Optical Sensor Package for Relative Exploration

— Preliminary Design Review —

October 11th, 2016

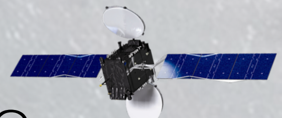
PROJECT DESCRIPTION

MISSION

PRIMARY OBJECTIVE: Use optical relative navigation to determine a spacecraft's state vector and state error during a lunar transfer orbit

Mission based on the NASA CubeQuest Challenge

- Lunar Mission
- Launch on SLS EM-1



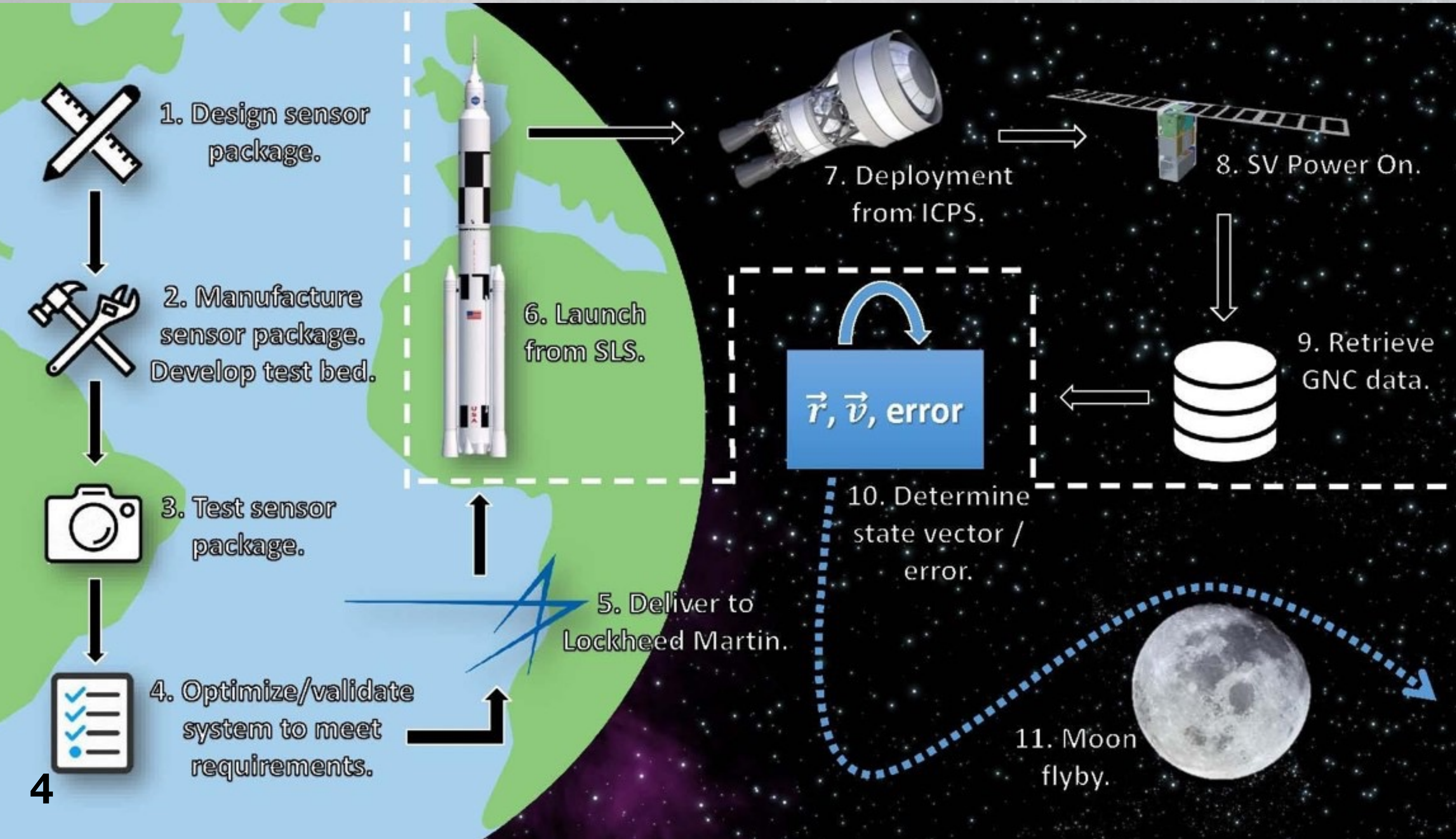
Images — pengall.com
unawe.org

AGENDA

1. Project Description
2. Evidence of Feasibility
    I. Error
    II. Interfacing, Size, Weight, & Power (iSWAP)
    III. Testing
3. Status Summary
4. Future Studies

PROJECT DESCRIPTION

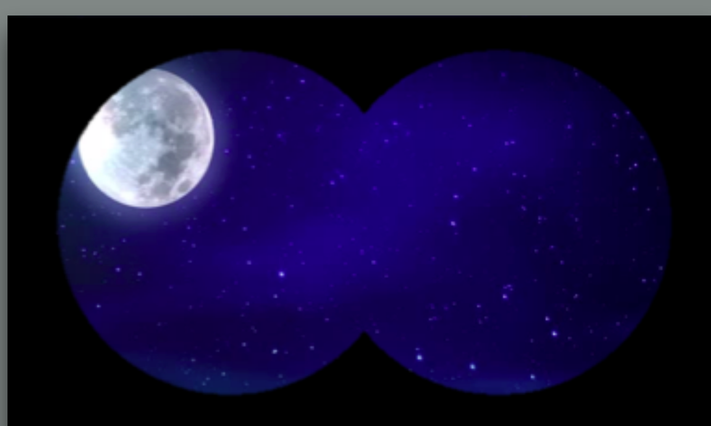
MISSION CONOPS



PROJECT DESCRIPTION

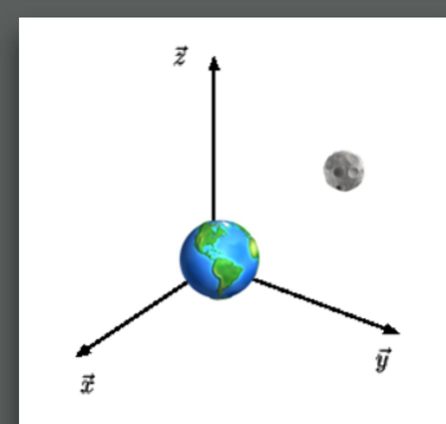
RELATIVE NAVIGATION

1
WHAT I SEE



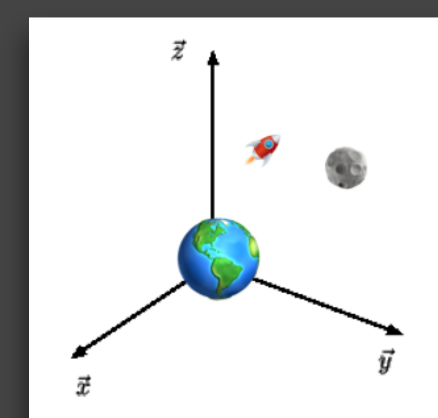
2
WHAT I KNOW

Location of the Earth & Moon



3
WHAT I CAN FIND OUT

Spacecraft Location

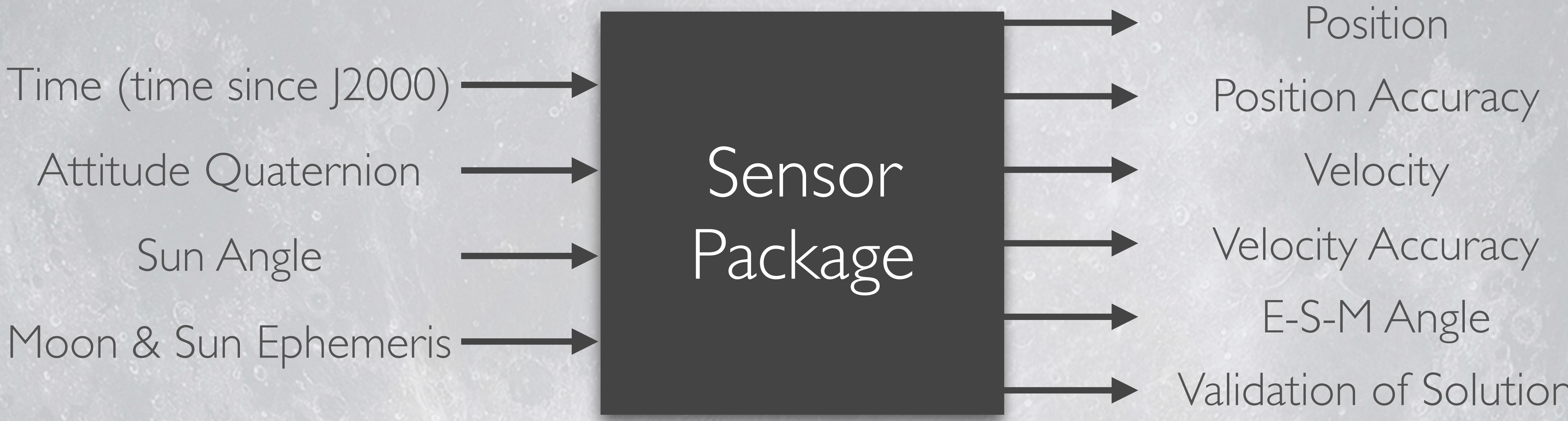


Images — videoblocks.com/video
3dcartoonmodels.com

PROJECT DESCRIPTION

CONTEXT

INPUT OUTPUT DIAGRAM



PROJECT DESCRIPTION

DESIGN DRIVERS

1 2 3

CONTEXT ▸ Starting scenario: lost in space

CONSEQUENCE ▸ Navigate with celestial bodies

KNOWN ▸ Attitude, ephemerides, time

ACTION ▸ Look at celestial bodies

PROJECT DESCRIPTION

DESIGN DRIVERS

1 **2** 3

CONTEXT ▸	Image with error
CONSEQUENCE ▸	Measure angles
KNOWN ▸	Pixel data (with error)
ACTION ▸	Reduce error and calculate angles

PROJECT DESCRIPTION

DESIGN DRIVERS

1 2 **3**

CONTEXT ▸ Angles with error

CONSEQUENCE ▸ Imperfect state vector

KNOWN ▸ Algorithms

ACTION ▸ Compute state vector

PROJECT DESCRIPTION

FUNCTIONAL REQUIREMENTS

1. Provide state vector within desired error bounds

   Position — 1000 km   Velocity — 250 m/s

2. Meet dimensional requirements

   5 cm. X 5 cm. X 1cm.

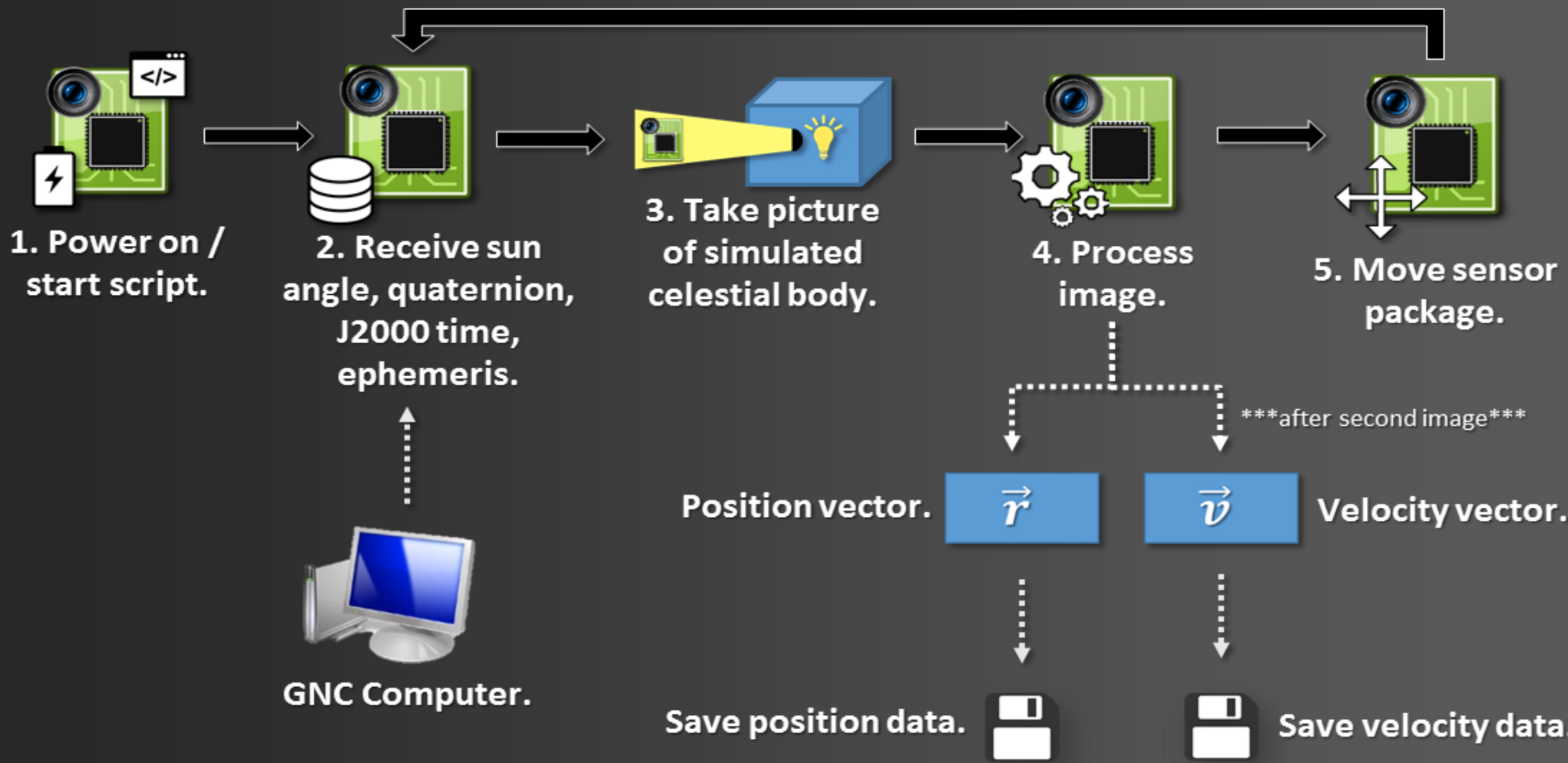
3. Create testing environment to validate all of the above

4. Meet interfacing / electrical requirements

5. Provide health and status to simulated spacecraft

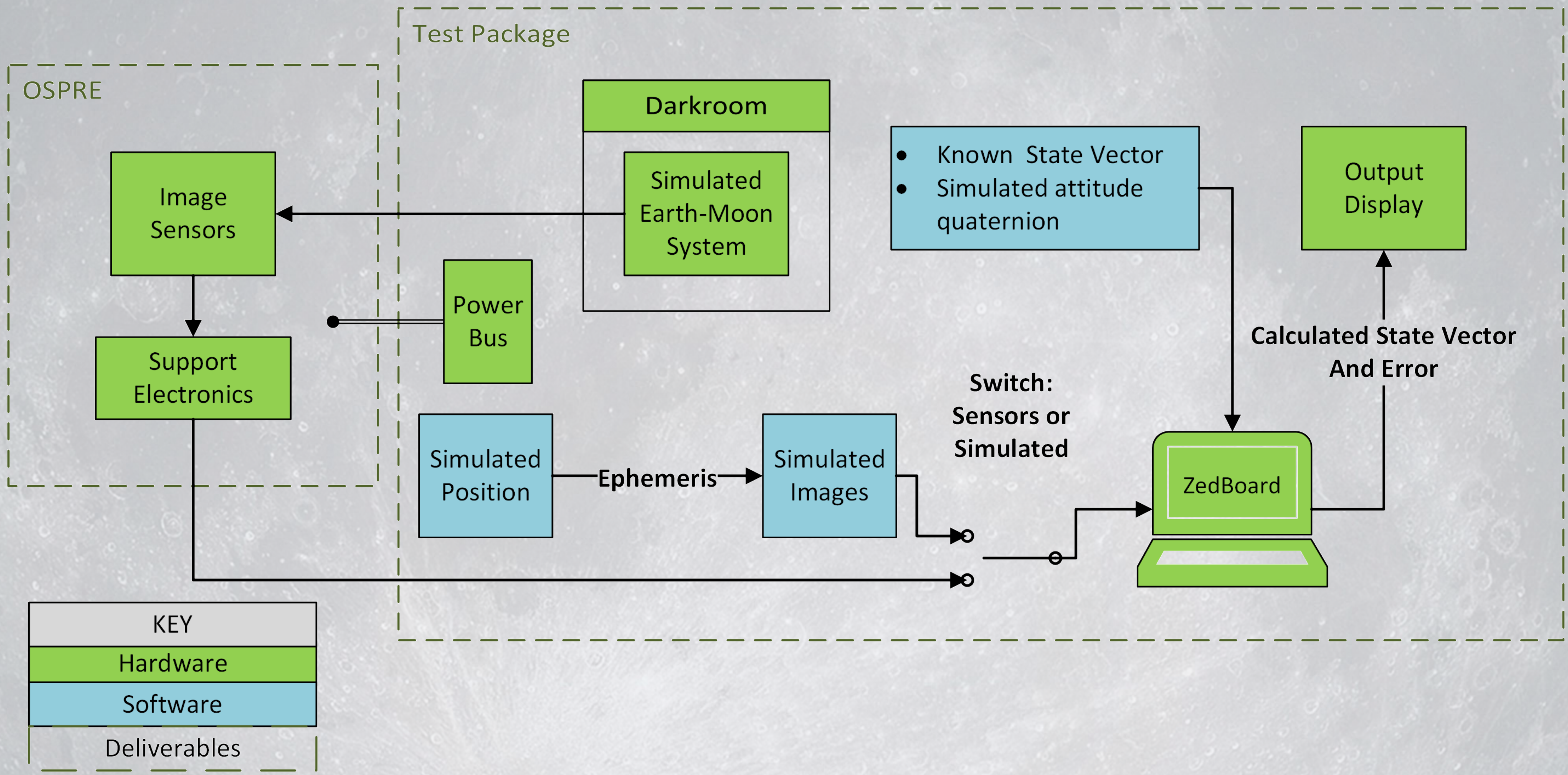
PROJECT DESCRIPTION

TESTING CONOPS



PROJECT DESCRIPTION

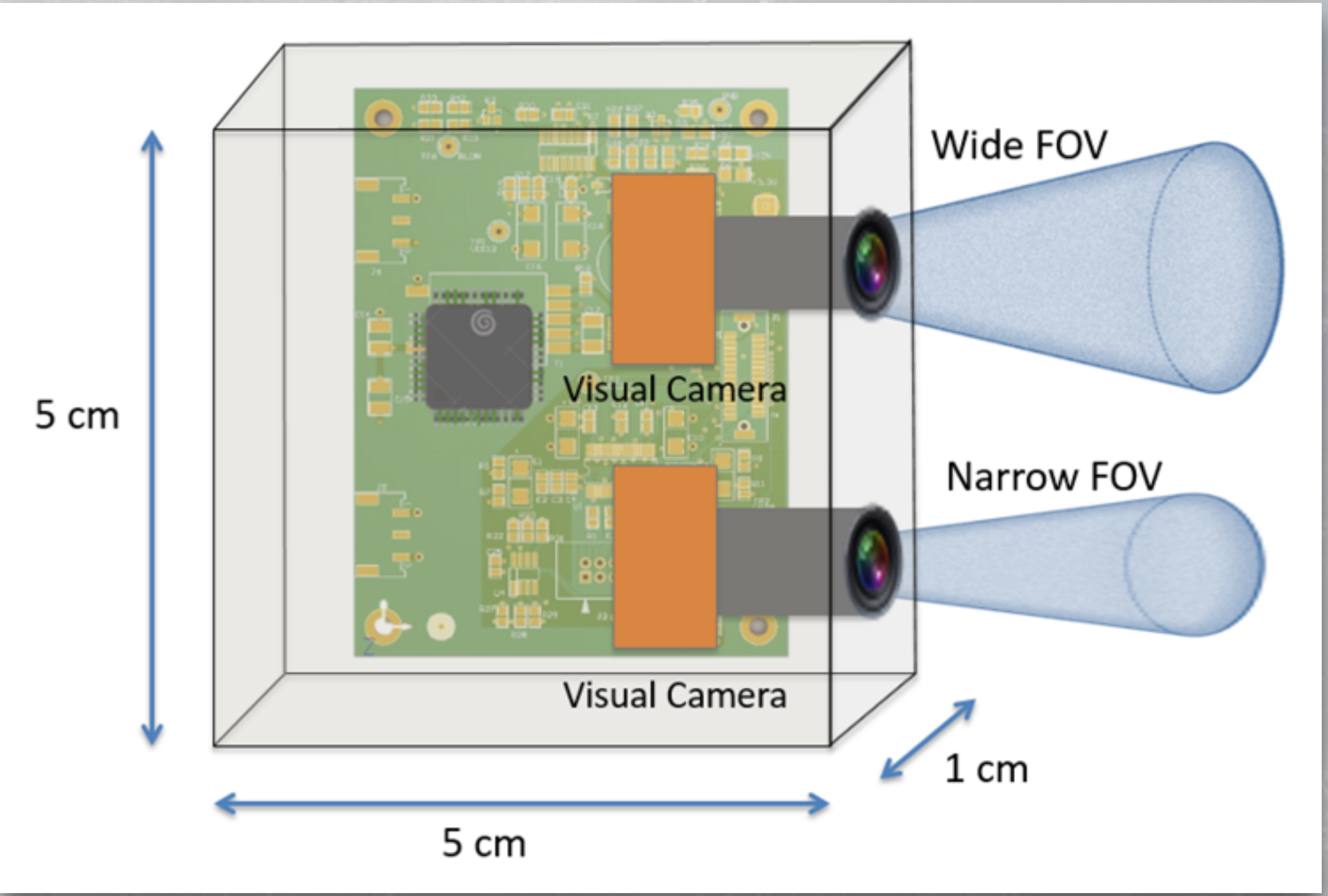
FUNCTION BLOCK DIAGRAM



BASELINE DESIGN

SENSOR PACKAGE

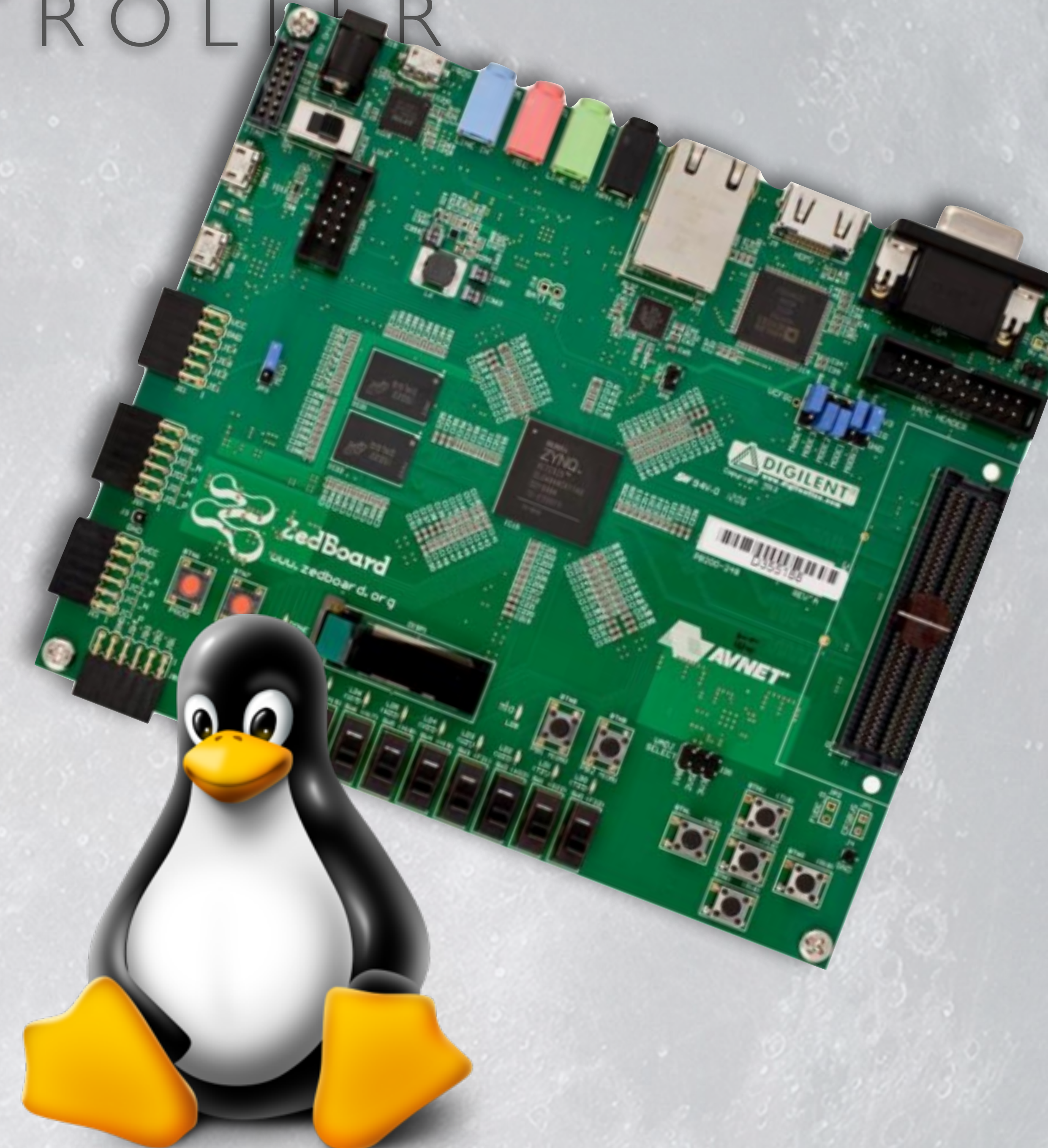
- **System with 2 FOVs in the visual light spectrum**
  - One wide (~50°) field of view
  - One narrow (~20°) field of view
- **Adaptable**
- **Easily tested**
  - Visual light is easy to produce & manipulate



