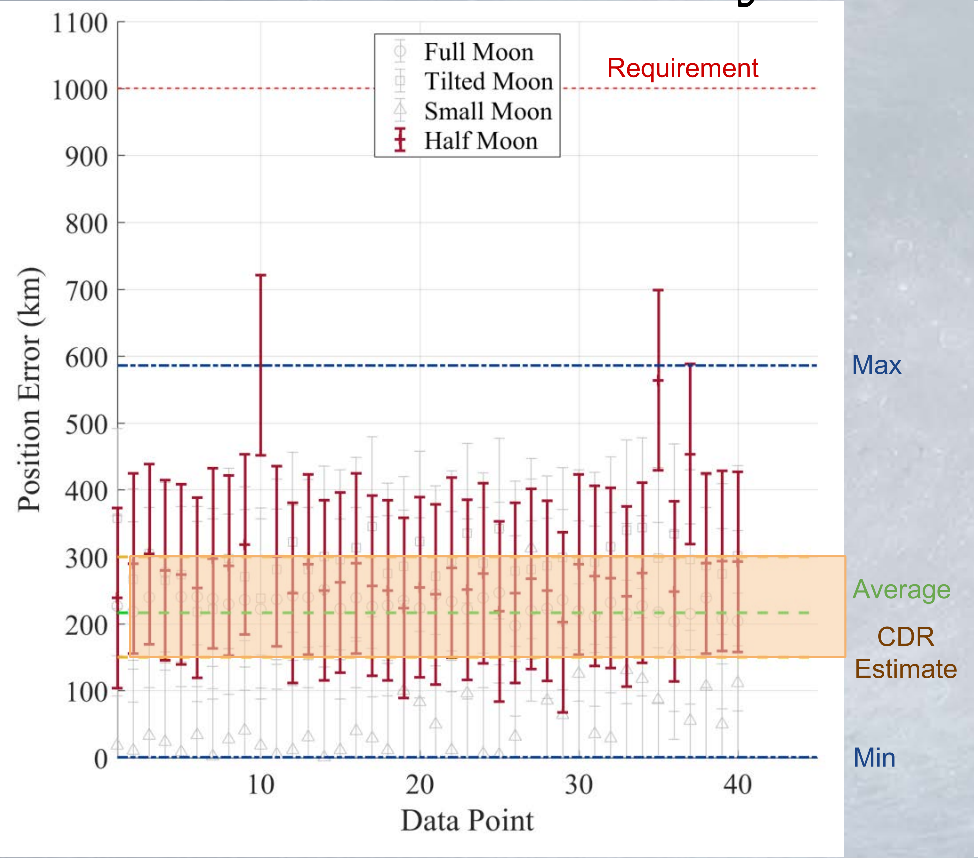
Performance Testing

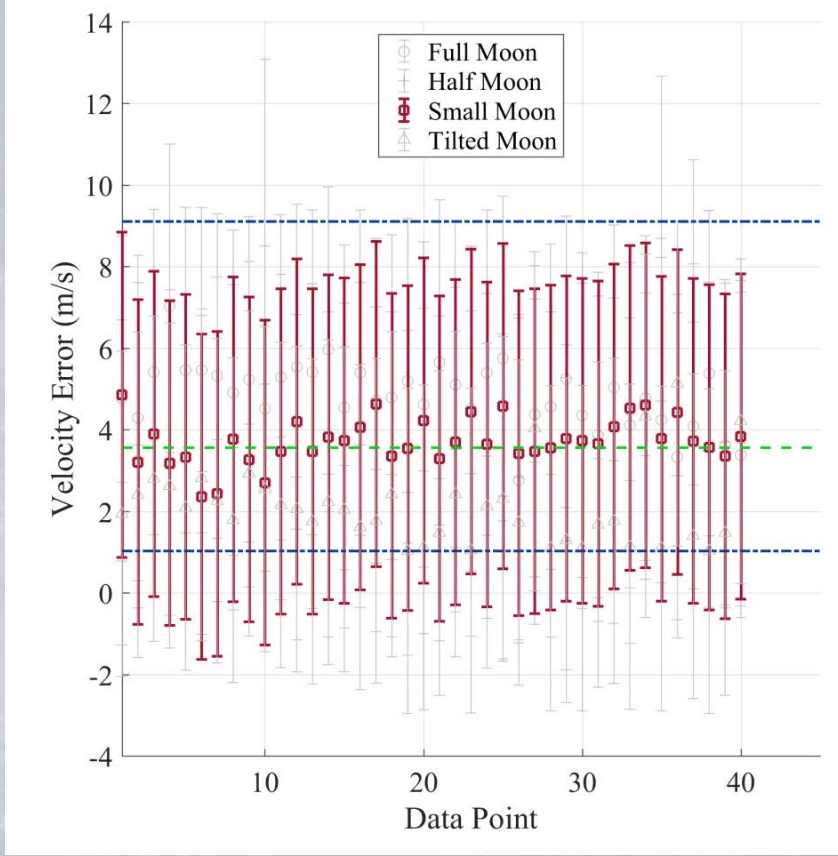
Position and Velocity Results





Performance Testing
Position and Velocity Results

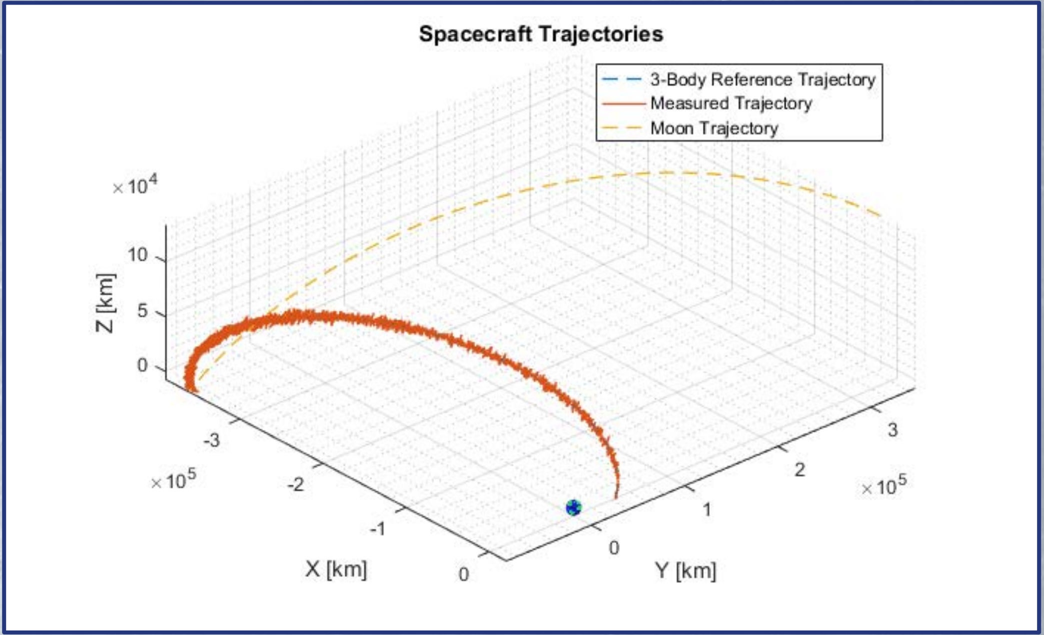




Model Overview

Looking at the entire mission trajectory…

- Created a 7-day lunar orbit in STK
- Assumed an average image processing error of 2 pixels (upper bound estimate)
- Generated position and velocity error estimates for the entire mission



Performance Testing
Software Model Improvement

SIMULATED DATA

Known Radius & Center

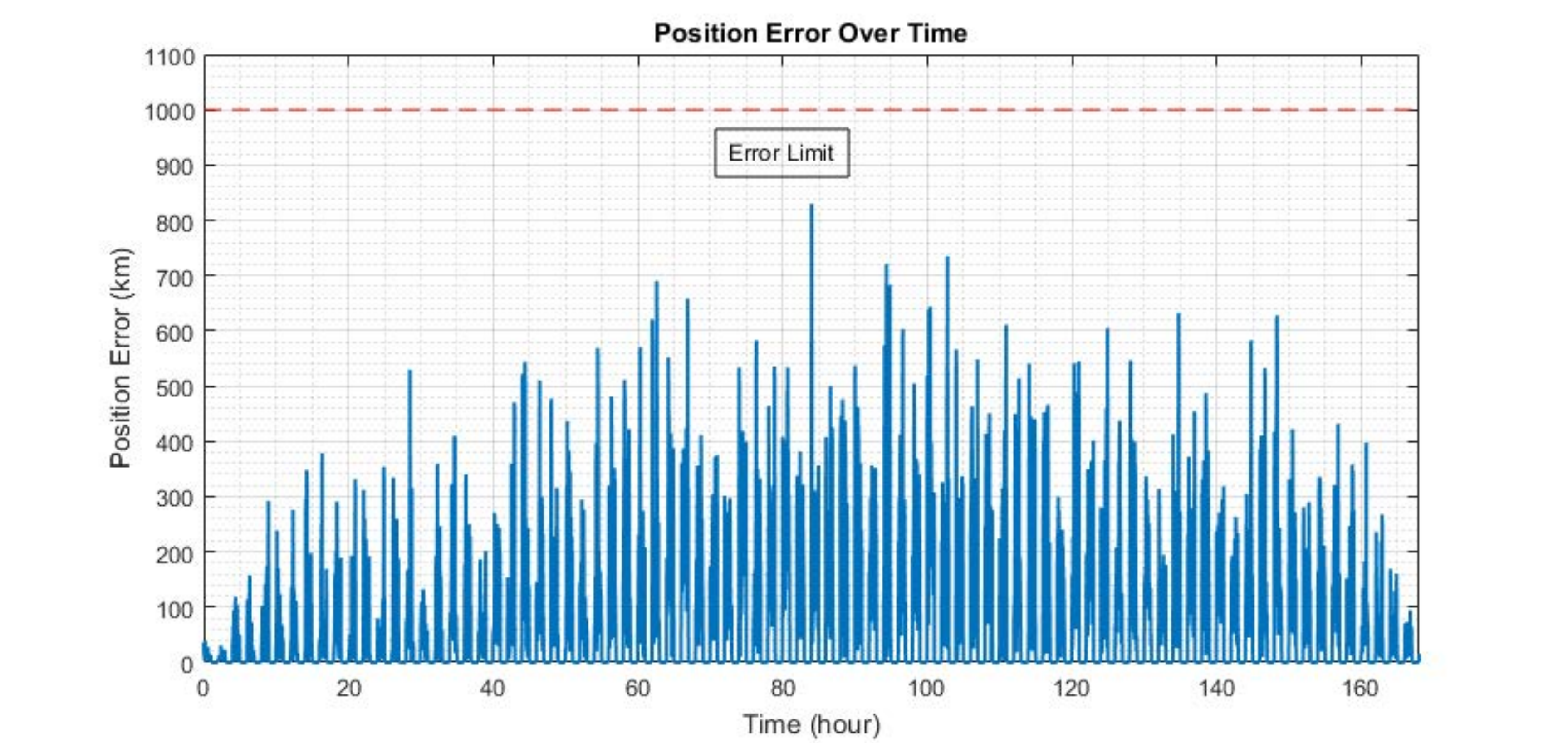
Realistic Textures, Lighting Conditions

1
Image Processing

2
Radius & Center Finding Error

3
Incorporate Error Trends Into Mission Simulation

Model Results



PIXEL ERROR - 2 pixels

Performance Testing
Software Model Improvement

TEST DATA

Sensor Performance Characteristics
Noise
Clarity
Dynamic Range
Consistency

Optics
Distortion
Field of View
Light Bleed
Focus

1
Image Processing

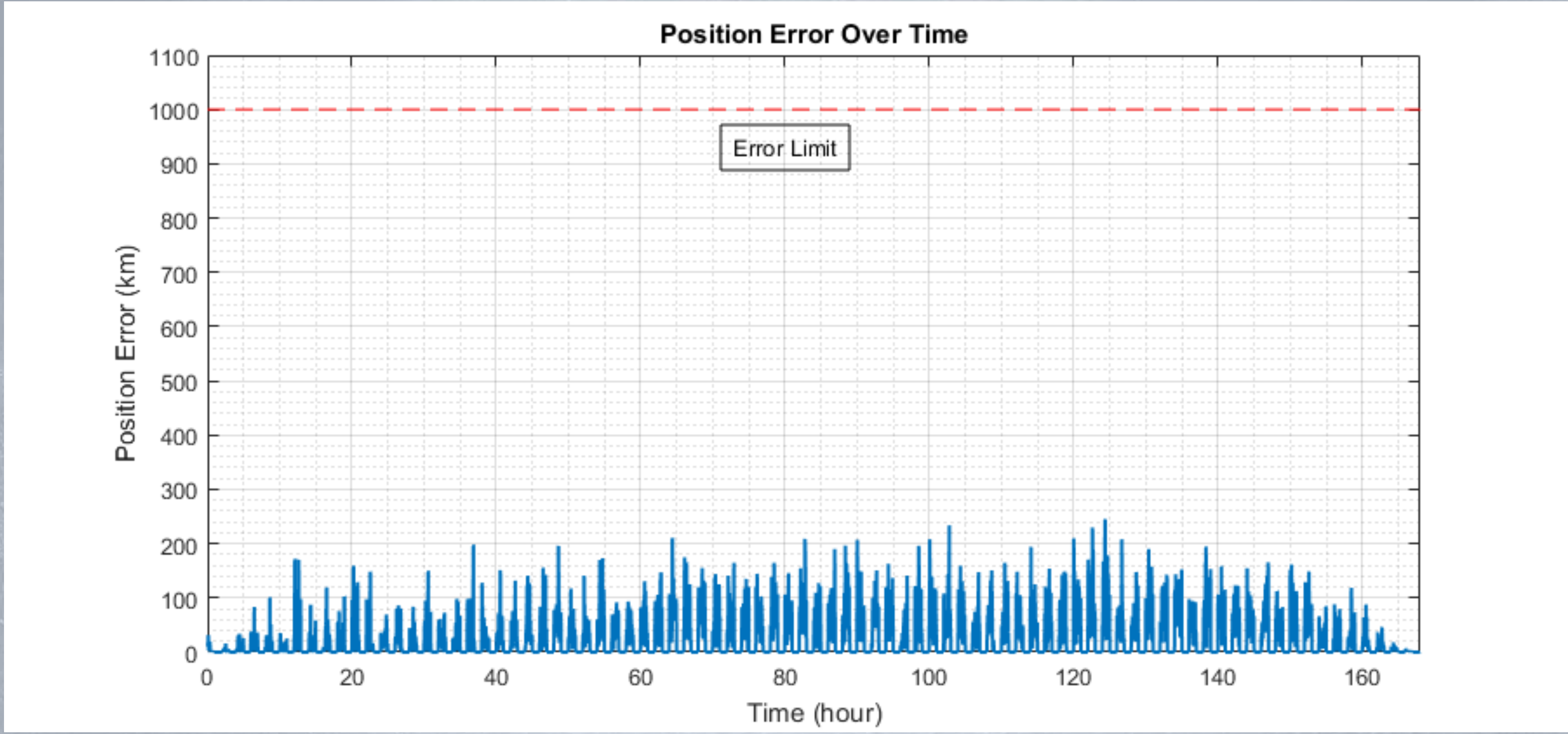
→

2
Radius & Center Finding Error

→

3
Incorporate Error Trends Into Mission Simulation

New Model Results



PIXEL ERROR - 1.14 pixels

Systems Engineering

Approach

Subsystem-Led Design and Development

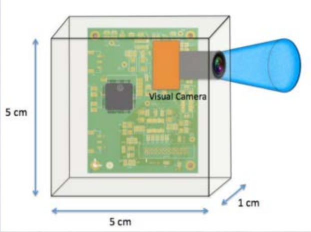
- High level of subsystem autonomy
- Design and Development decisions reviewed and okayed by Systems
- Independent nature of most subsystems and key design elements

Requirements-Driven

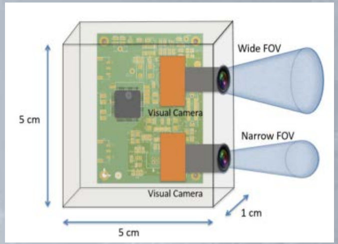
- When necessary to iterate design, ability to meet the requirements was foremost consideration in off-ramp selection

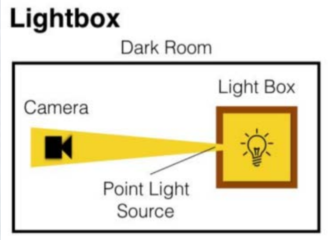
Trades

- IR Camera vs. Color Camera
  - Color cameras have much higher resolutions
- 1 camera vs. Multiple cameras
  - 1 camera is much less complex
  - Can meet requirements with 1 camera
- Kalman filter vs. Curve-fitting velocity
  - Kalman filter provided more accurate results & the uncertainties
- Lightbox vs. Projector vs. 3D model
  - Projector was limited by resolution
  - 3D model would be more difficult to manipulate

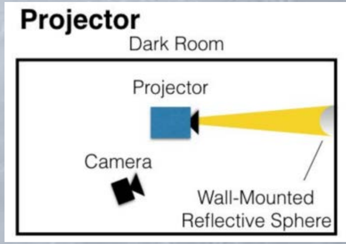


vs.





vs.



Requirements Flowdown

FR0.0 OSPRE shall provide relative navigation from an image sensor package for a Lockheed Martin CubeSat on a lunar trajectory.

FR1.0 OSPRE shall determine the state vector and state vector error of the simulated Spacecraft.

1.1 OSPRE shall use a method of angles-only navigation to determine the state vector of the simulated spacecraft.

1.2 OSPRE shall determine the position of the simulated spacecraft to within 1000 km of the true position.

1.3 OSPRE shall determine the velocity of the simulated spacecraft to within 250 m/s of the true velocity.

1.4 OSPRE shall determine the angle between the earth, the spacecraft, and the moon.

1.5 OSPRE shall determine validity of the solution.

Requirements Flowdown

FR2.0 OSPRE shall comply with all Lockheed Martin integration requirements in accordance with the "Customer Requirements Document" listed in Section 1.3, included below for Reference.

2.1 OSPRE shall comply with all Lockheed Martin electrical integration specifications.

2.2 OSPRE shall comply with all Lockheed Martin communication protocols.

2.3 OSPRE shall be controlled with a ZedBoard development board.

2.4 OSPRE shall output telemetry for the simulated spacecraft.

2.5 OSPRE shall acquire image data for no more than one hour continuously and wait at least one hour between these acquisition periods.

