Smallsat Connected Optical Positioning Entity

Customer: Steve Thilker, Raytheon
Faculty Advisor: Zoltan Sternovsky

Group Members: Mattia Astarita, Nick Cenedella, Connor Kerry, Greg Kondor, Nolan Lee, Guy Margalit, Mason Markle, Jakob Mitchell, Zach Schira, Pepe Feu Vidal, Alec Viets

Presentation Outline

Sections	Presenter(s)
Project Description	Connor
Design Solution	Alec and Guy
Critical Project Elements	Guy
Requirement Satisfaction	Nick, Alec
Risk Analysis	Nick
Testing Feasibility	Jake and Nolan
Budget and Schedule	Nolan

Project Purpose and Objectives

Motivation

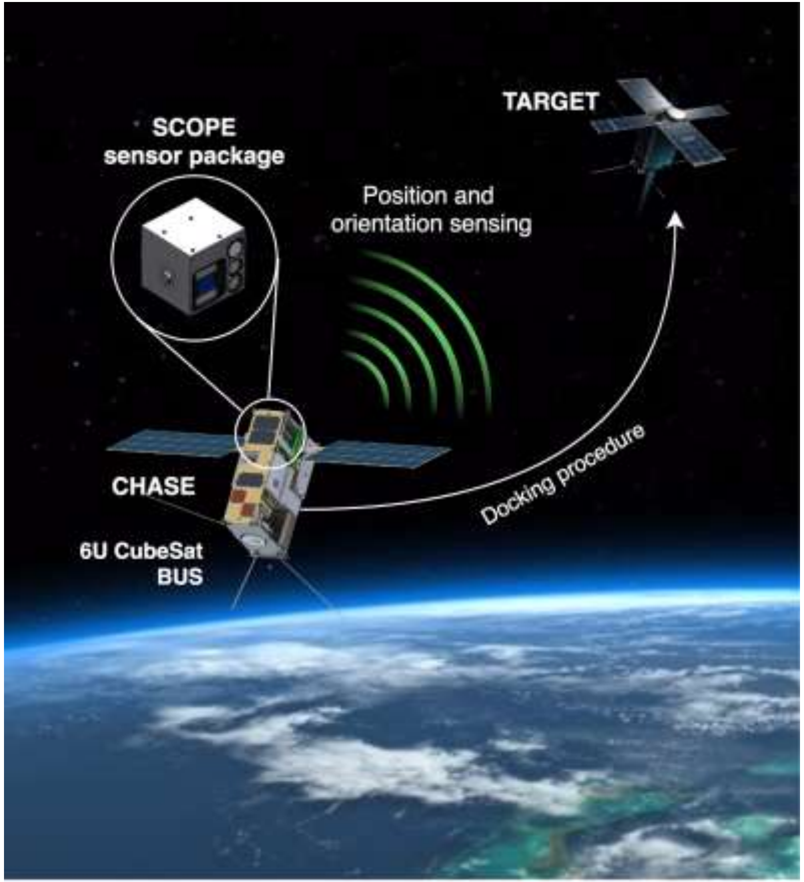
→ Need **relative motion** and **orientation** of nearby spacecraft in **proximity operations**
→ Find **inexpensive**, **autonomous**, and **accurate** solution

Proximity Operations and Rendezvous
Cygnus 1 approaching ISS

Docking, Resupply, and Repair Missions
Soyuz docking with the ISS

Project Objectives

Design, build, and test a proof-of-concept sensor package that collects **relative motion** and **orientation** data of a TARGET satellite for output to the CHASE satellite on-board attitude control system.



Acronyms and Definitions

CHASE - Satellite housing design sensor package (SCOPE)

FLOOD - Flash Lidar Object Orientation Determination

FOV - Field Of View

ICP - Iterative Closest Point

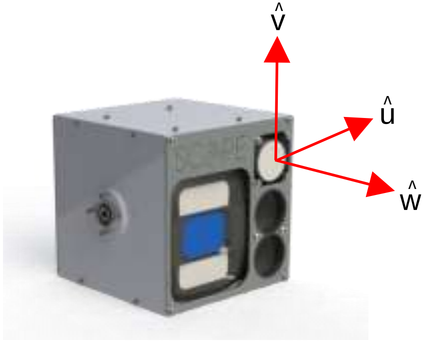
IR - InfraRed light

LiDAR - Light Detection And Ranging

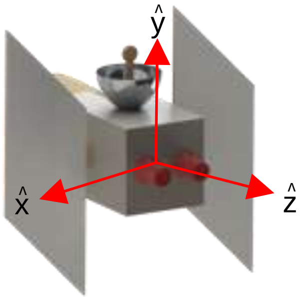
LRF - Laser Range Finder

SCOPE - Designed sensor package, housed on CHASE

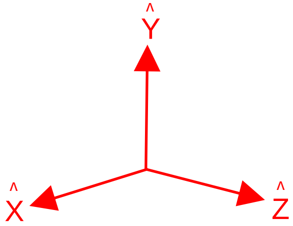
TARGET - Target satellite to sense with design sensor package (SCOPE)



SCOPE Body Frame



TARGET Body Frame



Inertial Frame

SCOPE Shall...

FR 1	Be capable of detecting a target satellite.
FR 2	output the target satellite’s relative position upon detection.
FR 3	output the target satellite’s relative velocity upon detection.
FR 4	output the target’s relative orientation upon detection.
FR 5	output the target satellite’s relative rotation rate upon detection.
FR 6	output target satellite data at a set frequency.
FR 7	formatted to fit within a 1(U) platform (as defined by standard CubeSat protocol) upon launch.

Levels of Success

Level 1

Detect and return data outputs for a target satellite with known markers.

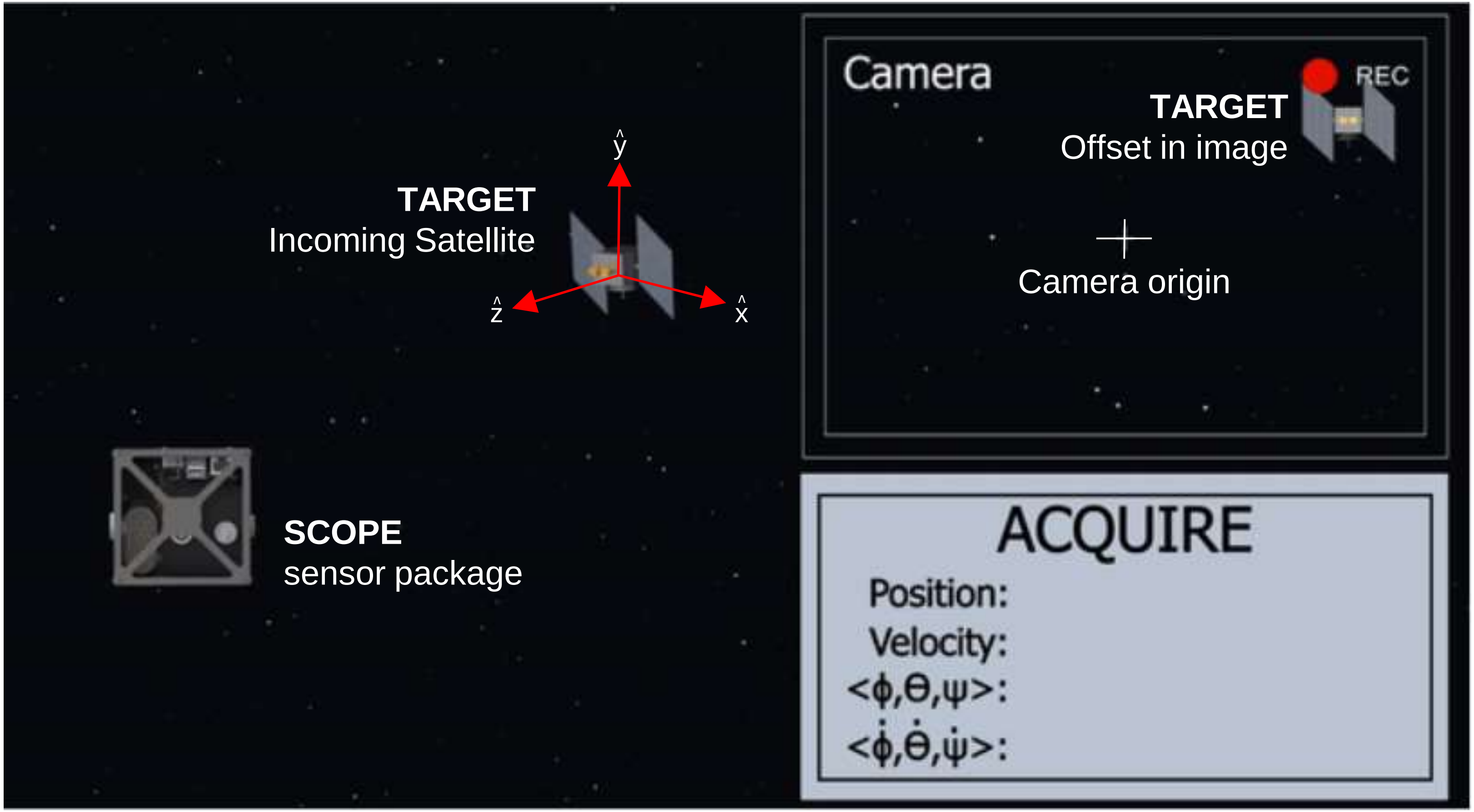
Level 2

Detect and return data outputs of a target satellite with no markers, but with a known 3-D model.

Level 3

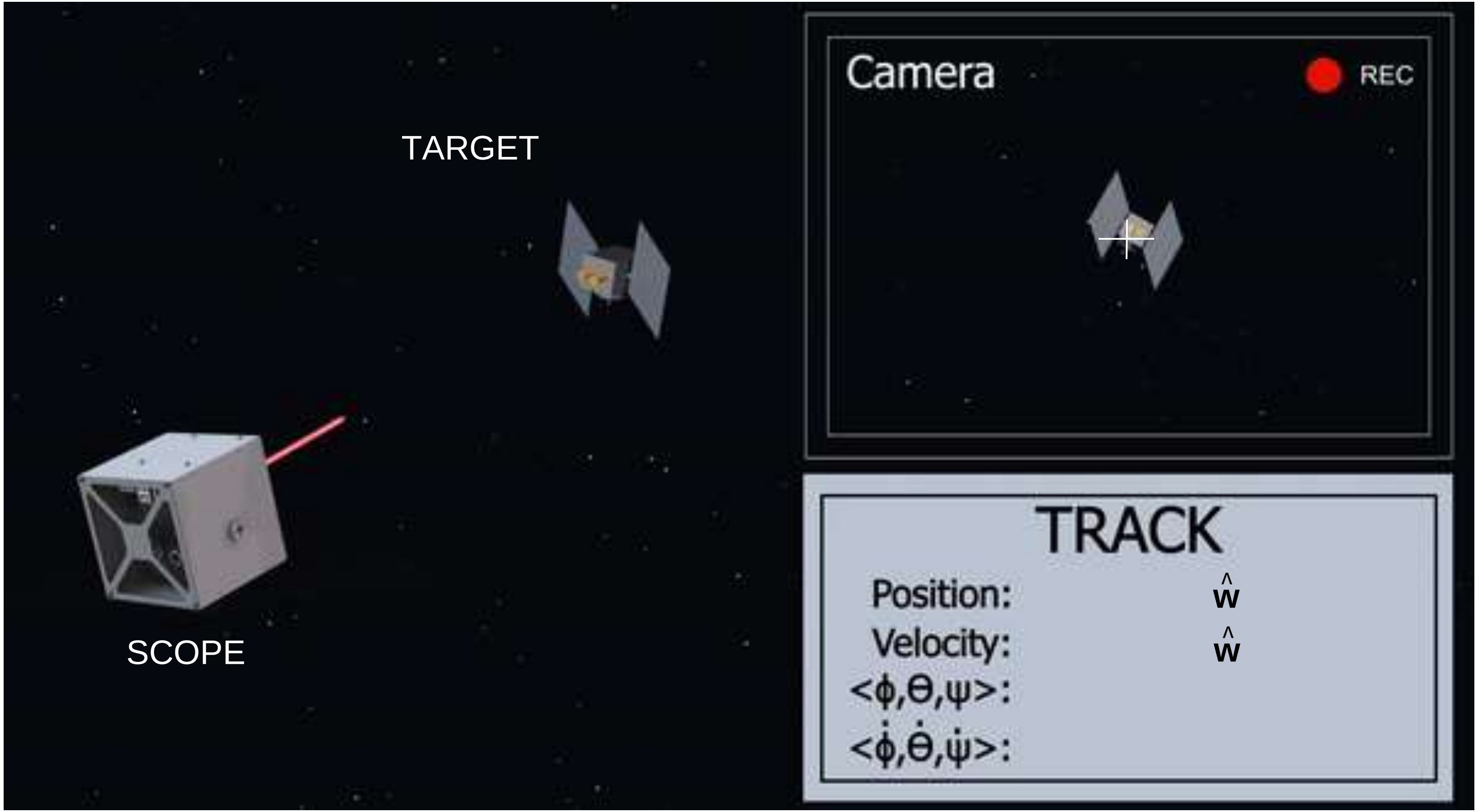
Detect and return data outputs of an unknown target satellite