BASELINE DESIGN

MICROCONTROLLER

- **ZedBoard running a Linux OS**
- **Interfacing**
  - Ethernet, 60 GPIO, HDMI, VGA, JTAG, USB-UART, etc.
- **Low Complexity**
  - No external breakouts necessary
- **Memory**
  - 4GB SD card, 512MB DDR3, 32MB flash



Images — zedboard.org/product/zedboard
Open Source

BASELINE DESIGN

TESTING METHOD

Lightbox

Dark Room

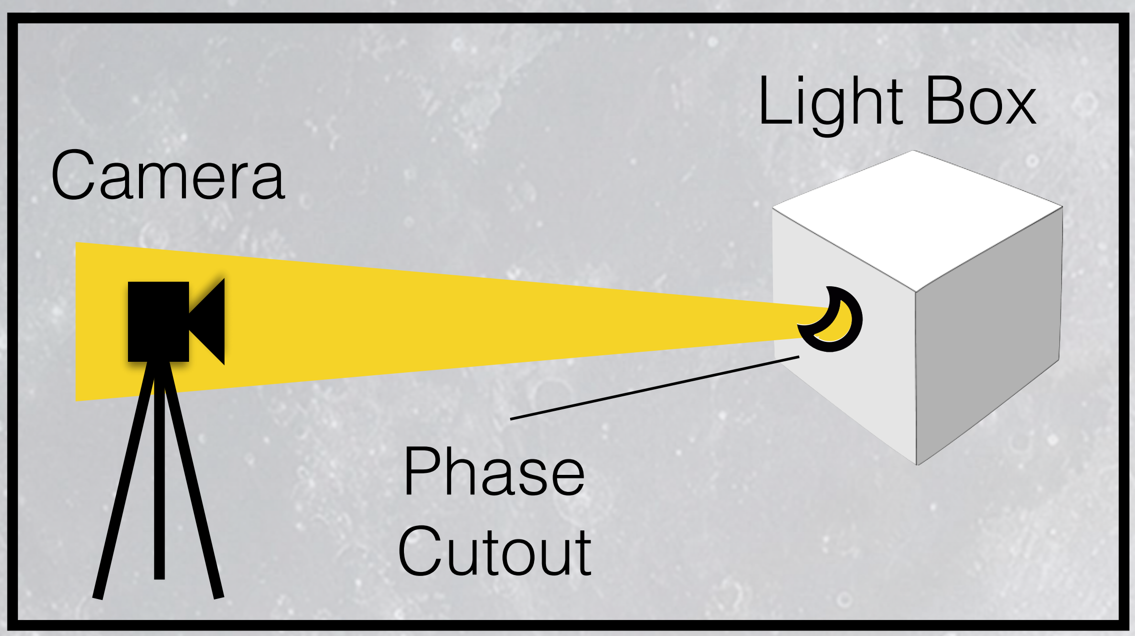
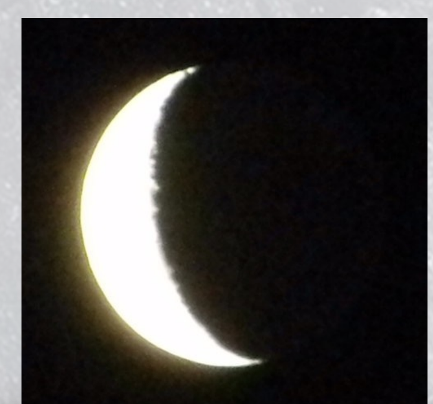


IMAGE CAPTURED



System Error Test

Projector

Dark Room

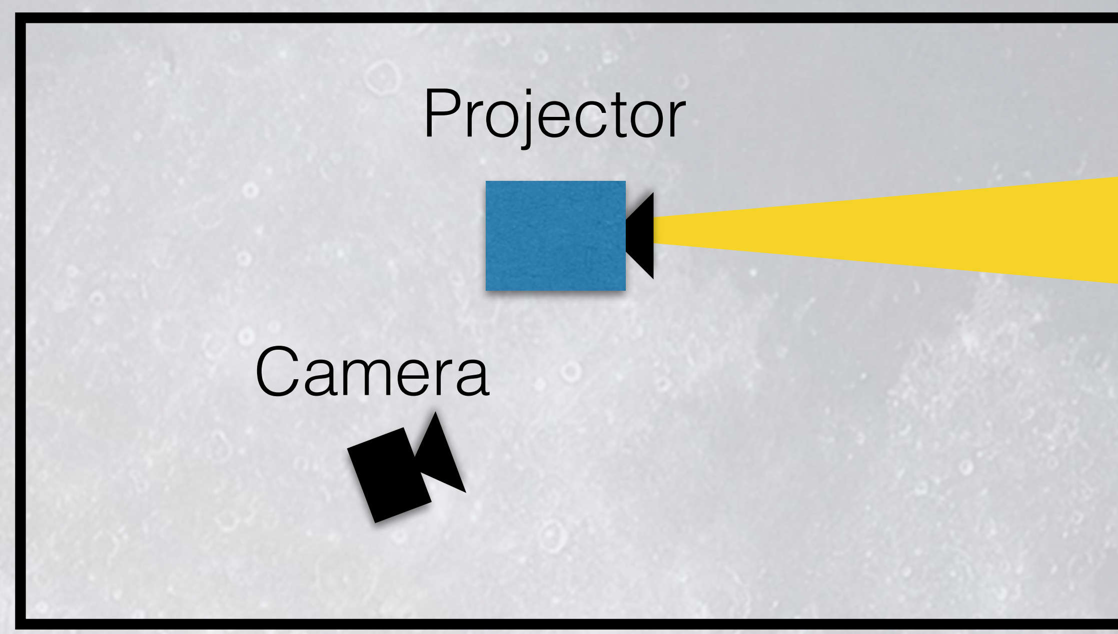


IMAGE CAPTURED

Image Processing Test

Images — kurld.com
coffeecurls.co.uk

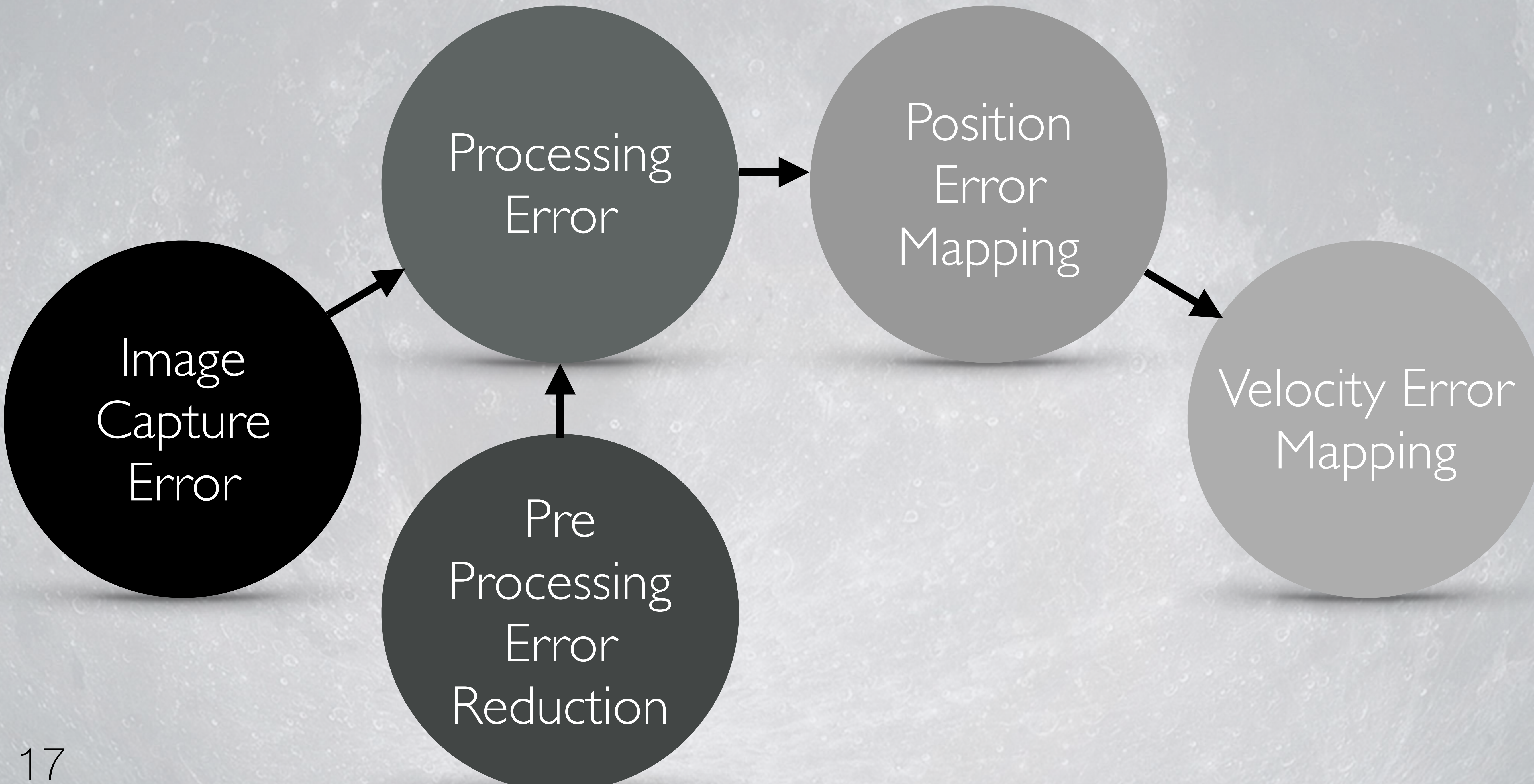
EVIDENCE OF FEASIBILITY

CRITICAL PROJECT ELEMENTS

ERROR	Will OPSRE be able to determine position and velocity within required accuracy?
INTERFACING, SIZE, WEIGHT, & POWER (iSWAP)	Will OPSRE be able to do this while staying within physical and electrical constraints and provide proper interfacing?
TEST	Can the accuracy be quantified through testing?

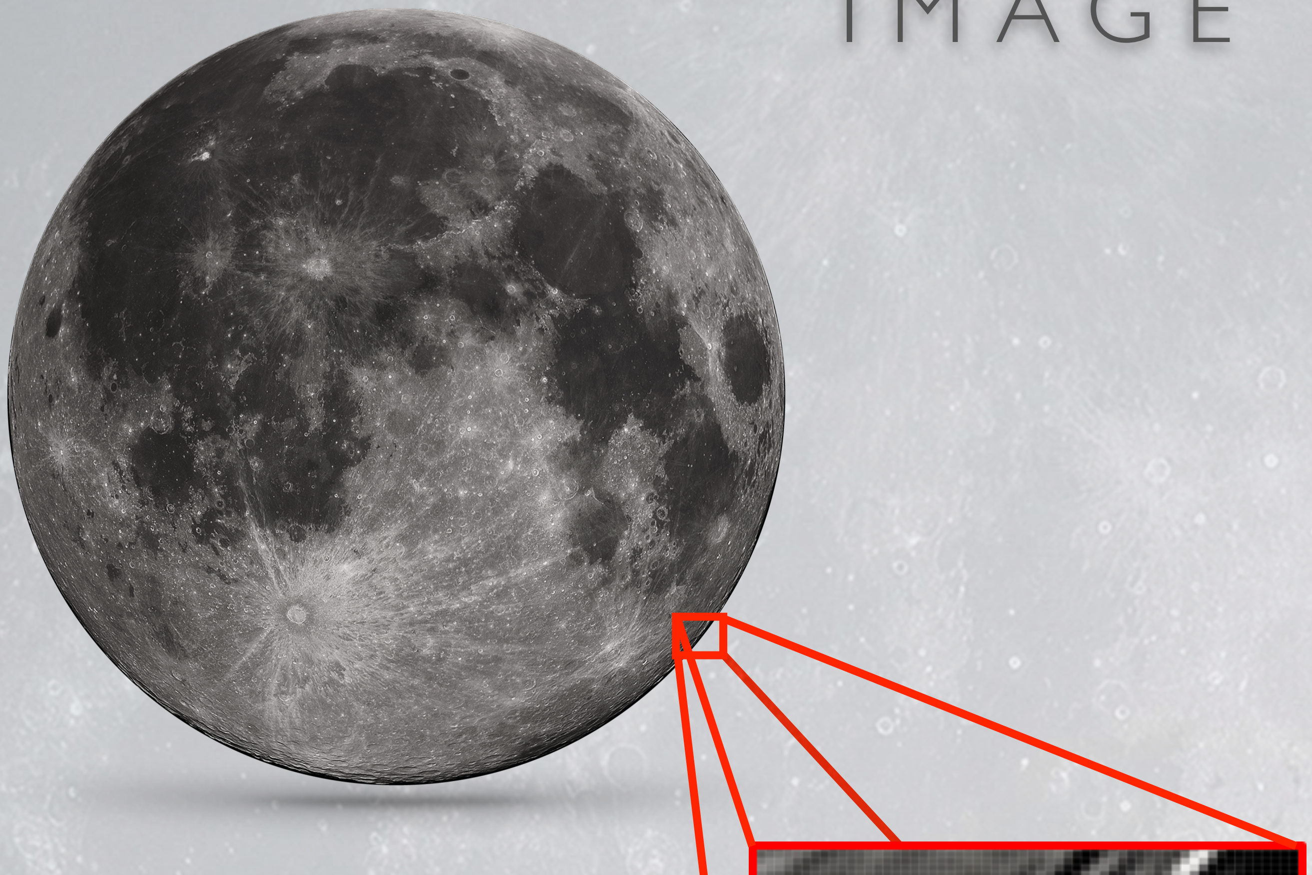
EVIDENCE OF FEASIBILITY

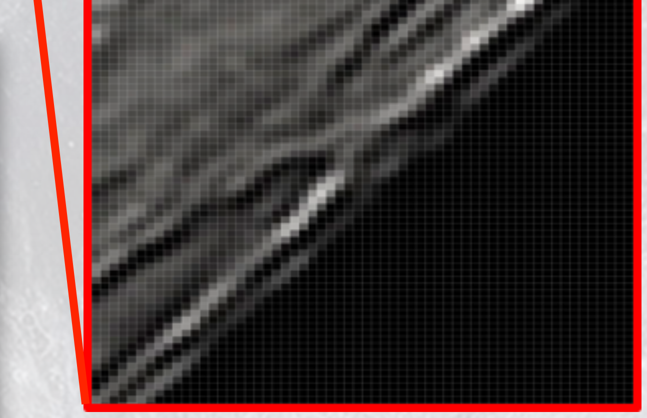
SOURCES OF ERROR

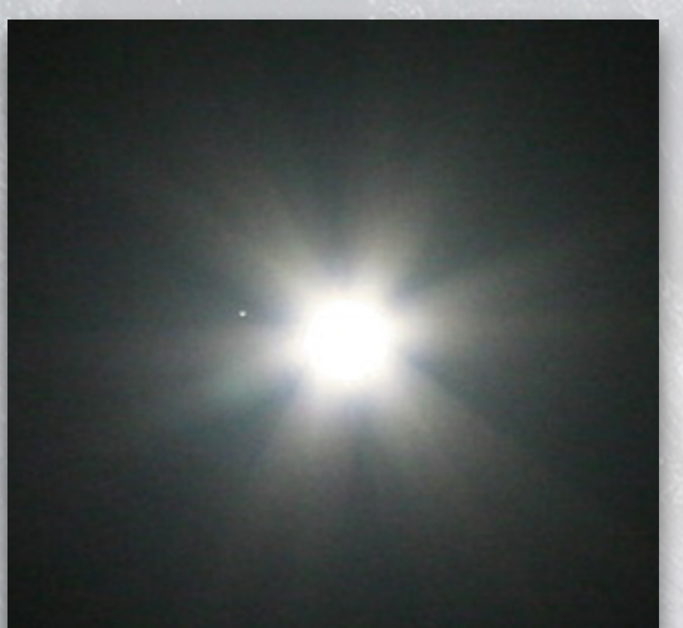


EVIDENCE OF FEASIBILITY

IMAGE ERROR







Errors associated with imaging hardware

- Pixelated lines reduce image processing accuracy
- Blur (over exposure, spacecraft motion)

Ways to account for this:

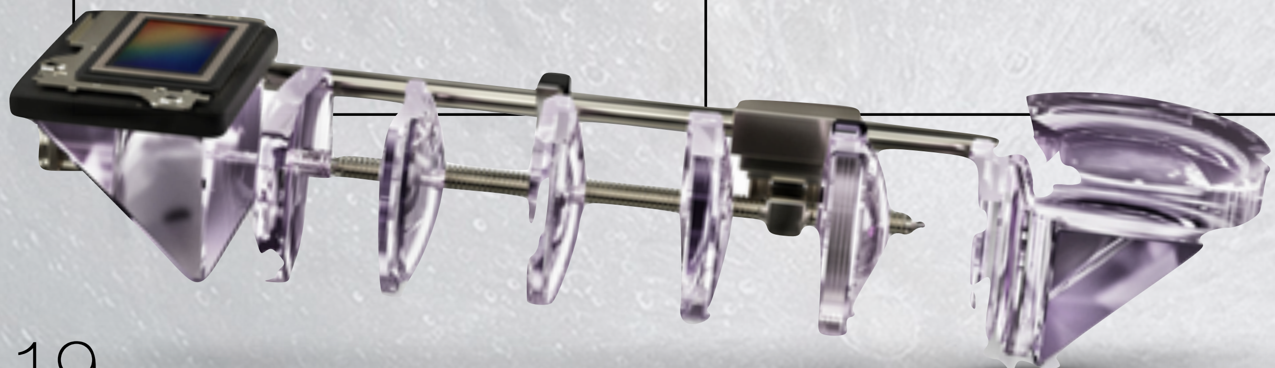
- High pixel to degree ratio
- Optimal exposure
- Faster shutter speed
- Neutral density filters

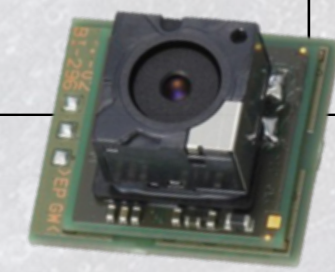
Images — http://pics-about-space.com/star-moon-saturn-and-spica?p=4
https://en.wikipedia.org/wiki/File:Full_Moon_Luc_Viatour.jpg

EVIDENCE OF FEASIBILITY

CAMERA OPTIONS

Option	ZenFone Zoom	Sony Compact Color Camera	Custom Lens
Pros	- Both wide and narrow field of view - High pixel/degree ratio (232 max) - Complete module	- Good for close proximity - Complete module - Easy integration	- Designed to fit - Narrow field of view options (~21°) - Sensor selection advantage
Cons	- Difficult to integrate	- Slightly too big (10.3 mm) - Poor for far proximity	- Sensor integration difficult - Quality of optics less known





Images — interest.com/cameras
asus.com/us/Phone/ZenFone-Zoom

EVIDENCE OF FEASIBILITY

PREPROCESSING TECHNIQUES

- Super Resolution Processing -

- Thresholding -

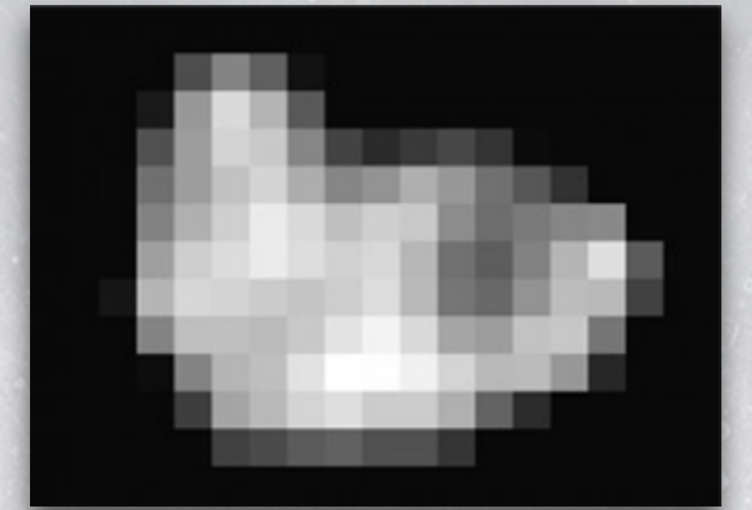
- High Dynamic Range Photography (HDR) -