Risks

CDR Risks

Likelihood						
	10					
	8					
	6			3	1	
	4		8	5,6	4	2
	2		14		9,10,11, 12,13	7
		2	4	6	8	10
		Severity				

Risks

1-Testing Takes Too Long

Severity decreased by collecting all necessary testing data in one test

2-Testing Error Too Large

Severity decreased with increased accuracy of position calculation and with manual calibration; Likelihood increased due to human error in test

CDR Risks

Likelihood \ Severity	2	4	6	8	10
10					
8					
6			1,3	2	
4		8	5,6	4	
2		14		9,10,11, 12,13	7

Project Management

Approach

Customer
- ➢ Dr. Jim Russell

Advisor
- ➢ Dr. Jay McMahon

Project Management:
- ➢ PM: Paige Arthur
- ➢ Systems: Ryan Cutter
- ➢ Financial: Anthony Torres

Systems:
- ➢ Mechanical: Zach Folger
- ➢ Software:
  - Architecture: Seth Zegelstein
  - Navigation: Cameron Maywood
  - Image Processing: Anthony Torres
- ➢ Remote Sensing: Dylan Richards
- ➢ Electrical: Michael Ricciardi

Testing
- ➢ Test: David Walden

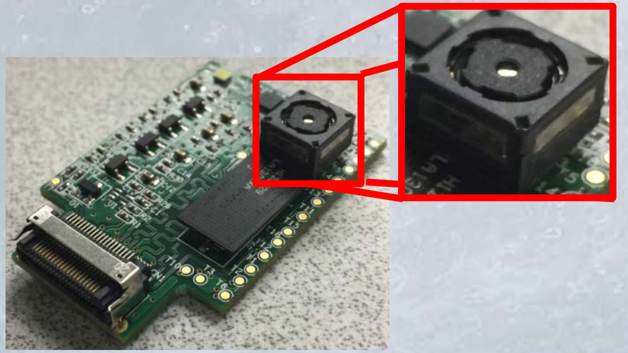
- Team meetings twice a week
  - Status updates
  - Determine action items
- Group communication with messaging app
  - Real-time communication
- Gantt Chart to assign and track progress
  - Effective in visually observing how tasks were progressing
  - Showed us when to take camera off-ramp
- Delegate work to other system leads when needed
  - Ensure everyone has something to do
  - Mechanical and remote sensing leads helped with test setup

Lessons Learned

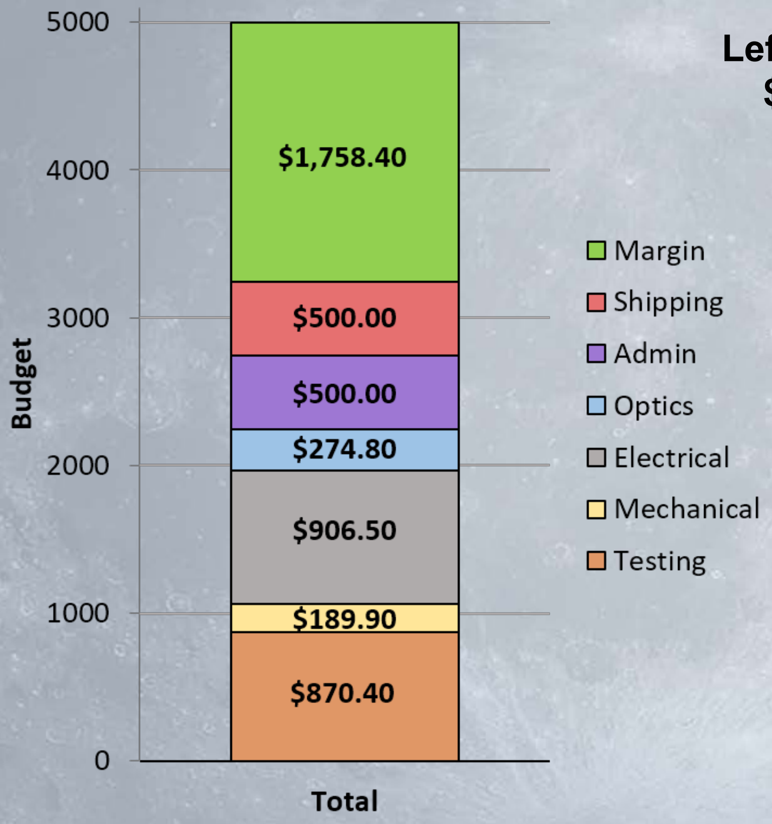
- Time for testing
  - Allow for more time to test and work out problems in test setup
  - Did not originally account for camera lens distortion, skewed data
- Hardware selection
  - Choose hardware that comes with supporting software
  - Imaging sensor originally chosen would not work with OSPRE system
- Component Design
  - Don’t underestimate challenge of component design
  - Carrier board took multiple iterations to drive down cost while maintaining small size and functionality
    - Reduce number of layers
    - Eliminate blind vias

Next Steps

- Develop or find camera driver for imaging sensor
- Develop or find supporting software for SPI communication with Zedboard
- Develop automatic closed loop control of imaging sensor

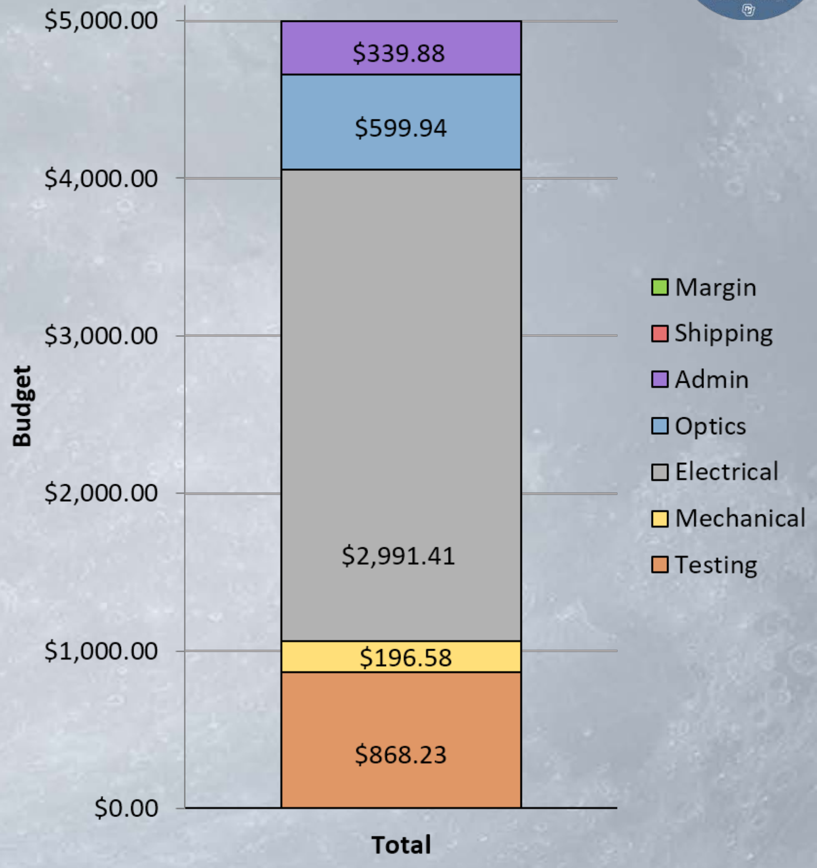


Budget



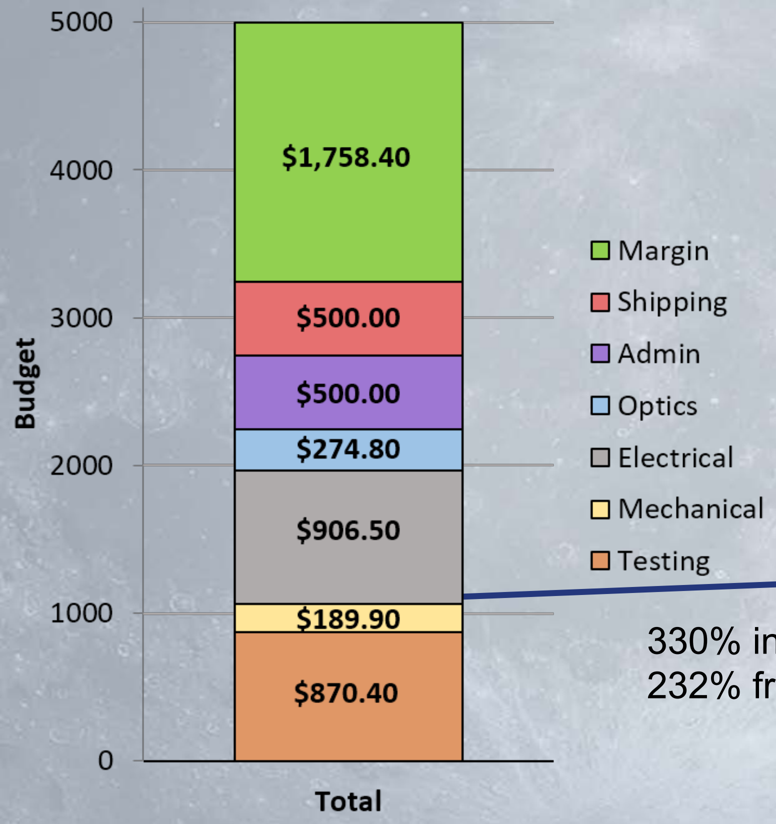
CDR Budget

Left Over:
$3.96



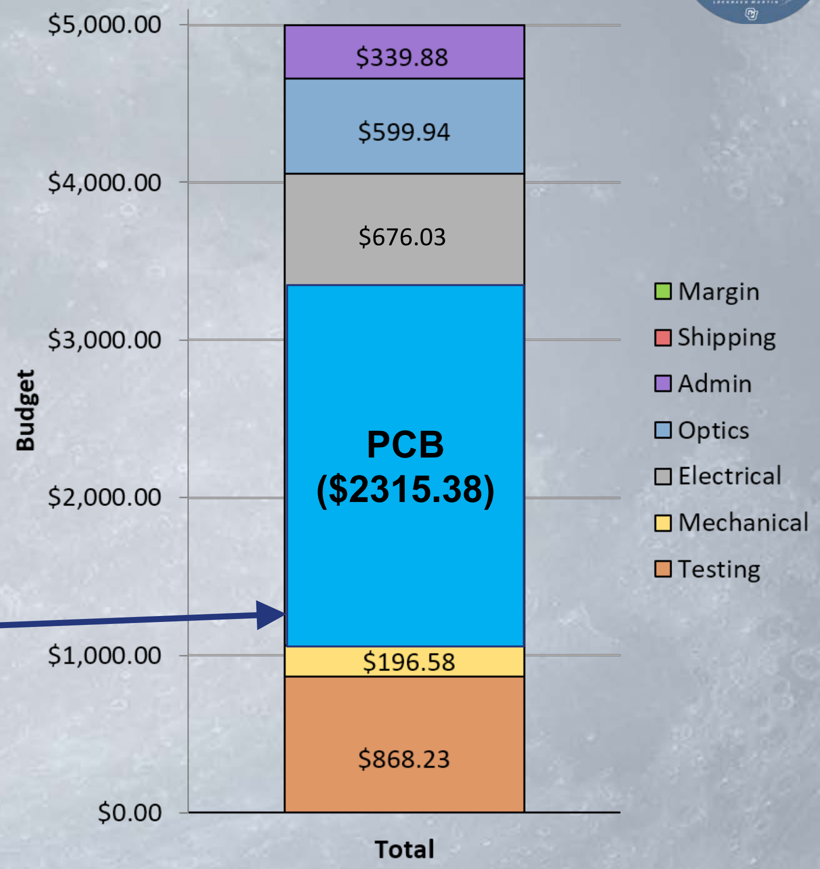
Current Budget

Budget



CDR Budget

330% increase
232% from PCB



Current Budget

Industry Cost

Assumptions:

- Salary of $65,000 for 2080 hours of work
- Overhead cost is 200% of cost of labor

Team Average per Week	146.70 hours
Total Hours	3667.50 hours
Labor Cost:	$114,609.38
Overhead Cost	$229.218.76
Materials Cost	$4996.04
Total Cost	$348,824.18

Thank You

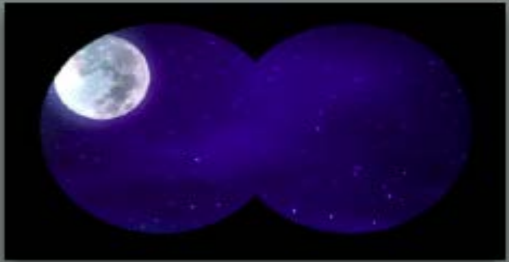
Acknowledgments

Dr. Jay McMahon	University of Colorado
Dr. James Russell	Lockheed Martin
Dr. James Nabity	University of Colorado
Dale Howell	Lockheed Martin
Matt Rhode	University of Colorado
Evan Sneath	Lockheed Martin
Trudy Schwartz	University of Colorado
Denver Powell	Lockheed Martin
Dr. Samuel Siewert	Embry-Riddle Aeronautical University

SARLACC PIT

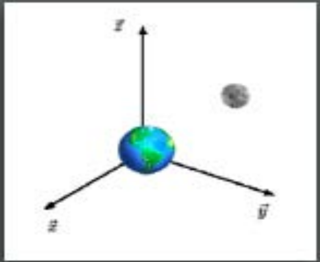
Optical Relative Navigation

1
WHAT I SEE



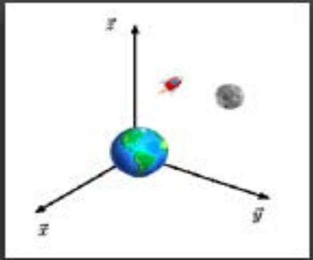
2
WHAT I KNOW

Location of the Earth & Moon

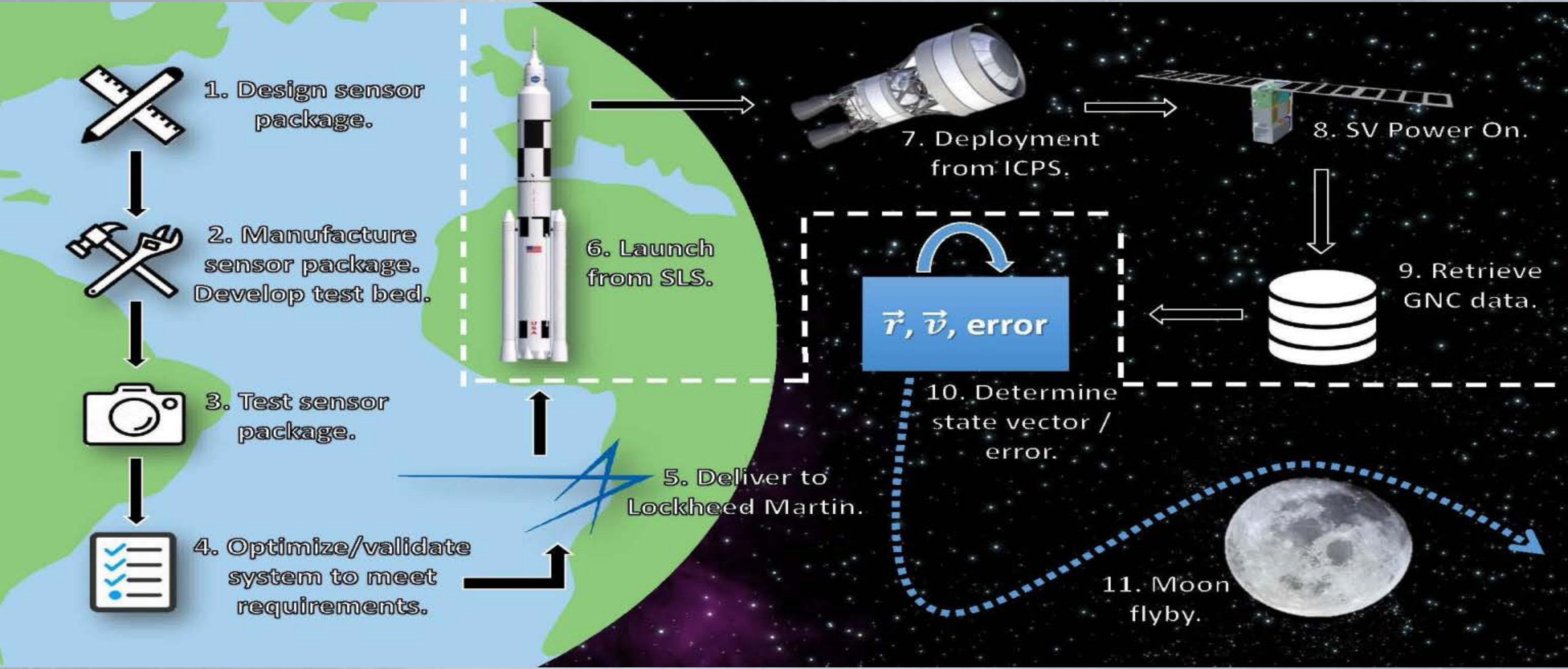


3
WHAT I CAN FIND OUT

Spacecraft Location



Mission CON-OPS



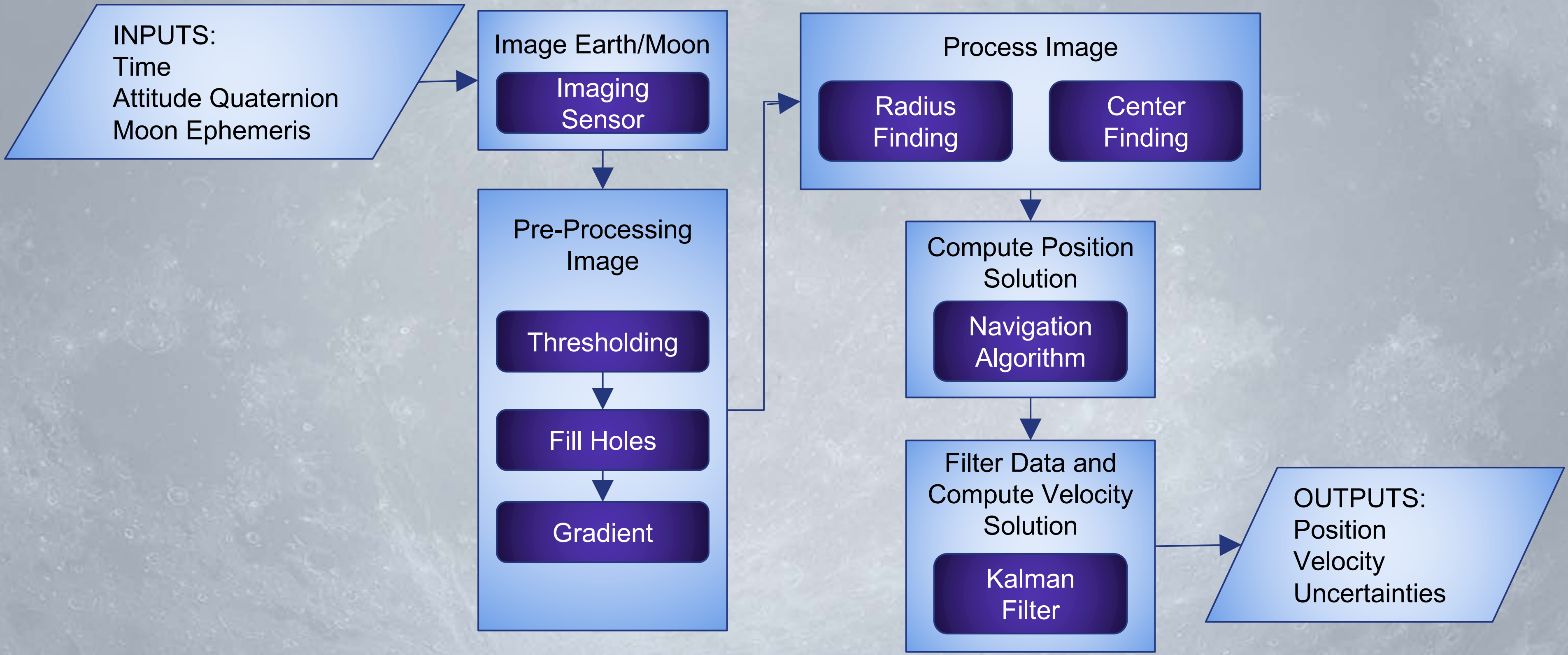
Requirements Flowdown

FR 0.0 -	Provide relative navigation from an image sensor package on a lunar trajectory.
FR 1.0 -	Provide state vector within desired error bounds: • Velocity: ± 250 m/s Position: ±1000 km
FR 2.0 -	Meet dimensional requirements: • 50 x 50 x 10 mm
FR 2.1 -	Meet electrical requirements: • 3.3, 5, or 12VDC, 0.5A (max), 3W (max)
FR 2.2 -	Meet interfacing requirements: • SPI or I^2C

Levels of Success

	Level 1	Level 2	Level 3
Data Processing	OSPRE shall output a state vector for full Moon and Earth disks and shall gather data for no longer than an hour at a time.	OSPRE shall estimate the error of the state vector.	OSPRE shall provide the state vector error within an accuracy of 1000km and 250m/s and shall function for all Moon and Earth phases.
Electrical	OSPRE shall operate nominally provided 3.3V, 5V, or 12V electrical power, and interface with the ZedBoard and image sensor(s) using SPI, I^2C, or Cameralink.	OSPRE shall have a peak current of no more than 500mA and maximum power draw of no greater than 3W.	The system shall provide voltage sense and current sense telemetry.
Structural	OSPRE's mass shall not exceed 0.8kg.	OSPRE's dimensions shall not exceed 5cm x 5cm x 1cm.	-
Testing	OSPRE's testing shall include testing the accuracy of the algorithm. OSPRE shall create a software test capable of quantifying the navigation software's error.	OSPRE's testing shall include a physical simulation. OSPRE shall create an Earth-Moon testbed that quantifies the error of the navigation hardware.	OSPRE's testing shall incorporate hardware and software testing simultaneously. The system shall compute the state vector **autonomously** in a test environment.