Mission CONOPS

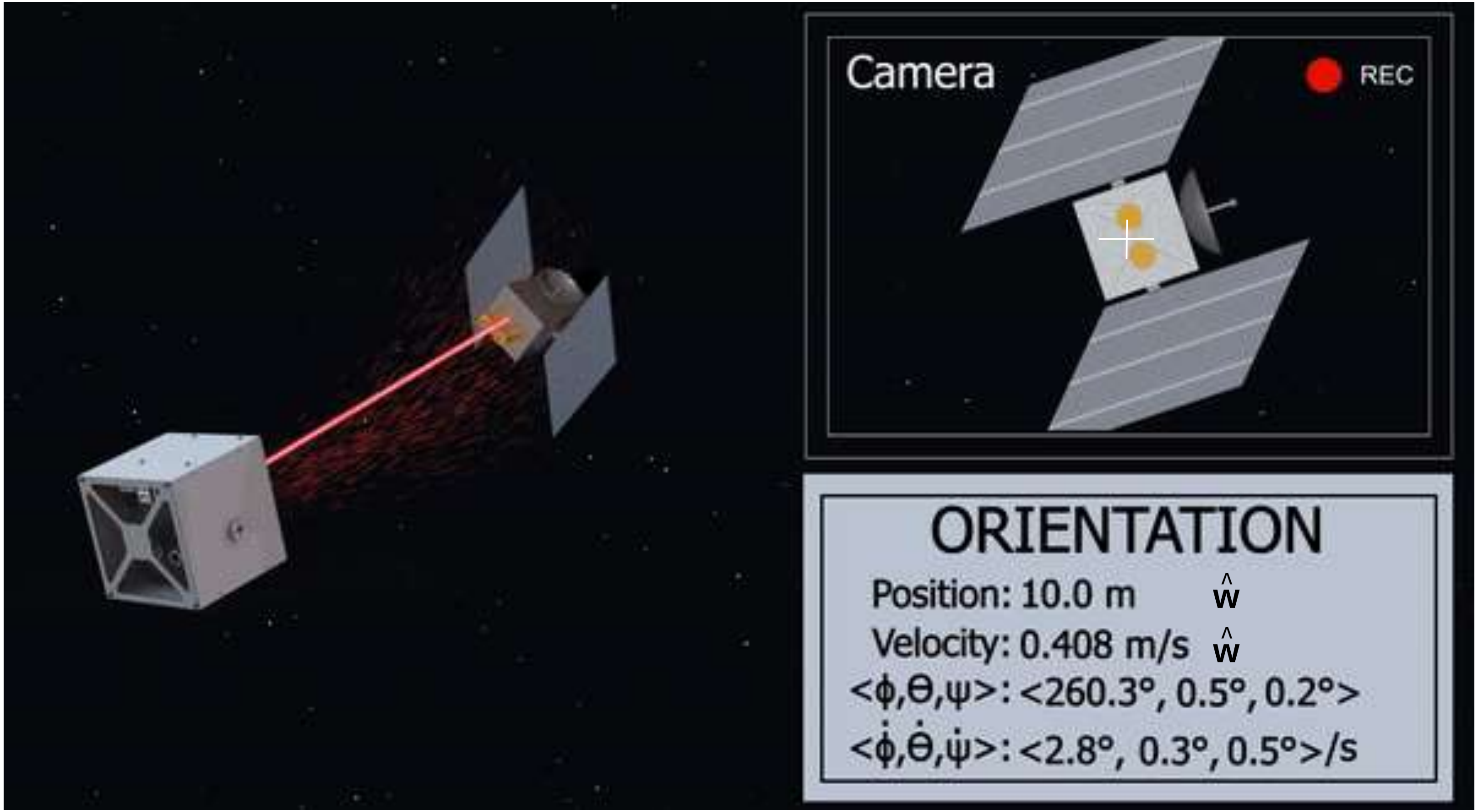


Mission CONOPS

Mission CONOPS

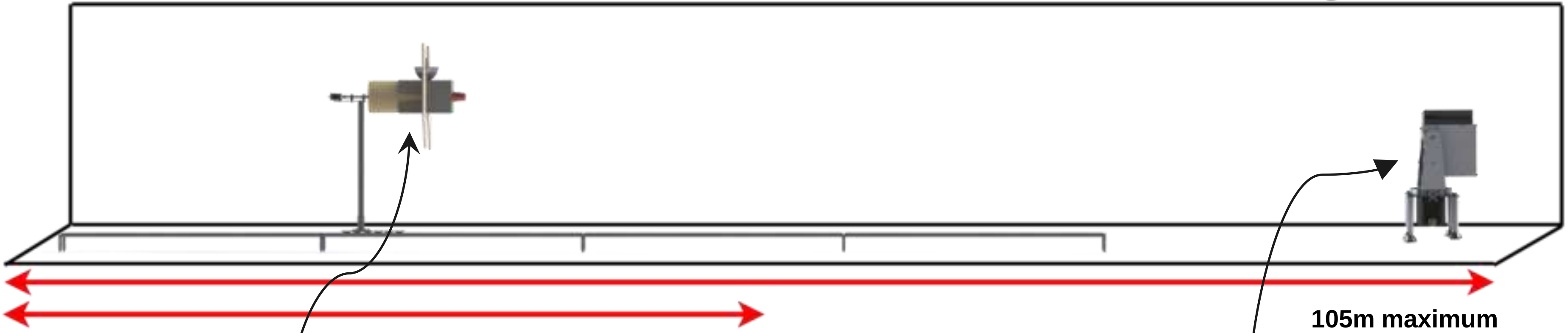


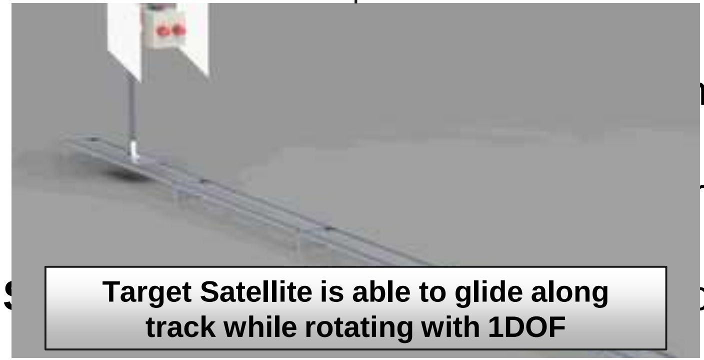
Mission CONOPS



Test Setup

Image not to scale





Target Satellite is able to glide along track while rotating with 1DOF

Manually rotating test stand simulates **ADCS**

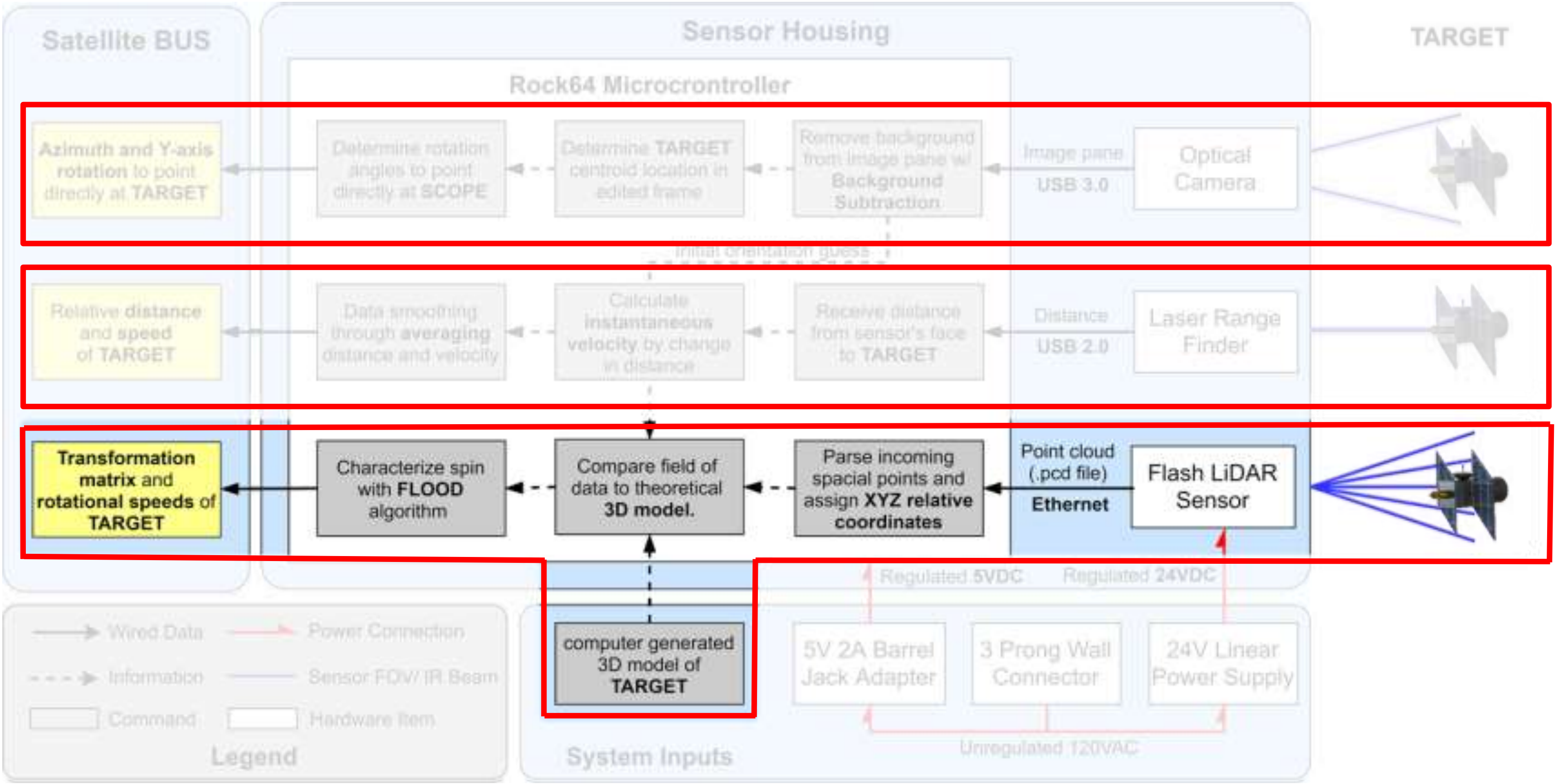
mall background interferenc **lighting**