- Sharpening -

- Noise Reduction -

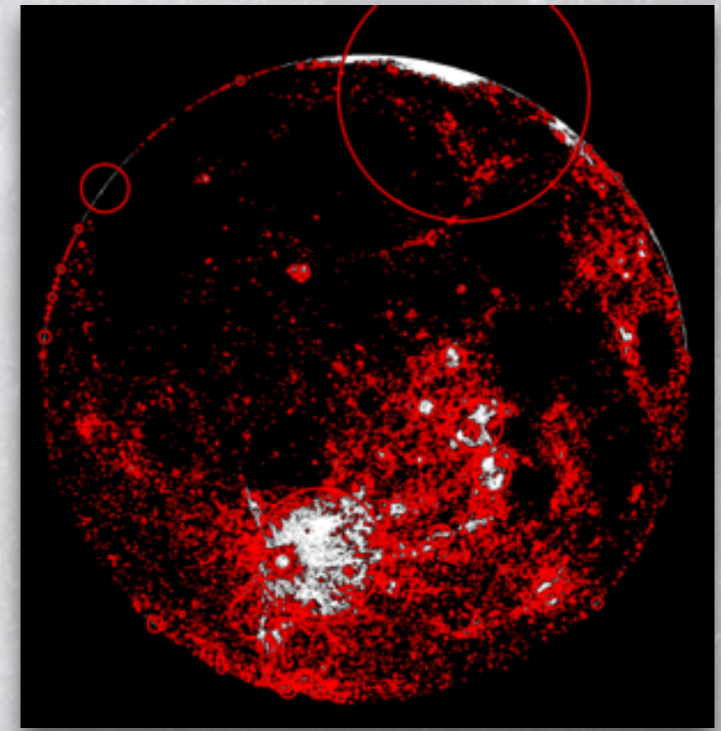
EVIDENCE OF FEASIBILITY

IMAGE PROCESSING ERROR



Sources of Error

- Image processing
- Edge detection



Ways to account for this:

- Image processing optimization
- Experimentation

Images — http://www.ign.com/boards
http://pics-about-space.com/

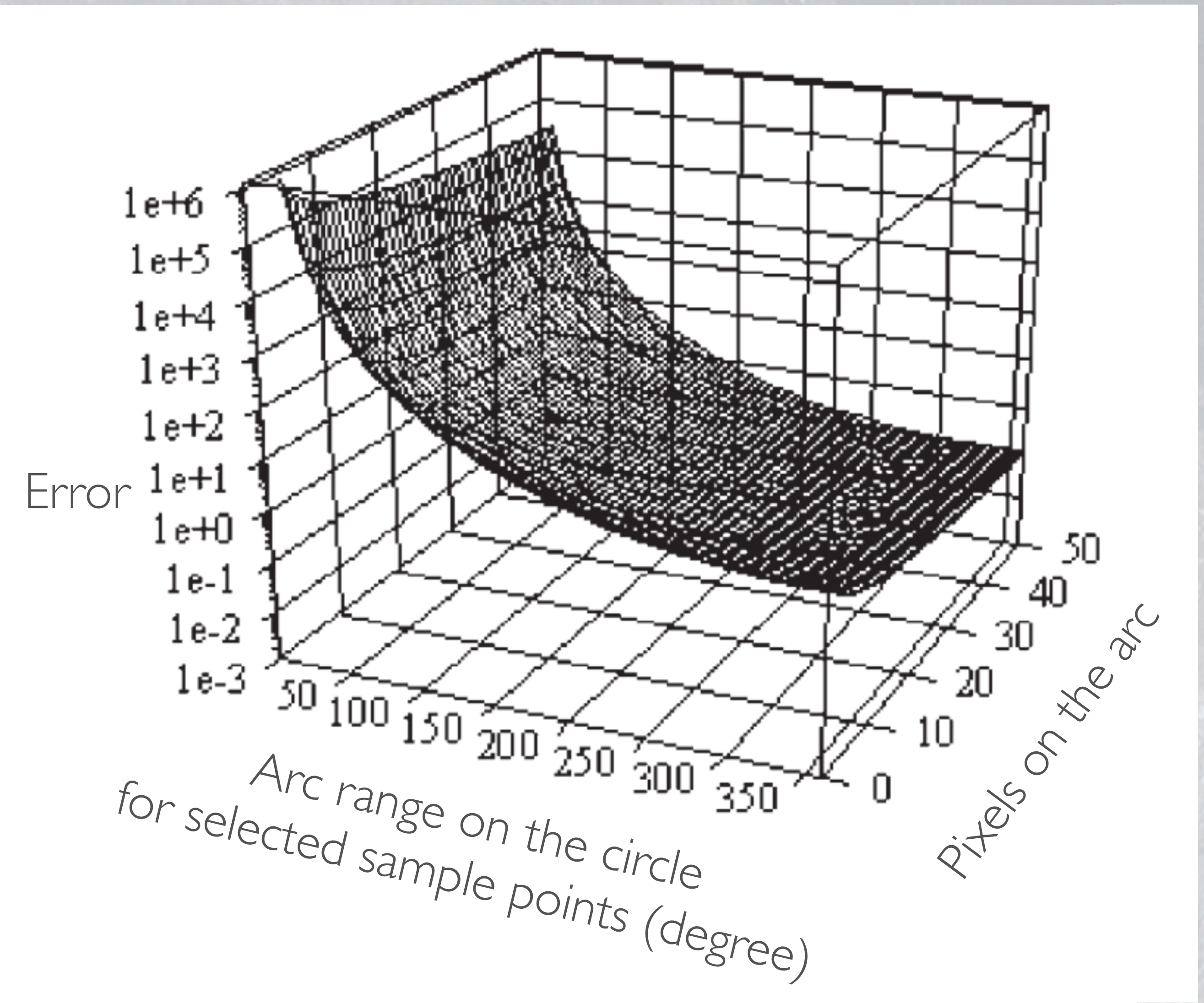
EVIDENCE OF FEASIBILITY

IMAGE PROCESSING ERROR

Error propagation studies from Q. Ji et. al. for circle fitting

With the Sony sensor, our baseline performance is limited to half phases

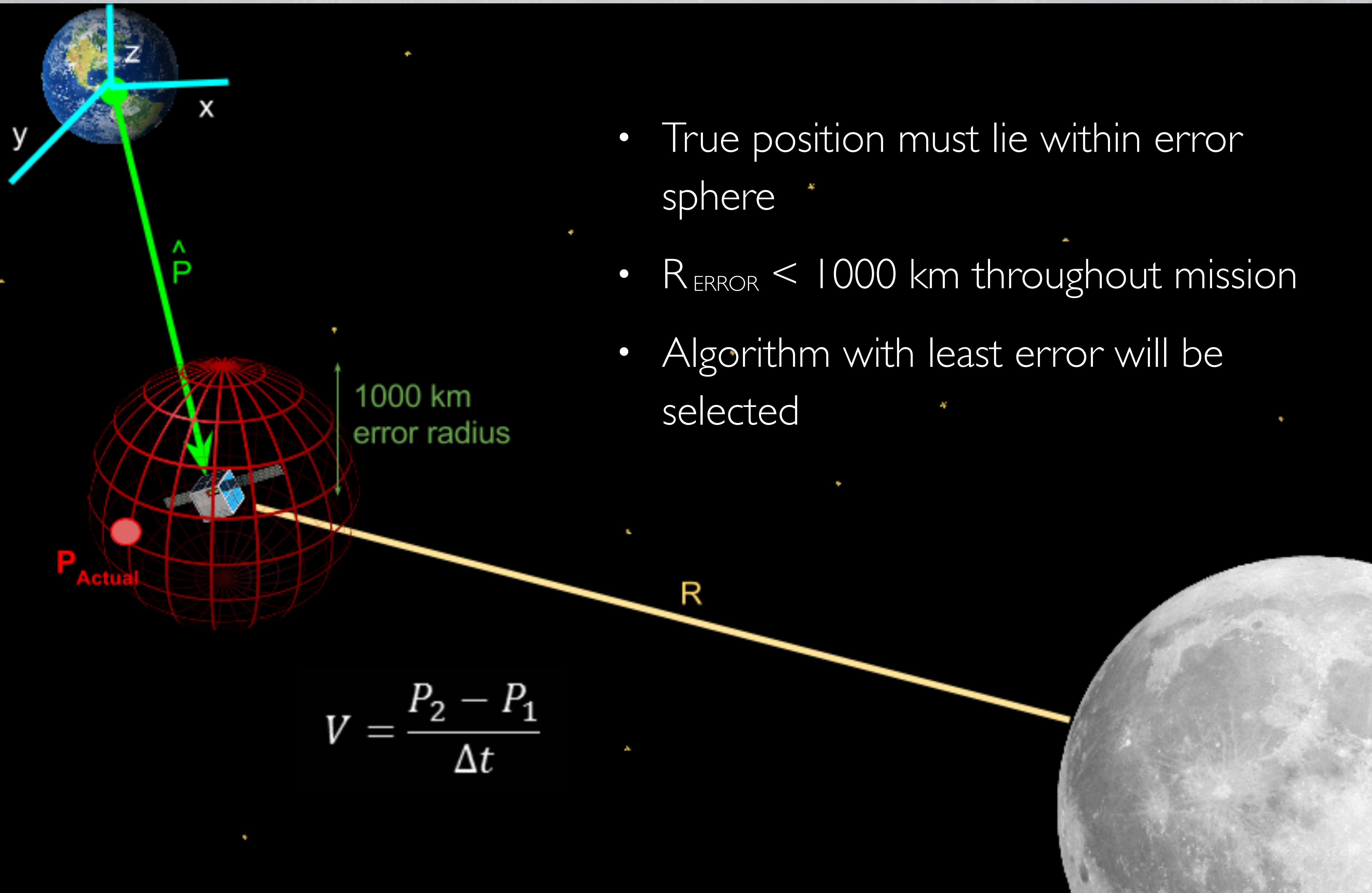
Higher resolution sensors and preprocessing can increase this capability



"Randomized through transform with error propagation for line and circle detection", Q. Ji, Y. Xie

EVIDENCE OF FEASIBILITY

POSITION & VELOCITY ERROR

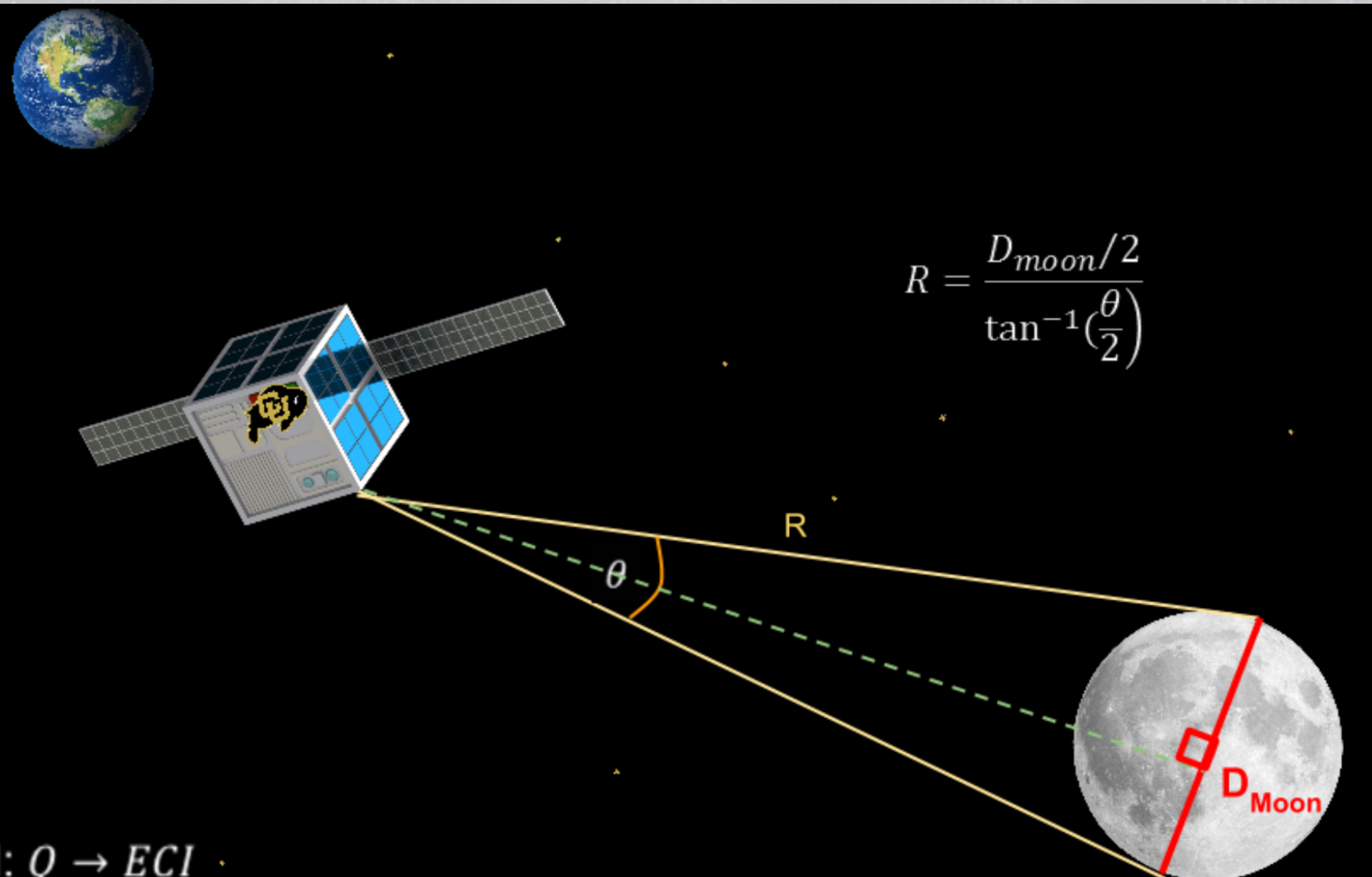


- True position must lie within error sphere
- R_{ERROR} < 1000 km throughout mission
- Algorithm with least error will be selected

$$V = \frac{P_2 - P_1}{\Delta t}$$

EVIDENCE OF FEASIBILITY

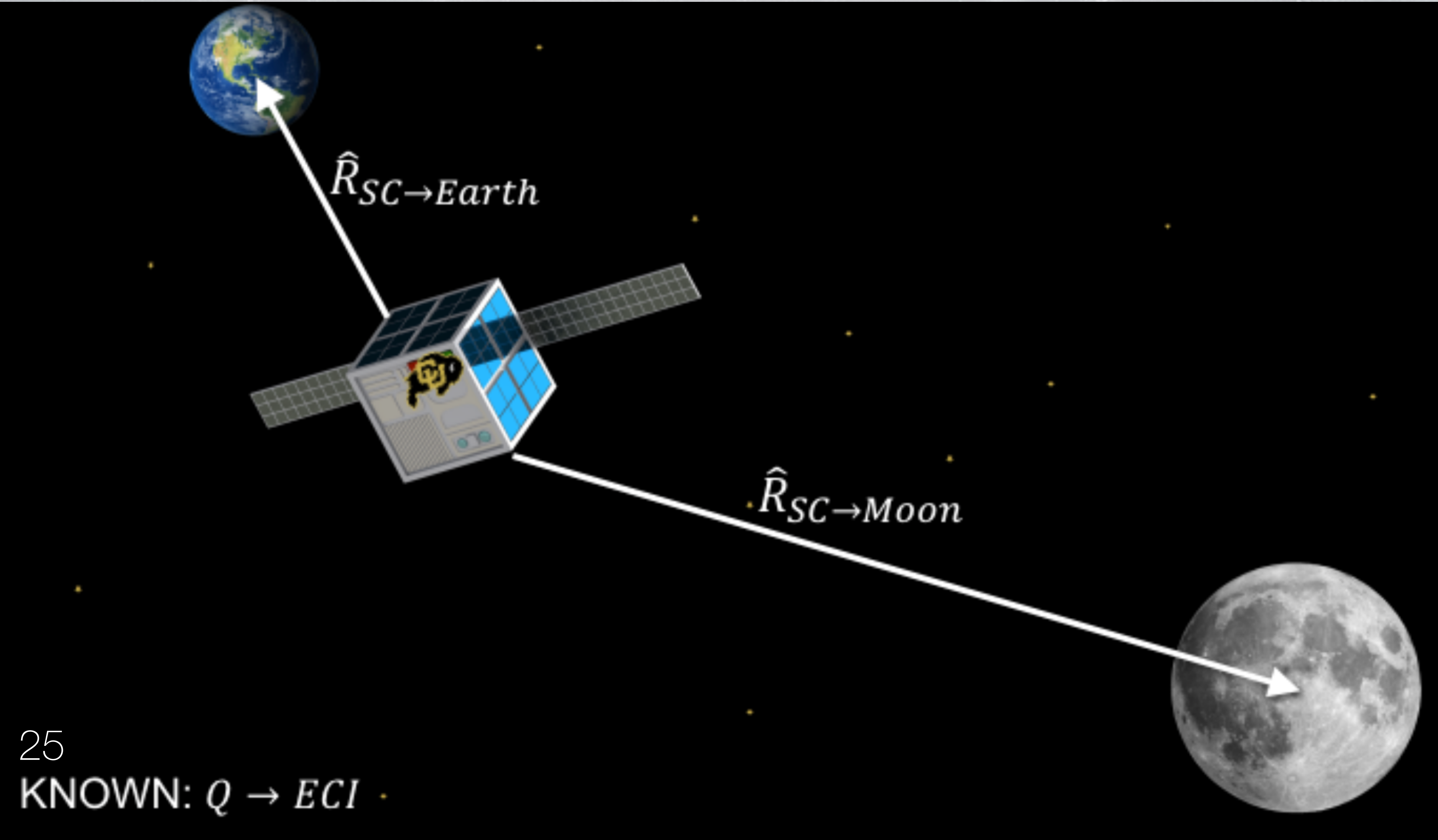
RANGING METHOD



KNOWN: $Q \rightarrow ECI$

EVIDENCE OF FEASIBILITY

ANGLES METHOD



KNOWN: $Q \rightarrow ECI$

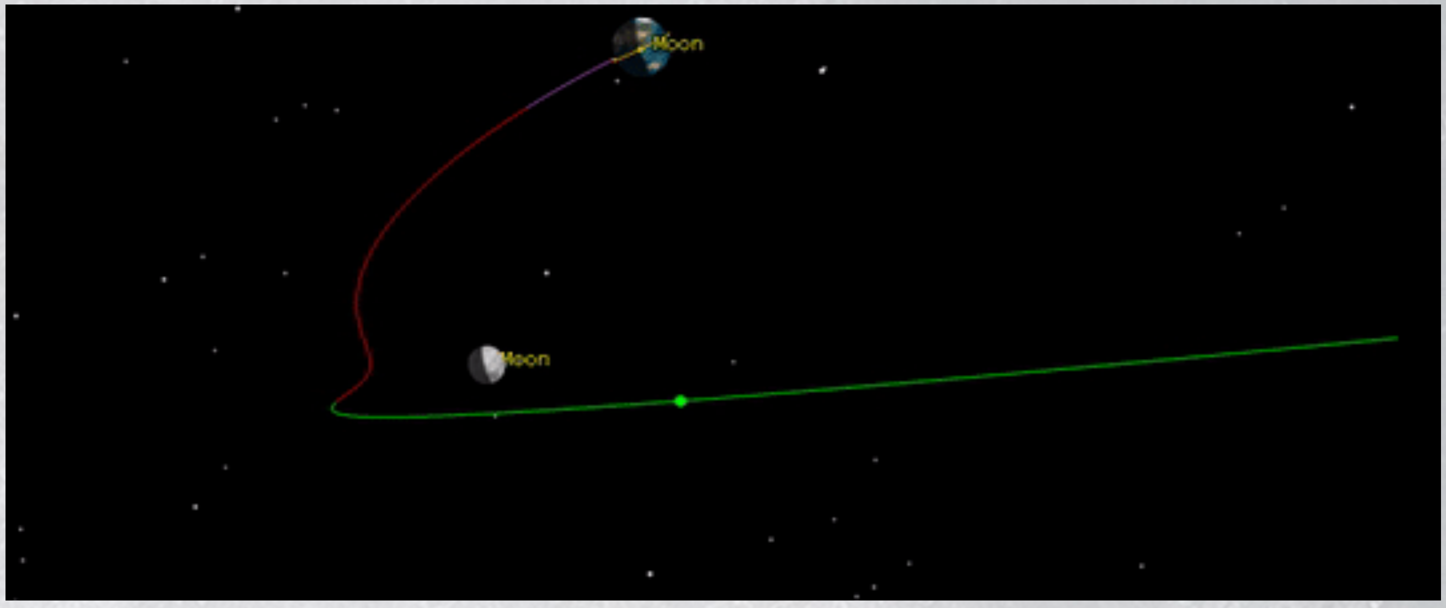
EVIDENCE OF FEASIBILITY

ORBIT DETERMINATION

STK Astrogator

Independent variables

- Launch epoch
- Maneuver thrust vector
- Duration in LEO

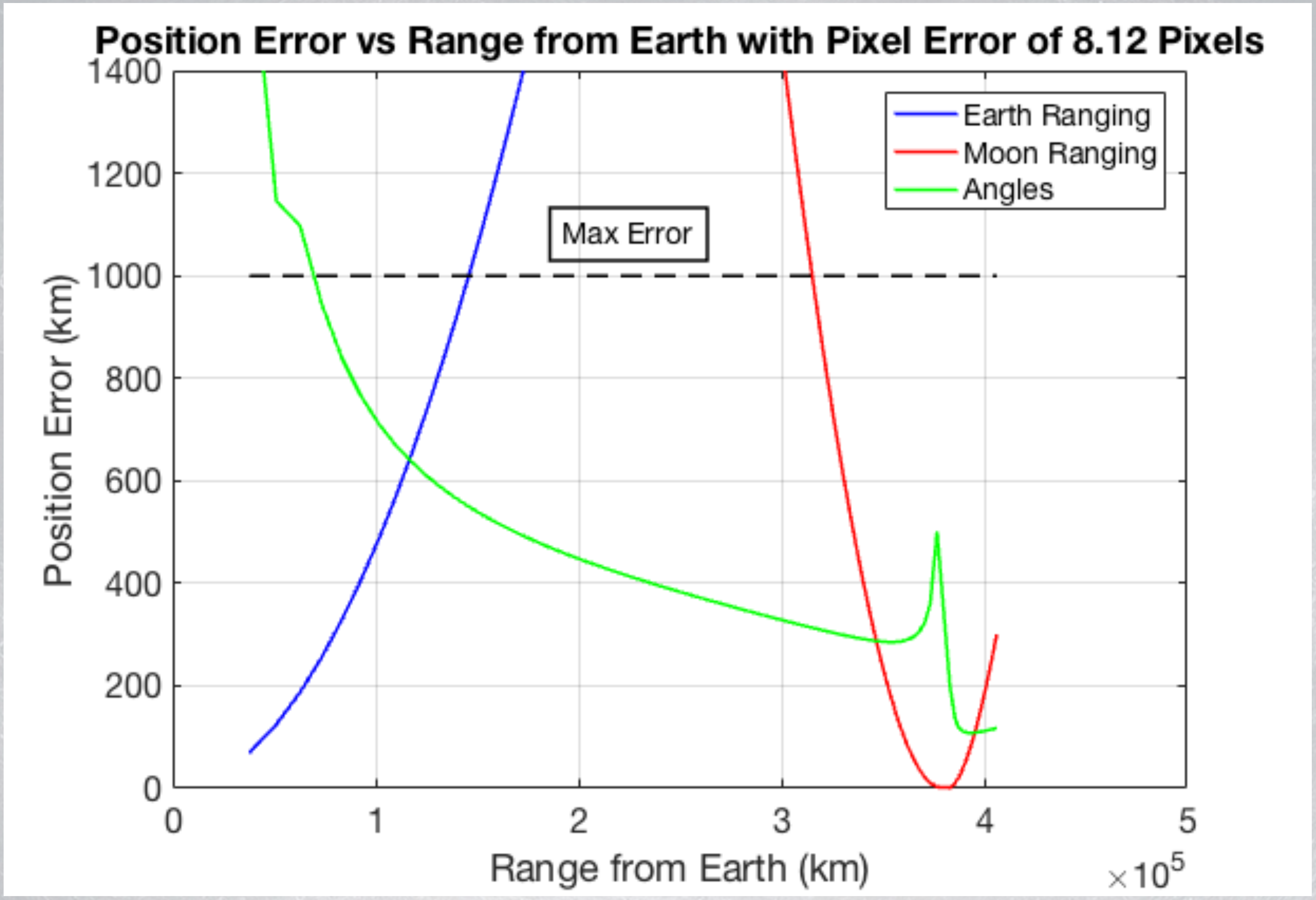


Dependent Variables

- Deploy altitude (30,000 km)
- 5 day transit
- Moon attitude (~300 km)