Functional Flow Diagram



Lessons Learned

- Time for testing
  - Allow for more time to test and work out problems in test setup
  - Did not originally account for camera lens distortion, skewed data
- Hardware selection
  - Choose hardware that comes with supporting software
  - Imaging sensor originally chosen would not work with OSPRE system
- Scheduling
  - Make more effort to stick to schedule
  - Optimize number of hours spent in meetings each week
    - Too much → not enough time to work
    - Too little → don't know what to work on
  - Suffered schedule slip near end of project

Risk #	Failure Mode	Cause(s)	Occurrence	Effects	Severity	Score
1	Testing takes too long	Precise measurement and set up for only 1 data point	(40-60%) **6**	Can't test the desired amount to prove success	Significant **8**	48
2	Testing introduces too much error	Machining	(20-40%) **4**	Impossible to tell if within requirements -> success level 2	Catastrophic **10**	40
		Measuring	(20-40%) **4**			
3	SOM can't interface w/ image sensor	Camera drivers	(40-60%) **6**	Redesign	Concerning **6**	36
		Hardware	(20-40%) **2**			
4	SOM can't interface with ZedBoard	Hardware	(20-40%) **4**	Redesign	Significant **8**	32
		Software	(0-20%) **2**			

5	Bad image (hardware effects)	Too much blur	(20-40%) **4**	Requirement failure (accuracy)	Minimal **4**	24
		Too much noise	(20-40%) **4**	Harder on Navigation and processing	Concerning **6**	
		Improper exposure	(20-40%) **4**			
6	Image processing produces wrong centers	Insufficiently robust processing algorithm(s)	(20-40%) **4**	Requirement failure (error)	Minimal **4**	24
				Harder on Navigation and processing	Concerning **6**	
7	Use of testing room/facility falls through	Room owners change their minds	(0-20%) **2**	Have to find new facility	Catastrophic **10**	20
8	Fail to meet accuracy requirements	Sensor	(20-40%) **4**	Requirement failure (accuracy)	Minimal **4**	16
		Processing				
		Navigation				

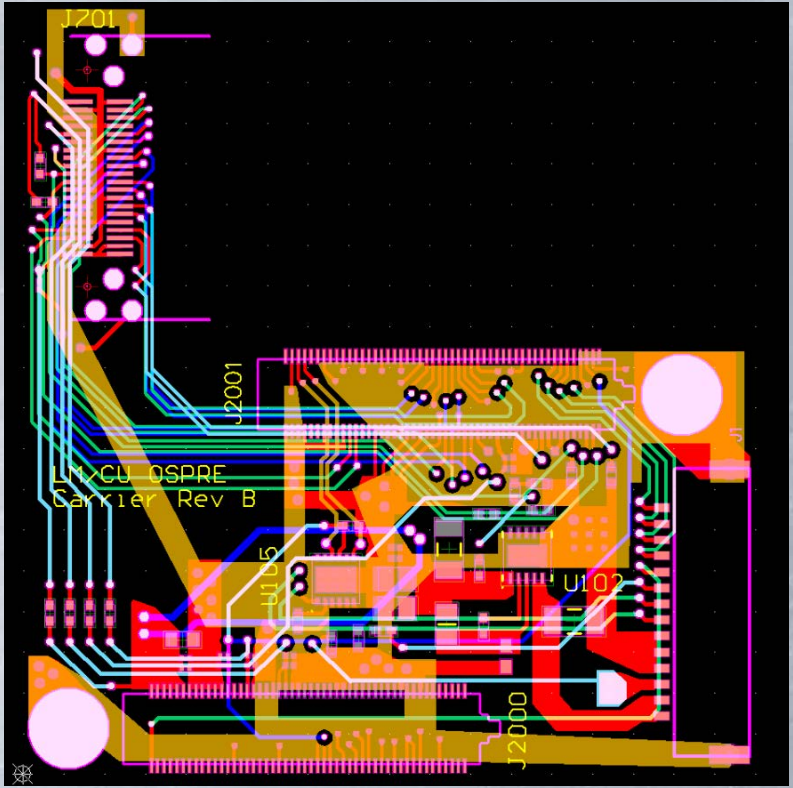
9	Can't report error in position and velocity	No working Kalman filter (or other method of reporting error)	(0-20%) **2**	Requirement failure (system outputs)	Significant **8**	16
10	Data on either zedboard or SOM is insufficient	Need to save lots of data (picture or otherwise)	(0-20%) **2**	Integrate more data storage	Concerning **6**	16
				Change algorithms	Significant **8**	
11	Draw too much power	Image sensor	(0-20%) **2**	Redesign	Significant **8**	16
		SOM	(0-20%) **2**	Requirement Failure (electrical)	Concerning **6**	

12	No way to test velocity	Measuring actual velocity in test	(0-20%) **2**	Impossible to tell if within requirements -> success level 2	Significant **8**	16
13	Go over budget	Replacing parts	(0-20%) **2**	Scramble for money	Significant **8**	16
		Unaccounted for purchases	(0-20%) **2**			
14	Fail volume requirements	Image sensor too big	(0-20%) **2**	Requirement failure (volume)	Minimal **4**	8

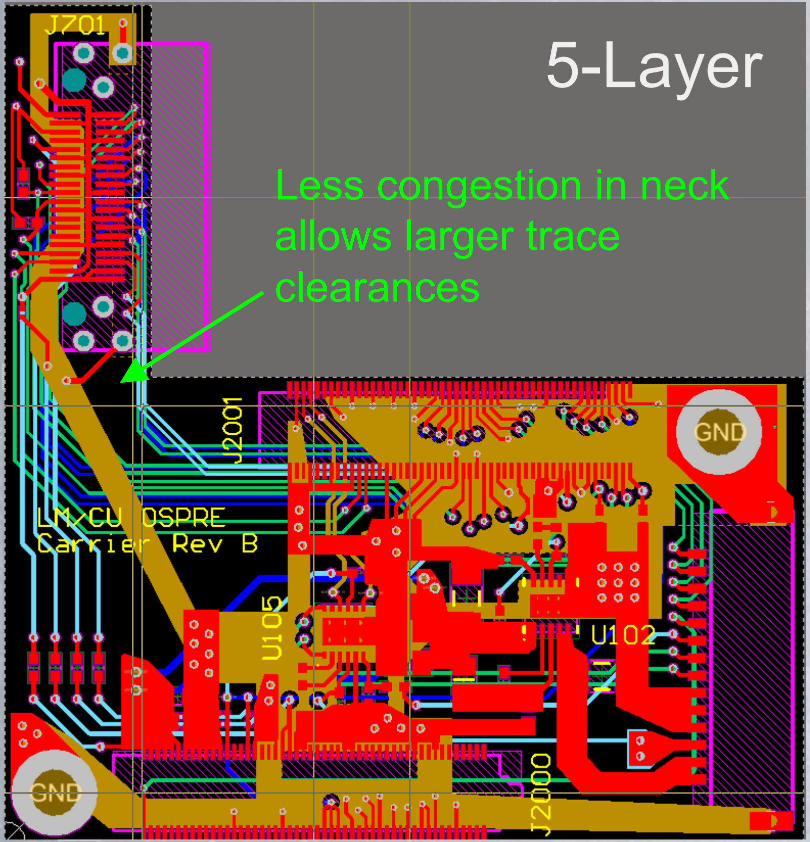
ELECTRONICS

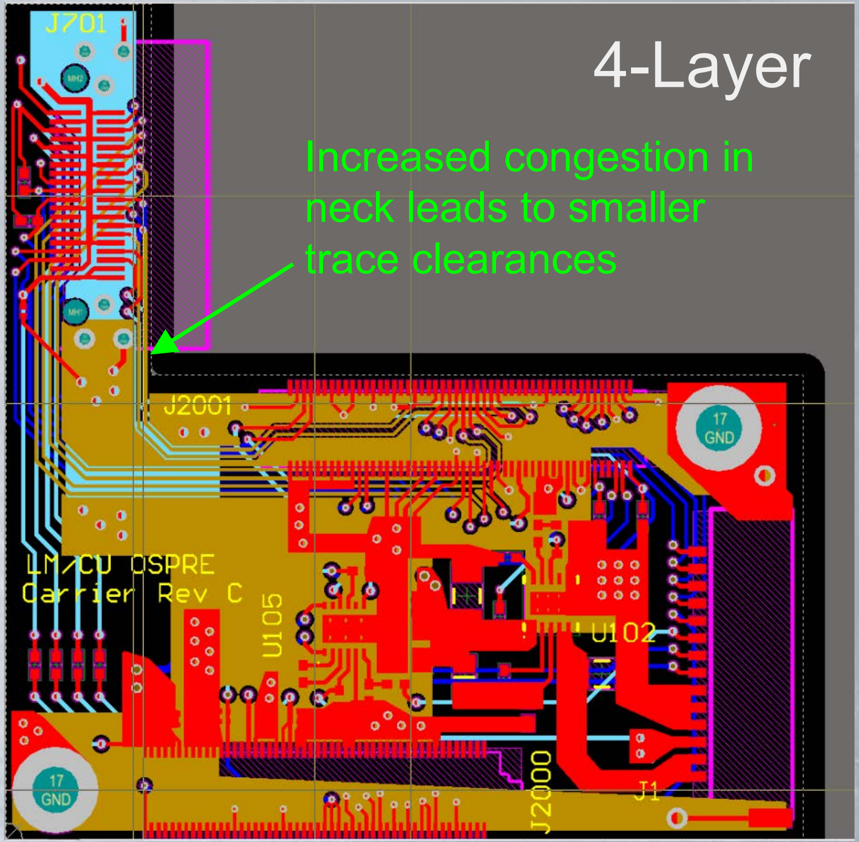
Carrier Board

- Driven by volume constraint
- 50 x 46 x 5 mm
- Iterated design numerous times to drive down cost while maintaining small size



Carrier Board Revision Tradeoff Example

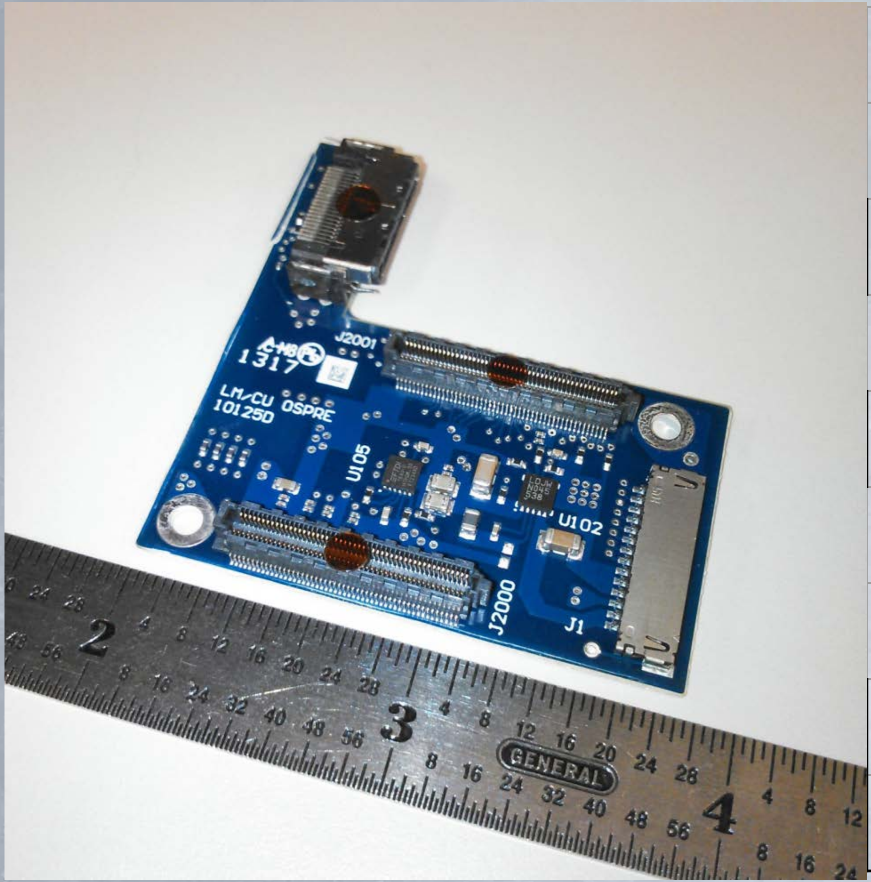




OSPRE Navigation Package

Measured SWAP Parameters	
Mass	37 g
Dimensions	5 x 5 x 1 cm
Supply Voltage	12 VDC
Supply Current, Peak (during image processing)	170 mA
Supply Power, Peak	2.04 W

OSPRE Carrier Board

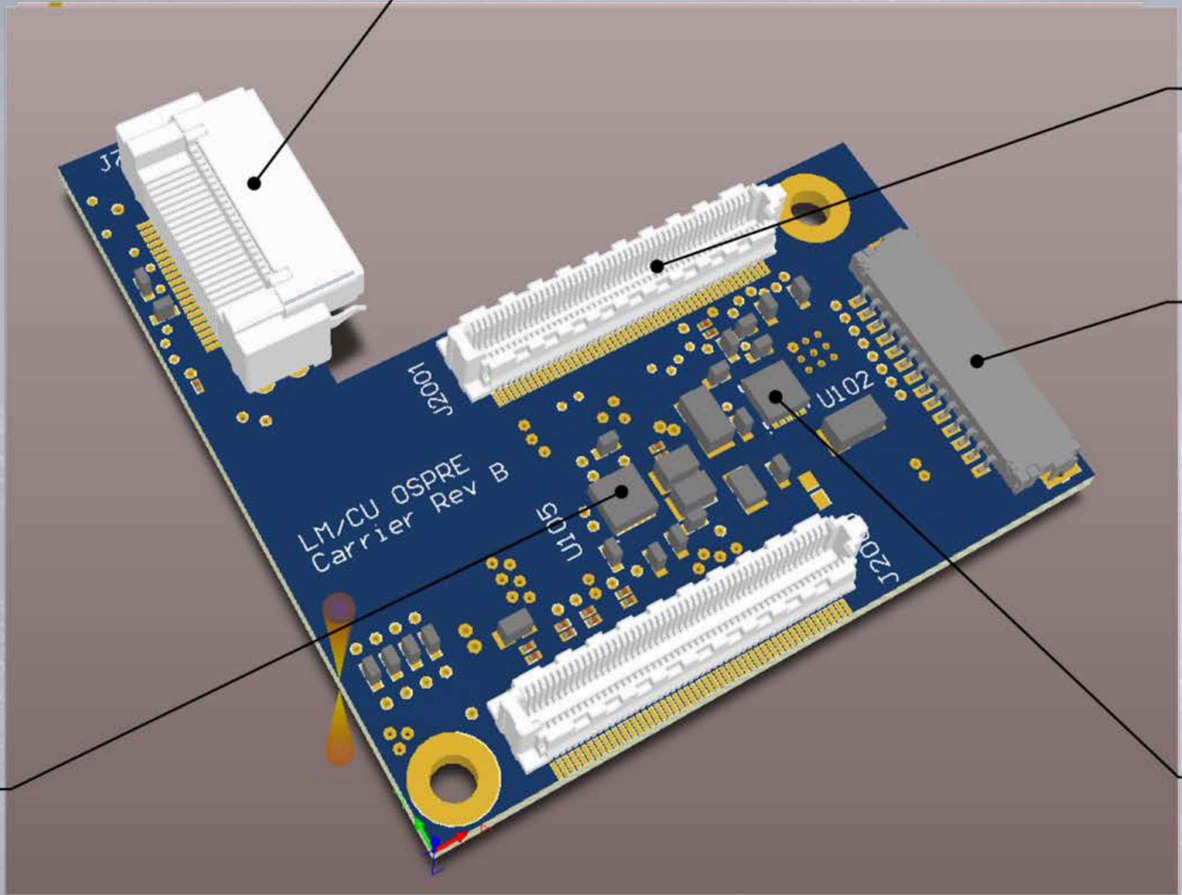


IPC Class 2-A600	
Components	45
Dimensions	4.8 x 4.6 cm
Material	FR4
Thickness	31 mil
Layers	4
Trace Width/Space	6 mil min.
Manufacturer	Advanced Circuits
End Cost	$2300

Camera Module Connector
(Samtek LSHM RH)

SOM
Connectors (2)
(Samtek SS4)

External
Connector
(Hirose DF19)



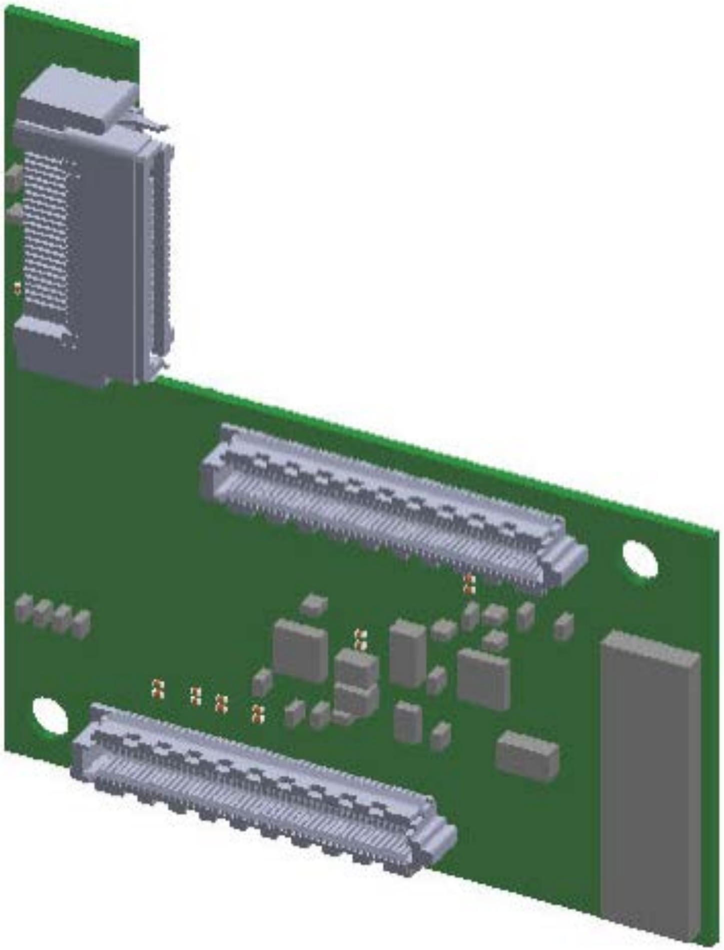
UART-USB
Interface
(FTDI FT234XD)