nd rotated at known rates - **tand track**

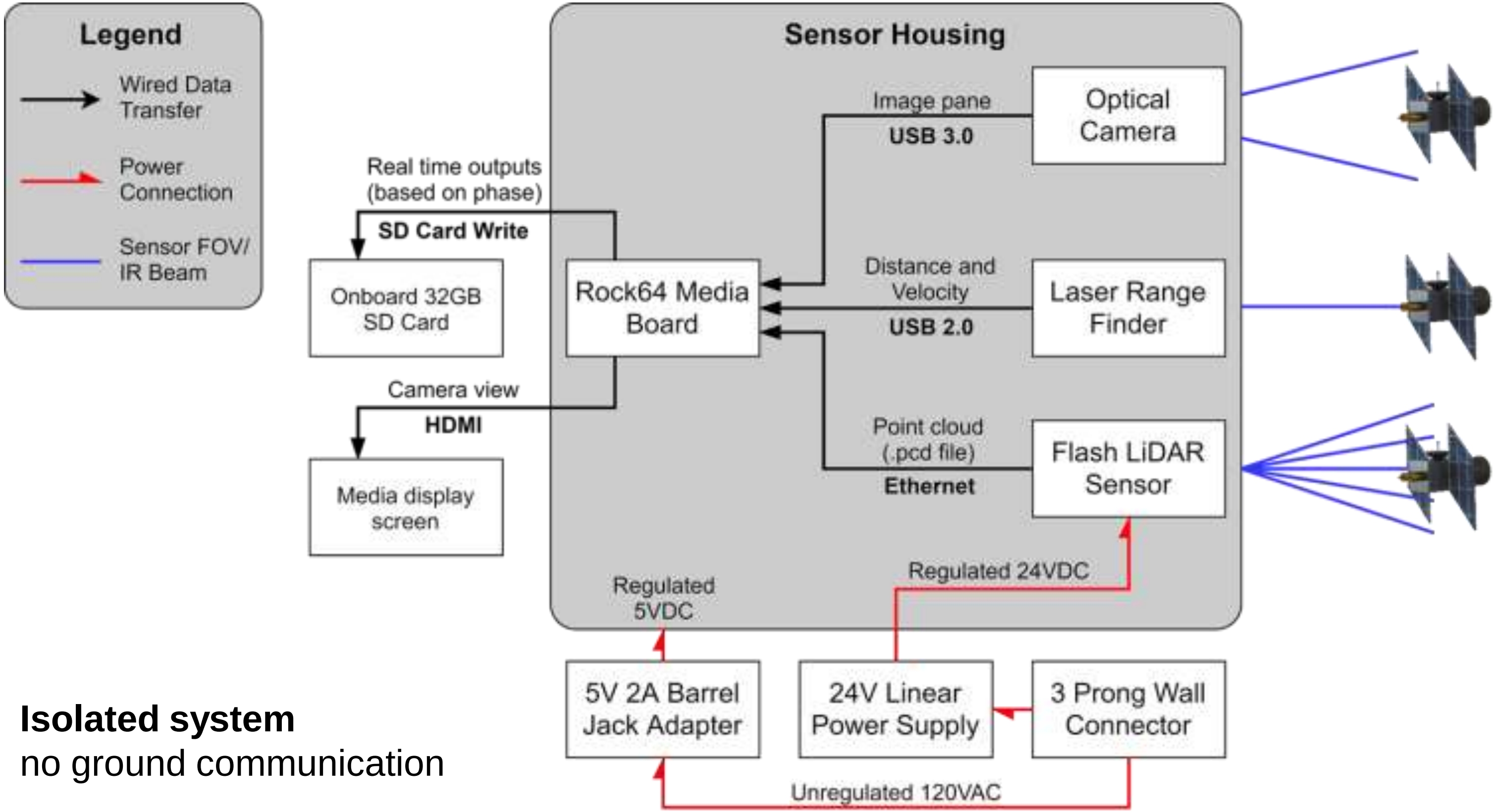
S otational capability for simulat **SCOPE test stand**