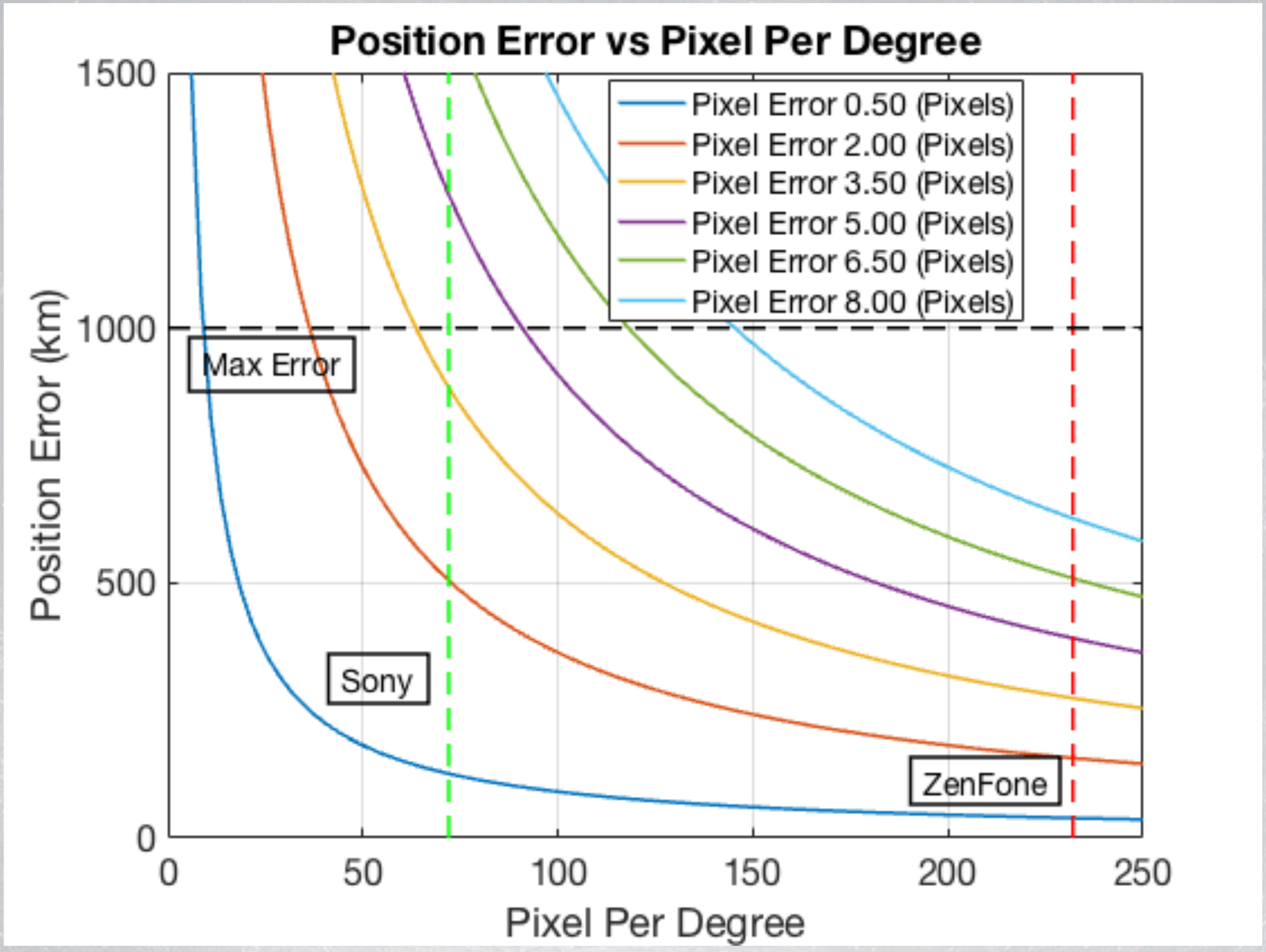
EVIDENCE OF FEASIBILITY

ERROR MODELING



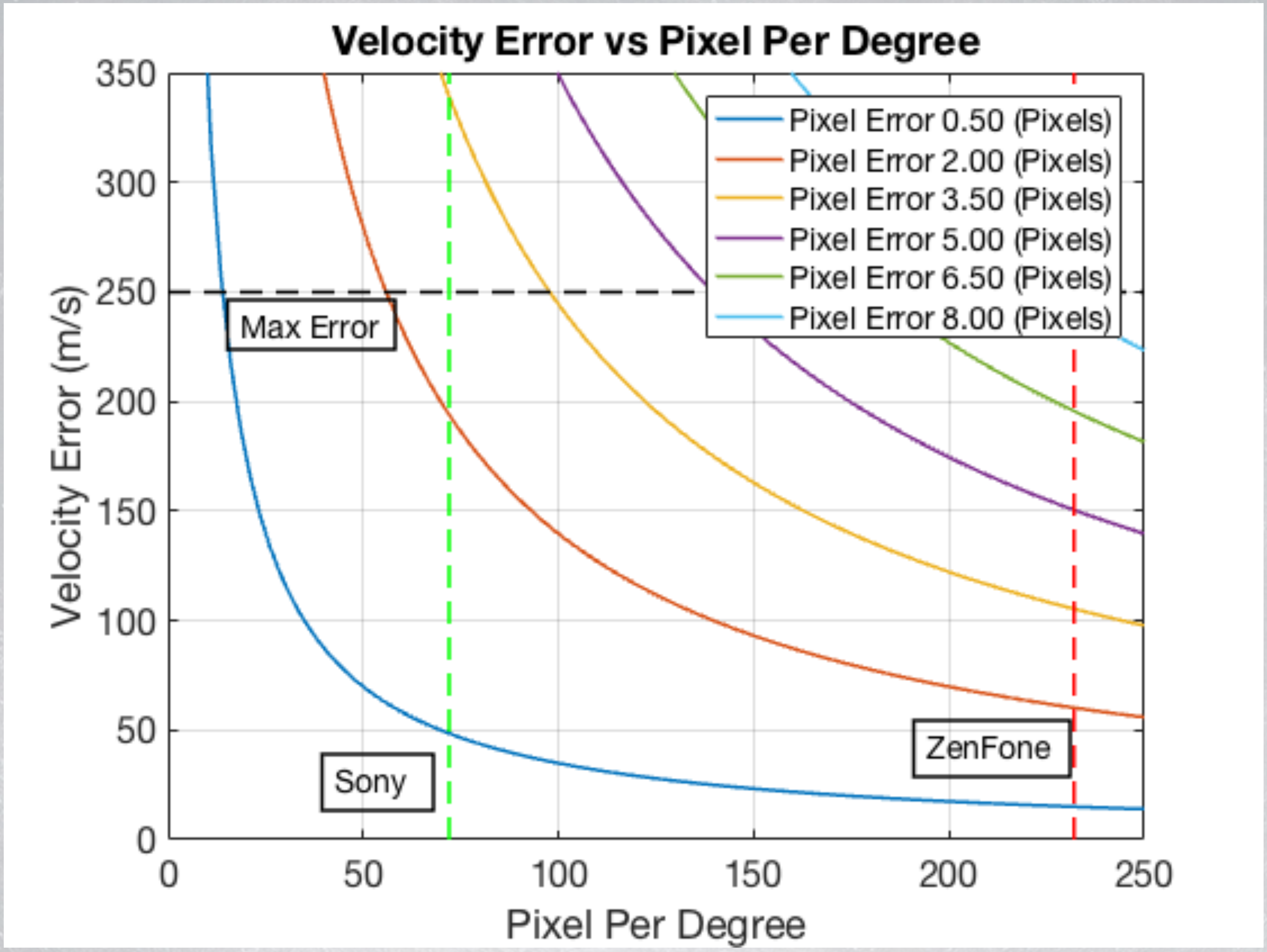
EVIDENCE OF FEASIBILITY

ERROR MODELING



EVIDENCE OF FEASIBILITY

ERROR MODELING



EVIDENCE OF FEASIBILITY

ERROR

Objective — Achieve accuracy requirements

With known values of pixel per degree, the necessary values of pixel error to meet position and velocity error requirements can be determined

	Sony Color Camera	**Asus ZenFone Optical Zoom Camera**
Pixel Error Requirement	2.52	8.12

EVIDENCE OF FEASIBILITY

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	Sony Color Camera	Asus ZenFone Optical Zoom Camera
Pixel Error Requirement	2.52	8.12

FEASIBLE

EVIDENCE OF FEASIBILITY

INTERFACING, SIZE, WEIGHT, & POWER

Purpose

- Determined feasibility of OSPRE hardware with respect to baseline design
- Conservatively identified non-trivial, required IC components
- Conducted dollar, mass, and volume cost analyses
- Built electrical power budgets
- Considered "manufacturability" within project limitations
- Addressed critical elements of interfacing
- **Primary Driver** — Image Sensor Package Integration
  - Remainder of PCB *supports* chosen sensor
  - 2 common interfaces — SPI and MIPI CSI-2

EVIDENCE OF FEASIBILITY

INTERFACING, SIZE, WEIGHT, & POWER

BOTH ARCHITECTURES	SPI & I^2C	SPI & MIPI CSI-2 with SOC
• Printed circuit board • Micro D-Sub/Molex connector • Input voltage regulators or filters • Temp. sensors, board-mounted (2) • SD storage and adaptor, SPI interface (1)	• Image sensors, SPI interface (2)	• Image sensors, MIPI CSI-2 and SPI interface (2) • System-On-Chip Microcontroller (e.g. Intel Atom, NXP, etc) • Image sensors, SPI interface (2)

EVIDENCE OF FEASIBILITY

INTERFACING, SIZE, WEIGHT, & POWER

Components, Arch. Option 1			**Cost (using Approx. Max)**				**Power Budget (Approx. Max)**		
Description	**QTY**	**Dollar**	**Mass**	**Real Estate**	**Height**	**Voltage**	**Current**	**Power**
		USD	**g**	**mm**	**mm**	**VDC**	**mA**	**mW**
PCB	1	100.00	20	NA	2	NA	NA	NA
I/O Connector, 15MDSub	1	25.00	10	15x24	8	NA	NA	NA
Voltage Regulators, Typical	4	8.00	4	6x24	2	As Req'd	24	120
Temp. Sensors, SPI	2	10.00	2	3x6	3	3.3,5	4.4	4
SPI/I2C Interface/Switch 1:4CH	1	5.00	1	8x5	3	5	0.02	0.1
Image Sensor Packages*	3	900.00	10	18x36	10	3.3,5	300	1400
SD Storage Package	1	8.00	4	32x26	4	3.3,5	150	750
	TOTAL:	1056.00	51	2042 mm^2	10		478.42	2274.1
	BUDGET:	2,000.00	800	2500 mm^2	10		500	3000
	MARGIN:	944.00	749	458	0		21.58	725.9

* Height includes PCB

EVIDENCE OF FEASIBILITY

INTERFACING, SIZE, WEIGHT, & POWER

Components, Arch. Option 1			Cost (using Approx. Max)			Power Budget (Approx. Max)		
Description	QTY	Dollar USD	Mass g	Real Estate mm	Height mm	Voltage VDC	Current mA	Power mW
PCB	1	100.00	20	NA	2	NA	NA	NA
I/O Connector, 15MDSub	1	25.00	10	15x[illegible]	8	NA	NA	NA
Voltage Regulators, Typical	4	8.00	4	6x4	2	[illegible]s Req'd	24	120
Temp. Sensors, SPI	2	10.00	[illegible]	[illegible]	3	3.3,5	4.4	4
SPI/I2C Interface/Switch 1:4CH	1	5.00	[illegible]	8x[illegible]	3	[illegible]	0.02	0.1
Image Sensor Packages*	3	900.00	10	8x[illegible]	10	3.3,5	300	1400
SD Storage Package	1	8.00	4	32x2[illegible]	4	3.3,5	150	750
TOTAL		1056.00	51	2042 mm^2	10		478.42	2274.1
BUDGET		[illegible],000.00	800	2500 mm^2	10		500	3000
MARGIN:		[illegible]4.00	749	458	0		21.58	725.9

* Height includes PCB

FEASIBLE

EVIDENCE OF FEASIBILITY

INTERFACING, SIZE, WEIGHT, & POWER

Components, Arch. Option 2		Cost Analysis (Approx. Max)				Power Budget (Approx. Max)		
Description	**QTY**	**Dollar**	**Mass**	**Real Estate**	**Height**	**Voltage**	**Current**	**Power**
		USD	**g**	**mm**	**mm**	**VDC**	**mA**	**mW**
PCB	1	100.00	20	NA	2	NA	NA	NA
I/O Connector, 15MDSub	1	25.00	5	15x24	8	NA	NA	NA
Voltage Regulators, Typical	4	8.00	4	6x24	2	As Req'd	24	120
Thermocouples, SPI	2	10.00	2	3x6	3	3.3,5	4.4	4
SOC Microprocessor	1	100.00	20	25x27	3	3.3,5	TBD*	TBD*
Image Sensor Packages*	3	800.00	6	18x36	10	3.3,5	300	1400
TOTAL		1,043.00	57	1845 mm^2	10		328.4	1524
BUDGET		2,000.00	800	2500 mm^2	10		500	3000
MARGIN		957.00	743	655	0		171.6	1476

* Height includes PCB

EVIDENCE OF FEASIBILITY

INTERFACING, SIZE, WEIGHT, & POWER

Components, Arch. Option 2		Cost Analysis (Approx. Max)				Power Budget (Approx. Max)		
Description	**QTY**	**Dollar**	**Mass**	**Real Estate**	**Height**	**Voltage**	**Current**	**Power**
		USD	**g**	**mm**	**mm**	**VDC**	**mA**	**mW**
PCB	[illegible]	100.0[illegible]	20	NA	2	NA	NA	NA
I/O Connector, 15MDSub	[illegible]	25.00	5	15x24	8	NA	NA	NA
Voltage Regulators, Typic[illegible]	[illegible]	8[illegible]	[illegible]	6x24	2	As Req'd	24	120
Thermocouples, SPI	[illegible]	[illegible]	[illegible]	[illegible]	3	3.3,5	4.4	4
SOC Microprocessor	[illegible]	[illegible]	20	[illegible]	3	[illegible]	TBD*	TBD*
Image Sensor Packages*	3	800.[illegible]	[illegible]	[illegible]36	10	[illegible]3.3,5	[illegible]	1400
TOTAL		1,043.00	57	1845 mm^2	[illegible]		[illegible]28.4	1524
BUDGET		2,000.00	800	2500 mm^2	[illegible]		500	3000
MARGIN		957.00	743	655	0		[illegible]	1476

* Height includes PCB

FEASIBLE

EVIDENCE OF FEASIBILITY

TESTING PHASES

1 Software Validation

2 Hardware Testing

3 Mission Simulation

EVIDENCE OF FEASIBILITY

TESTING STUDIES

Conducted Studies		Rationale
Introduction of Error	→	Most Vital to Test Design
Facility Requirements	→	Limited Facility Resources
Cost Estimate	→	Limited Budget
Manufacturing	→	Limited Time and Tools

EVIDENCE OF FEASIBILITY

LIGHTBOX ERROR

**LIGHTBOX
SOURCES OF ERROR**

Phase Shape
Cutting

Range from Camera
to Light Source

EVIDENCE OF FEASIBILITY

PHASE SHAPE ERROR

METHOD	ACCURACY	CONCERNS
Laser Cutter (ITLL)	±0.01”	Material limitations, accuracy
Self Machining	0.001” - 0.004”	Loss of sharp corners, measuring machine accuracy
Waterjet Machining	0.001” - 0.002”	Cost to manufacture

Laser Cutter Data — www.epiloglaser.com/products
Self Machining — www2.mae.ufl.edu/designlab/Lab%20Assignments/EML2322L-Tolerances.pdf
Waterjet Accuracy — waterjets.org

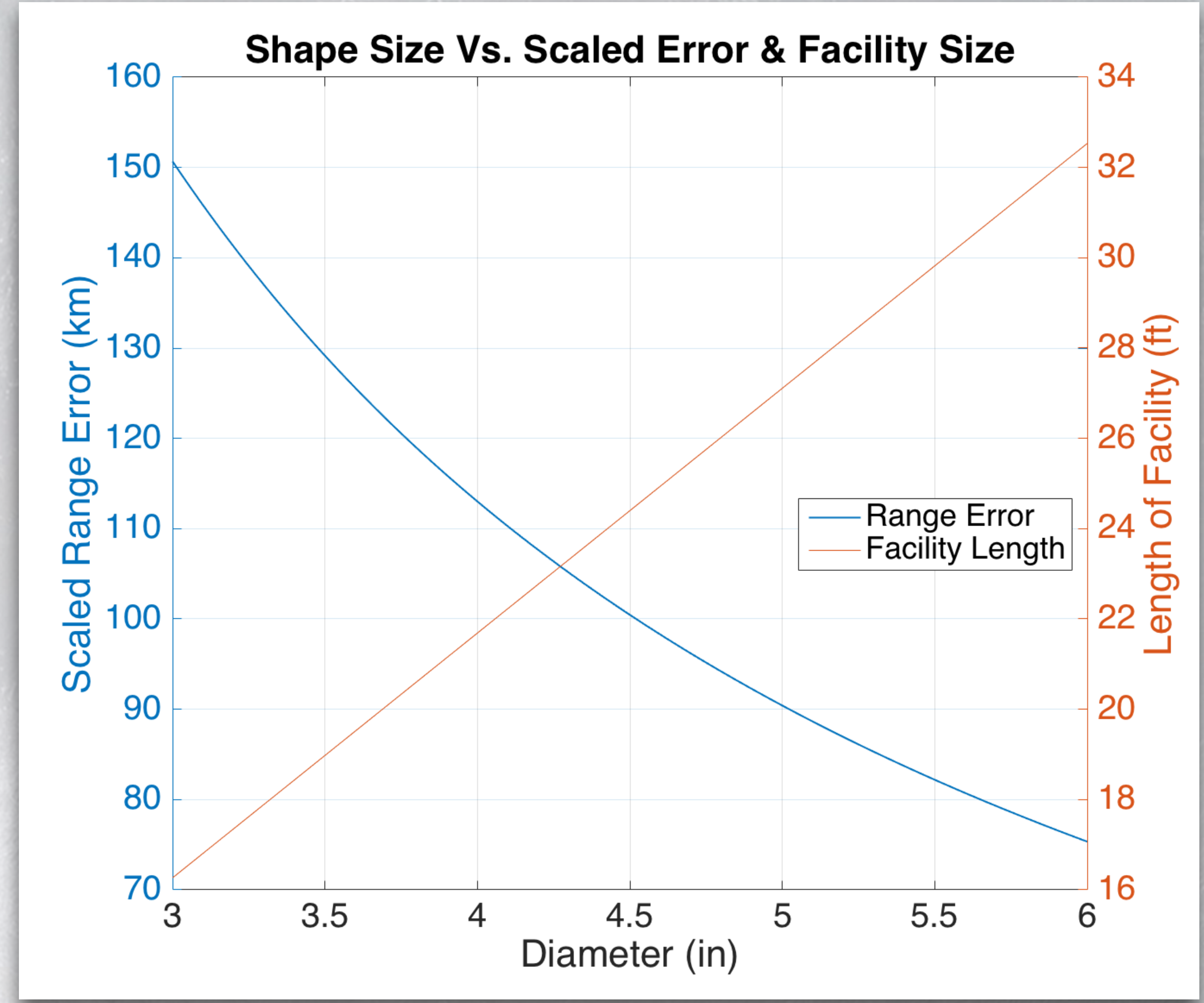
EVIDENCE OF FEASIBILITY

ERROR MODELING

MILLING TO 0.002" OF ACCURACY

WORST CASE TESTING SCENARIO

Angular Diameter = 0.8806°
Scaled Distance = 226,030 km



EVIDENCE OF FEASIBILITY

RANGE ERROR

APPROACH

What is the minimal error our team can achieve without adding significant cost (>$200), complexity, or time investment?

↓

Is that minimal error sufficient?