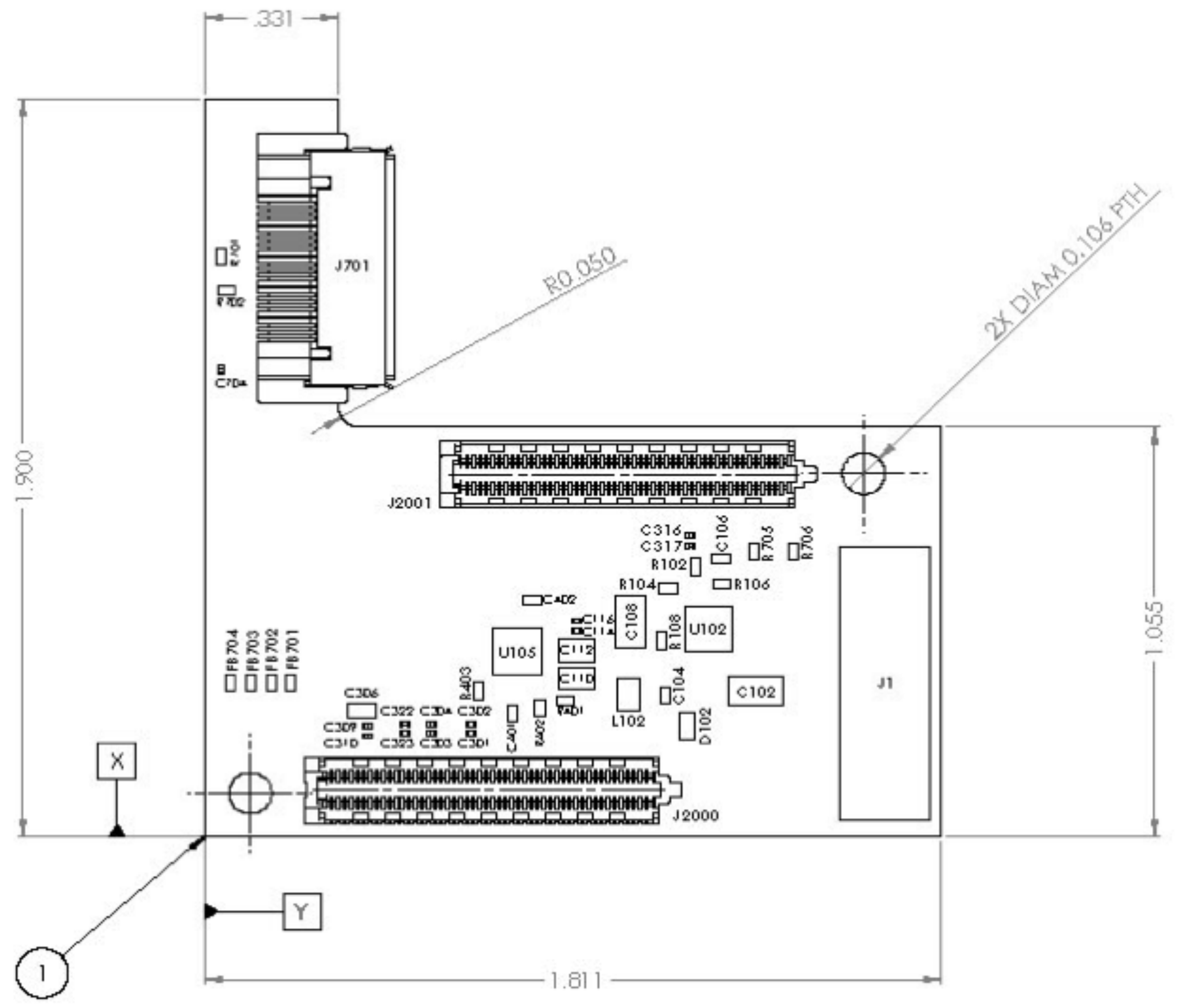
12 to 3.7 Volt
Regulation
(LT1913)

Carrier Board Specifications

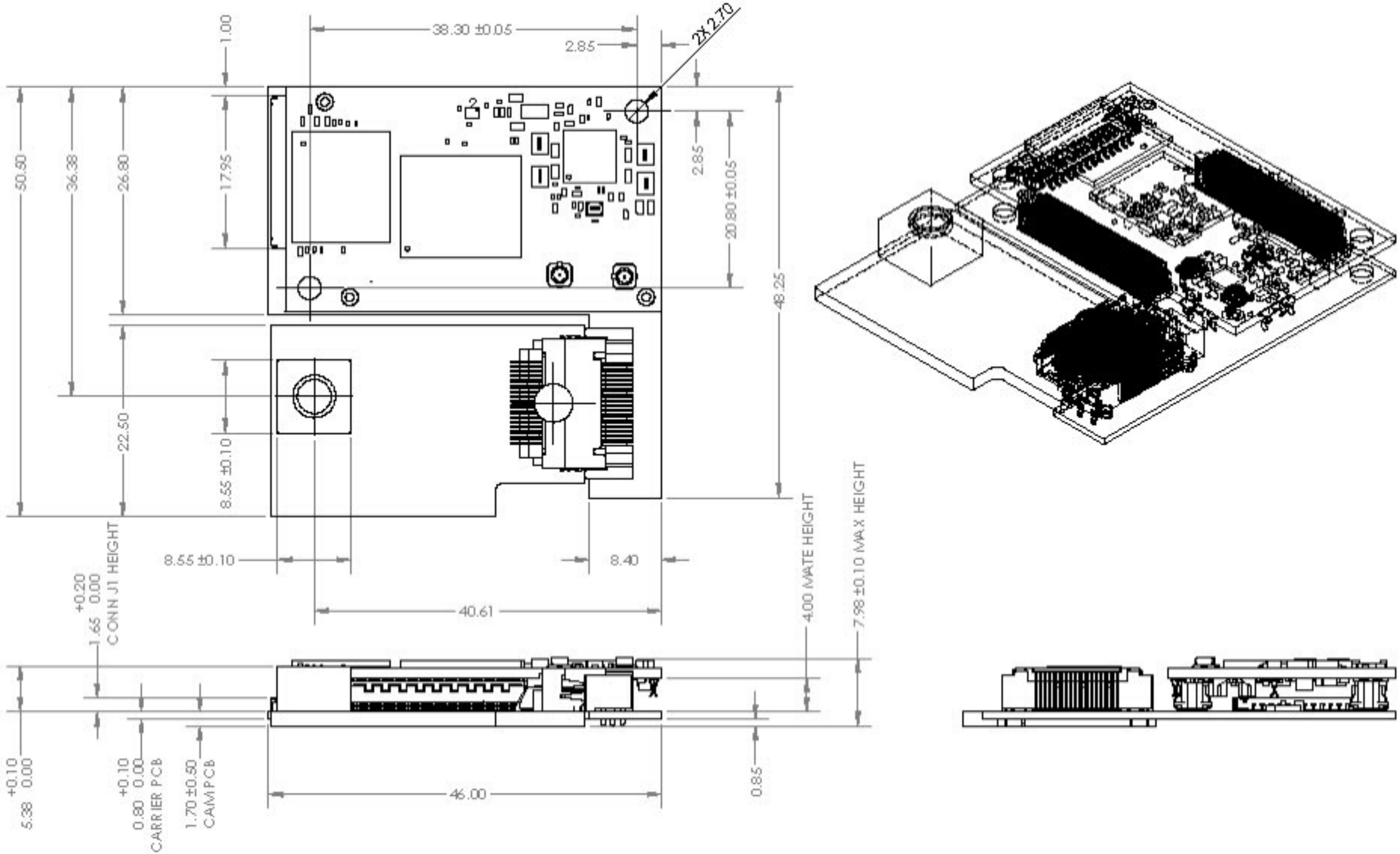
Board Specifications

Material Type:	FR4	Material Thickness:	0.031	Number of Layers:	4
First Dimension:	1.861	Second Dimension:	1.949	Finish Plating:	LFSolder
First Array Dimension:	2.861	Second Array Dimension:	2.949	Array Up:	1
Copper Outers:	1.0	Copper Inners:	1	Smallest Hole Size:	0.008
Top SMD Pads:	356	Bottom SMD Pads:	0	SMD Pitch:	0.016
Solder Mask Sides:	2	Solder Mask Type:	LPI	Solder Mask Color:	Blue
Silkscreen Sides:	Top Side	Silkscreen Color:	White	CNC Route Points:	4
Trace width/Space:	0.006	Tab Route:	No	Scoring:	Yes
Gold Fingers:	None	Plated Slots:	No	Plated Edges:	No
Counter Sinks:	No	Counter Bores:	No	Dielectric:	No
Impedance:	No	ITAR:	False	Certification:	IPC Class 2-A600
Blind/Buried Vias:	None	Micro Vias:	None	ViaInPad:	None





.331
1.900
1.055
1.811
R0.050
2X DIAM 0.106 PTH
J701
J2001
J2000
J1
U105
U102
C102
L102
X
Y
1



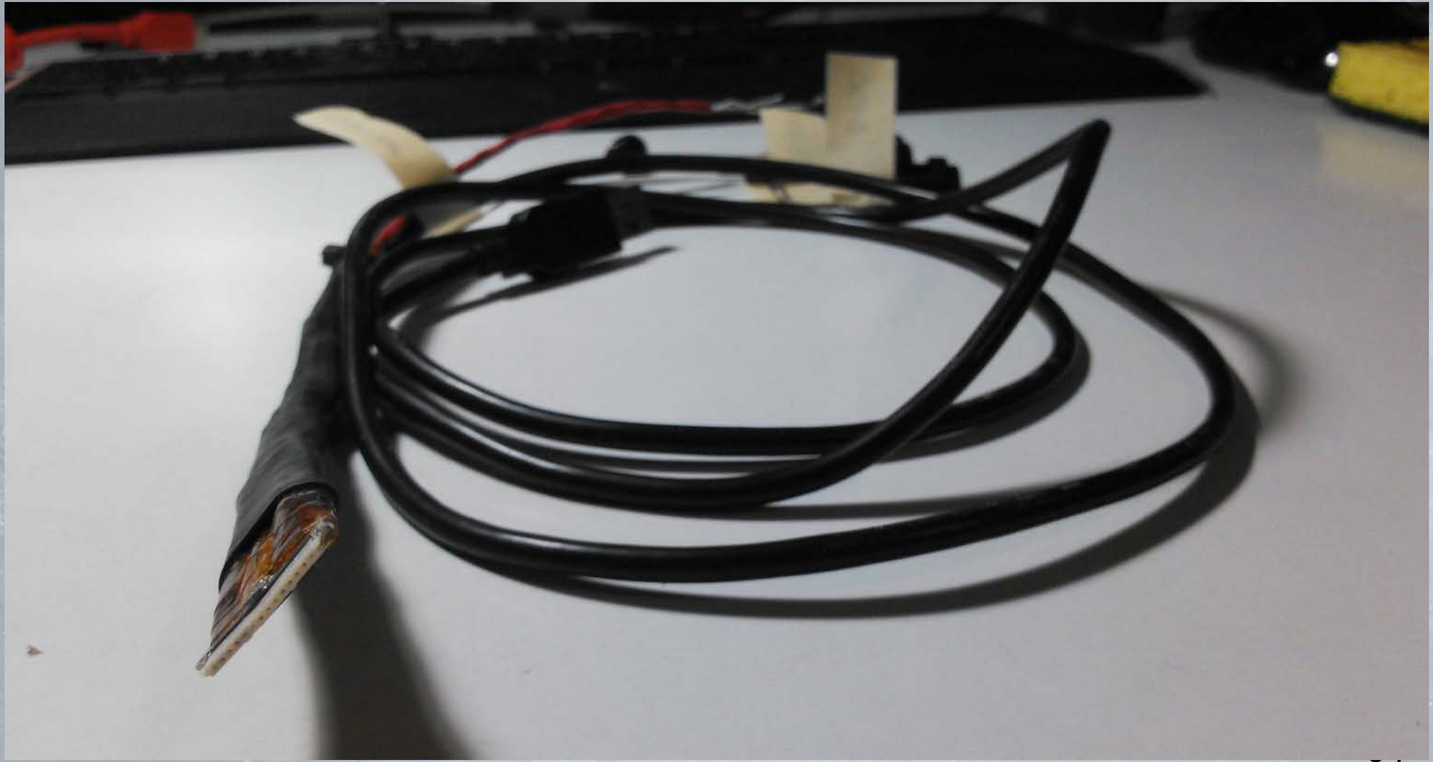
38.30 ±0.05
2.85
2X 2.70
1.00
50.50
36.38
26.80
17.95
2.85
20.80 ±0.05
48.25
22.50
8.55 ±0.10
8.55 ±0.10
8.40
40.61
+0.20
1.65 0.00
CONN J1 HEIGHT
4.00 MATE HEIGHT
7.98 ±0.10 MAX HEIGHT
+0.10
5.38 0.00
+0.10
0.80 0.00
CARRIER PCB
1.70 ±0.50
CAMPCB
0.85
46.00

OSPRE ICD, External Connector

CONNECTOR PARNO		Hirose DF19G-14P-1H(54)	J1		
REFDES	**CONTACT**	**SIGNAL NAME**	**SOM ITFC**	**DESTINATION**	**NOTE**
J1	1	12VDC		To Bench PS	
J1	2	12VDC			
J1	3	5VDC			
J1	4	GND			
J1	5	GND			
J1	6	GND			
J1	7	UART_USB_DATA_P		To Test PC (NONFLT)	Serial over USB 115200BPS
J1	8	UART_USB_DATA_N			
J1	9	UART_USB_VBUS			
J1	10	OSPRE_ENABLE	KPD_PWR_N	To ZedBoard	Hold LOW 4-5 sec to boot
J1	11	SPI_CLK	BLSP30,GPIO11		
J1	12	SPI_SS	BLSP31		
J1	13	SPI_DATA_MOSI	BLSP32,GPIO9		
J1	14	SPI_DATA_MISO	BLSP33,GPIO8		

Carrier Electrical & Integration Test

Test Cable Assembly



Carrier Electrical & Integration Test

Requirements Verification Matrix

REQ ID		REQ Summary	Verification Method
FR2.0	DR2.6	Total mass of less than or equal to 0.8 kg	Measured assembly
	DR2.7	Overall dimensions of 5 x 5 x 1 cm	
FR2.1 DR2.1	DR2.1.1	Operate on 3.3, 5, and/or 12VDC	Demonstrated with DC supply
	DR2.1.2	Peak Current NGT 500mA	Measured during operation
	DR2.1.3	Peak Power draw NGT 3W	P = V x I

Carrier Electrical & Integration Test

Test Results and Associated Requirements

PARAMETER	UNIT	VALUE	LIMIT, MIN	LIMIT, MAX	PASS/FAIL?	REQ ID
Mass	**g**	**37**	N/A	800	PASS	FR2.0/DR2.6
Dimensions (L x W x H)	**cm**	**5 x 5 x 1**	5 x 5 x 1	5 x 5 x 1	PASS	FR2.0/DR2.7
Voltage, Supply	**V**	**12**	3.3, 5, or 12VDC		PASS	FR2.1/DR2.1.1
Current, Supply, Peak (during image processing)	**mA**	**170**	N/A	500	PASS	FR2.1/DR2.1.2
Power, Supply, Max P = I*V	**mW**	**2040**	N/A	3000	PASS	FR2.1/DR2.1.3
Current, Supply, Standby (Q't)	**mA**	**1.38**	NA	NA	NA	Info Only
Power, Supply, Standby (Q't)	**mW**	**16.56**	NA	NA	NA	Info Only
Temp. at peak power, processor	**C**	**49**	NA	NA	NA	Info Only

Carrier Electrical & Integration Test

Requirements Verification Matrix

REQ ID		REQ Summary	Verification Method
FR2.0	DR2.6	Total mass of less than or equal to 0.8 kg	Measurement of assembled module
	DR2.7	Overall dimensions of 5 x 5 x 1 cm	
FR2.1 DR2.1	DR2.1.1	Operate on 3.3, 5, and/or 12VDC supply	Demonstration of operation with DC supply
	DR2.1.2	Peak Current NGT 500mA	Measurement during operation
	DR2.1.3	Peak Power draw NGT 3W	Analysis using current and voltage measurement

Carrier Electrical & Integration Test Facilities and Equipment Requirements

Facility	Status
Aerospace Electrical Shop	Access Received

Equipment	Status
Carrier Board	Received
DC Power Supply (5 & 12V output)	In Aerospace Electrical Shop
Digital Multimeter	In Aerospace Electrical Shop
Optical loupe (~4X)	Received
Thermal Meter or FLIR Camera	Rented from ITLL
Scale	In Aerospace Electrical Shop
OSPRE Test Cable	Constructed