Design Solution

Functional Block Diagram



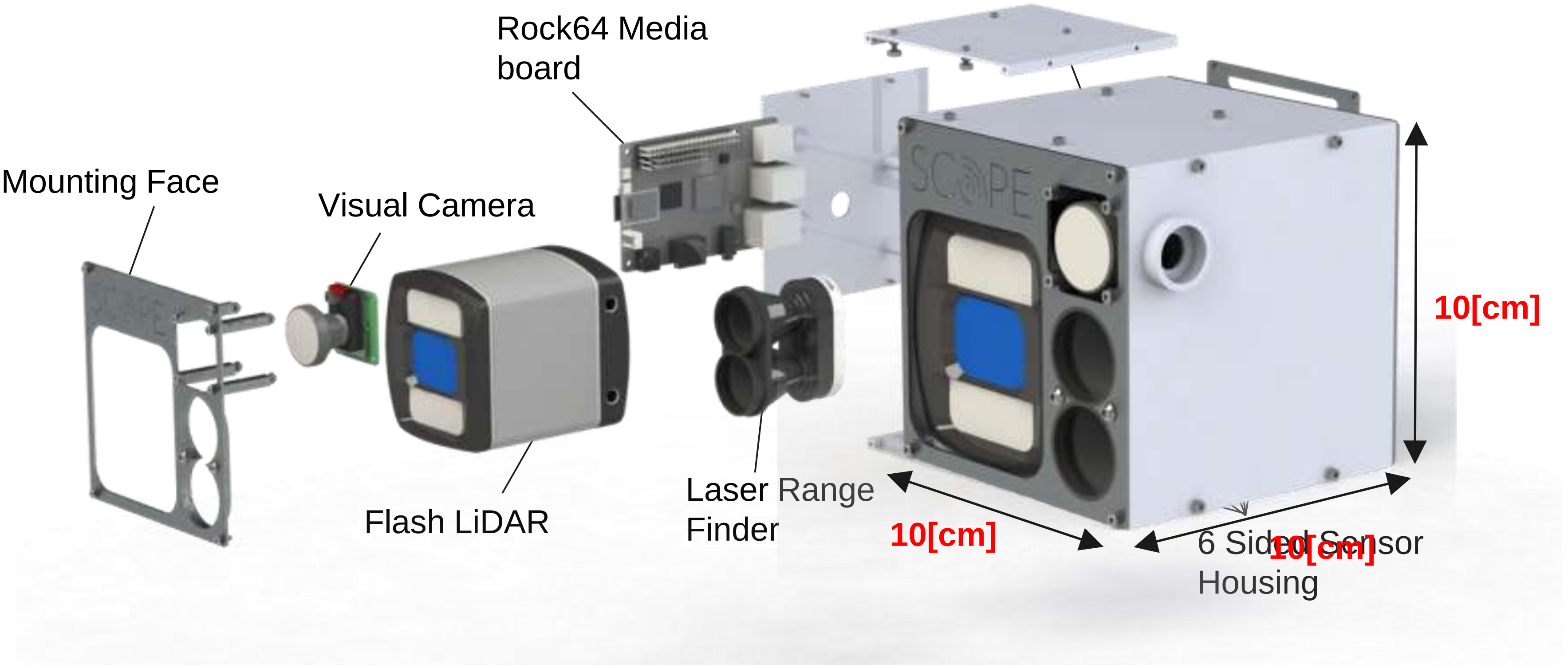
Hardware Flow Chart



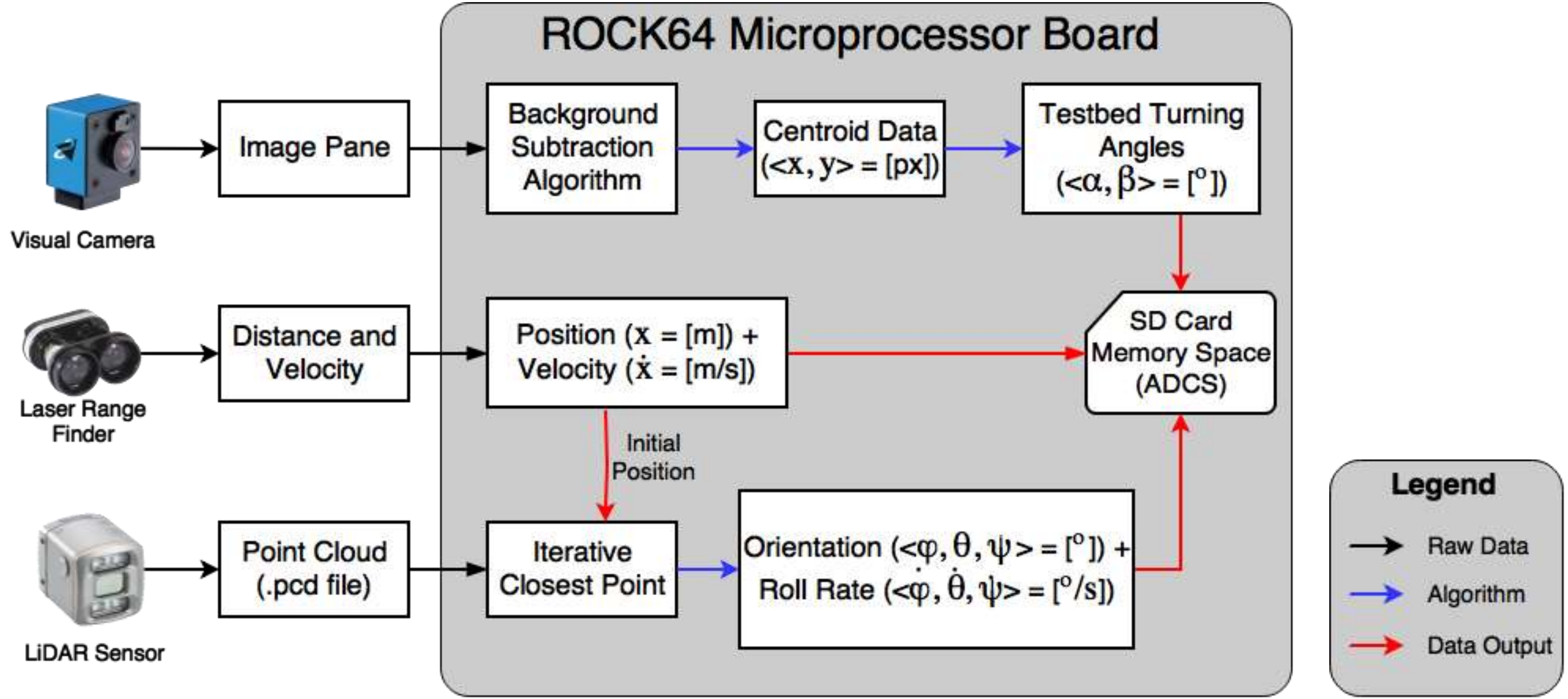
Isolated system

no ground communication

Hardware Overview



Overall Software Flow Chart



Background Subtraction

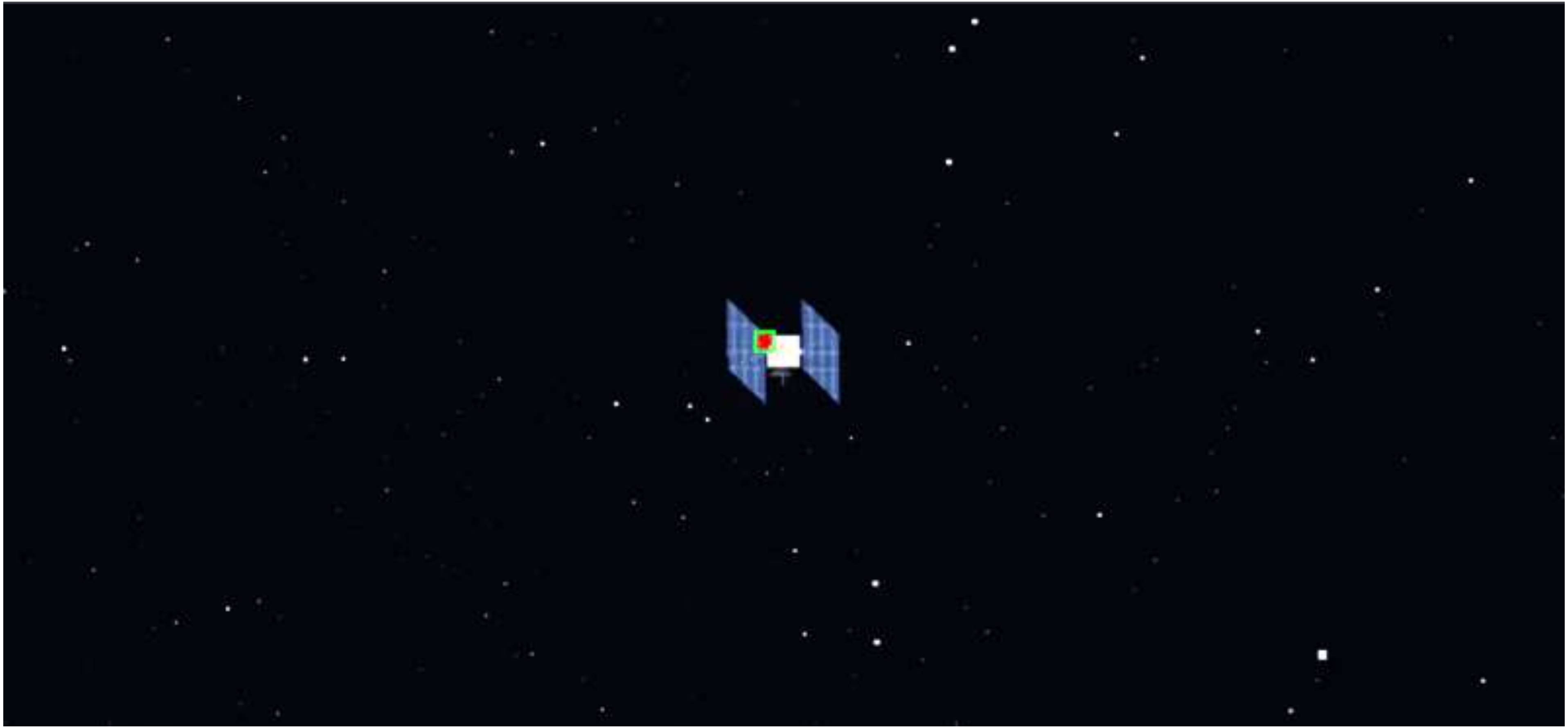
Assumptions

1. Only one moving object in frame
2. TARGET is always sun-facing

Results

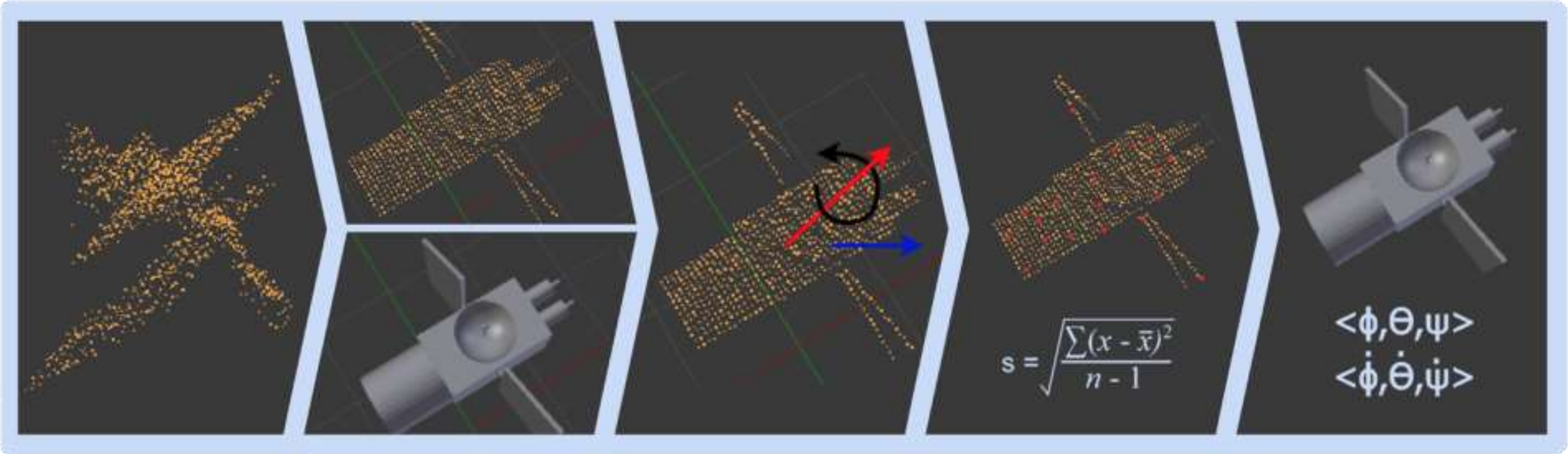
1. Centroid of object is found for Acquire/Track
2. Return initial centroid within 60s of boot

Background Subtraction in Action



Iterative Closest Point ~ FLOOD

Initial Rotation and Translation | Compare Point Cloud and 3D Model | Apply Ideal Rotation and Translation | Remove Error based on Threshold | Output Data to SD Card



<u>Assumptions</u>

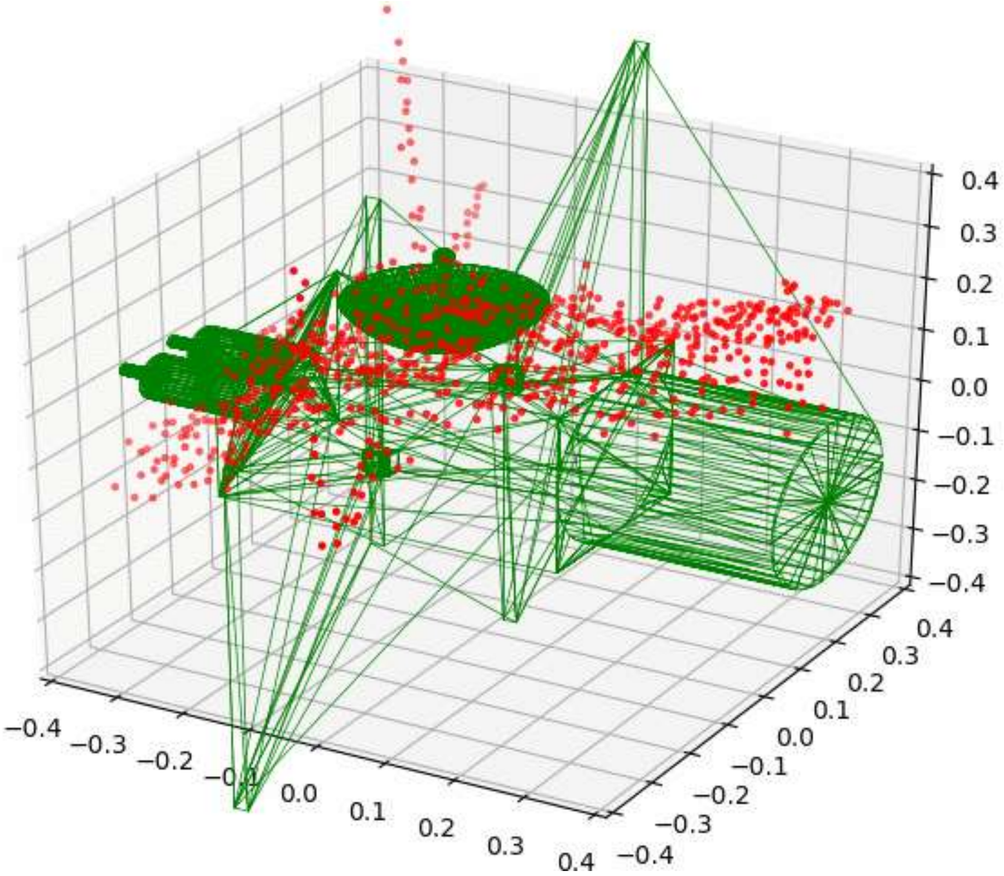
1. 3D model of TARGET is known
2. Initial position is known to within 1% of actual
3. Model is within frame of Flash Lidar sensor

<u>Results</u>

1. Outputs quaternion and translation vectors

FLOOD in Action

Visualization of FLOOD algorithm aligning point with 3D model of TARGET to find relative orientation and position



Critical Project Elements

Critical Project Elements

Centroid Determination

1. Use Background Subtraction to Detect **TARGET**.
2. Return Location in FOV for determining ADCS turning angles.

Position and Velocity Determination

1. Gather and smooth distance of **TARGET** data from laser rangefinder.
2. Return position and velocity of **TARGET** satellite.

Four main CPE's define SCOPES largest challenges

Orientation and Roll rate Determination

1. Return orientation of **TARGET** within 1 deg of actual.
2. Return angular rates of **TARGET** within 1% of actual.

1-U Satellite Constraints

1. Mass is less than **1.33[kg]**
2. Dimensions fit within **10x10x10[cm]**
3. Data is written at a rate faster than **2[Hz]**
4. Average power remains below **20W**

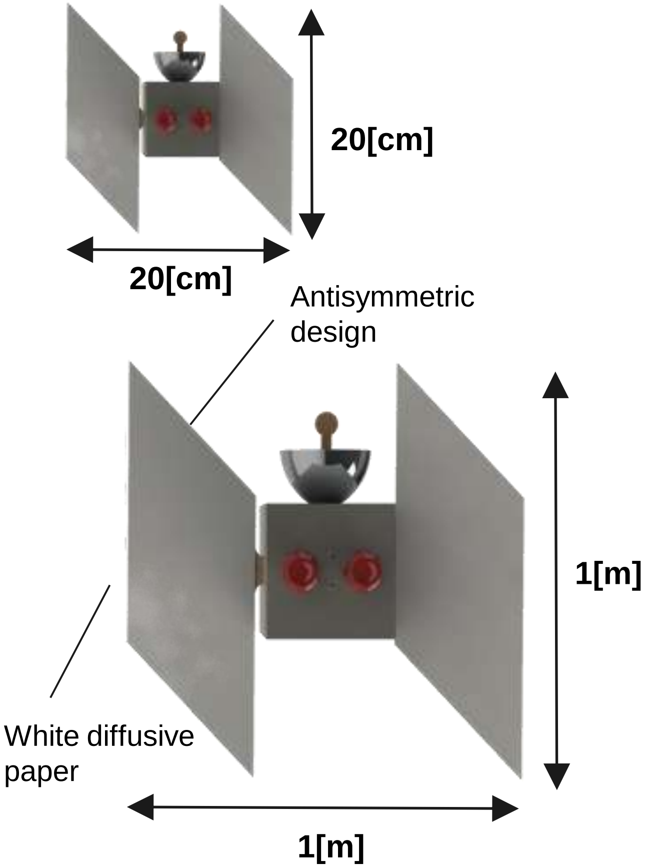
Design Requirements and their Satisfaction

TARGET Model

Driving Requirements for **Physical Characteristics**
DR 1.1: The sensor shall be able to detect a target satellite with volumetric dimensions between **20x20x30 [cm]** and **1x1x1 [m]**.
DR 1.4: The sensor shall be able to detect a target satellite under **favorable lighting conditions**.*

Driving Requirements for **Motion Characteristics**
DR 1.2: The sensor shall be able to detect a target satellite at a range of **100 [m].**
DR 3.1: The sensor package shall output the target satellite's relative velocity with an error of less than 1% with a relative velocity of **0.1[m/s]** to **1[m/s]**.
DR 5.2: The sensor shall be able to detect target satellite rotation rates between **1[deg/s]** and **5[deg/s]**.

*Favorable lighting conditions assumes diffusive white light on diffusive white paper



FR 1: The sensor package shall be capable of detecting a target satellite.