EVIDENCE OF FEASIBILITY

RANGE OPTIONS

METHOD	COST	ACCURACY	PREP DIFFICULTY	HUMAN ERROR
Steel tape measure	None	(±1.1mm)[1]	Minimal	Significant
Laser range finder	$127	±1.5 mm[2]	Minimal	Minimal
Optical measurement	None	Dependent on focal length accuracy (~5%)[3] & resolution	Significant	Minimal

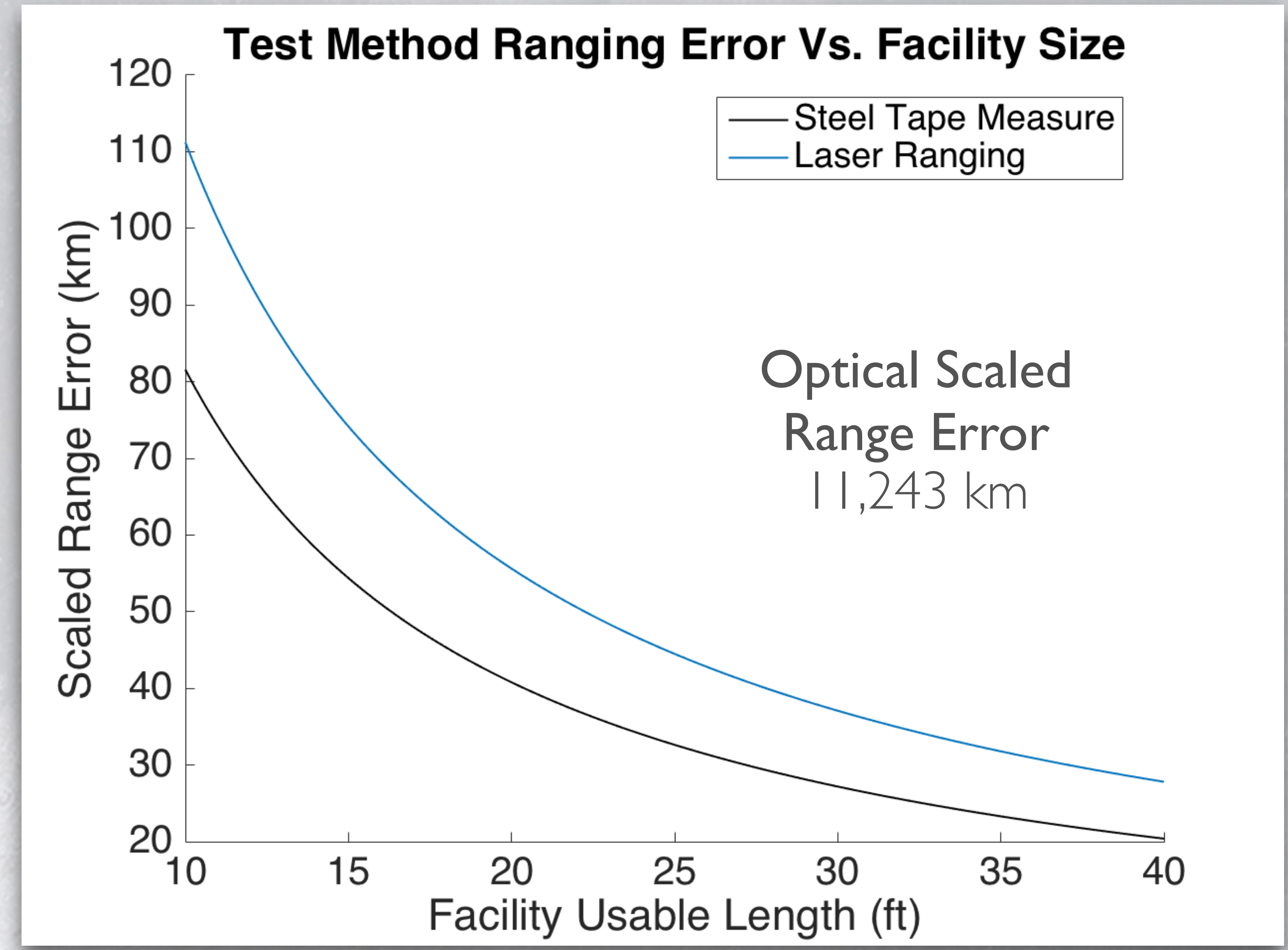
1 http://www.hultafors.com
2 https://www.pce-instruments.com
3 canon.com\products

EVIDENCE OF FEASIBILITY

ERROR MODELING

WORST CASE TESTING SCENARIO

Angular Diameter = 0.8806°
Scaled Distance = 226,030 km



Optical Scaled Range Error
11,243 km

EVIDENCE OF FEASIBILITY

TESTING SUMMARY

STUDIES

	LIGHTBOX	PROJECTOR
Error Reduction / Model	Falls within feasible range	NA
Facility Requirements	- Dark Room - - Larger the Better -	- Dark Room - - Projector -
Cost Estimate	$253	Negligible
Manufacturing Requirements	- Basic Wood Tools - - Laser Cutter - - Light Bulbs -	Negligible

EVIDENCE OF FEASIBILITY

TESTING SUMMARY

STUDIES

	LIGHTBOX	PROJECTOR
Error Reduction / Model	Falls within feasible range	NA
Facility Requirements	- Dark Room - - Larger the Better -	- Dark Room - - Projector -
Cost Estimate	$253	Negligible
Manufacturing Requirements	- Basic Wood Tools - - Laser Cutter - - Light Bulbs -	Negligible

FEASIBLE

STATUS SUMMARY

FEASIBILITY RECAP

- Image sensor system delivers high enough pixel/deg
- Nav Package architecture can be tailored to multiple sensor types
- Feasible options for detecting circles/centers
- Can implement multiple algorithms that drive down error at different locations in orbit
- Multiple options for testing all aspects of design (hardware and software)
- Prospective Dark Testing Area — **ECEE 2B49A**

STATUS SUMMARY

BUDGET

		Cost + Shipping (USD)	
Item	**Description**	**Architecture 1**	**Architecture 2**
Image Sensors	Cell phone or system on a chip sensor	$900	$800
Electrical Components	Components necessary for system operation	$156	$243
Test Equipment	Hardware/software necessary to experimentally validate system	$253	$253
Test Console	ZedBoard microcontroller simulating spacecraft GNC computer	$483	$483
	Sub-Total	$1,792	$1,779
	20% Margin	$1,000	$1,000
	TOTAL	$2,792	$2,779

STATUS SUMMARY

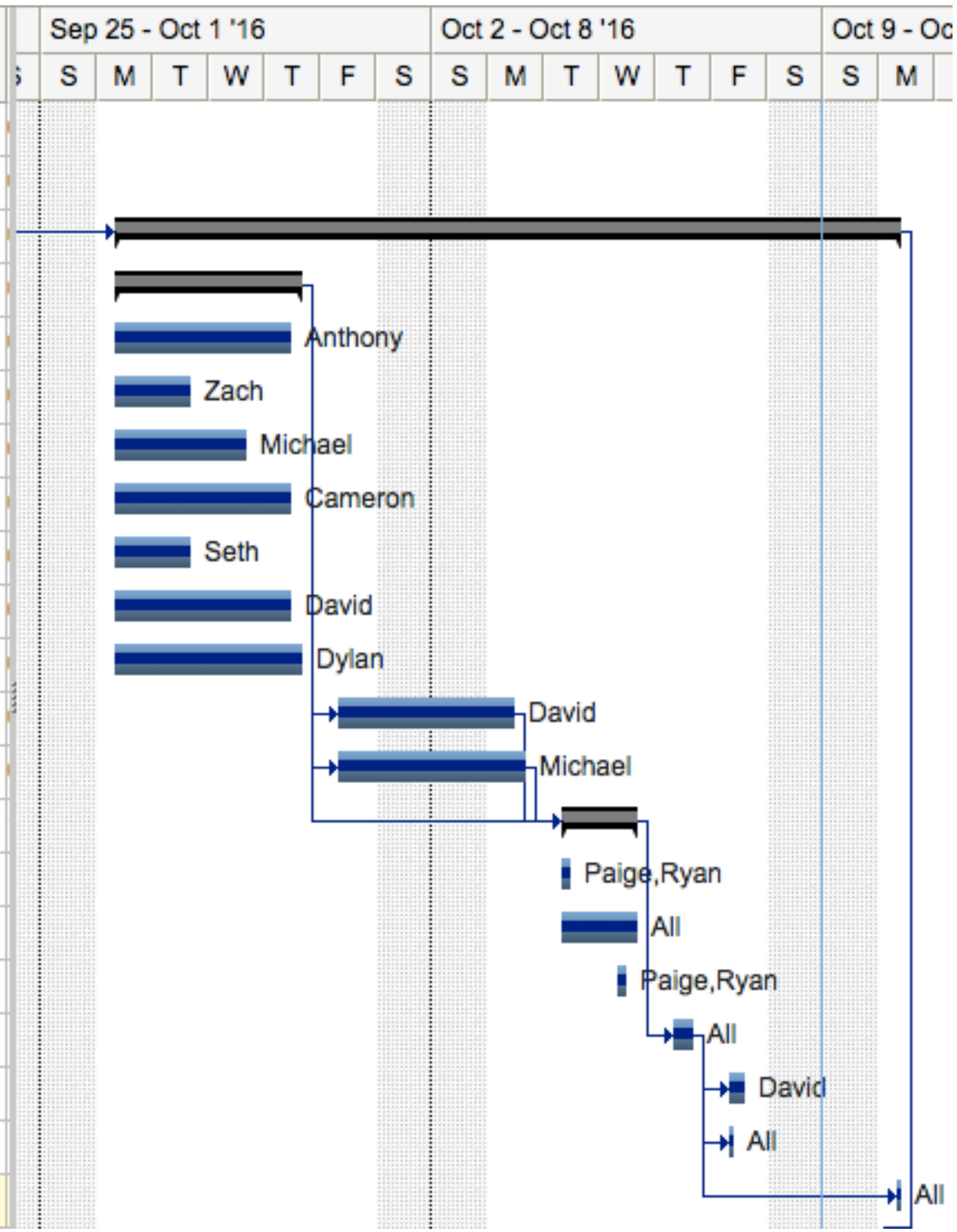
FURTHER STUDIES

- Image sensor system delivers high enough pixel/deg
- Nav Package architecture can be tailored to multiple sensor types
- Feasible options for detecting circles/centers
- Can implement multiple algorithms that drive down error at different locations in orbit
- Multiple options for testing all aspects of design (hardware and software)
- Prospective darkroom for testing **(ECEE 2B49A)**

STATUS SUMMARY

GANTT CHART

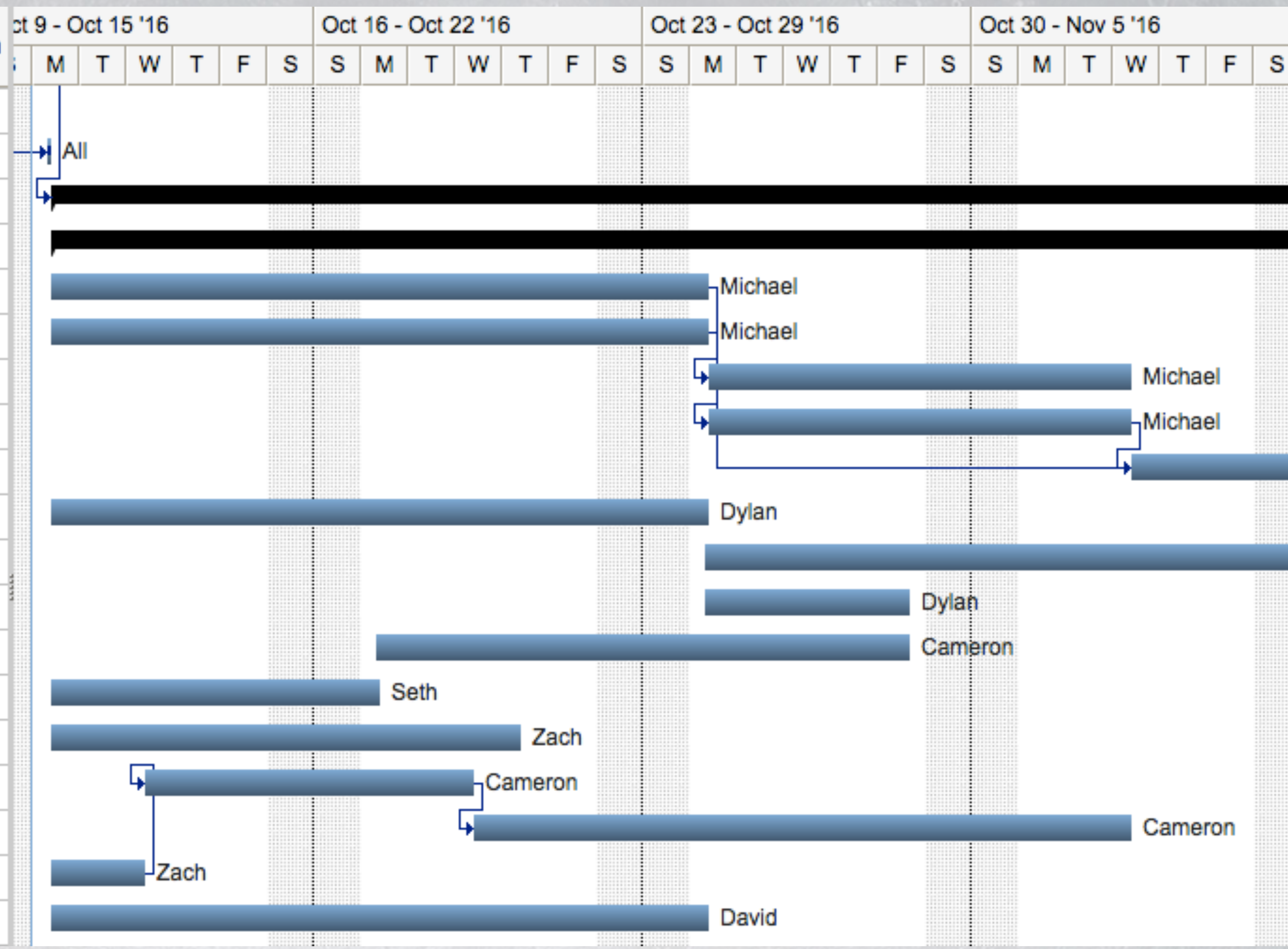
Name	Duration
PDD	10d
CDD	10d
⊟ **PDR Presentation**	**10.25d**
⊟ **Data Acquisition Research**	**4d**
Research Image Processing	3.5d
Create STK Ephemeris	2d
Research Electrical Components	3d
Research Positioning Algorithms	3.5d
Research Velocity Algorithms	2d
Research Exposure Software	3.5d
Research Optics Options	4d
Test Research	1.5d
Interfacing Research	2d
⊟ **Preliminary PDR Content**	**2d**
Project Description	0.5d
Feasability	2d
Summary	0.5d
Edits	1d
Format	0.75d
Dry Run	0.25d
Dry Run	0.25d



STATUS SUMMARY

GANTT CHART

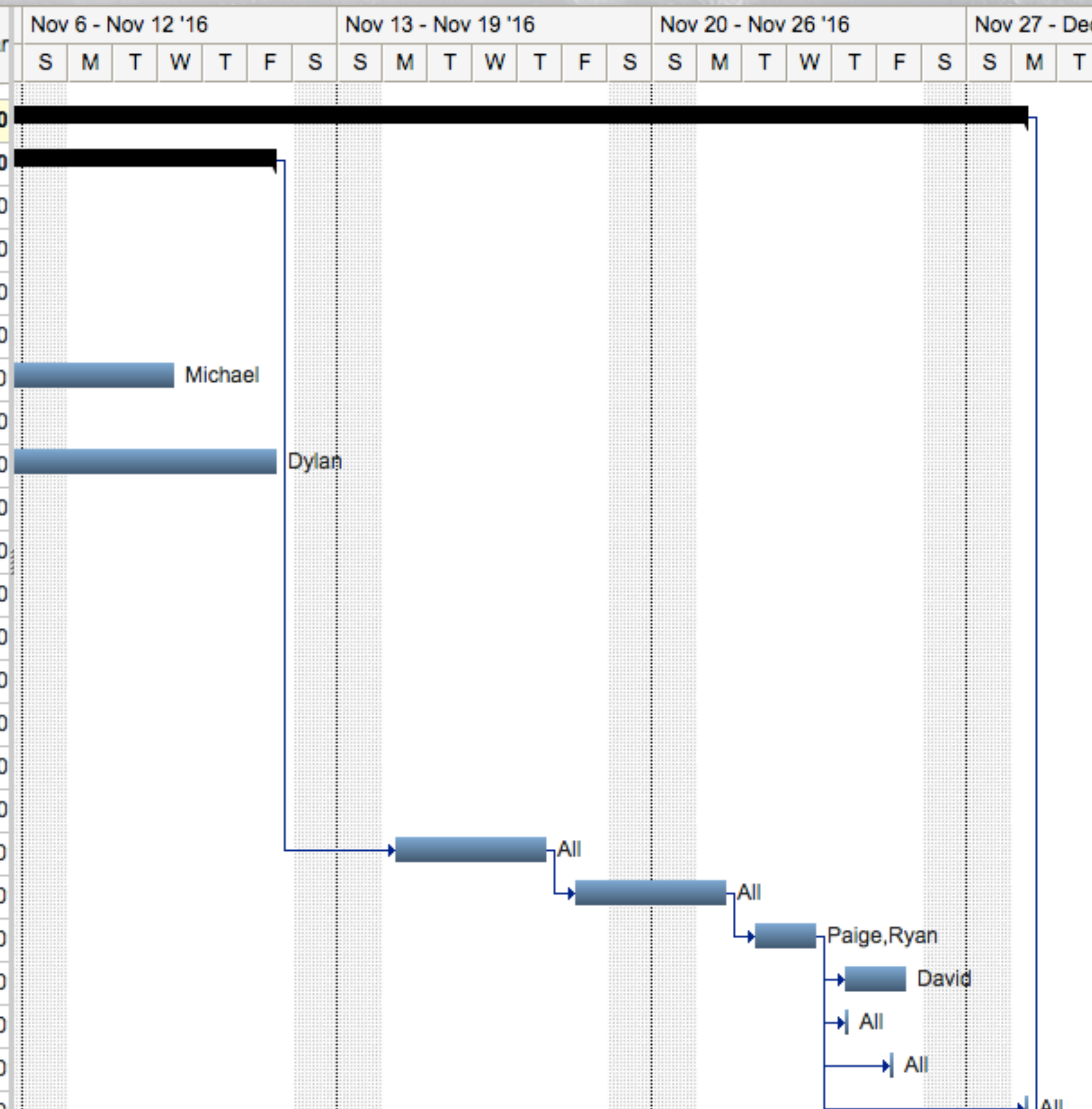
Name	Duration
Dry Run	0.25d
Dry Run	0.25d
⊟ **CDR**	**35d**
⊟ **Research**	**24.75d**
Component Research and Selection	10d
C Temp Sensor Research and Selecti	10d
Define EPS Requirements	7d
Define Data Distribution Requirements	7d
Define External Interface	5d
Research flight lighting conditions	10d
Research exposure time for cameras	15d
Research interfacing for cell phone ca	5d
Research filtering	10d
Create software flowdown	5d
Research material for physical interfa	8d
Research more robust position solutio	5d
Research more robust velocity solutio	10d
Create multiple trajectories in STK	2d
Devise image processing tests	10d



STATUS SUMMARY

GANTT CHART

Name	Duration	Star
⊟ **CDR**	35d	**10/10/20**
⊟ **Research**	24.75d	**10/10/20**
Component Research and Selection	10d	10/10/20
IC Temp Sensor Research and Selection	10d	10/10/20
Define EPS Requirements	7d	10/24/20
Define Data Distribution Requirements	7d	10/24/20
Define External Interface	5d	11/02/20
Research flight lighting conditions	10d	10/10/20
Research exposure time for cameras	15d	10/24/20
Research interfacing for cell phone camera	5d	10/24/20
Research filtering	10d	10/10/20
Create software flowdown	5d	10/10/20
Research material for physical interface	8d	10/10/20
Research more robust position solution	5d	10/12/20
Research more robust velocity solution	10d	10/19/20
Create multiple trajectories in STK	2d	10/10/20
Devise image processing tests	10d	10/10/20
Preliminary Content	4d	11/14/20
Edits	2d	11/18/20
Finalize Edits	2d	11/22/20
Format	2d	11/24/20
Dry Run	0.25d	11/24/20
Dry Run	0.25d	11/25/20
Dry Run	0.25d	11/28/20



THANK YOU

Paige Arthur	PM
Ryan Cutter	Systems
Zach Folger	Mechanical
Cameron Maywood	GNC
Michael Ricciardi	Electrical
Dylan Richards	Remote Sensing
Anthony Torres	CFO & Image Processing
David Walden	Testing
Seth Zegelstein	Software Integration

References

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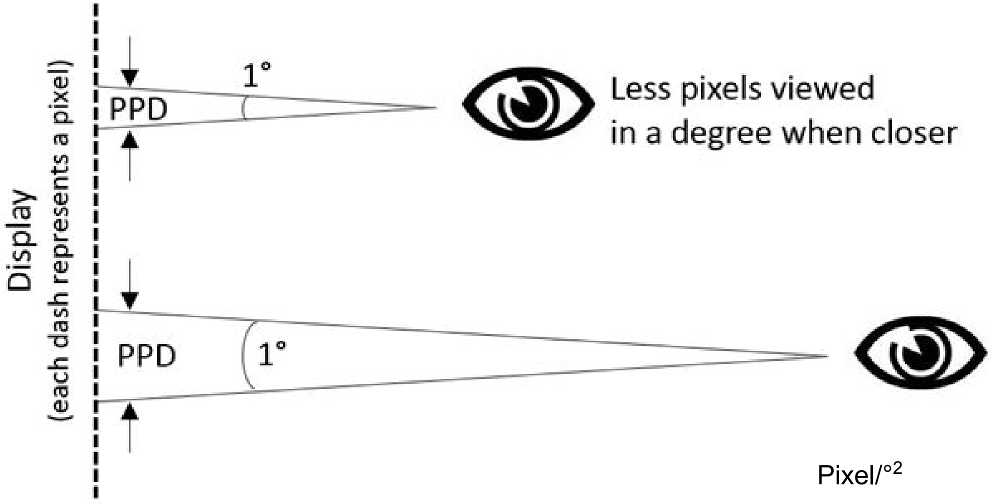
Error

Pixel-to-Degree (Pixel/°) Ratio

- Measure of how many pixels span one degree in the camera's field of view (FOV)
- Self-defined metric that can be computed for any lens/sensor combination
- Used for evaluating cameras during trade studies and for estimating the instrumentation error