Completed

In Progress

Pending

Carrier Electrical & Integration Test

Test Overview

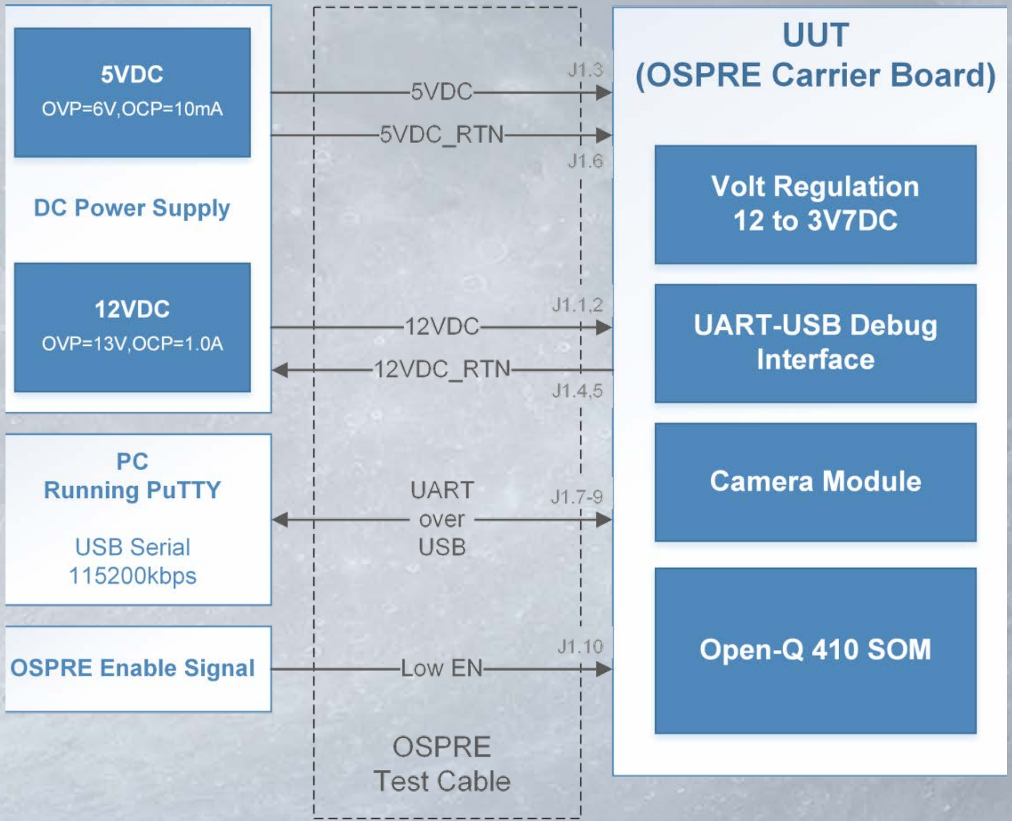


IMAGE PROCESSING

Image Pre-Processing

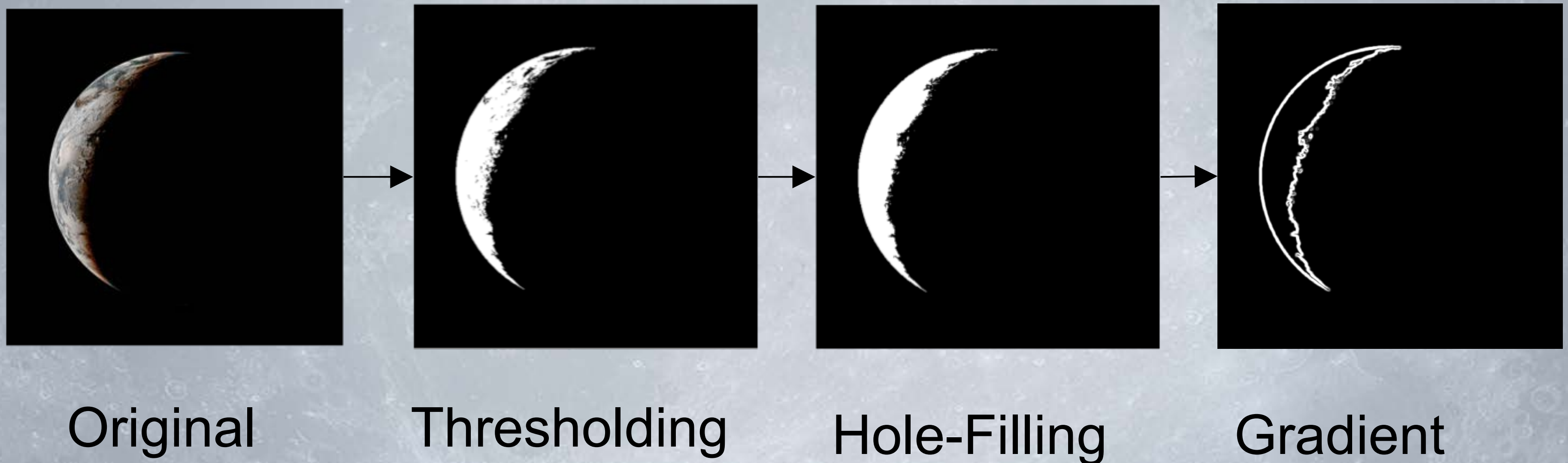


Image Pre-Processing

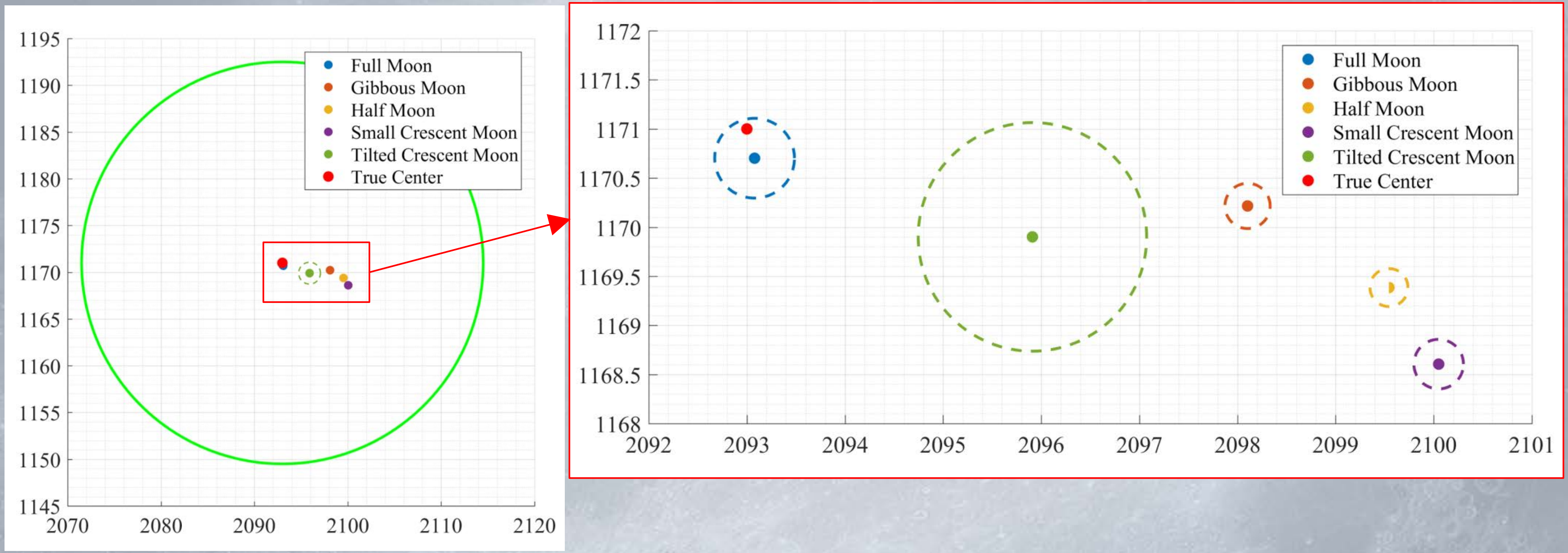
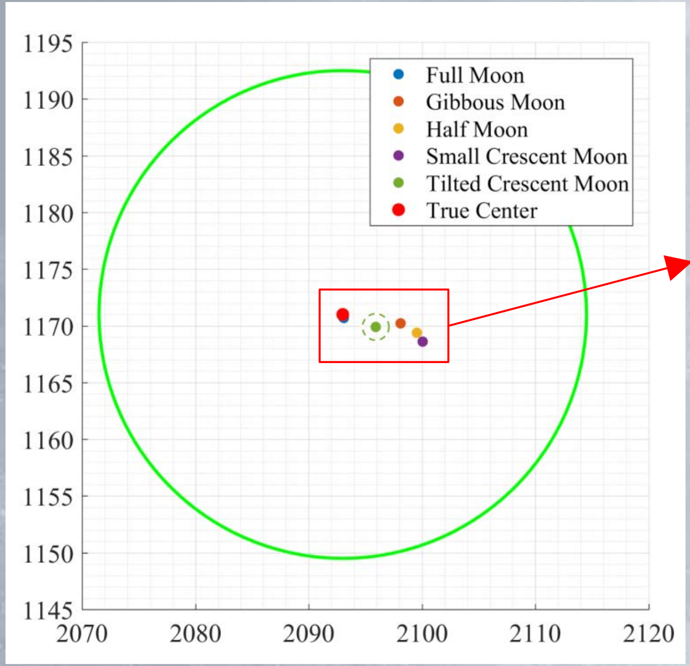


Image Pre-Processing



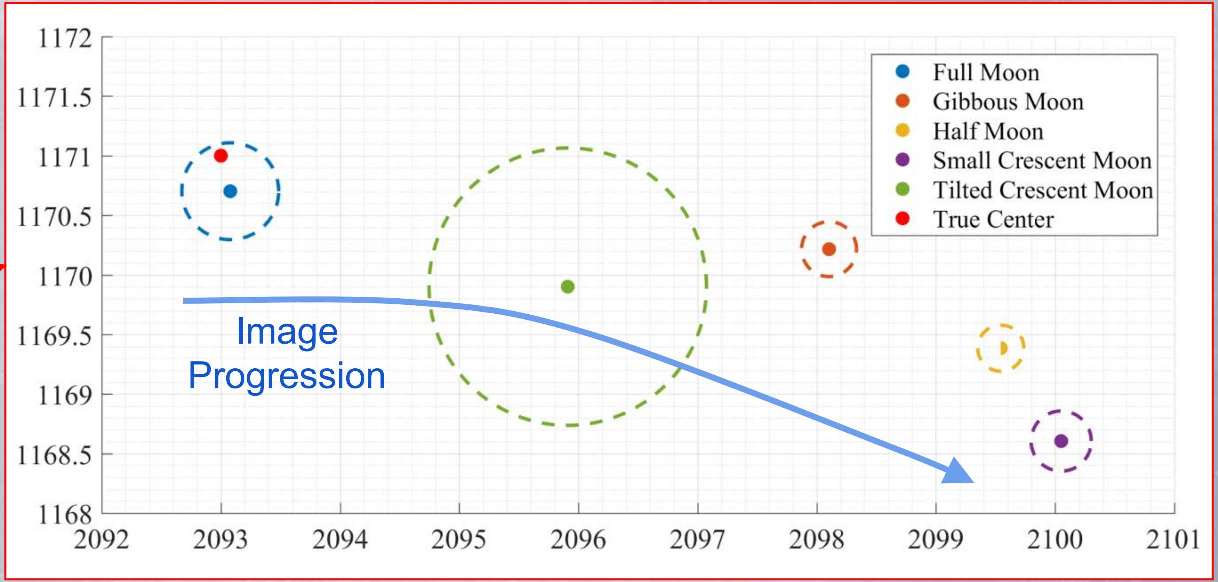
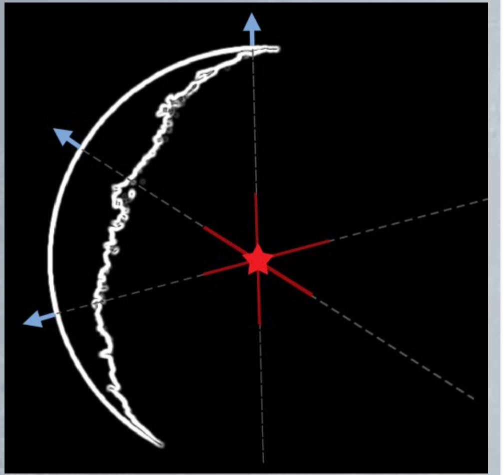
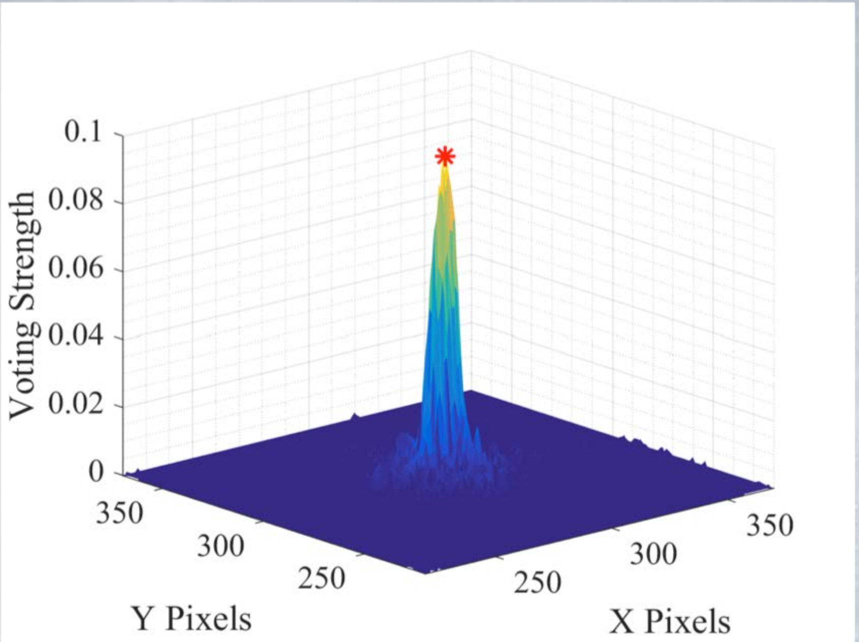
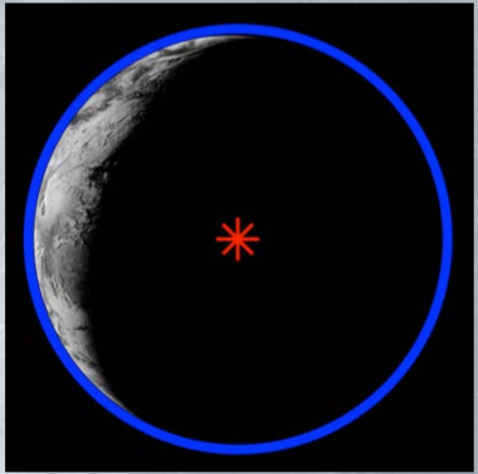


Image Processing

Image Processing





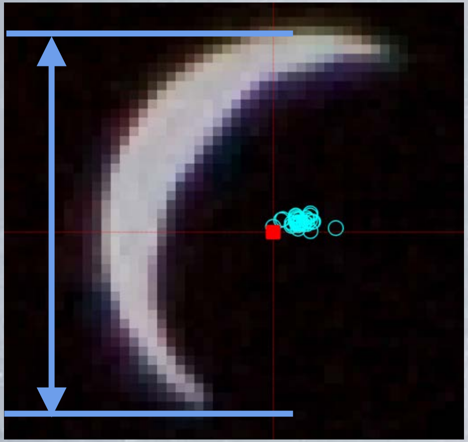


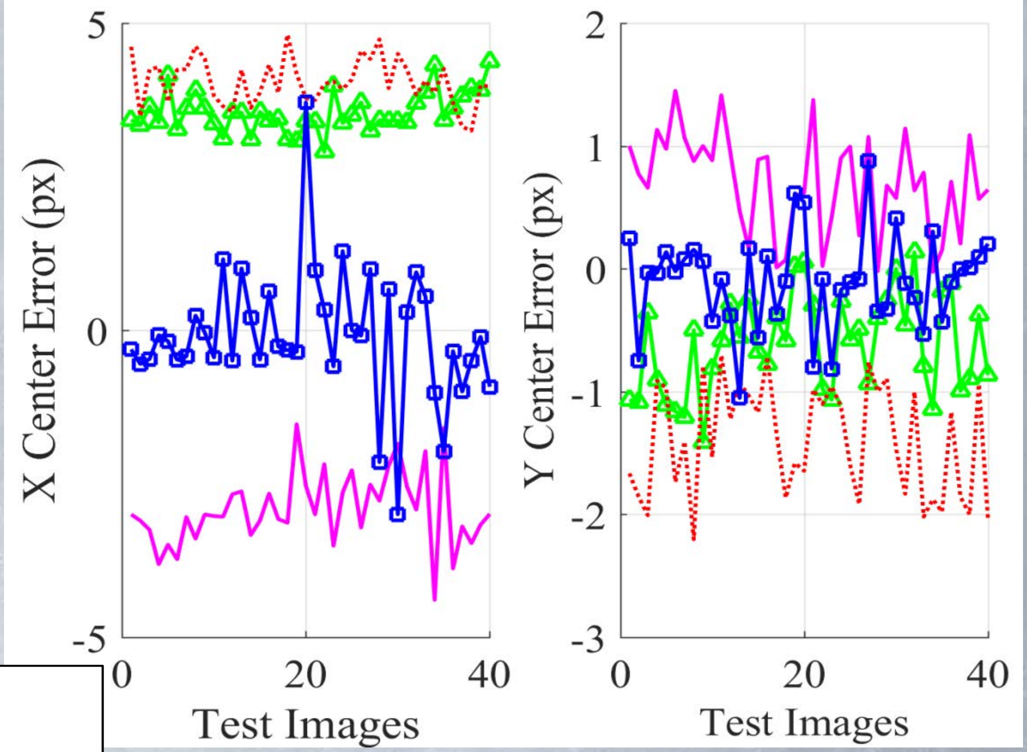
Coherent Circular Hough Transform

Performance Testing
Image Processing Results

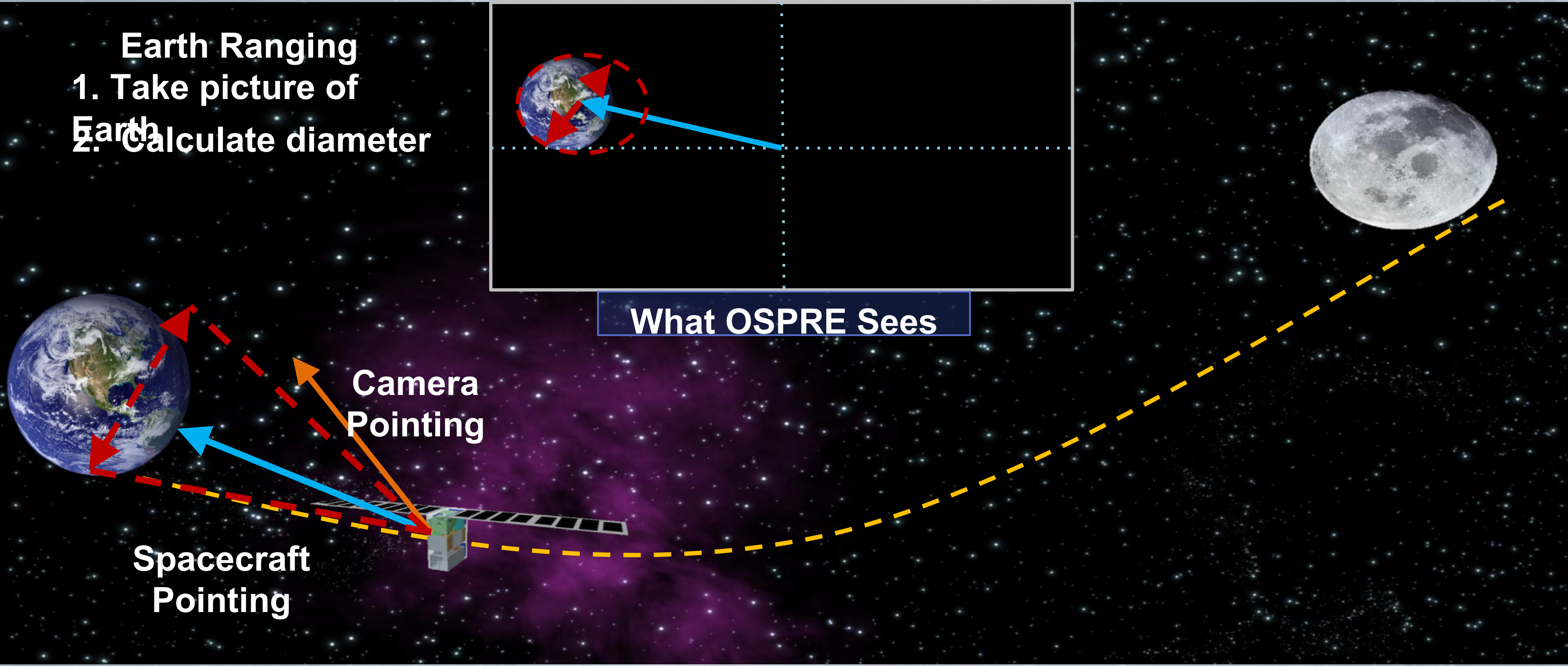
- 4 different moon phases
- 40 images for each phase

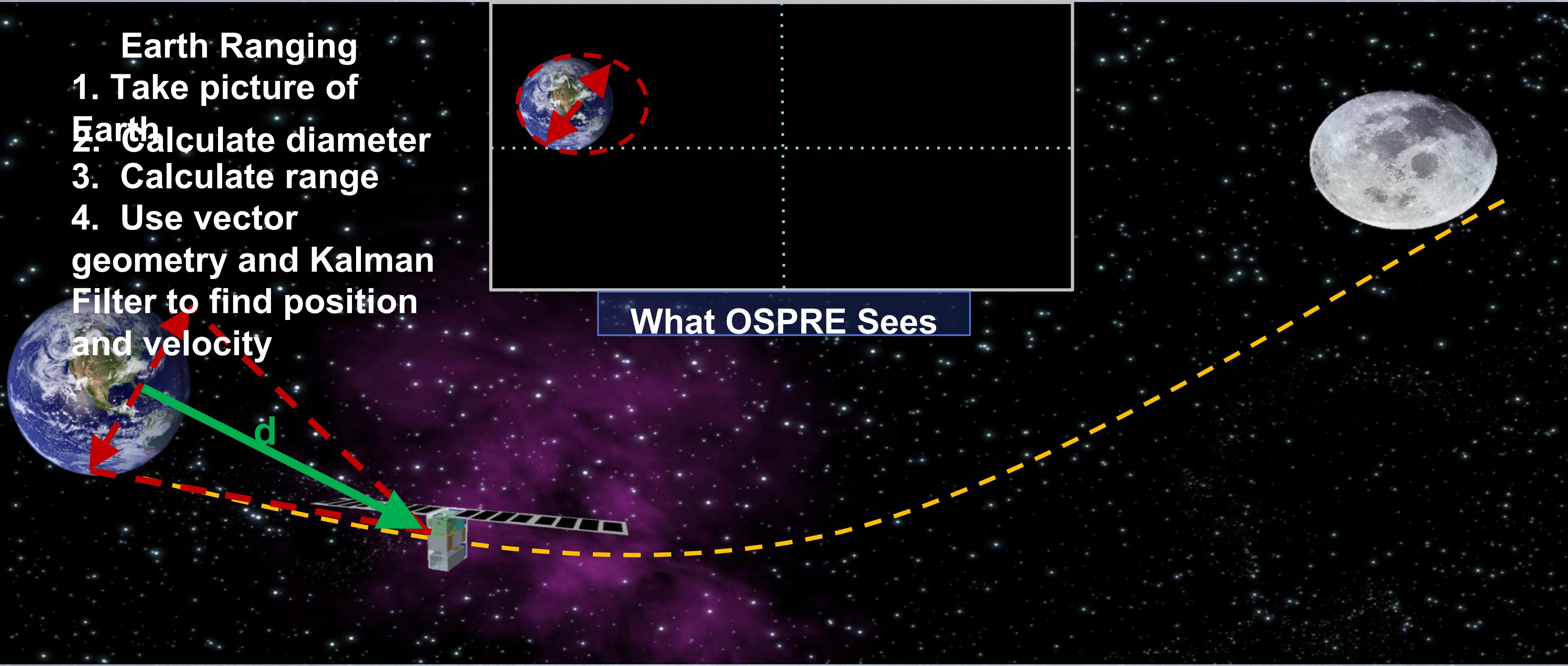
43 pixel diameter
Within 4192 x 3104 pixel image