Acquire Sensor Requirement Satisfaction

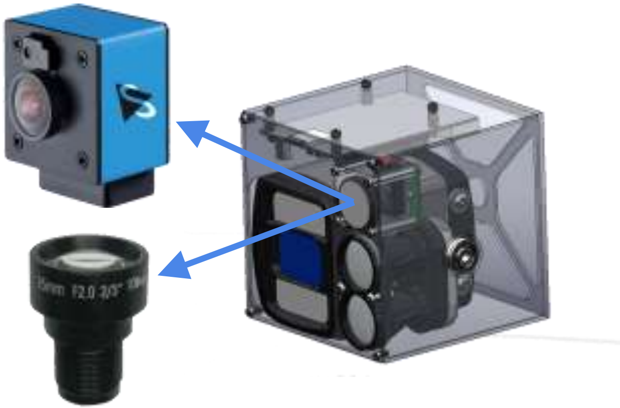
Driving Requirement	Design Parameter defined by Requirement	Sensor Capability	Requirement Fulfilled
DR 1.1	**TARGET**'s volume between **20x20x30[cm]** and **1x1x1[m].**	A total of **420 pixels** are illuminated by TARGET at maximum distance and minimum volume	**Yes**
DR 1.2.1	Detect **TARGET** at a distance of **100[m]**		
DR 1.4.1	Detect **TARGET** under favorable lighting conditions	Visual camera → operates best under well-lit conditions	**Yes**

DFK Autofocus Camera

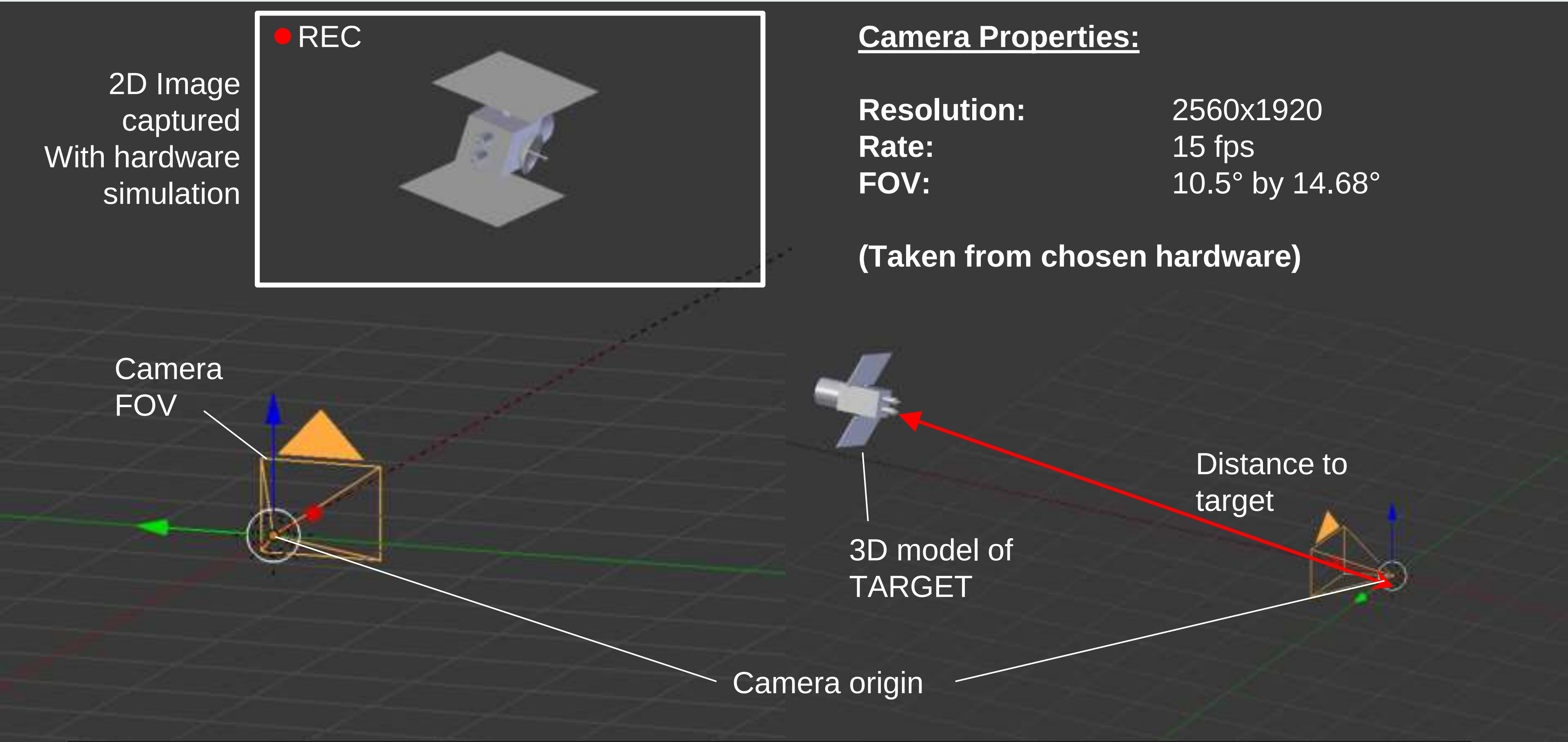
- Resolution: 5MP (2560x1920[px])
- Frame rate: 15 fps

Aico 25mm Lens

- FOV: 10.50°V x 14.68°H



Centroid Determination Satisfaction- Blender



Camera Properties:

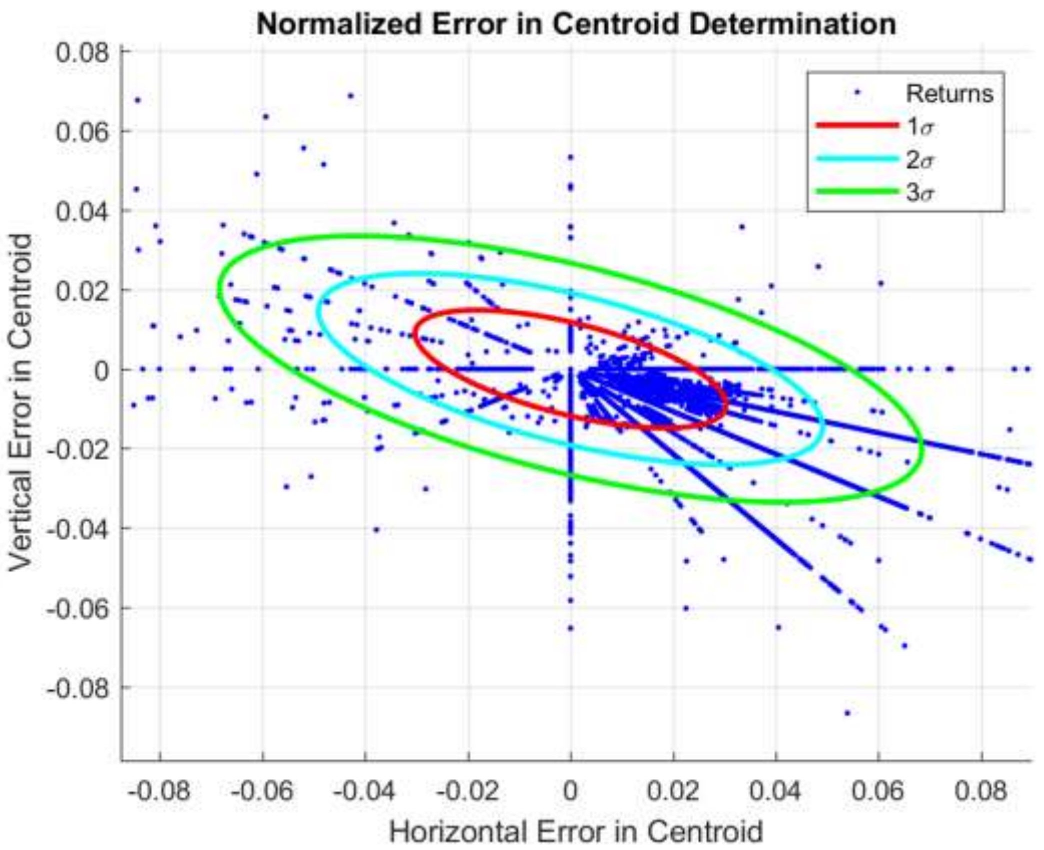
Resolution:	2560x1920
Rate:	15 fps
FOV:	10.5° by 14.68°

(Taken from chosen hardware)

Centroid Determination Achieved

Driving Requirements
DR 1.2: The sensor shall be able to detect a target satellite at a range of **100 [m]**.
DR 1.3: The sensor shall detect the target satellite within **60(s)** of turn-on.
DR 1.4: The sensor shall be able to detect a target satellite under favorable lighting conditions.

Percent Confidence for Satisfying DR 1.3 > 99%



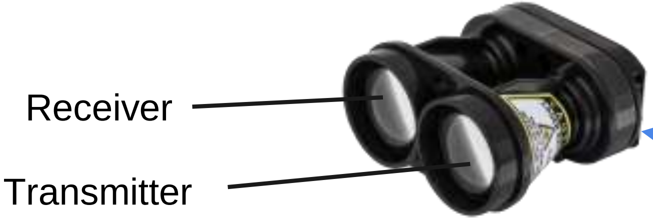
FR 2: The sensor package shall output the target satellite's relative position upon detection.

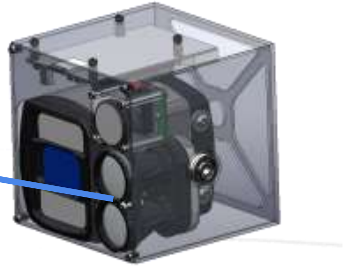
FR 3: The sensor package shall output the target satellite's relative velocity upon detection.

Laser Range Finder Requirement Satisfaction

SF30-C Laser Rangefinder 100m

Driving Requirement	Design Parameter defined by Requirement	Sensor Capability	Requirement Fulfilled
DR 1.2.1	Detect **TARGET**'s at a range of 100 m	Measurement range **+100[m]**	**Yes**
DR 2.1	Output **TARGET**'s satellite relative position with an error of less than 1%	Frame rate of **18,317 [Hz]** Accuracy of **+/- 10 [cm]** Std position **0.0388 [m]**	**Yes**
DR 3.1	Output **TARGET**'s satellite relative velocity with an error of less than 1%	Frame rate of **18,317 [Hz]** and Accuracy of **+/- 10 [cm]** Std velocity **0.0548 [m/s]**	**Yes**



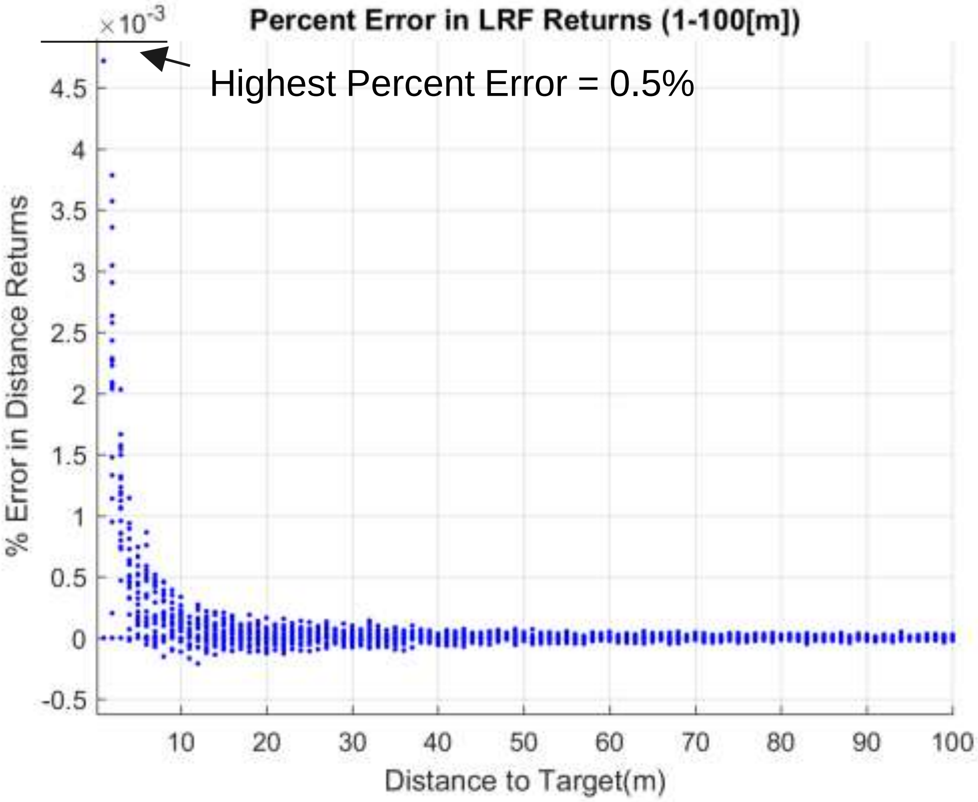


1-100m Position Determination is a Success

Driving Requirements
DR 2.1: The sensor package shall output the target satellite's relative position with an error of less than **1%** up until a relative position of **1[m]**.