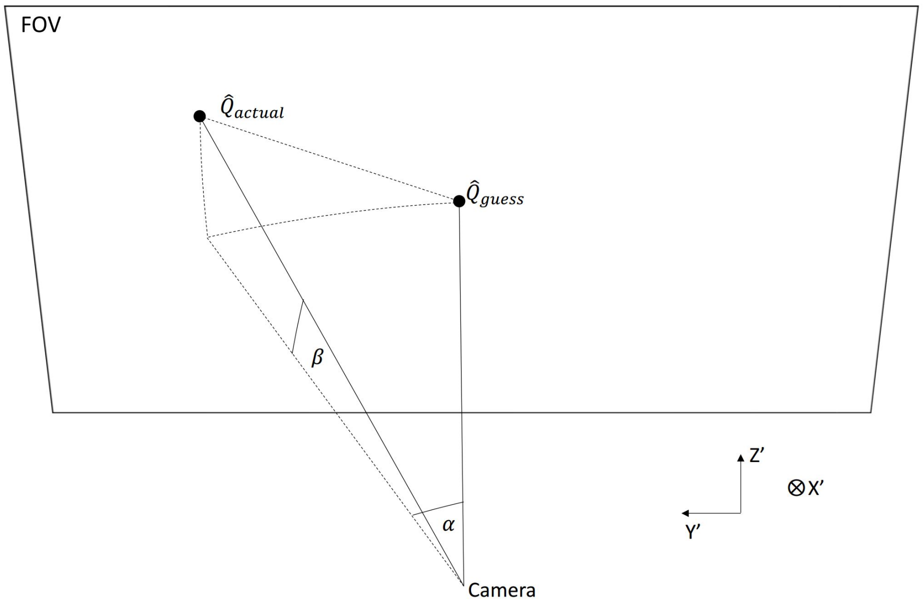


Pixel/°[2]

Definitions

$$\sigma_{pix} = |P_{actual} - P_{Measured}|$$

$$\sigma_{deg} = \frac{deg}{pix} * \sigma_{pix}$$



Sensor Exposure/Shutter Specs

- SONY FCB-MA130
  - Shutter speed: 1/25s to 1/5000s, 24 step
  - Manual (programmable) exposure control
  - I^2C control interface
- ASUS ZenFone Zoom Cellphone Camera
  - Up to 32s exposure
  - ISO 50

https://www.asus.com/Phone/ZenFone-Zoom-ZX551ML/specifications/

http://www.intertest.com/cameras/18190-sony-fcb-ma130-hd-compact-color-camera-16x-digital-zoom

Error Feasibility

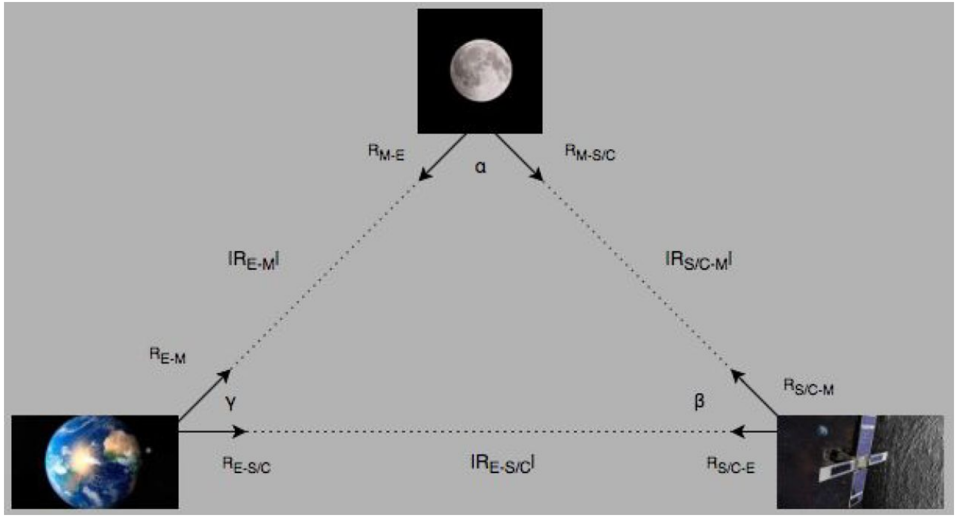
- Objective: Achieve accuracy requirements
- First Piece of Evidence: can achieve position accuracy of 1000 km with a degree error 0f 0.055 degrees
- Second Piece of Evidence: can achieve velocity accuracy of 250 m/s with a degree error of 0.035 degrees
- Third Piece of Evidence: specific camera options can provide necessary degree errors given specific values of pixel error from processing (slide 29)
- Fourth Piece of Evidence: these values of pixel error are all feasible

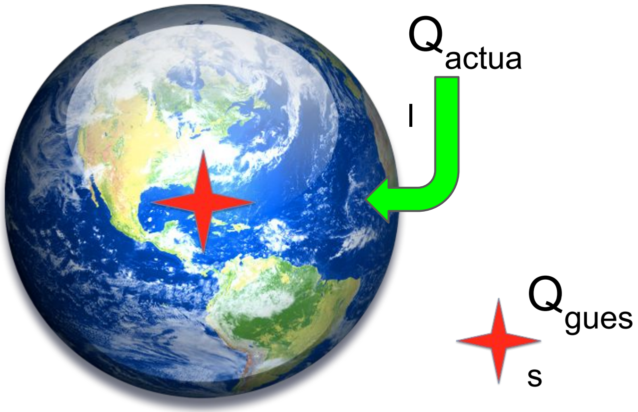
Algorithms

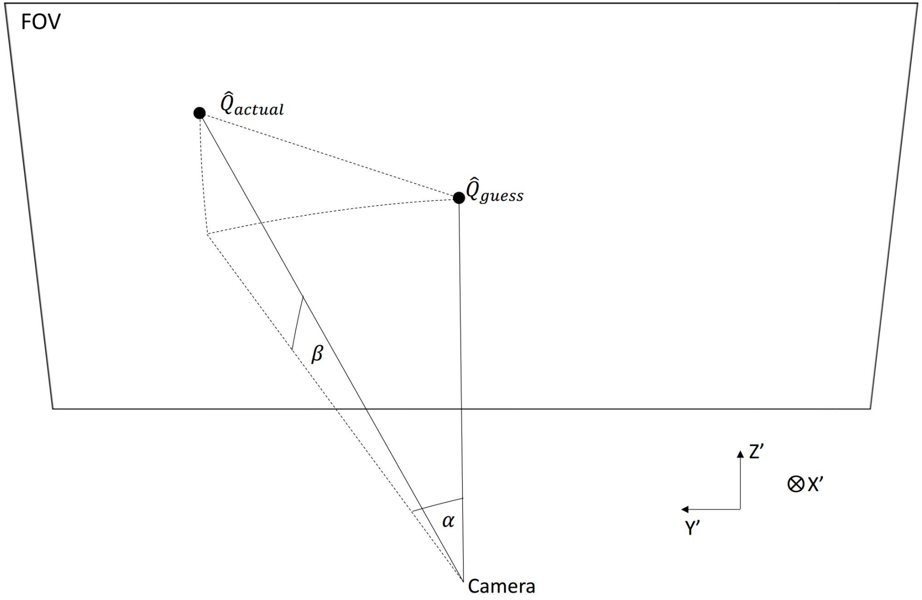
Algorithm Assumptions

1. The STK orbit model perfectly represents the actual flight trajectory.
2. There is a 1° horizontal and vertical error in the given quaternion (α and β).
3. Values for α and β are held constant because varying them within OSPRE's FOV resulted in negligible changes in error.
4. Velocity measurements will be provided every hour.

Angles Position Method







Angles From Earth and Moon

1) $[\vec{r}_{E\to M}]$ = known from ephemeris

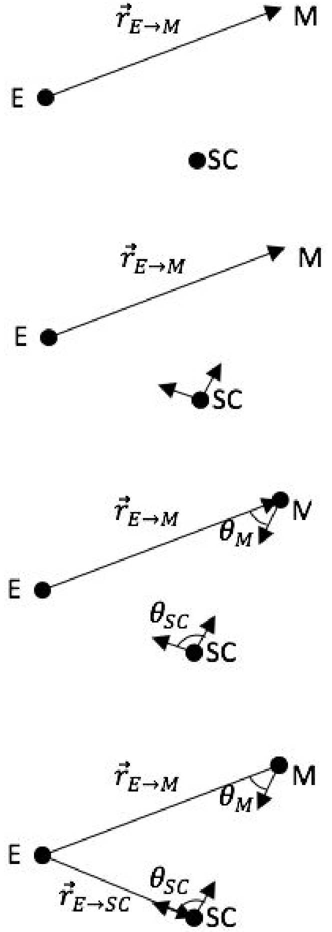
2) $[\hat{r}_{SC\to E}] = [\vec{R}_{Q_{guess}\to Q_{actual}}][\vec{R}_{Q,E\to DCM}][\hat{r}_{initial}]$

3) $[\hat{r}_{SC\to M}] = [\vec{R}_{Q_{guess}\to Q_{actual}}][\vec{R}_{Q,M\to DCM}][\hat{r}_{initial}]$

4) $\theta_M = \cos^{-1}\left(\frac{-[\vec{r}_{E\to M}]\cdot-[\hat{r}_{SC\to M}]}{\|[\vec{r}_{E\to M}]\|}\right)$

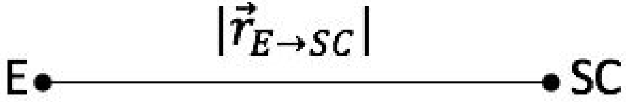
5) $\theta_{SC} = \cos^{-1}([\hat{r}_{SC\to E}]\cdot[\hat{r}_{SC\to M}])$

6) $\vec{r}_{E\to SC} = \frac{|[\vec{r}_{E\to M}]|\sin(\theta_M)}{\sin(\theta_{SC})} * -[\hat{r}_{SC\to E}]$

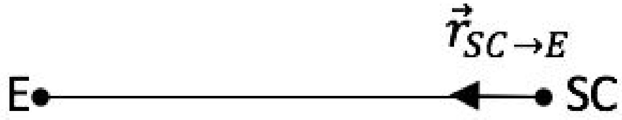


Ranging From Earth

5) $|[\vec{r}_{E\to SC}]| = \frac{R_E}{\tan(\theta/_2)}$

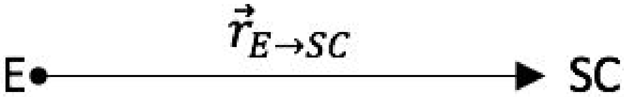


6) $[\hat{r}_{SC\to E}] = [\vec{R}_{Q_{guess}\to Q_{actual}}][\vec{R}_{Q\to DCM}][\hat{r}_{initial}]$



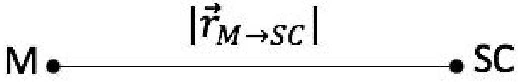
7) $[\vec{r}_{E\to SC}] = -|[\vec{r}_{E\to SC}]|[\hat{r}_{SC\to E}]$

8) $[\vec{r}_{E\to SC}] = -\frac{R_E}{\tan(\theta/_2)}[\vec{R}_{Q_{guess}\to Q_{actual}}][\vec{R}_{Q\to DCM}][\hat{r}_{initial}]$

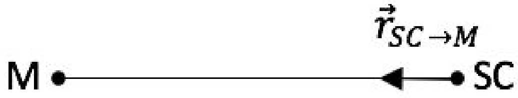


Ranging From Moon

7) $|[\vec{r}_{M\to SC}]| = \frac{R_M}{\tan(\theta/_2)}$

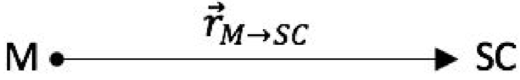


8) $[\hat{r}_{SC\to M}] = [\vec{R}_{Q_{guess}\to Q_{actual}}][\vec{R}_{Q\to DCM}][\hat{r}_{initial}]$



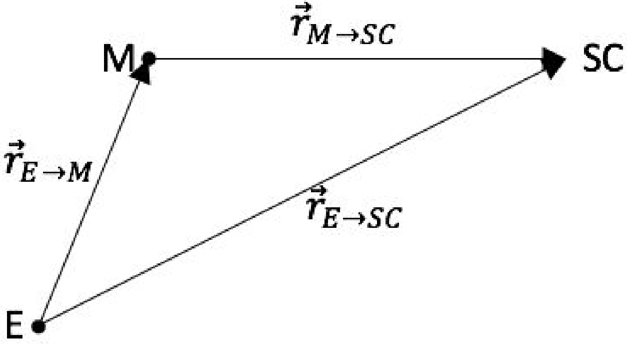
9) $[\vec{r}_{M\to SC}] = -|[\vec{r}_{M\to SC}]|[\hat{r}_{SC\to M}]$

10) $[\vec{r}_{M\to SC}] = -\frac{R_M}{\tan(\theta/_2)}[\vec{R}_{Q_{guess}\to Q_{actual}}][\vec{R}_{Q\to DCM}][\hat{r}_{initial}]$



11) $[\vec{r}_{E\to M}]$ = known from ephemeris

12) $[\vec{\boldsymbol{r}}_{E\to SC}] = [\vec{\boldsymbol{r}}_{E\to M}] + [\vec{\boldsymbol{r}}_{M\to SC}]$



Orbit Determination

Initial Conditions upon research for similar CubeQuest Challenge flight.

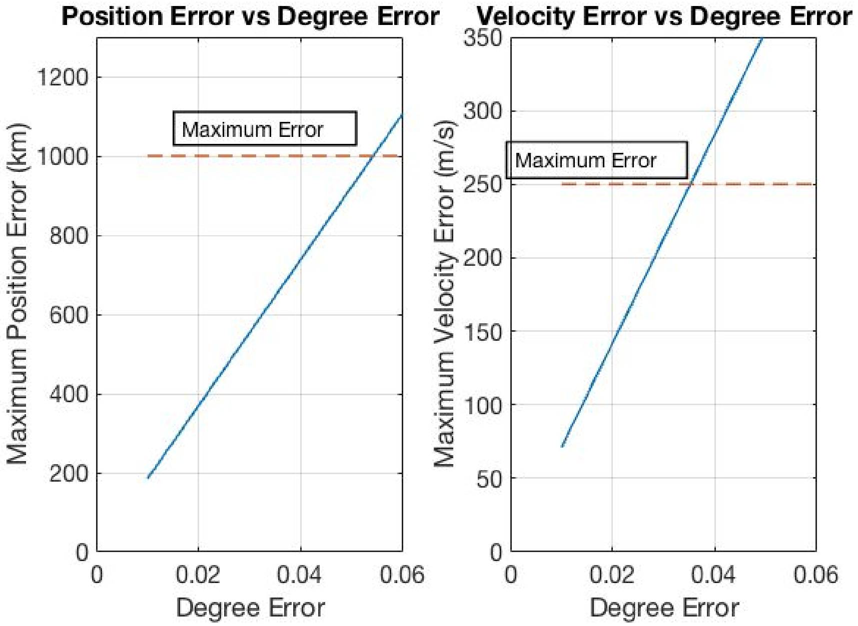
- Estimated Launch Date: August 1, 2018
    - Launch from Kennedy Space Center
- Duration: 5 day transit
- Size: ~6U CubeSat
- Deployed: ~30,000 km
- Lunar Flyby -- Does not stay in orbit

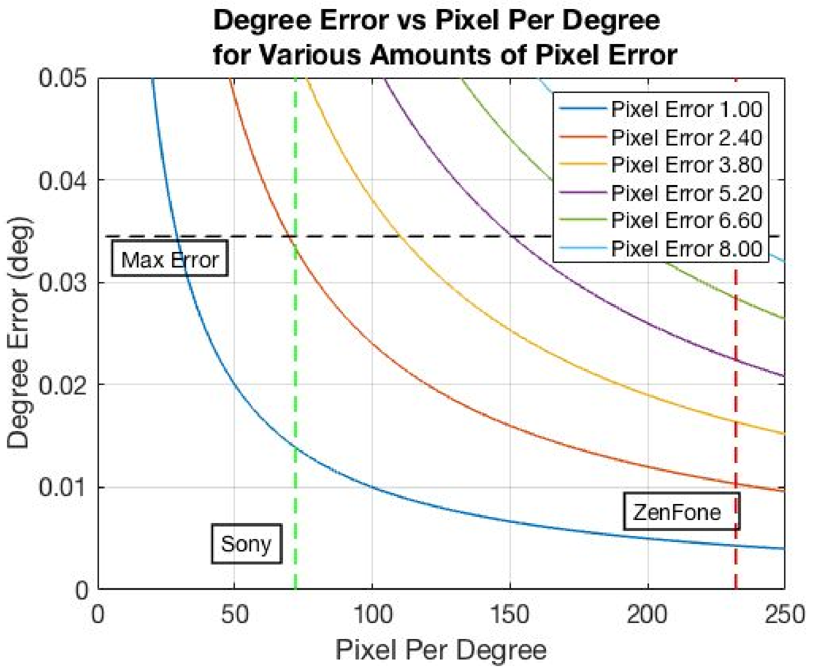
NasaSpaceflight.com\SLS Mission Trajectory

SLS-SPIE-HDBK-005 (Secondary Payload User's Guide)