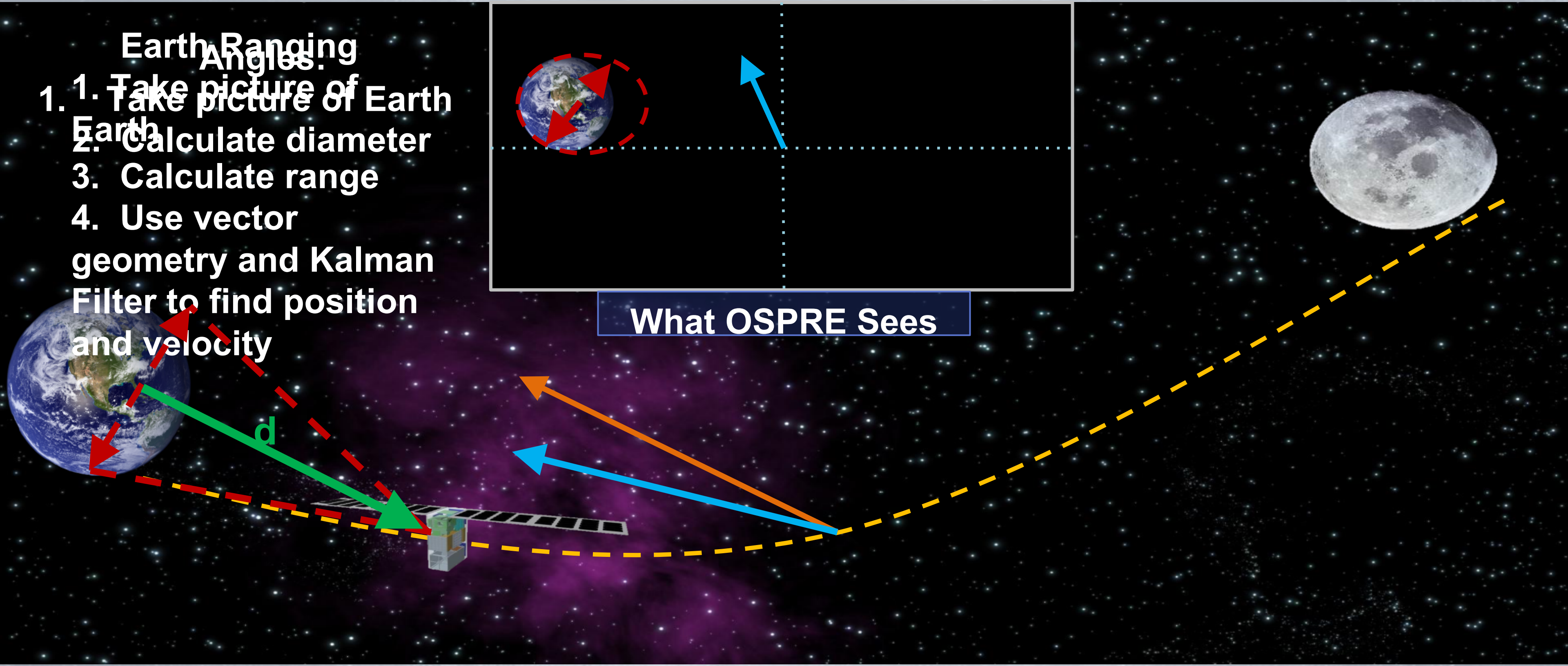




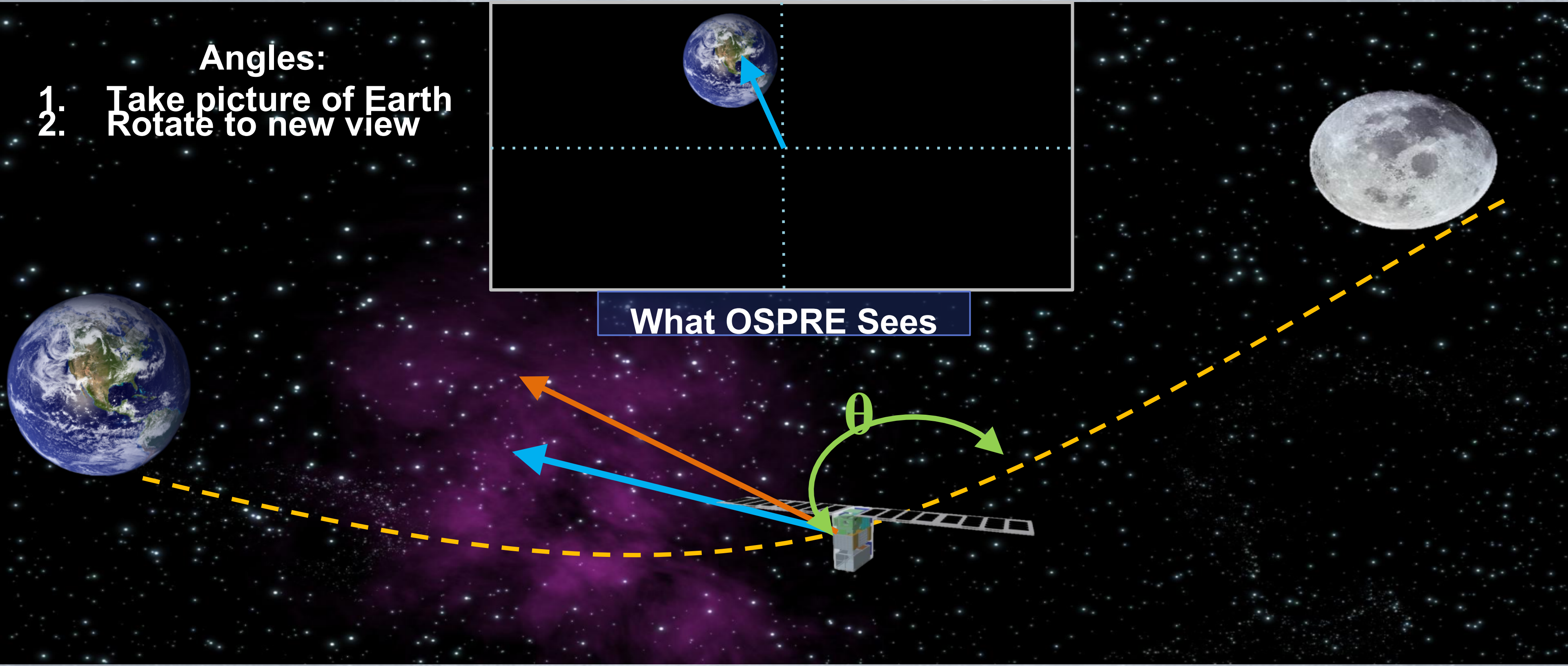
Navigation


Earth Ranging
1. Take picture of Earth
2. Calculate diameter
What OSPRE Sees
Camera Pointing
Spacecraft Pointing


Earth Ranging
1. Take picture of Earth
2. Calculate diameter
3. Calculate range
4. Use vector geometry and Kalman Filter to find position and velocity
What OSPRE Sees
d

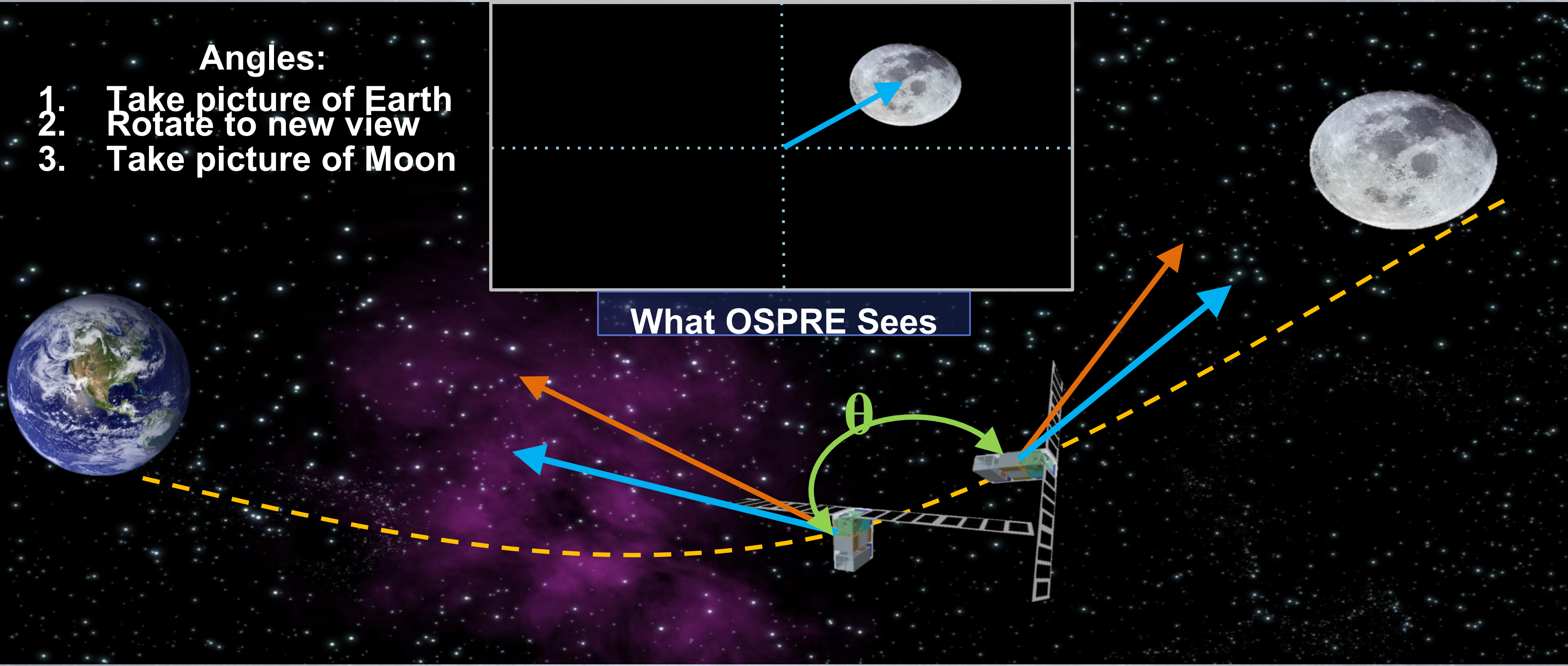


Earth Ranging
Angles:
1. Take picture of Earth
1. Take picture of Earth
2. Calculate diameter
3. Calculate range
4. Use vector geometry and Kalman Filter to find position and velocity
d
What OSPRE Sees


Angles:
1. Take picture of Earth
2. Rotate to new view
What OSPRE Sees
θ

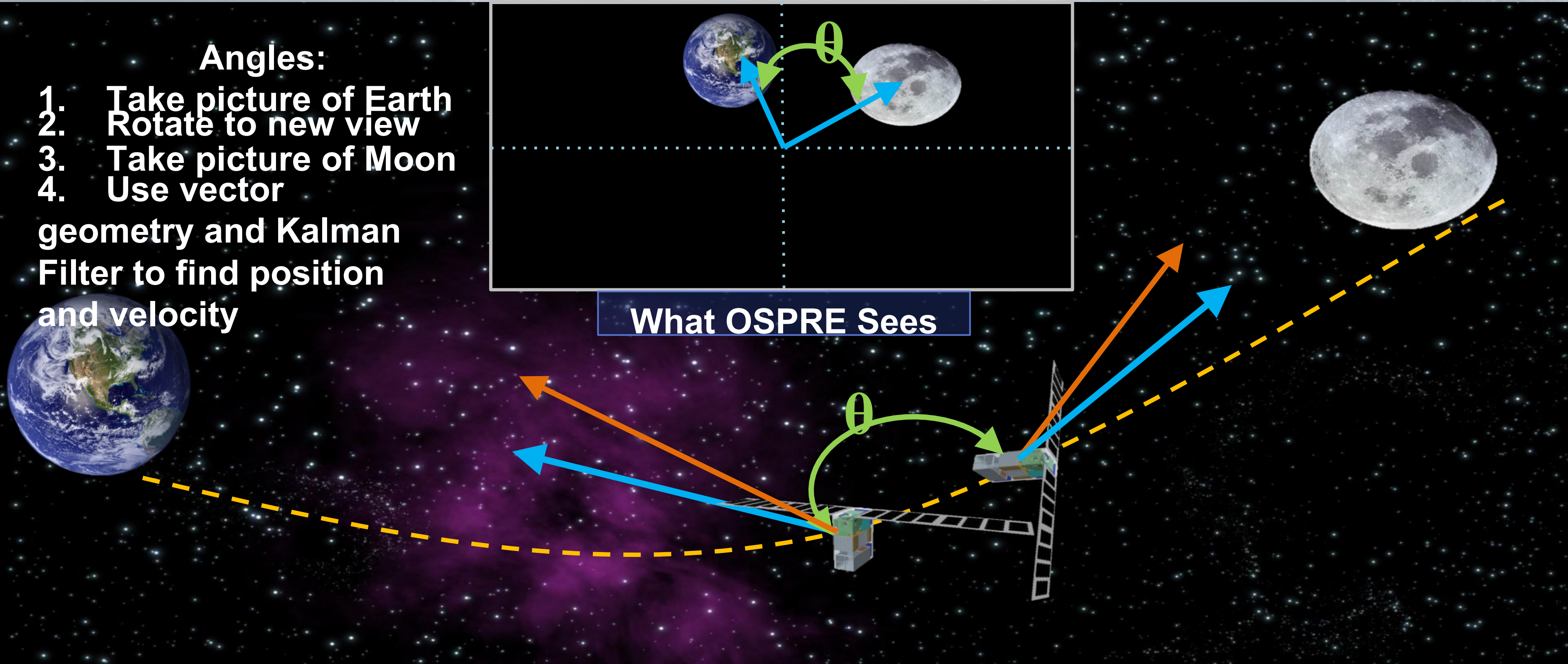
Angles:

1. Take picture of Earth
2. Rotate to new view
3. Take picture of Moon



Angles:

1. Take picture of Earth
2. Rotate to new view
3. Take picture of Moon
4. Use vector geometry and Kalman Filter to find position and velocity

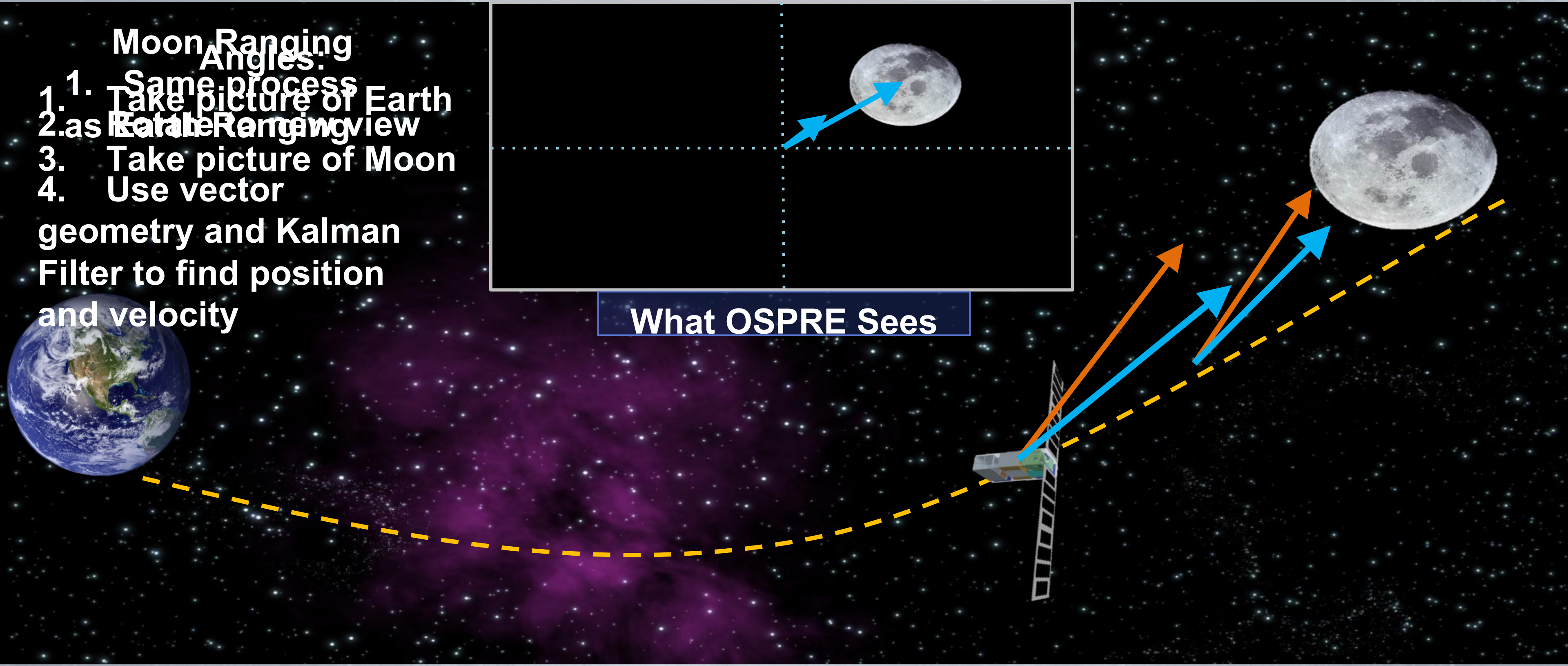


Moon Ranging

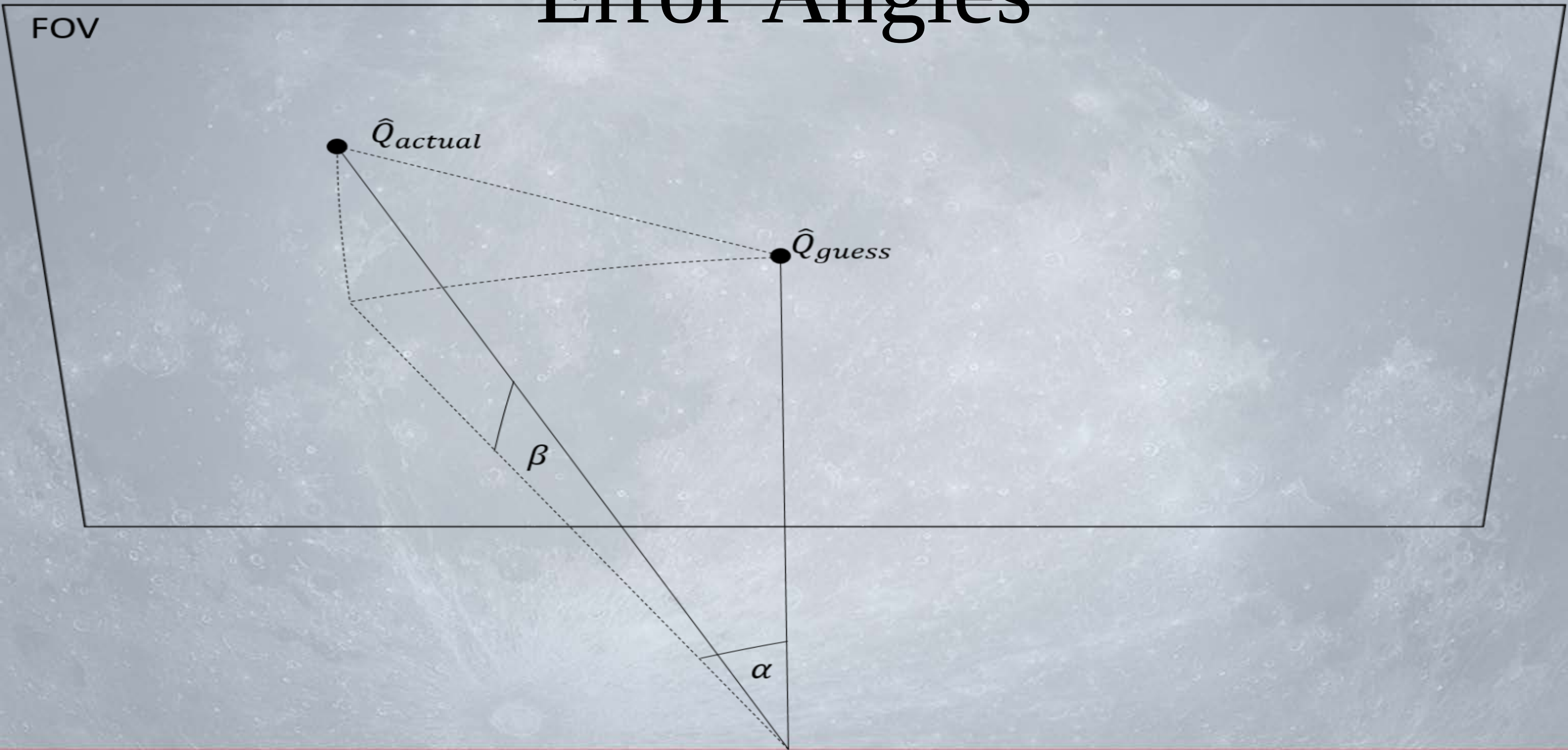
Angles:

1. Same process as Earth Ranging

1. Take picture of Earth
2. Rotate to new view
3. Take picture of Moon
4. Use vector geometry and Kalman Filter to find position and velocity

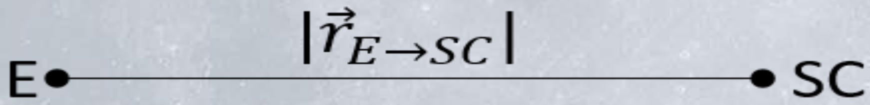


Error Angles



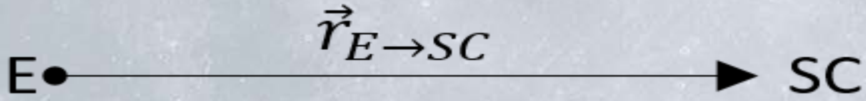
Ranging Method

Ranging Method

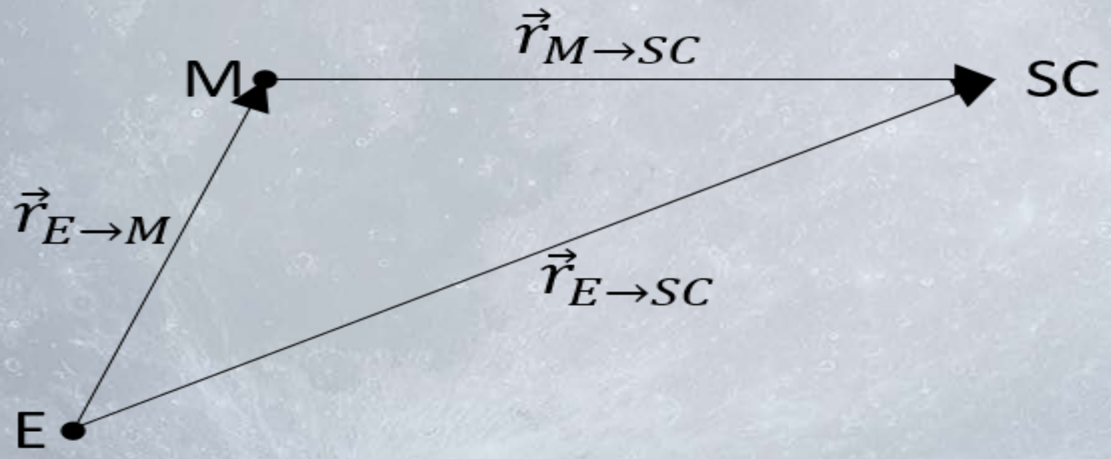


Ranging Method

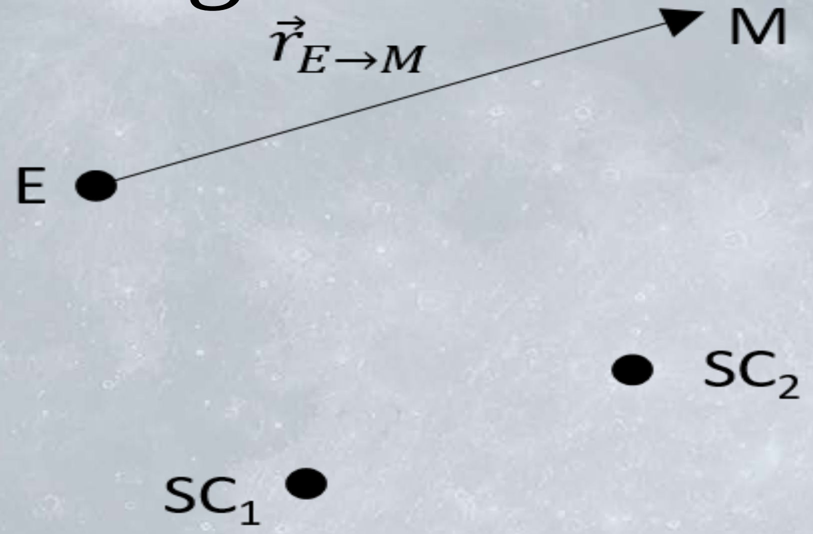
Ranging Method



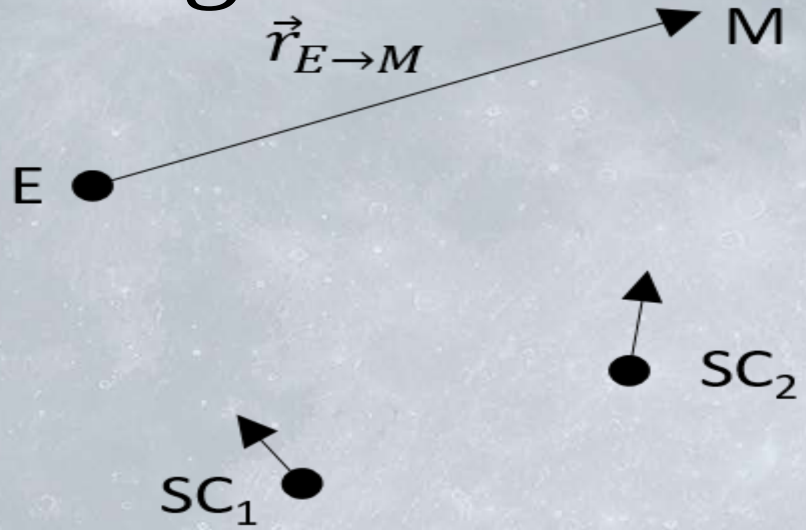
Ranging Method



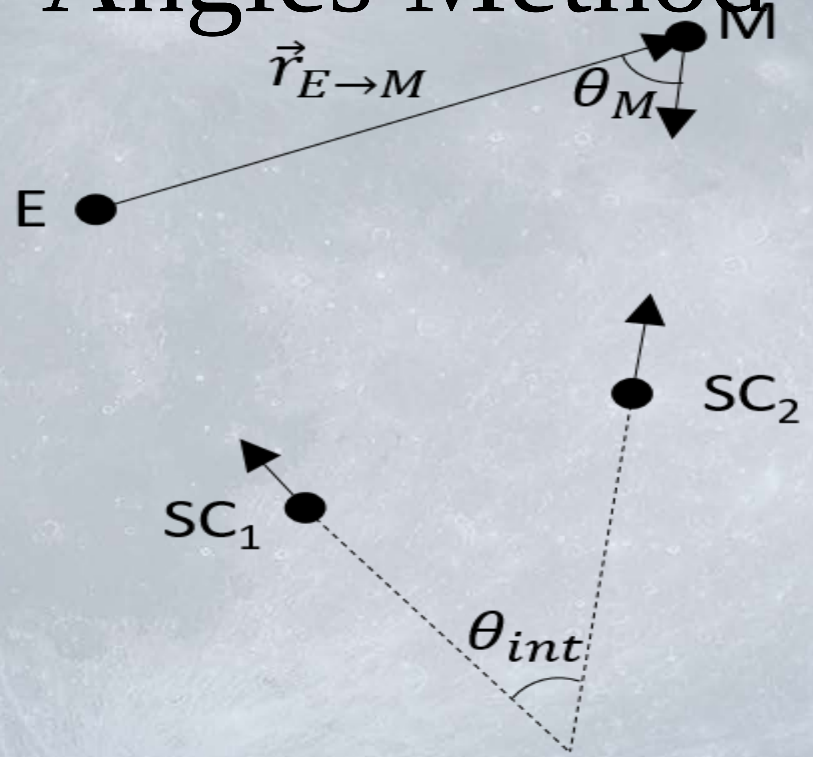
Angles Method



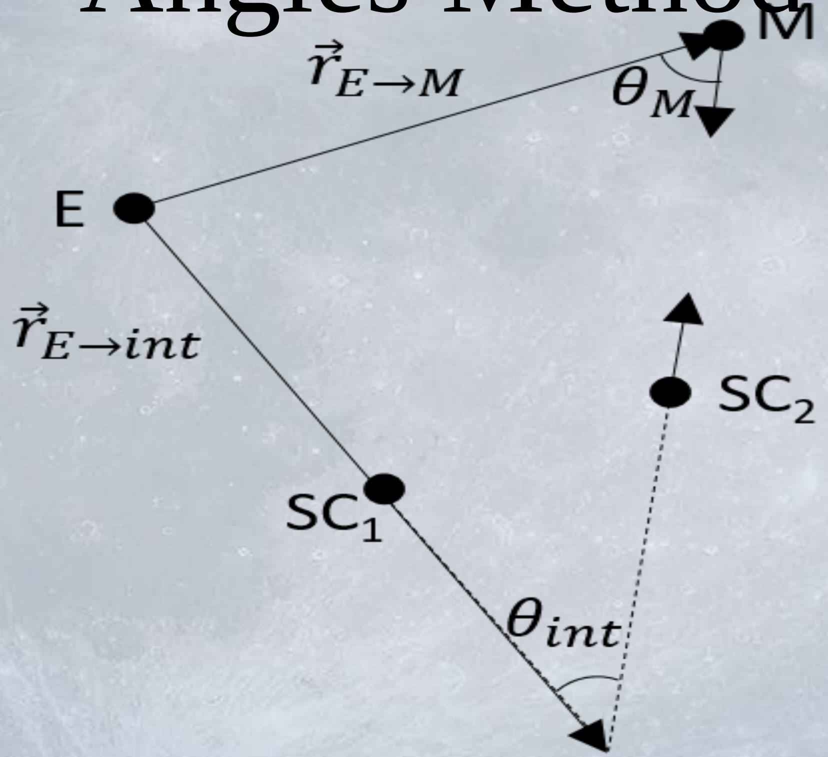
Angles Method



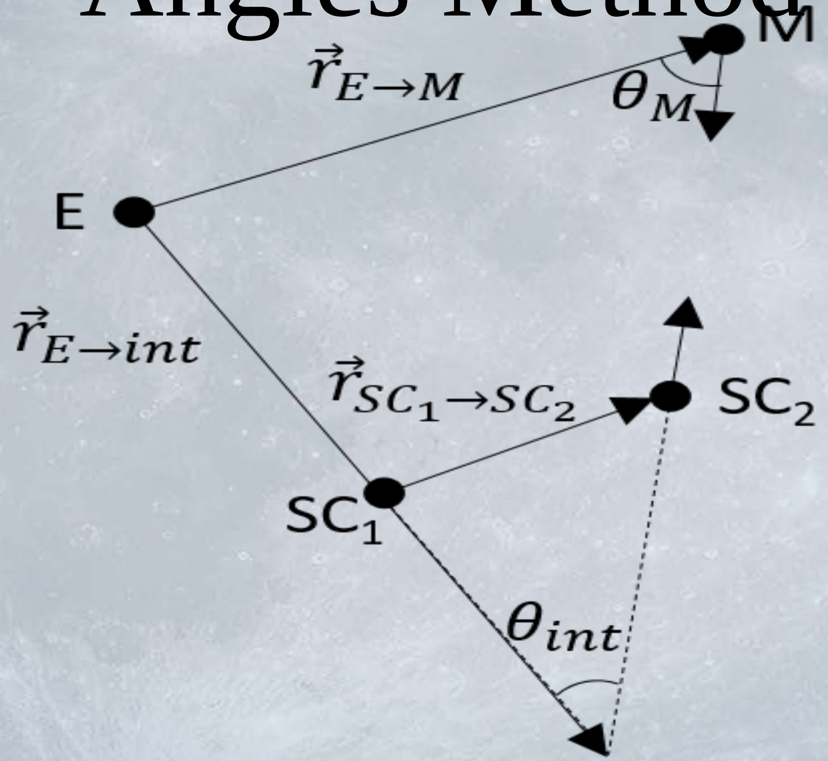
Angles Method



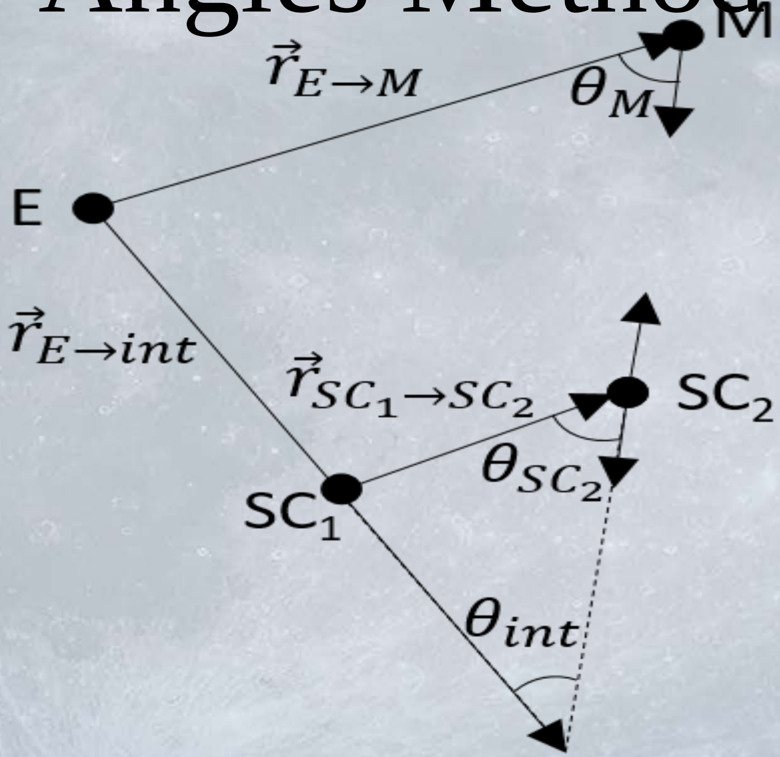
Angles Method



Angles Method



Angles Method



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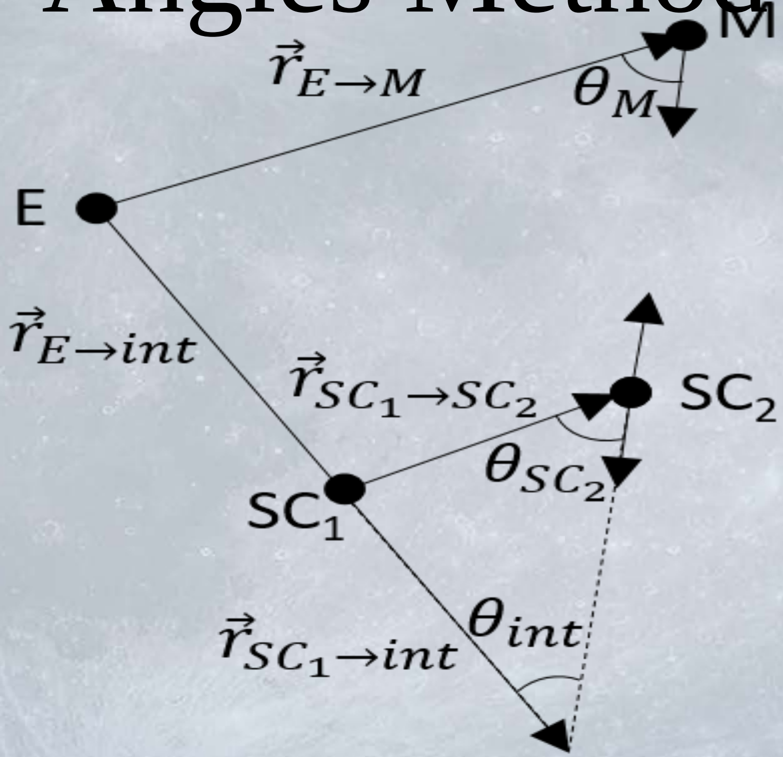
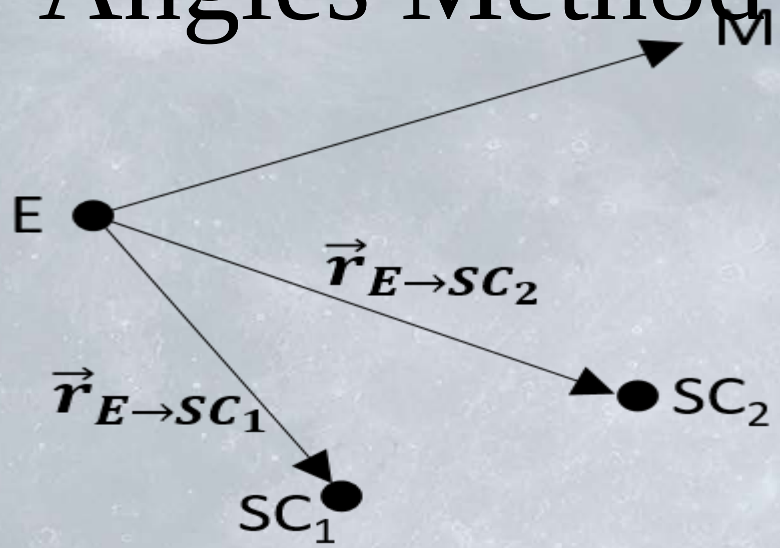
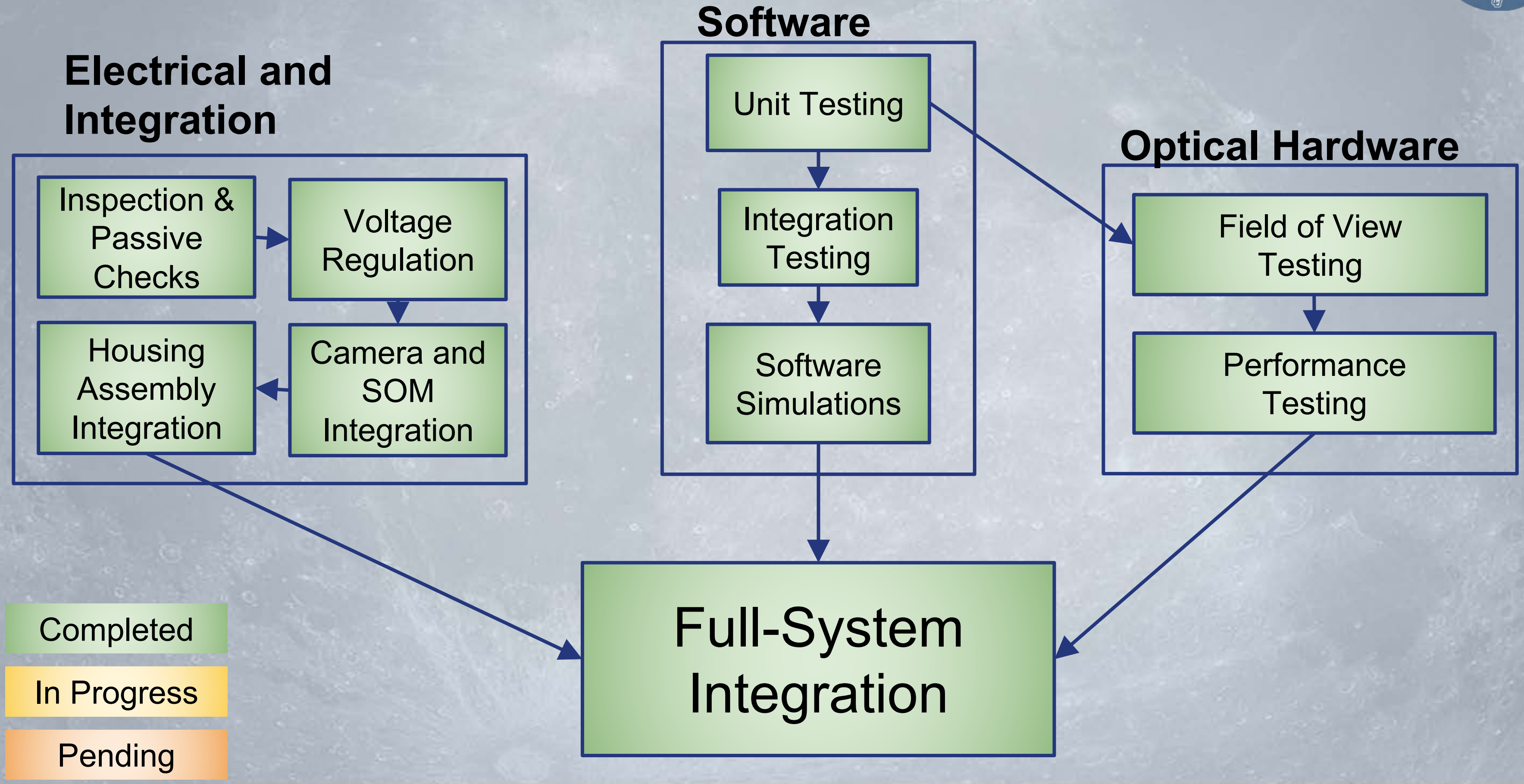