Percent of Points Above Error = 0%

Percent Confidence of Satisfying DR 2.1 > 99%



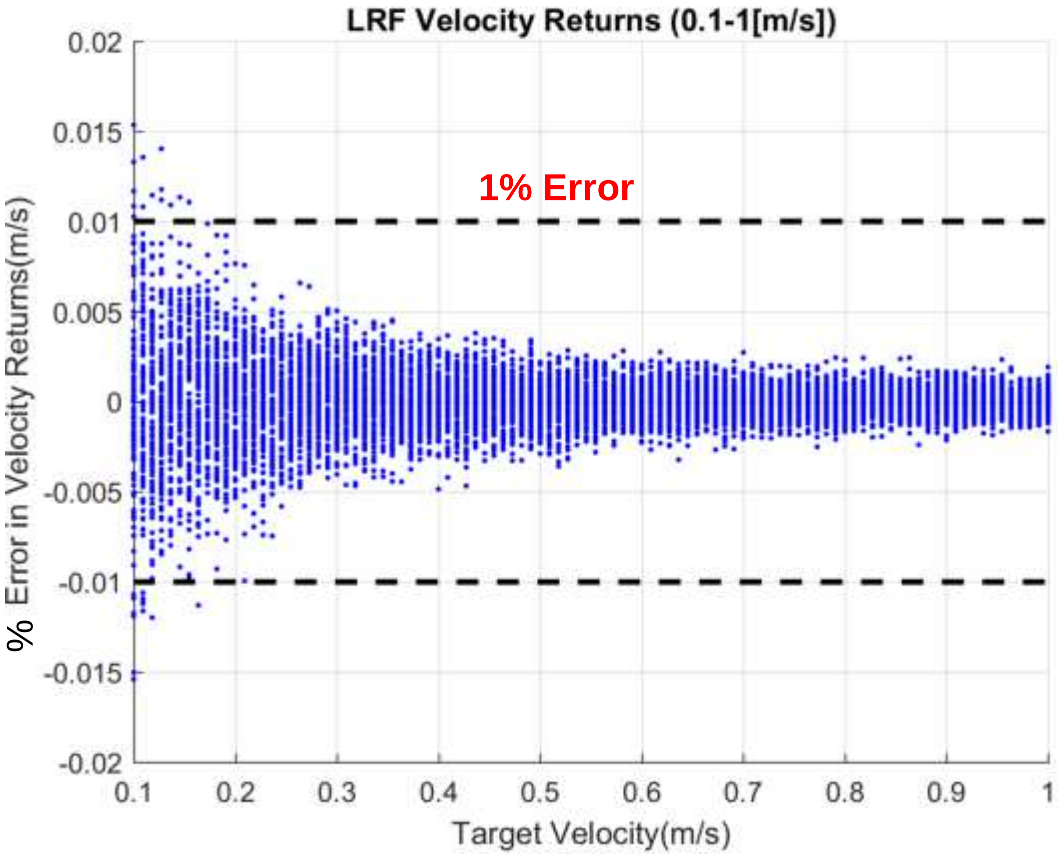
Velocity Determination Satisfied

LRF error is not a function of distance or velocity so highest error occurs at lowest velocity

Driving Requirements
DR 3.1: The sensor package shall output the target satellite's relative velocity with an error of less than 1% up until a relative velocity of **0.1[m/s].**

Percent of Points Above Error = 0.0015%

Percent Confidence of Satisfying DR 3.1 > 99%



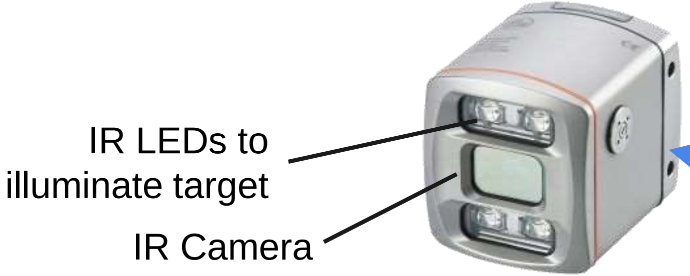
FR 4: The sensor package shall output the target's relative orientation upon detection.

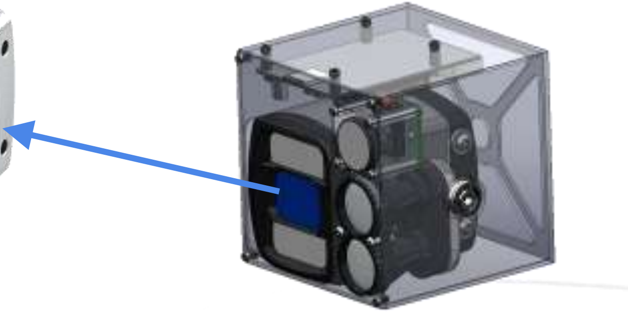
FR 5: The sensor package shall output the target satellite's relative rotation rate upon detection.

LiDAR Sensor Requirement Satisfaction

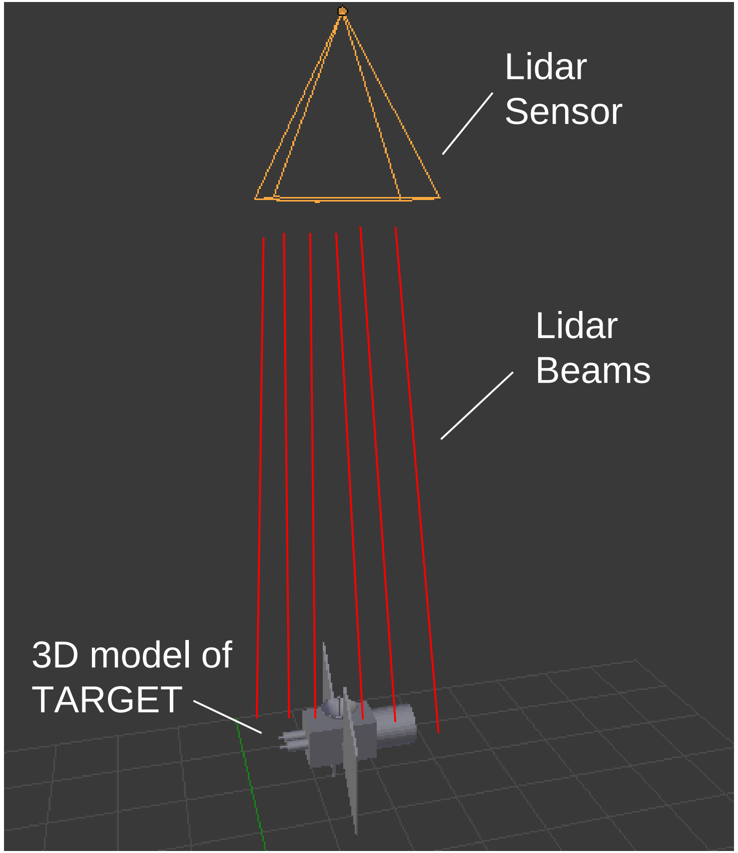
IFM Electronics O3D301

Driving Requirement	Design Parameter defined by Requirement	Sensor Capability	Requirement Fulfilled
DR 4.1	Output **TARGET**'s relative orientation between **1[m]** and **10[m].**	Measurement range up to **10[m]**, and background up to **30[m]**.	**Yes**
DR 4.2	Output **TARGET**'s relative orientation with an error off less than **1[deg]**	Individual point accuracy is **+/- 2[cm]**	More analysis required
DR 4.3	Determine orientation of **TARGET** through comparison with known 3D model.	**.pcd (point cloud)** file output	**Yes**





Orientation Determination Satisfaction - Blender



Lidar Properties:

Resolution:	**176x132**
Rate:	**2 FPS**
Accuracy:	**7-20 mm**
FOV:	**40°x30°**

(Taken from hardware)

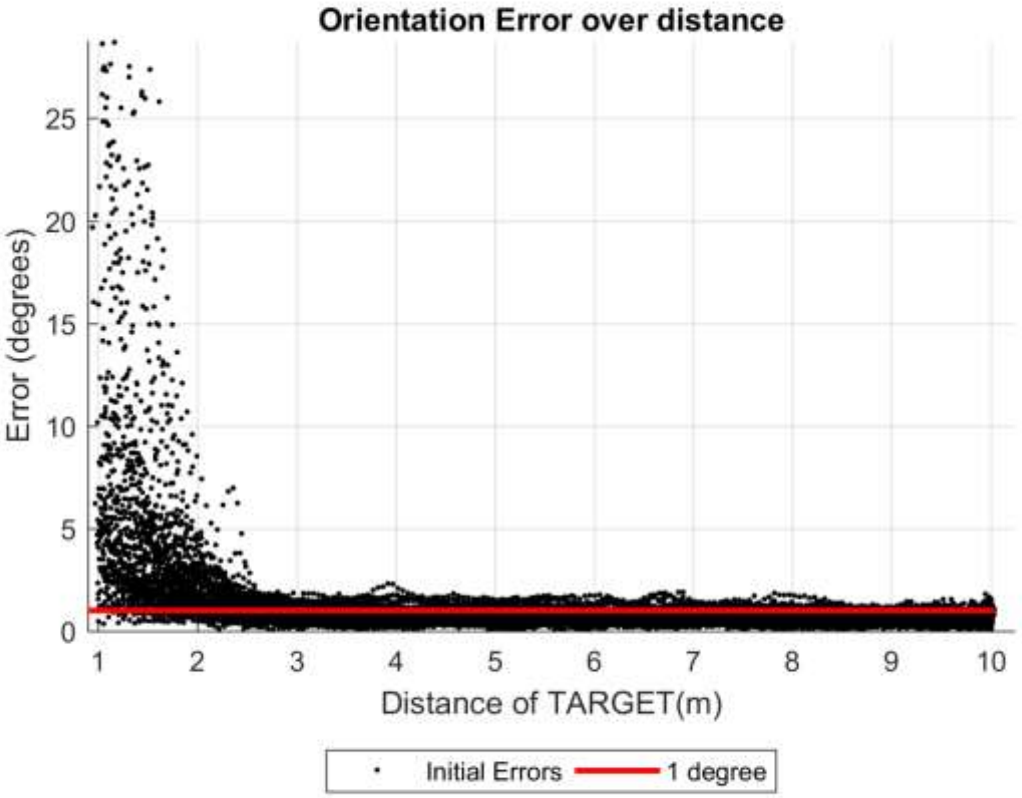
- **100 simulations performed**
- **Model moves from a distance of 10m to 1m during each simulation**
- **Simulated Lidar sensor uses ray tracing to develop a 3D point cloud of TARGET every half second**
- **FLOOD algorithm finds the orientation and position of each point cloud**

Orientation Determination Achieved

Driving Requirements
DR 4.1: The sensor package shall output the target satellite's relative orientation at a starting range of **10[m]**.
DR 4.2: The sensor package shall output the target satellite's relative orientation with an error of less than **1[deg]**.
DR 4.3.2: The sensor will be able to determine the target satellite's relative orientation through a comparison with a known 3D model of the target satellite.

Percentage above 1 deg = 29%
Over 2m = 18%
Under 2m = 93%

Percent Confidence of Satisfying DR 4.2 = 70%

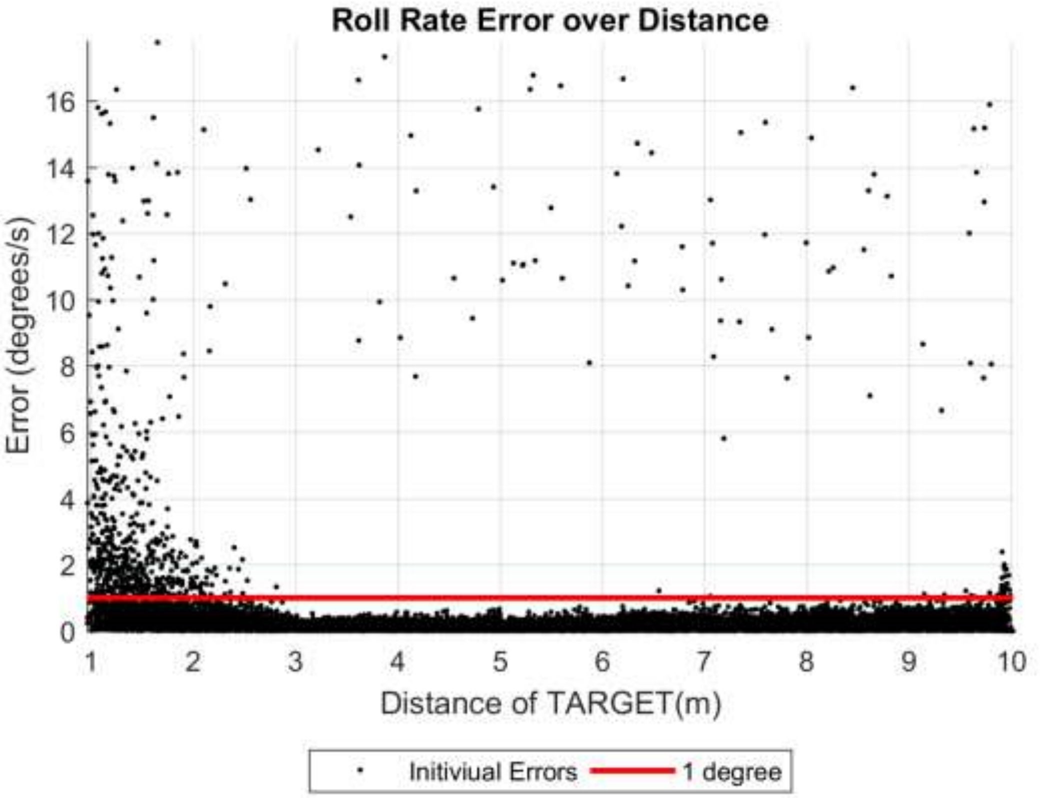


Roll Rate Determination Satisfied

Driving Requirements
DR 5.1: The error of the sensor package's relative rotation rate output shall be less than **1[deg/s]**.
DR 5.2: The sensor shall be able to detect target satellite rotation rates between **1[deg/s]** and **5[deg/s]**.