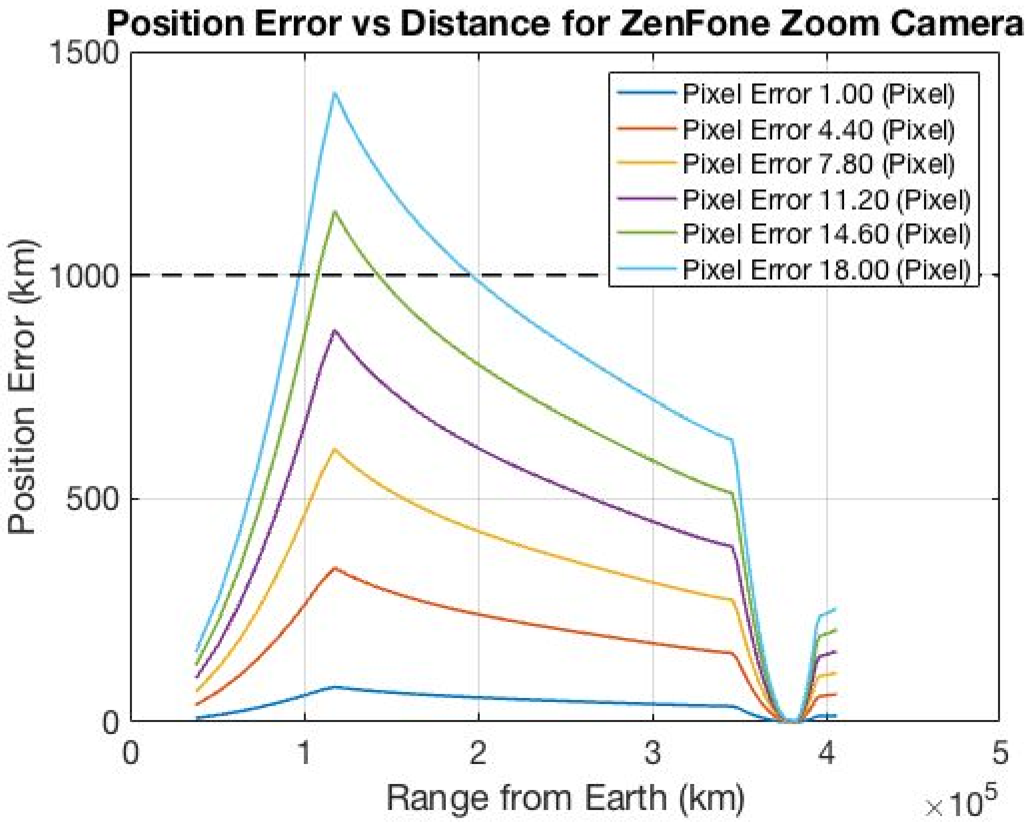
Orbit Determination

Error Feasibility - Relate Pixel/Degree to Degree Error

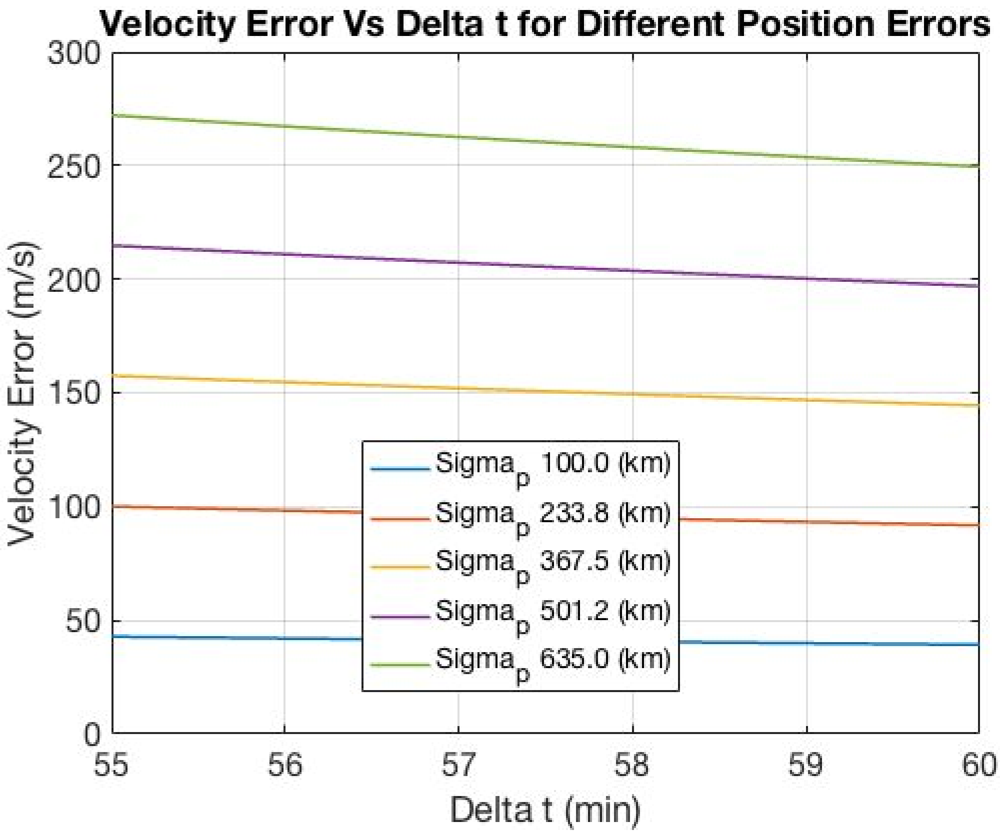




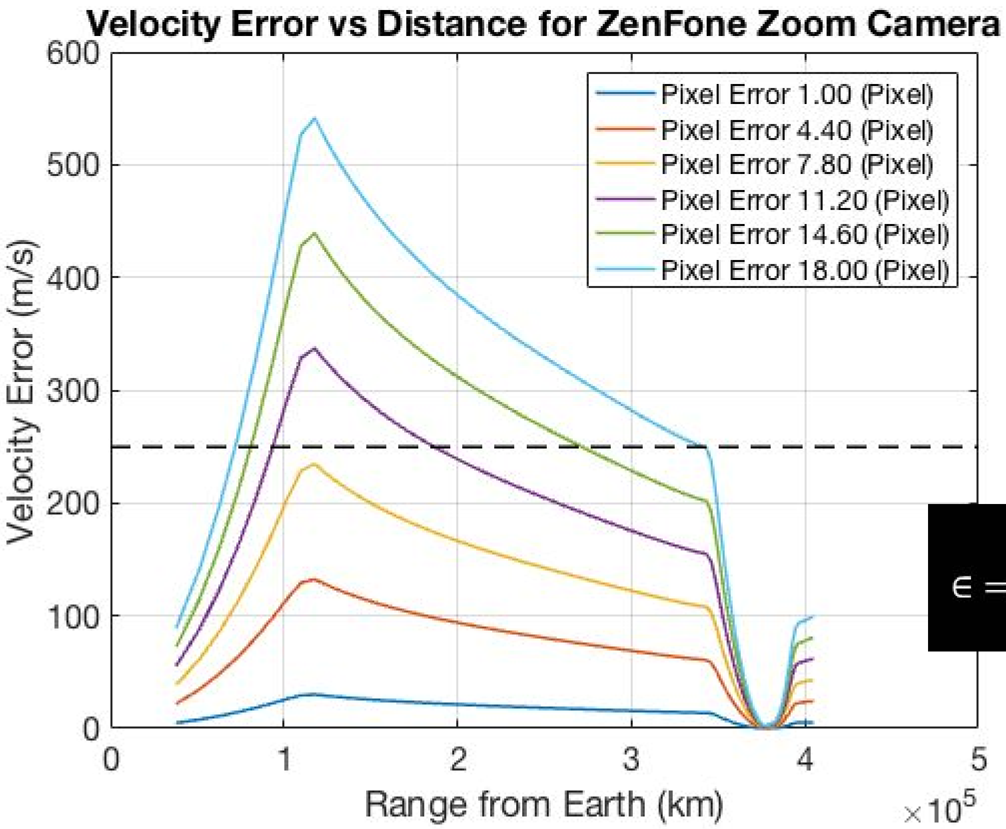
Error Feasibility - Position



Error Feasibility - Velocity

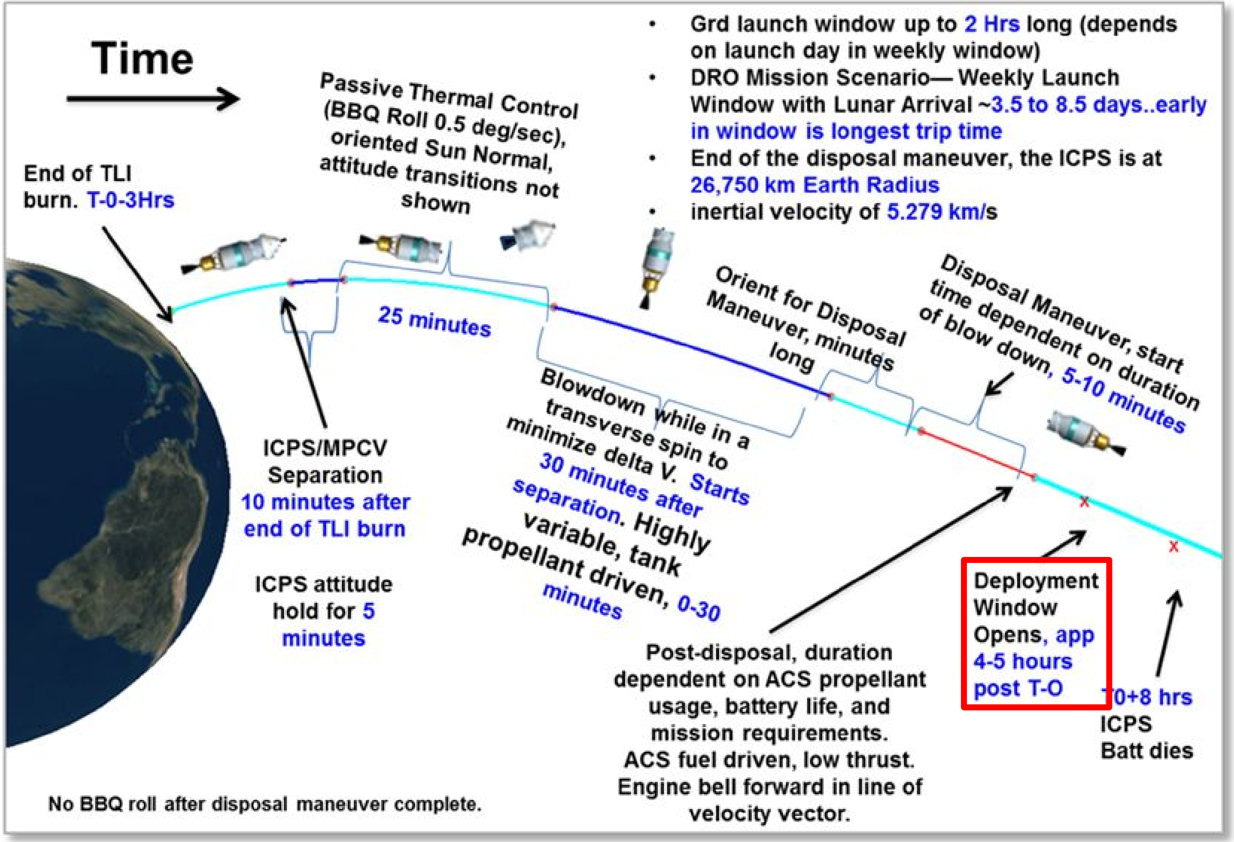


Error Feasibility - Velocity



$$\epsilon = \sqrt{\left(\frac{\partial V}{\partial P_2} * \partial P_2\right)^2 + \left(\frac{\partial V}{\partial P_1} * \partial P_1\right)^2 + \left(\frac{\partial V}{\partial \Delta t} * \partial \Delta t\right)^2}$$

Payload Deployment Window



NASA, SLS-SPIE-HDBK-005

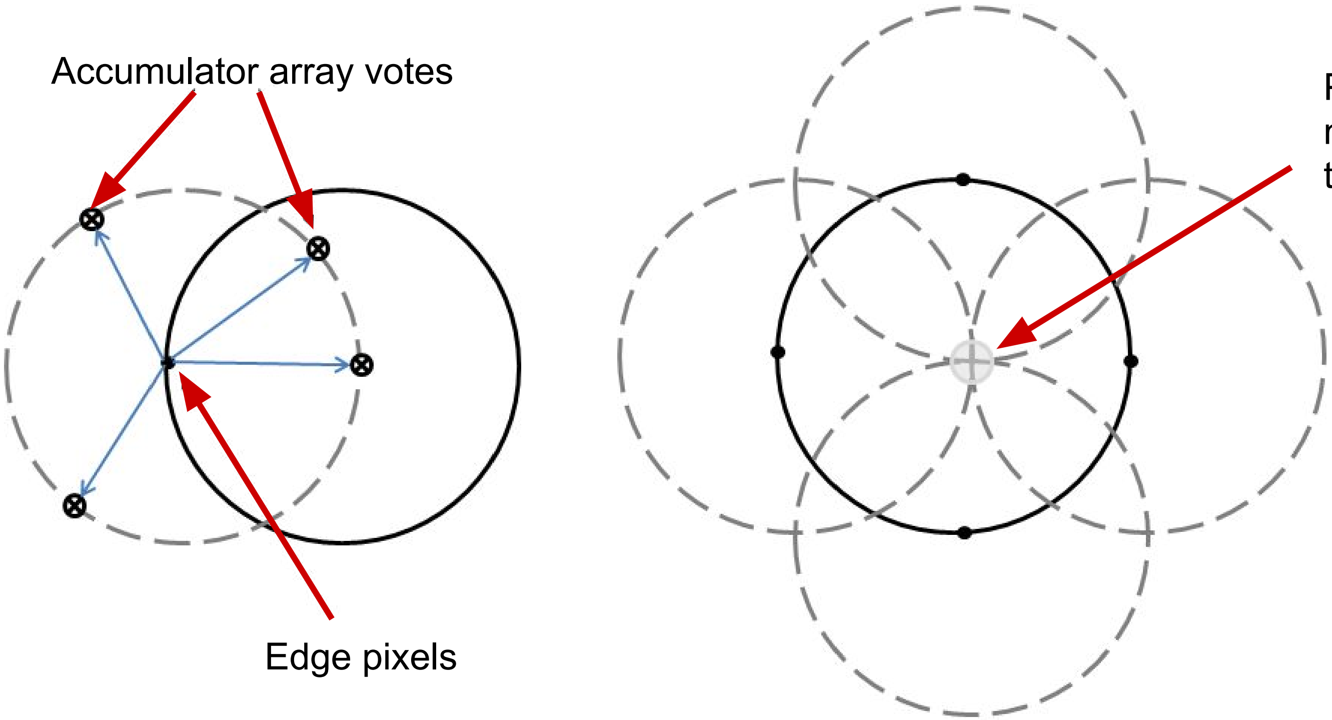
Processing

Image Processing - Available Software

- OpenCV
  - Open source image processing software with interfaces in C/C++, Python, Java
- Matlab Image Processing
  - Many different packages available to use
  - Most functions exportable to C
  - Familiarity through Matlab
- VLFeat
  - Open source image processing software written in C with interfaces to Matlab

http://opencv.org/
https://www.mathworks.com/products/image/
http://www.vlfeat.org/

Circle Detection with Hough Transform



(a) Vote (b) Analyze

https://www.mathworks.com/help/images/ref/imfindcircles.html

Image Processing - Phases

<u>Sources of Error:</u>

- Less arc length
- Additional processing complexity

<u>Ways to Account for this:</u>

- Pre-processing techniques
- Radius prediction
- Selection of processing algorithm(s)

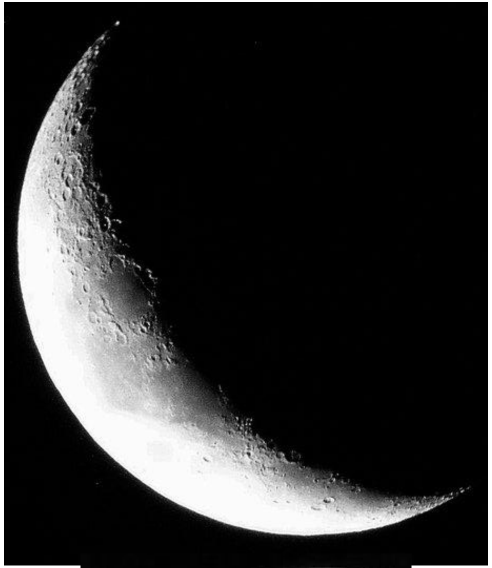



Image Processing - Phase Analysis

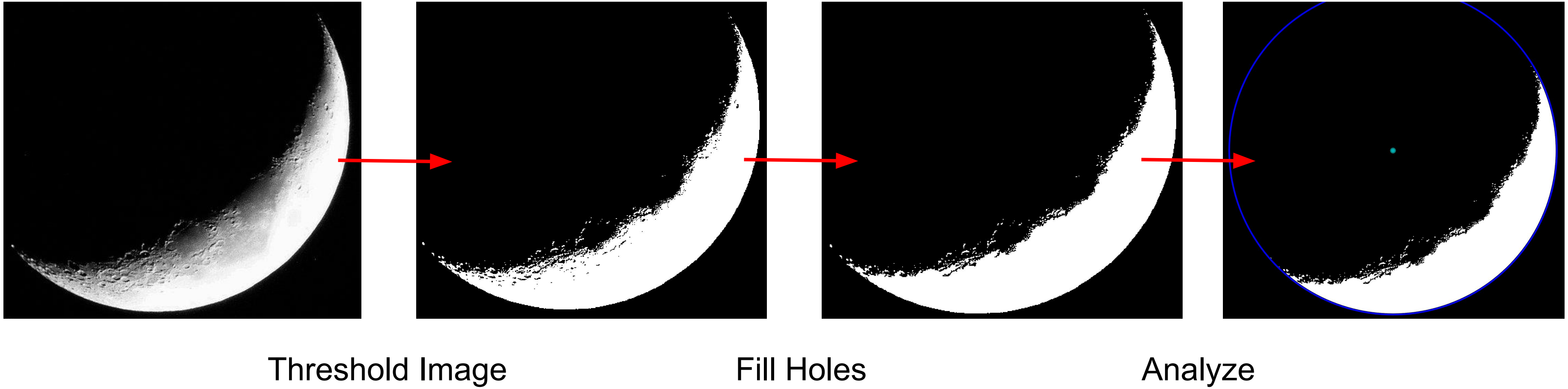
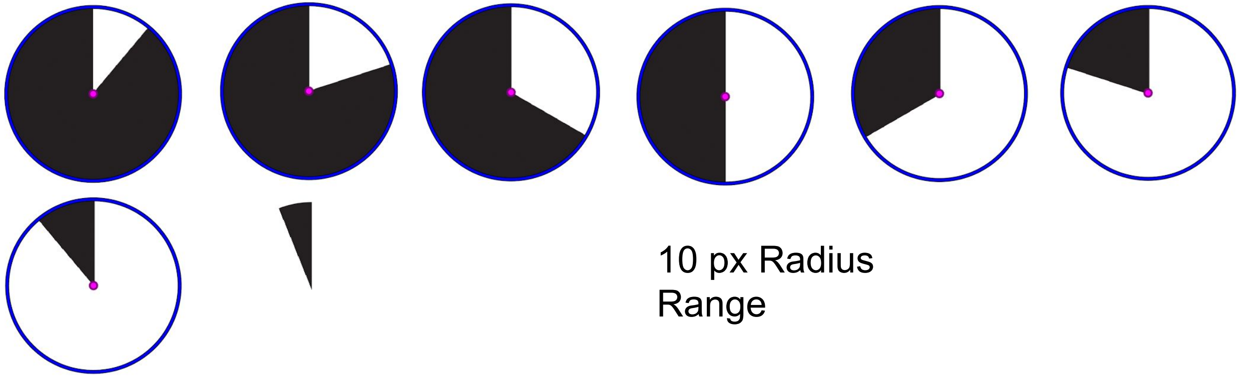


Image Processing - Arc Feasibility

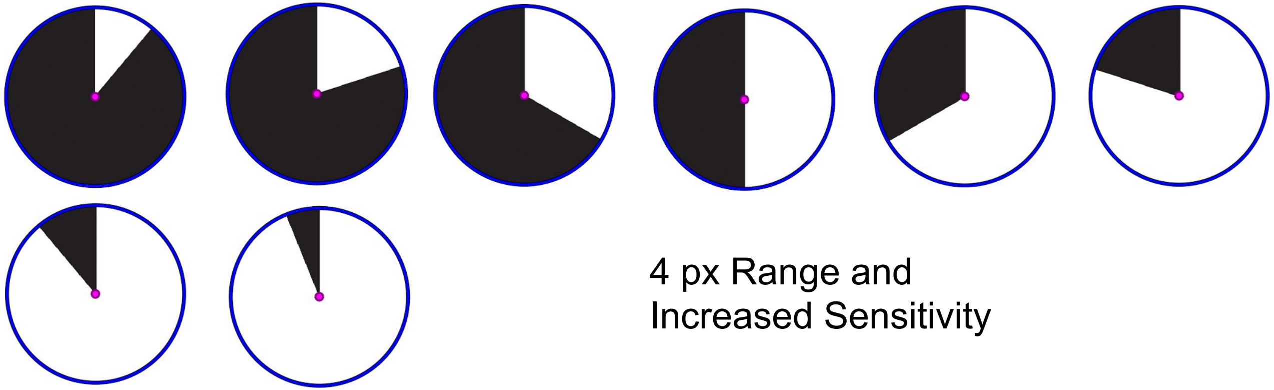
- Better picture estimates lead to better results

- Knowing rough trajectory allows for better estimations to be made

- Further studies to determine systematic sensitivity control

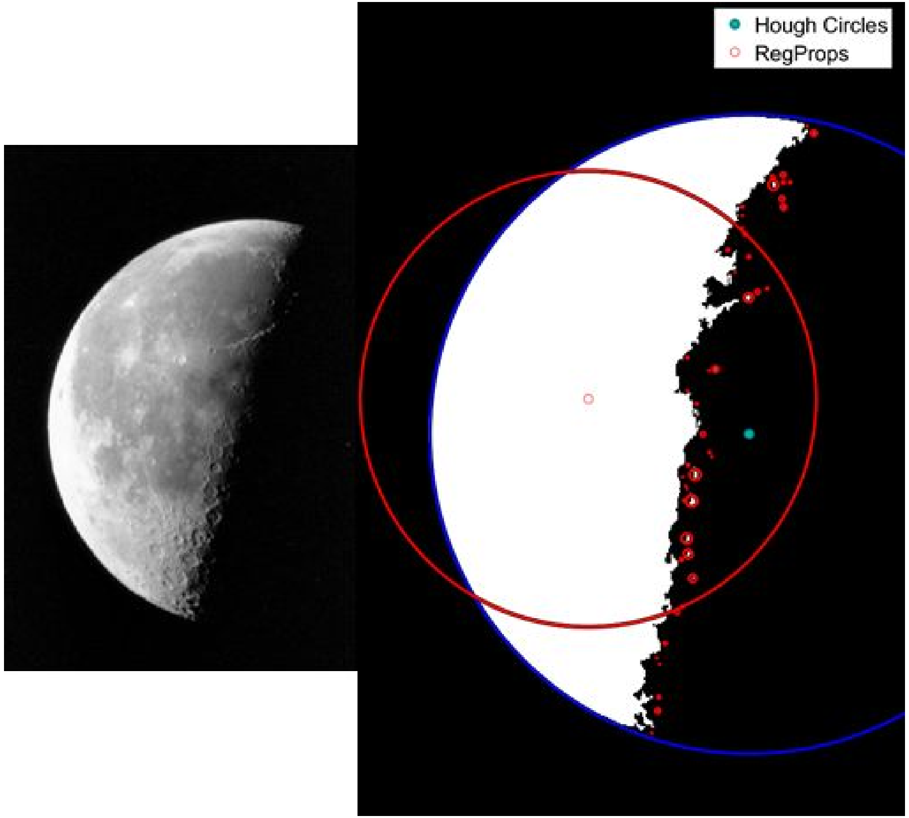


10 px Radius Range



4 px Range and Increased Sensitivity

Image Processing - Phase Analysis Comparison

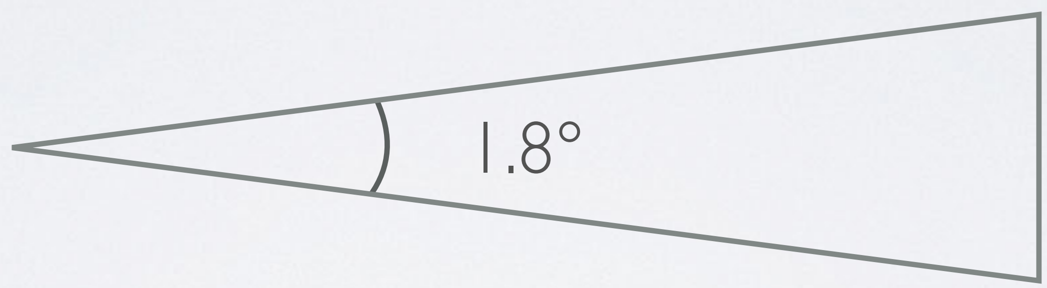


TESTING METHOD

FEASABILITY

\- Facility Requirements -

Largest Distance Case



Lightbox Limitation

Comparable Error
to Projector

Distance — 45 feet!

Projector Limitation

Maximum Pixel Resolution
(whole 30” screen)

Distance — 95 feet!

TESTING METHOD

FEASABILITY

\- Range Measurement -

Laser Range Finding — ± 0.07"
Steel Tape Measure (30 ft) — ± 0.06"

Error Data — http://www.hultafors.com
http://www.porcupinelabs.com/lr4/

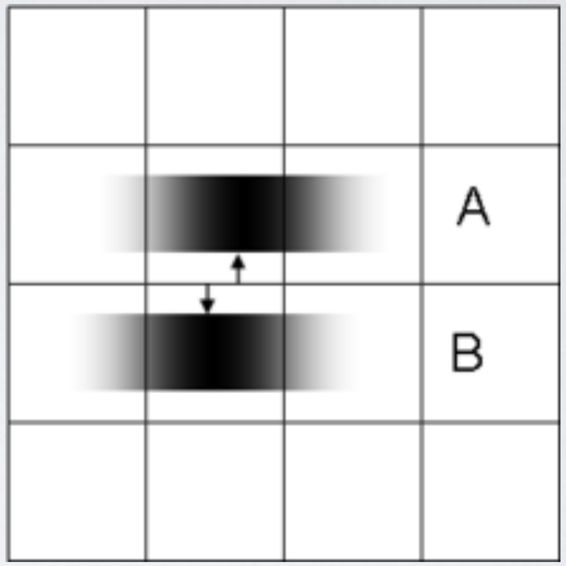
PRE-PROCESSING

TECHNIQUES

- Super Resolution Processing -

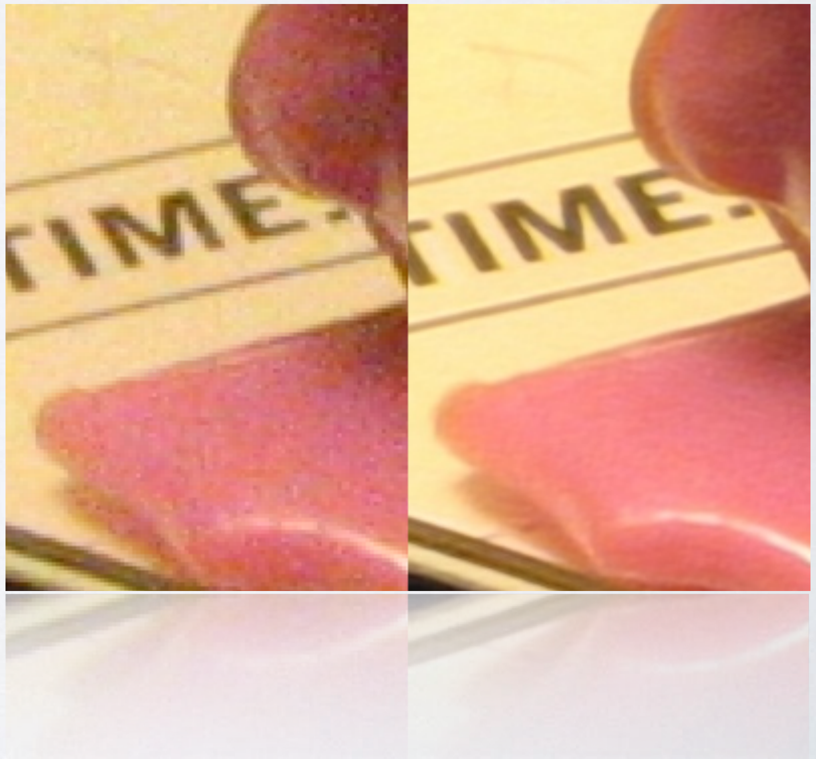
OBJECTIVE

Achieve sub-pixel image resolution with minimal distortion



PROCESS

1. Multiple Image Capture
2. Pixel Noise Processing
3. Combine Images



Images — wikipedia.org/wiki/Super-resolution_imaging

PRE-PROCESSING

TECHNIQUES

- Super Resolution Processing -

PROS

- Reduce image resolution dependence
- Improve overall system accuracy
- Existing imaging processing software