Angles Method



TESTING

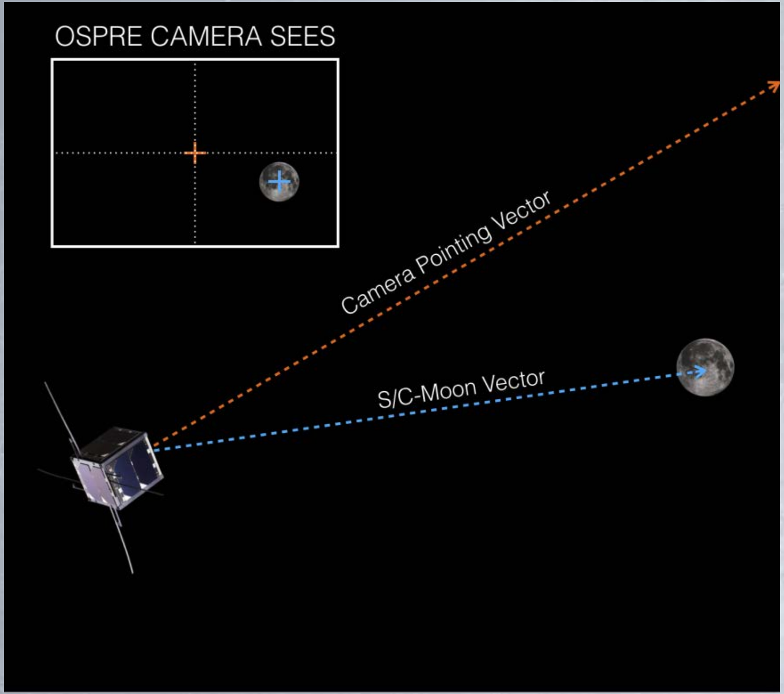
Test Breakdown



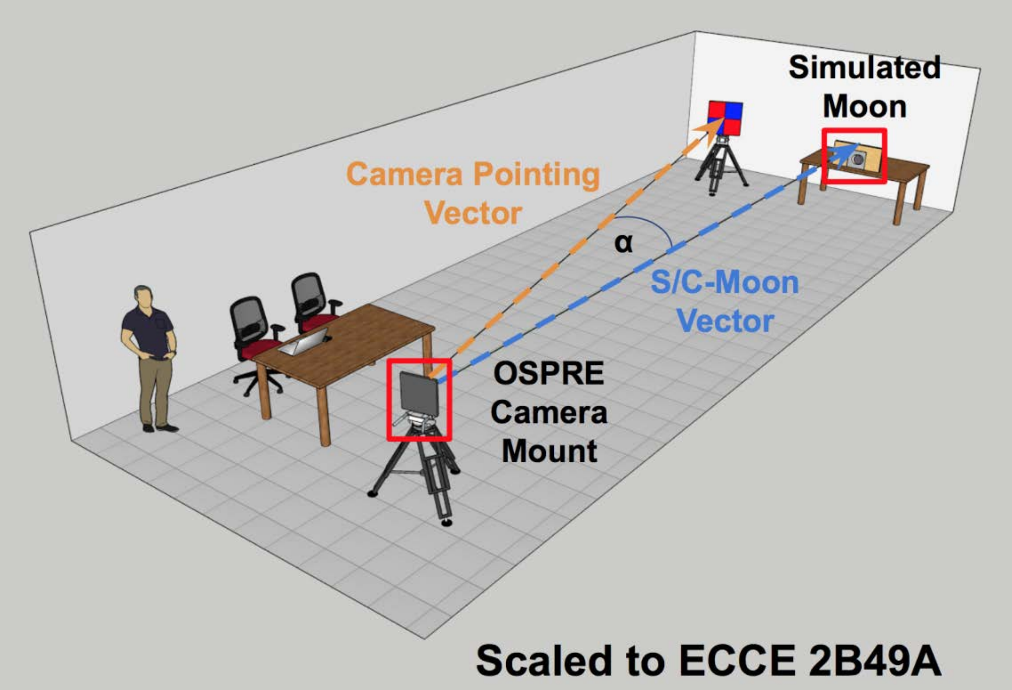
Performance Testing

Test Setup

MISSION ENVIRONMENT

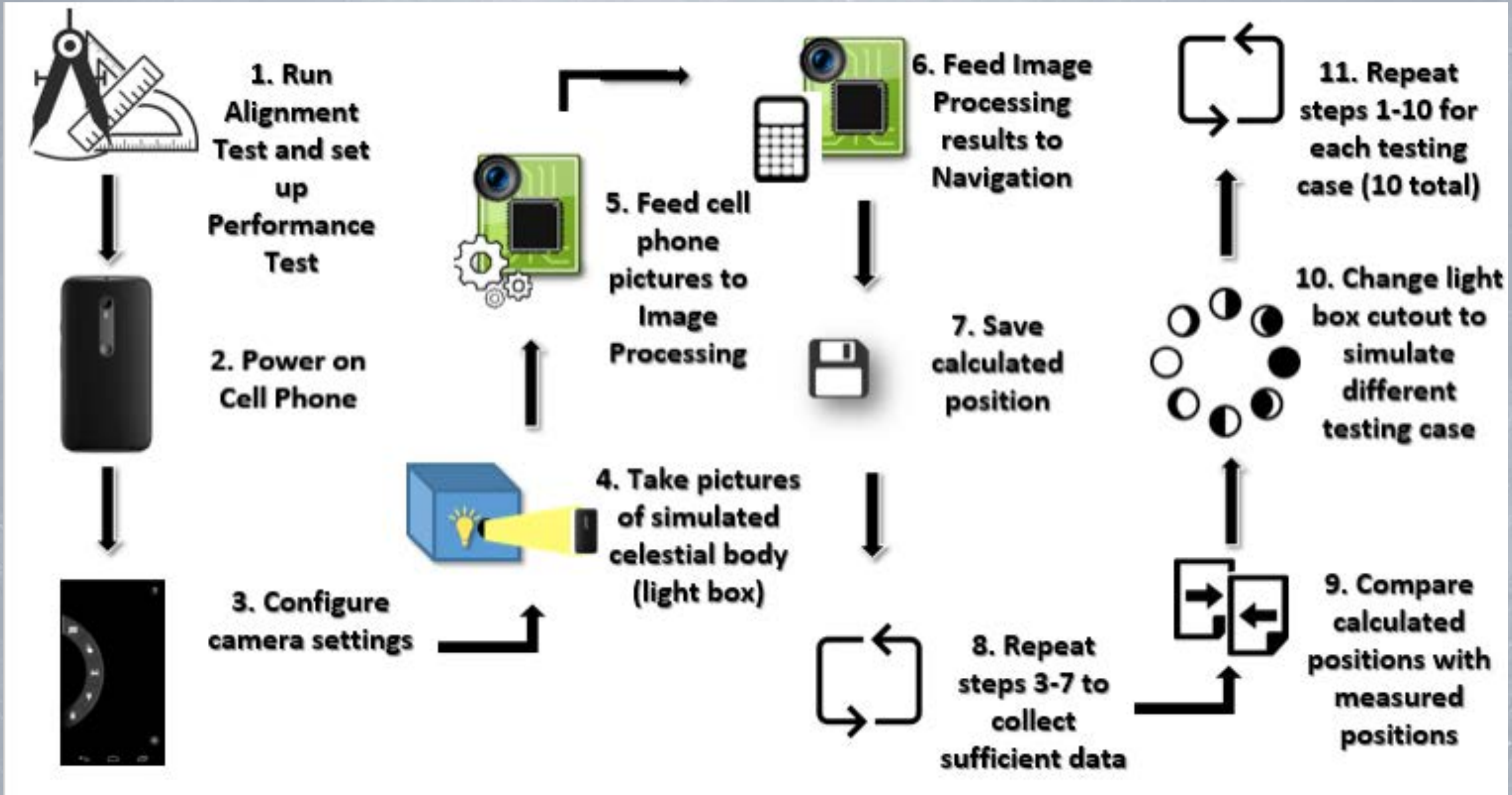


TEST ENVIRONMENT

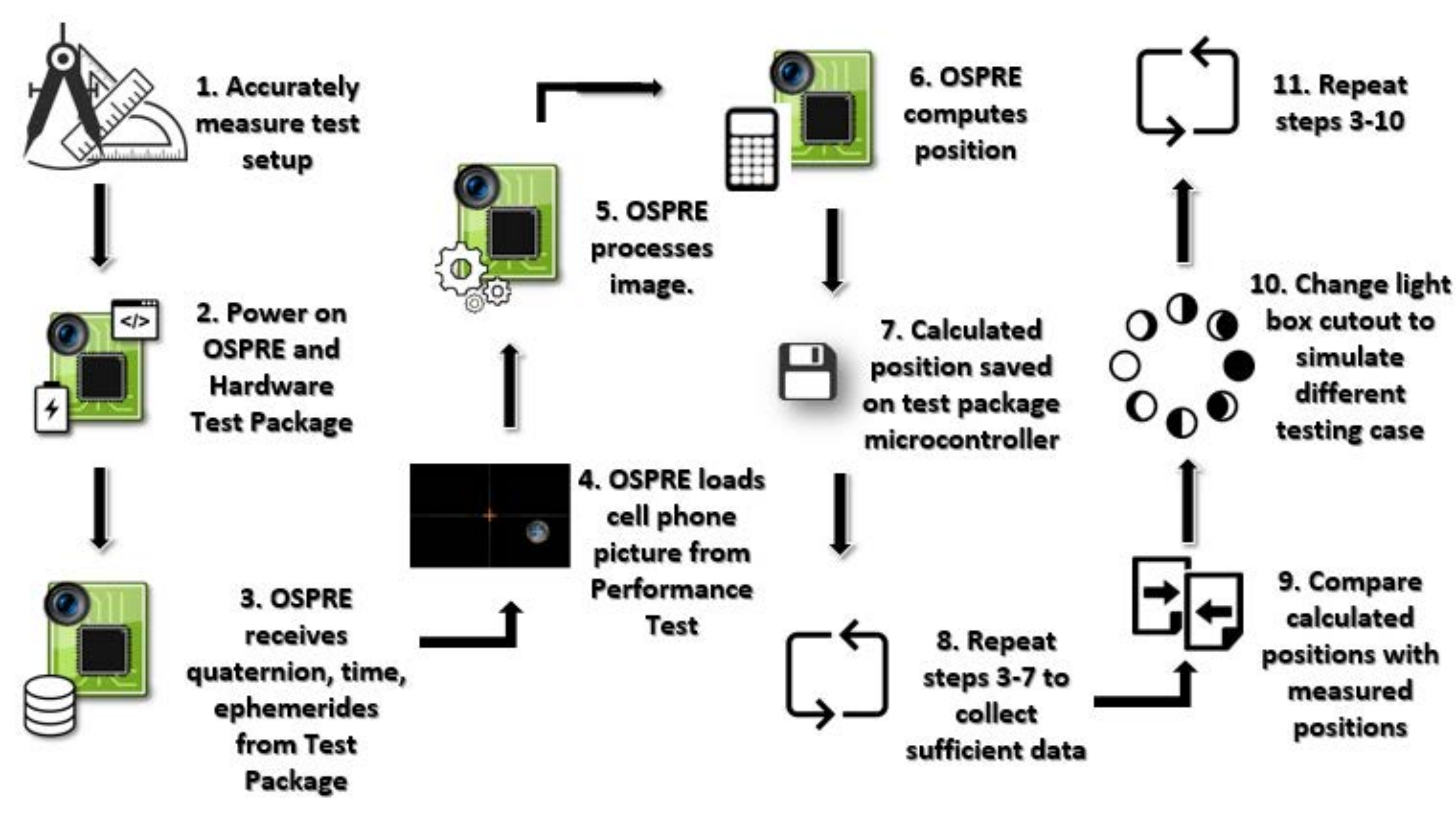


Performance Testing

CONOPS



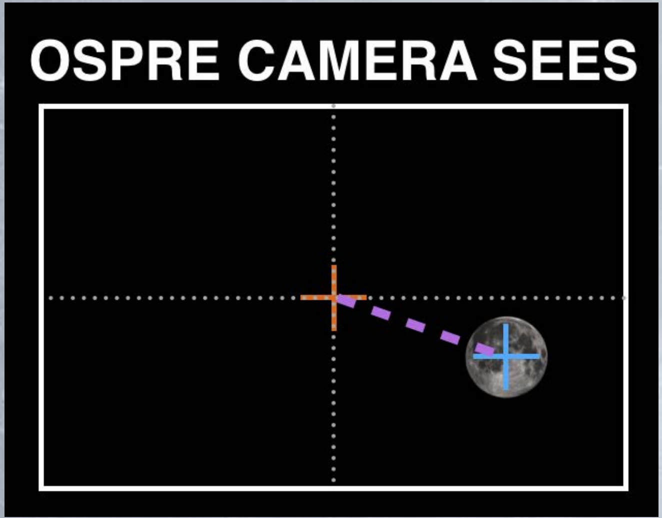
System-Level Testing
CONOPS



Optical Hardware Testing

Field of View

Chosen method of navigation relies heavily on understanding the camera’s field of view



INPUTS: Distance between center of body and center of image (pixels)

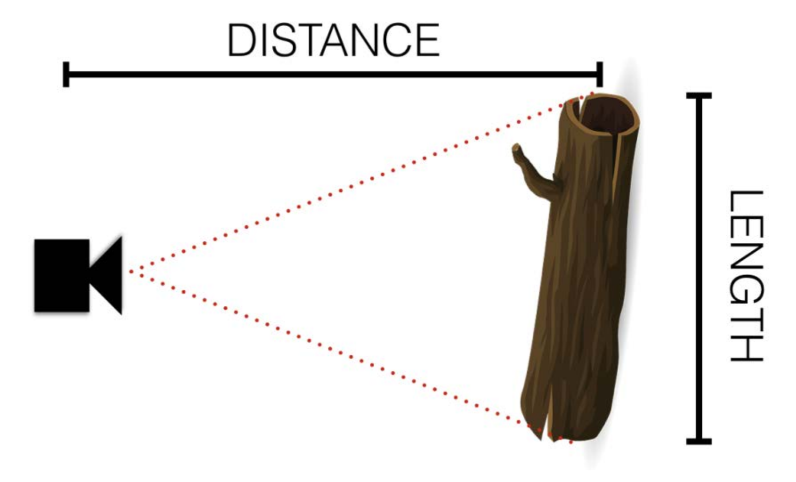
Pixels correlated to degrees via field of view and sensor resolution (pixels/degree)

OUTPUT:
An angle can be calculated (degrees)

Optical Hardware Testing
Field of View Test Overview

BASIC PRINCIPLES:

An object of known length at a known distance from the optical sensor allows field of view to be calculated



Performance Testing

Testing Error

Source	Associated Error	Primary Causation	Human Error Margin	Sensitivity
Lightbox Pointing	± 0.2°	Alignment error due to equipment	x 1.5	LOW
Camera Pointing	± 0.03°	2 pixel error	None	HIGH
Calipers	± 0.025 mm	Advertised equipment error	x 1.5	AVERAGE
Steel Tape Measure	± 1.1 mm	Advertised equipment error	2 mm	HIGH
Laser Ranger	± 1.1 mm	Certified equipment error	2 mm	AVERAGE
Center Finding	± 1 mm	Machining & mount accuracy	0.5 mm	HIGH

Performance Testing

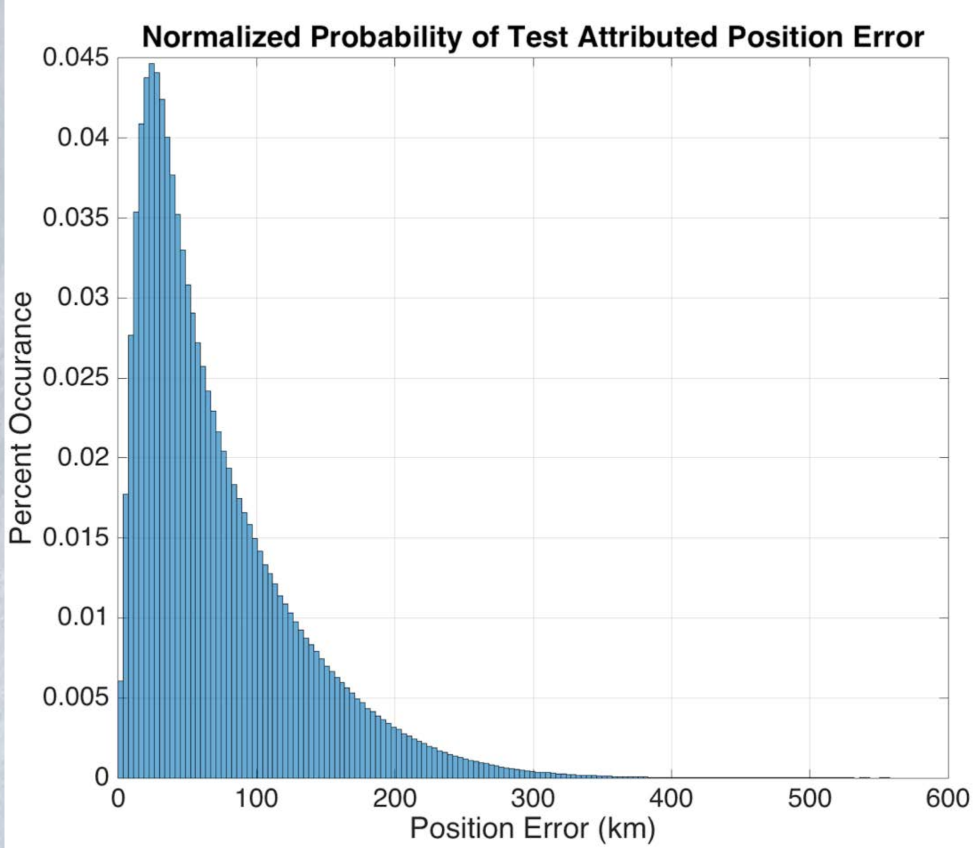
Testing Error

Worst Case Error Scenario

5,000,000 trials
Gaussian randomized error

<u>< 100 km Error</u>
75.16% of the time

<u>< 500 km Error</u>
100% of the time



System-Level Testing

Requirements Verification Matrix

REQ ID		REQ Summary	Verification Method
FR1.1	DR1.1 - DR 1.5	OSPRE shall use angles-only navigation to determine a state vector.	System-Level Testing
FR1.2 & FR 1.3	DR1.2 & DR1.3	OSPRE shall determine the position and velocity to within 1000 km and 250 m/s of the true value.	
FR1.4	DR1.4	OSPRE shall calculate the Earth, spacecraft, Moon angle	
FR1.5	DR1.5	OSPRE software shall include solution validation.	
FR2.0	Various	OSPRE shall meet integration requirements.	