Percentage above 1 deg: 5.2%
Over 2m: 1.3%
Under 2m: 35.7%

Percent Confidence of Satisfying DR 5.1 = 94.8%



FR 6 The sensor package shall output target satellite data at a set frequency.

FR 7 The sensor package shall be formatted to fit within a 1(U) platform (as defined by standard CubeSat protocol) upon launch.

Overall Power Consumption Fulfilled

Assumptions

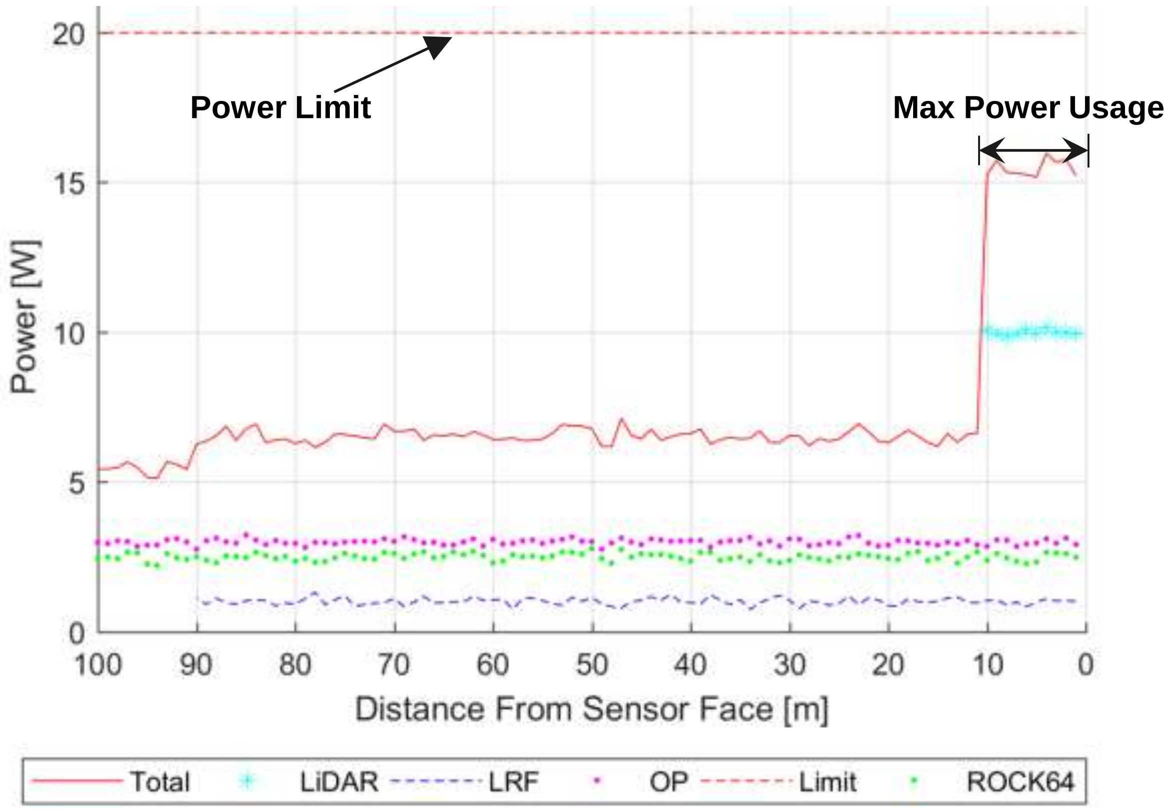
1. Highest power consumption during orientation phase (all sensors in operation)
2. Peak power reached 10% of time to take one measurement.

Requirement

Average power must continuously remain below 20W.

Result

Overall power consumption meets requirements. (FR7 DR7.3)



Operational Temperature

Assumptions

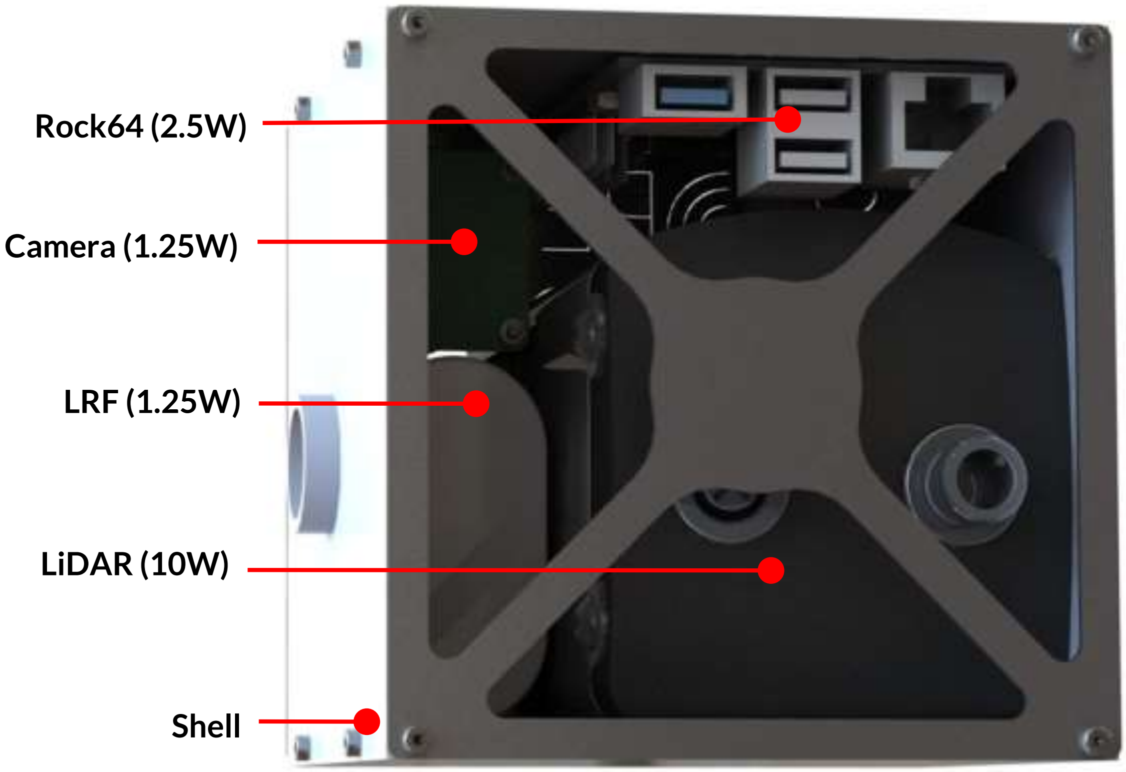
1. Heat transfer through conduction, radiation, and convection.
2. Components emit thermal power from surfaces.
3. Surface contacts assumed ideal (bonded).
4. Ambient temperature is 22°C