CONS

- May introduce image distortion in some cases
- Increases necessary computing power notably

PRE-PROCESSING

TECHNIQUES

- Super Resolution Processing -

NEXT STEPS

- Source Several Processing Softwares
- Test Sub-pixel Accuracy Achieved
- Test for Image Distortion
- Implementation

PRE-PROCESSING

TECHNIQUES

- Super Resolution Processing -

Distortion Testing Chart

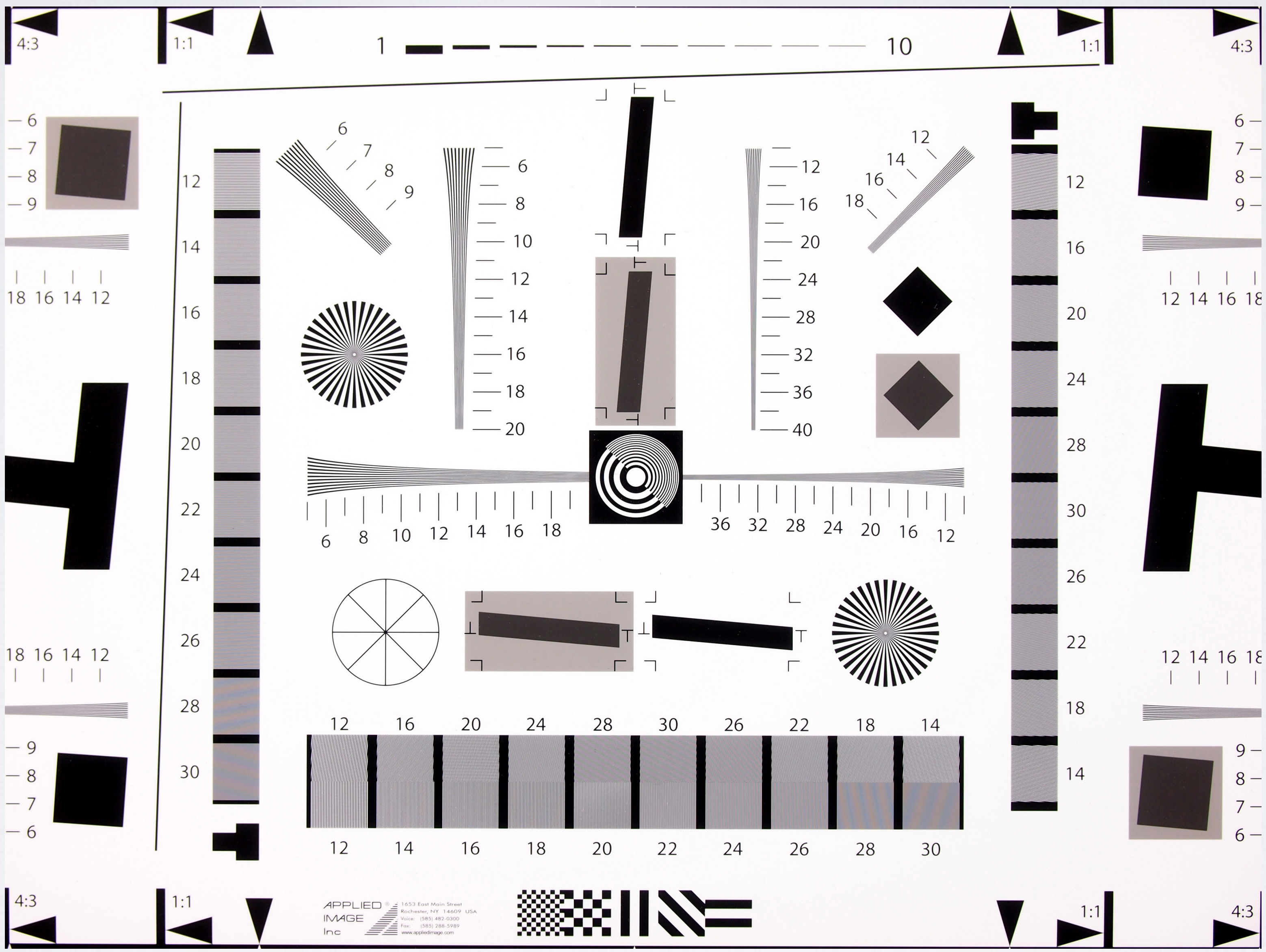


Image — www.techradar.com

PRE-PROCESSING

TECHNIQUES

- Thresholding -

BEFORE

→

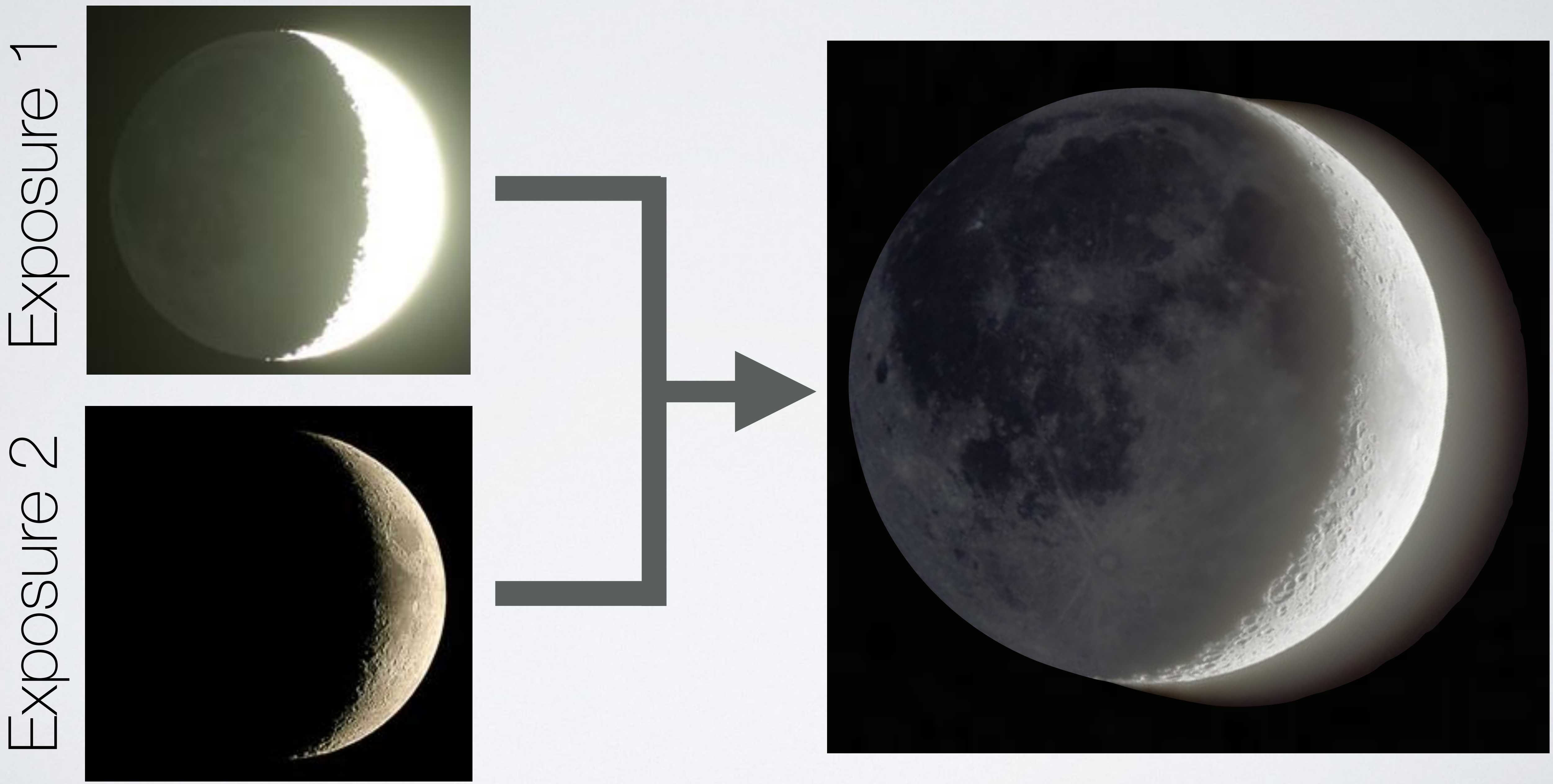
AFTER

Images — http://www.ericsunlee.com

PRE-PROCESSING

TECHNIQUES

\- High Dynamic Range Photography -



Images — http://lakefx.deviantart.com/art/HDR-Moon-2-114518713

PRE-PROCESSING

TECHNIQUES

- Sharpening -

Sharpening Kernel

$$\left\{ \begin{matrix} 0 & -1 & 0 \\ -1 & 5 & -1 \\ 0 & -1 & 0 \end{matrix} \right\}$$

BEFORE

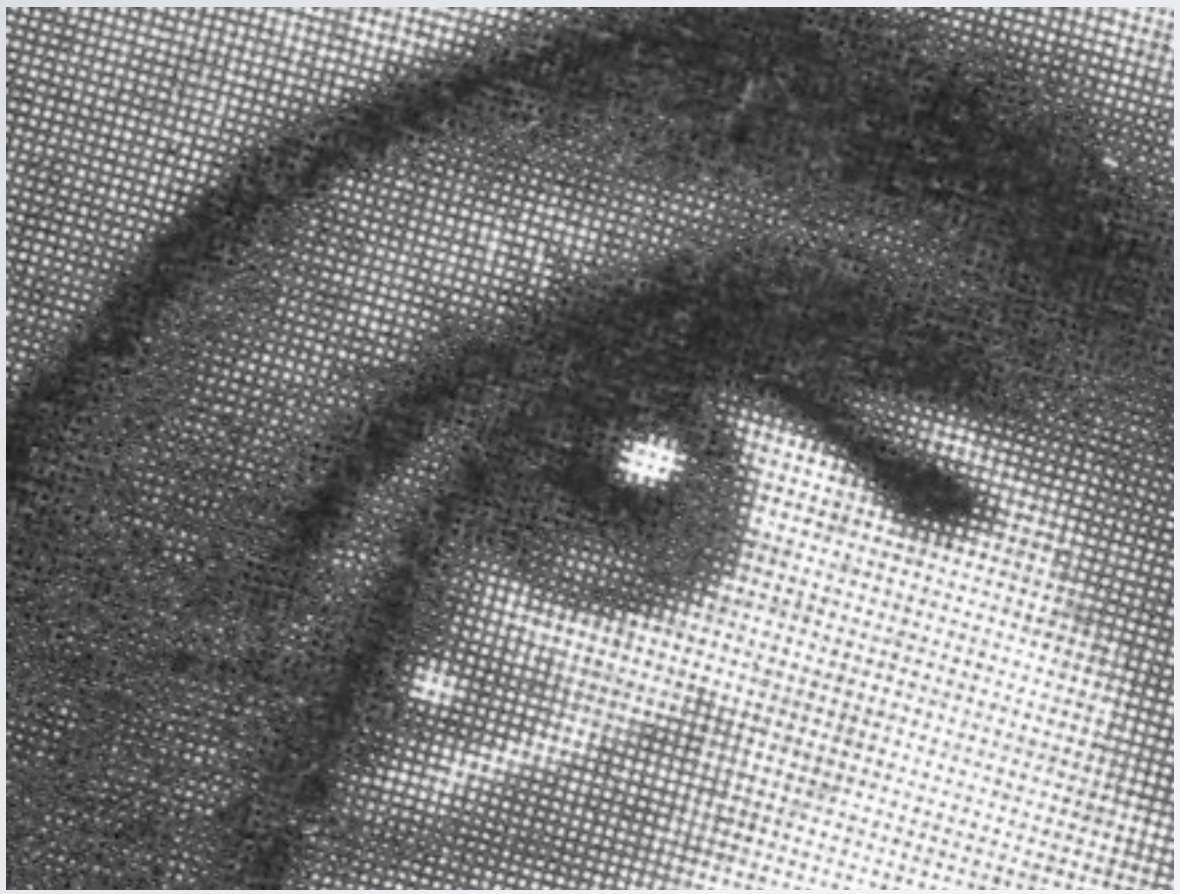
AFTER

Image — cambridgeincolour.com/
Kernel — http://setosa.io/ev/image-kernels/

PRE-PROCESSING

TECHNIQUES

- Noise Reduction -



BEFORE

AFTER

Introduce a Slight
Amount of Gaussian Blur

Image — wikipedia.org/wiki/Gaussian_blur

Projector

PROS

- Realistic light intensity difference between dark and bright sides
- Color and texture factors

CONS

- More error anticipated test design
- Light output limitations
- Facility requirements
- More complex setup

Lightbox

PROS

- Highly accurate manufacturing and test measurements
- Adjustable light intensity
- Low facility requirements
- Simple setup
- Less stray light

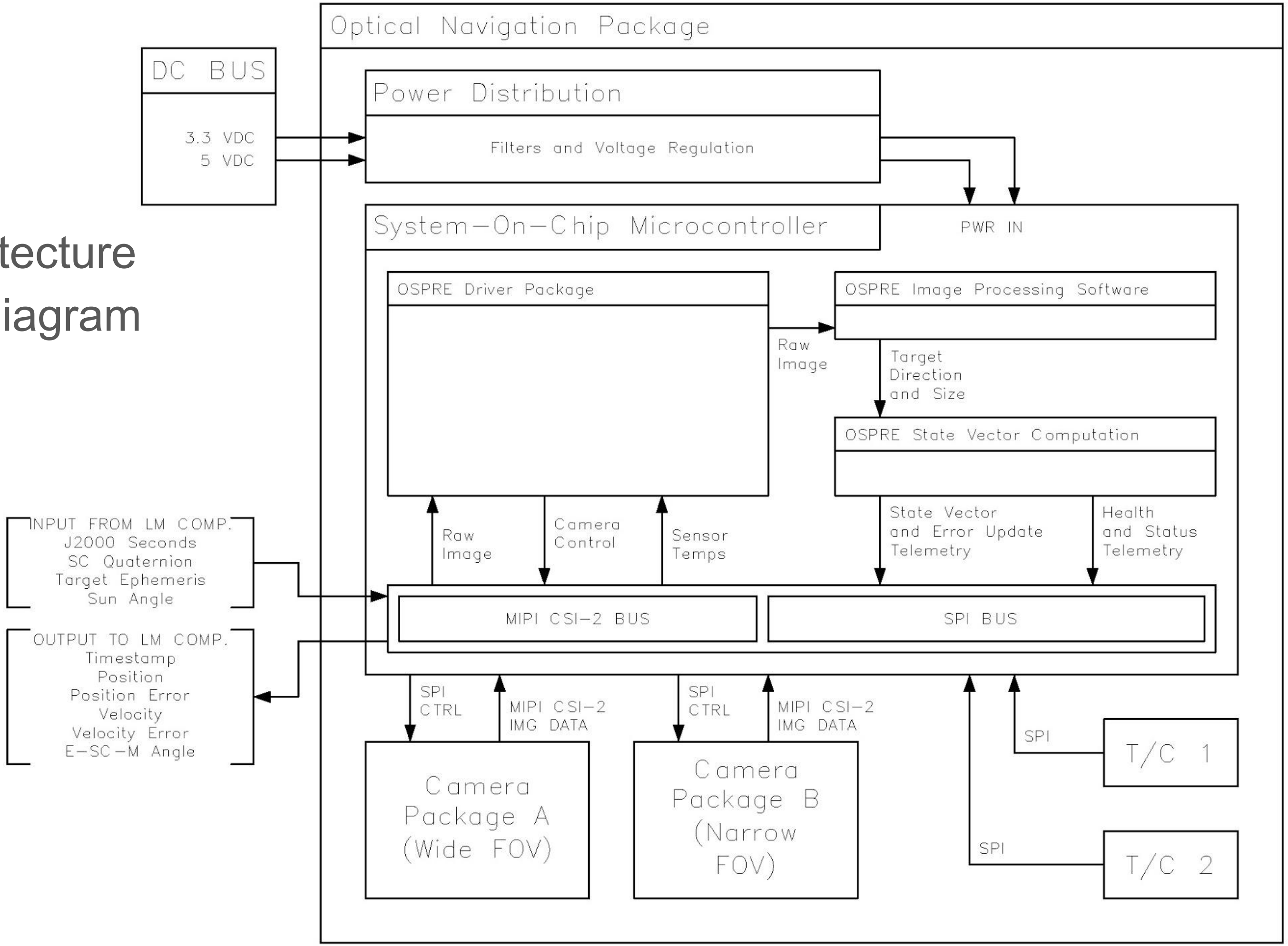
CONS

- Increased cost
- More manufacturing required
- No dark side of the body illuminated
- No color or texture

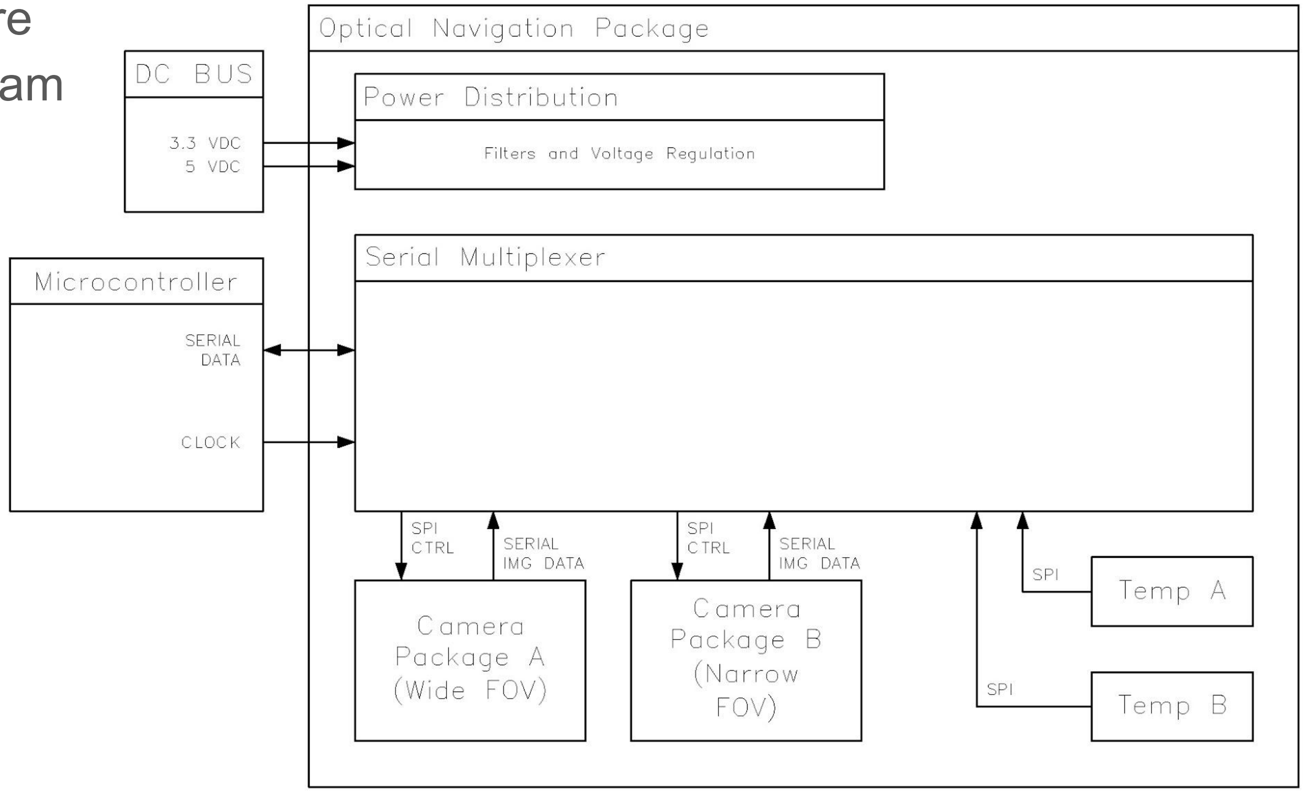
iSWAP

4.5 minutes!

SOC-Based Architecture Functional Flow Diagram



SPI-Based Architecture
Functional Flow Diagram



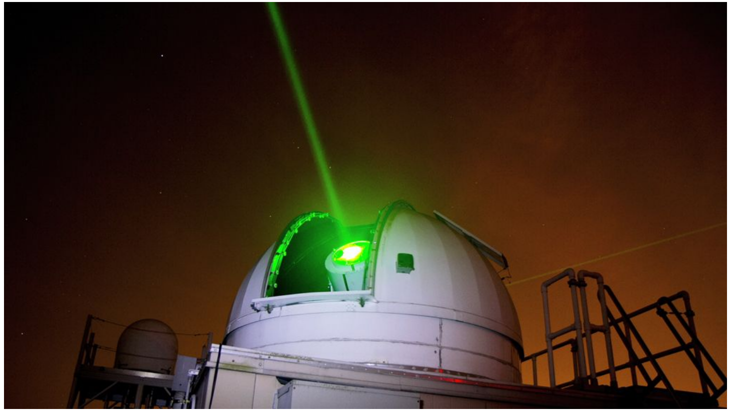
iSWAP Feasibility Requirements

Summary of Associated Design Requirements (DR):

(Do not apply to the connected ZedBoard Microcontroller or associated wiring harness)

- DR0.0 Include one or more imaging sensors (baseline = 2)
- DR1.5 Inclusion of “health”/“status” sensors
- DR2.1.1 Voltage, Supply = 3.3, 5, and/or 12 VDC
- DR2.1.2 Current, Max <= 500 mA
- DR2.1.3 Power, Max <= 3 W
- DR2.2.1 Ext. Comm. with SPI, I2C, or CameraLink Protocols
- DR2.6 Mass, Total <= 0.8 kg
- DR2.7 Dimensions, Total = 5x5x1 cm

Why use an Imaging Sensor?



Alternative approaches considered:

1. Laser Ranging - would require a great deal of power and a high cost laser
2. Photodiodes - doesn’t provide sufficient resolution to achieve the necessary accuracy

Conclusion: Imaging Sensor is the most feasible approach

https://svs.gsfc.nasa.gov/11283
http://www.alliedelec.com/vishay-small-signal-opto-products-ssp-bpw21r/70061725/?mkwid=sabYU23qn&pcrid=30980760979&gclid=CInf67_Hws8CFZaIaQodOMMBpg

Time

1:00

PRE-PROCESSING

TECHNIQUES

NEXT STEPS

- Individually Test and Optimize Each Method
- Combine Methods to Optimize Overall Process
- Run Simulations to Validate
- Integrate with System

Time

1:00

TESTING METHODS

NEXT STEPS

- Develop More Advanced Error Model
- Optimize Error Reduction
- Research Facilities Based on New Req.
- Select Optimal Test Method