Governing Equations

Convection: $\dot{q} = h(T_{Hot} - T_{Cold})A$

Conduction: $\dot{q} = \frac{kA(T_{Hot} - T_{Cold})}{L}$

Radiation: $\dot{q} = (\varepsilon \alpha T_{Hot}^4)A$



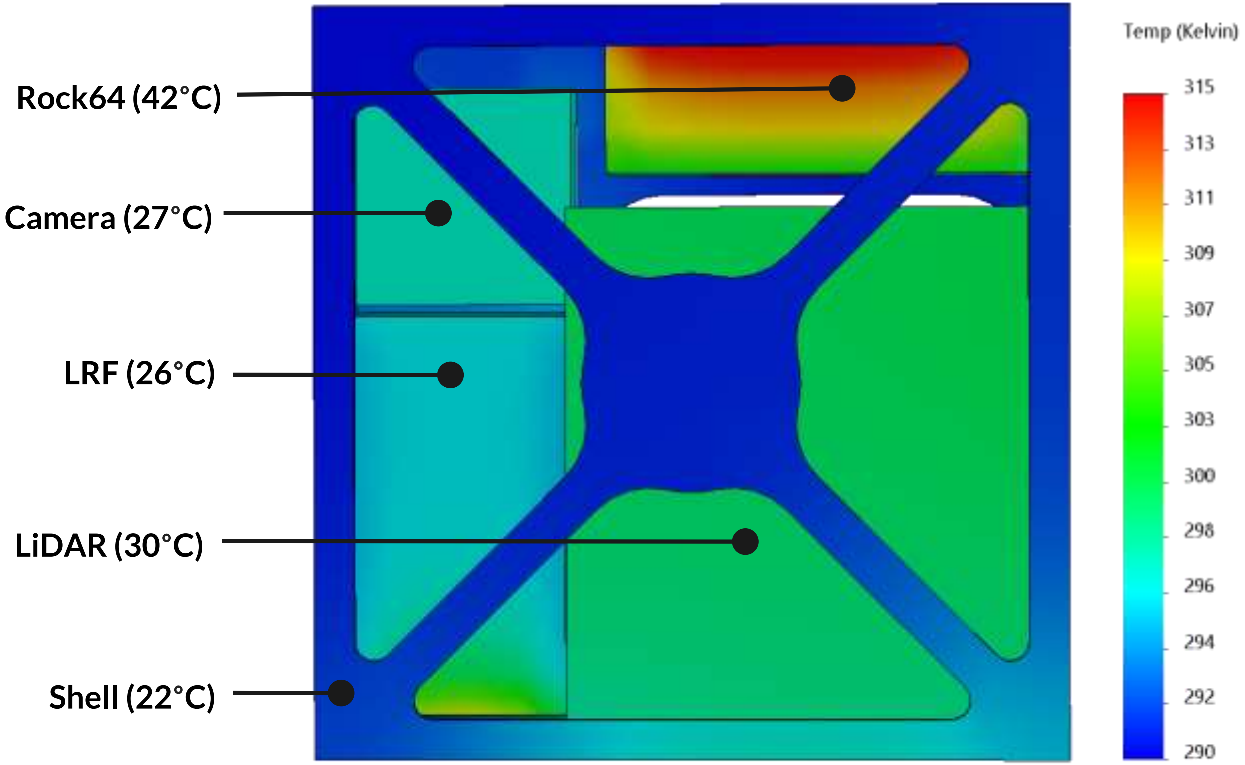
Operational Temperature

Results

1. Highest temperature reached is 42°C. (by Rock64)
2. Shell helps to dissipate heat by the flash LiDAR

Conclusion

1. All temperatures remain within operational temperature.
2. No heat sinks (besides shell) required.



Output Frequency Validated

Rock64 Board
Quad Core 1.8GHz
4GB DRAM

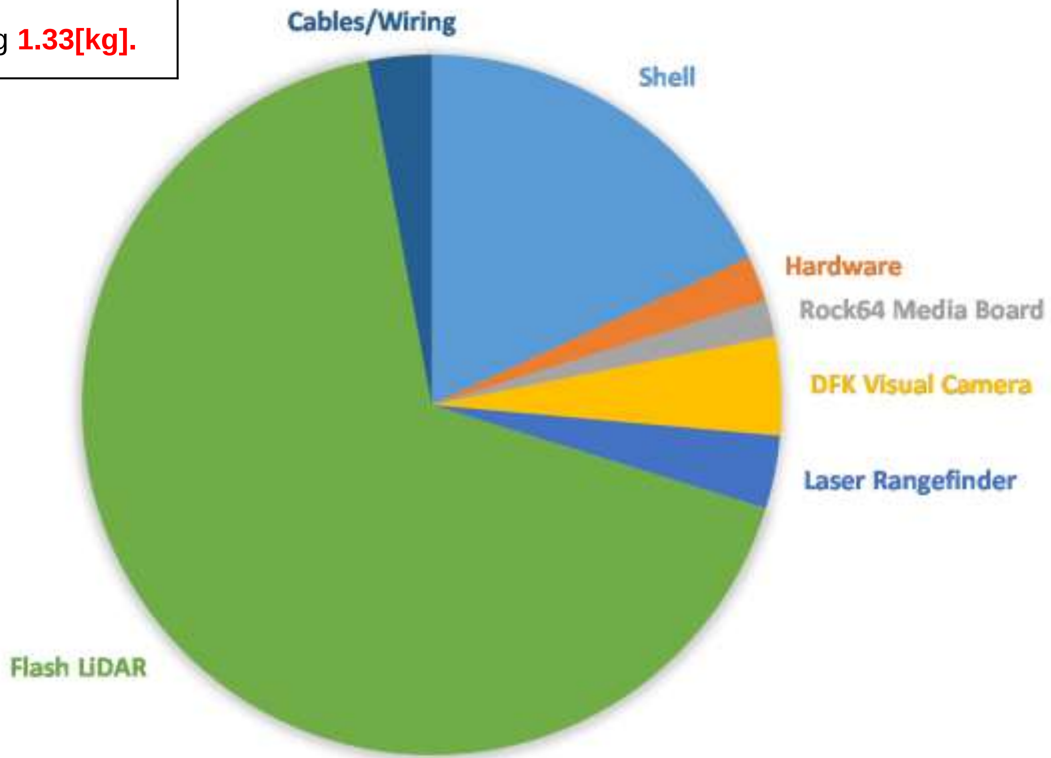
Driving Requirements
DR 6.1: The sensor shall output target satellite data at a frequency of **2[Hz].**
DR 6.2: The sensor may output target satellite data at a frequency of **5[Hz].**

Algorithm	Testing device	Output Frequency [Hz]	Requirement Fulfilled
Background Subtraction	**2.4 GHz** Mac computer	**18.63**	**Yes**
FLOOD	**1.2 GHz** Raspberry Pi	**7.23**	**Yes**

Mass Requirement Fulfilled

Driving Requirement
DR 7.3: The sensor shall not have a mass exceeding **1.33[kg].**

Component	Mass [kg]
Shell and Hardware	0.230
Rock64 Board	0.020
Visual Camera	0.054
Laser Rangefinder	0.040
Flash LiDAR	0.800
Cables/Wiring	0.035
Total	**1.189**
Margin	**0.141**



Project Risk

Risk Matrix

Frequency/ Consequence	1-Very Unlikely	2-Remote	3-Occasional	4-Probable	5-Frequent
4-Catastrophic	Failure to Detect Target Satellite				
3-Critical			Over Budget	Data Accuracy Failure	
2-Major		Board Overheat			
1-Minor			Power Overload		

Computational Board Overheating: Rock 64 Microprocessor exceeds maximum operating temperature

Failure to Detect Target Satellite: Background Subtraction returns a centroid location that is not on the target satellite

Budget Exceeds allotted amount: Cost of Sensors is too high

Data Accuracy Failure: Not returning position, velocity, orientation, and/or roll rate data within specified accuracy thresholds

Power System Overloads: System as a whole consumes more power than provided by the satellite bus

Risk Mitigation

Frequency/ Consequence	1-Very Unlikely	2-Remote	3-Occasional	4-Probable	5-Frequent
4-Catastrophic	Failure to Detect Target Satellite				
3-Critical		Over Budget	Over Budget	Data Accuracy Failure	
2-Major		Board Overheat	Data Accuracy Failure		
1-Minor			Power Overload		

Mitigation Methods:

Data Accuracy Failure:

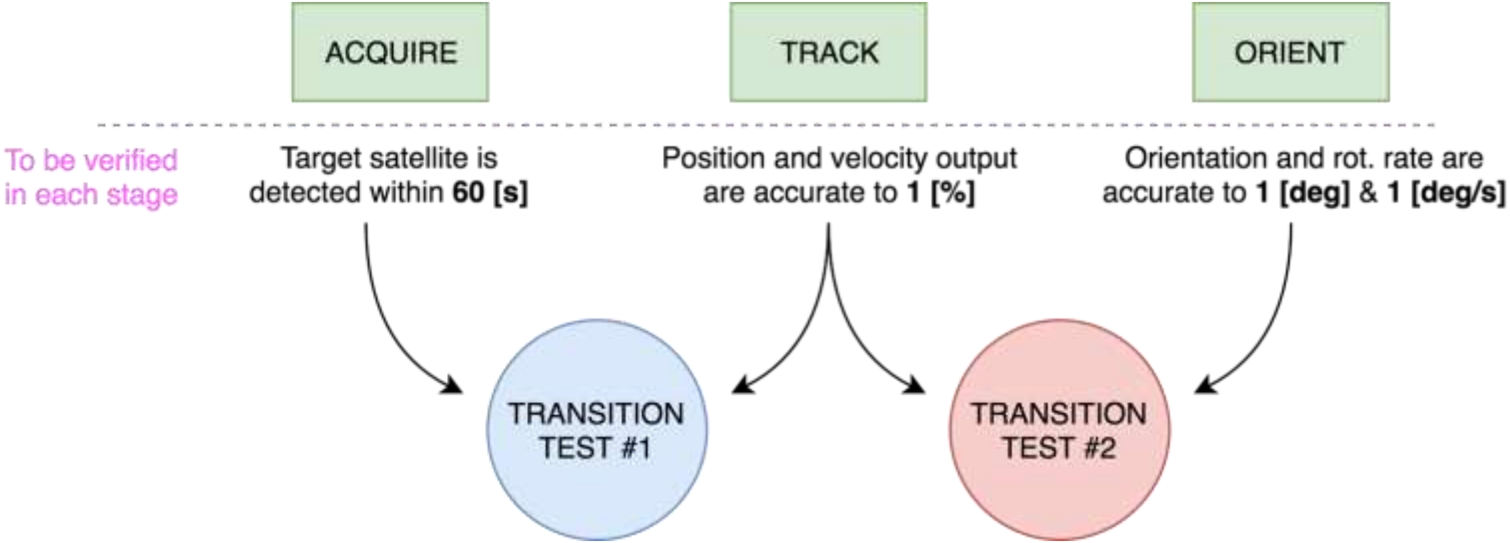
- Kalman filtering with LiDar, optical camera, LRF (reduces risk)
- Algorithm Optimization (reduces likelihood)
- LiDar with wider FOV (reduces likelihood)

Over Budget:

- Address accuracy requirements in order to reduce sensor cost (reduces likelihood)

Verification and Validation

Testing Overview

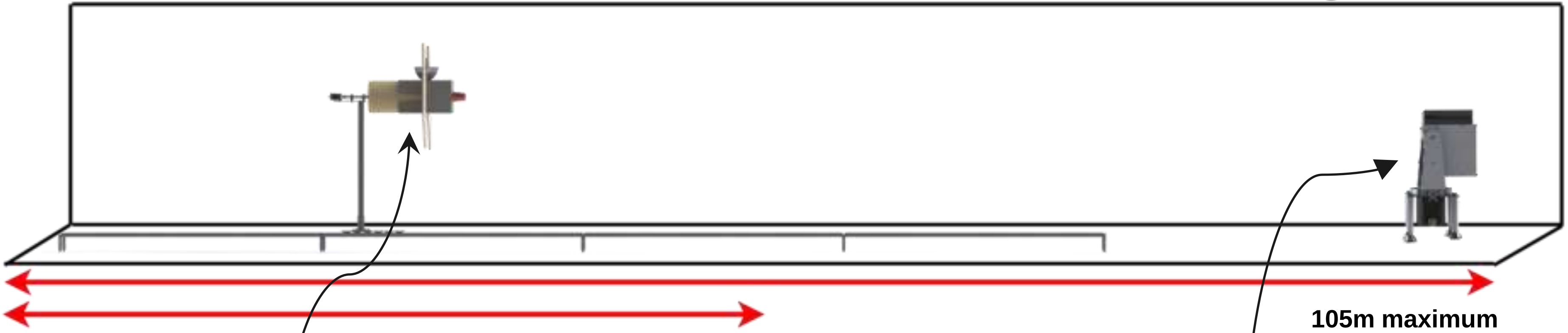


<u>Conclusions:</u>

1. Hardware and Software integration support transitions between stages
2. A manufactured model of the target satellite is needed in order to collect data
3. A track to simulate at best orbiting conditions

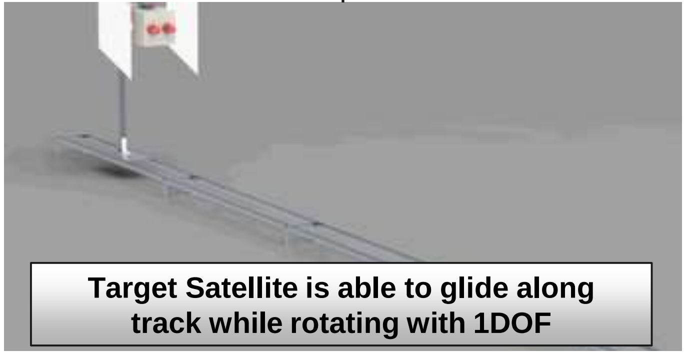
Test Setup

Image not to scale



15m of translation possible

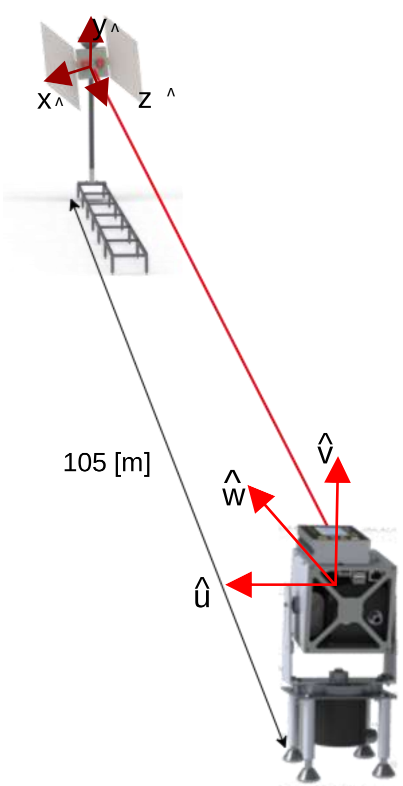
105m maximum distance



Target Satellite is able to glide along track while rotating with 1DOF

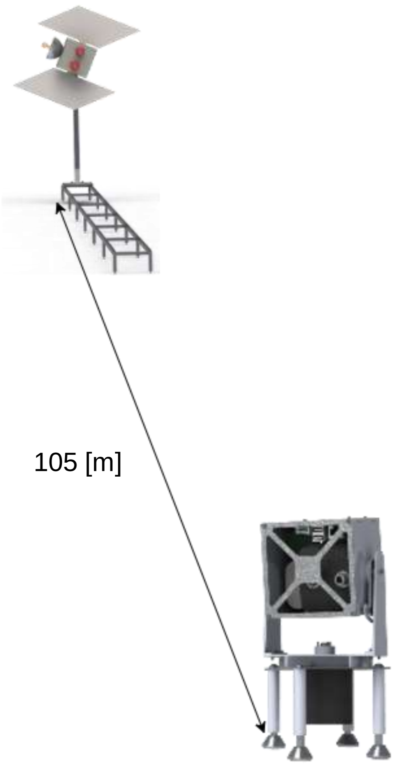
Manually rotating test stand simulates **ADCS**

Test 1: Acquire and Track



Setup/Calibration

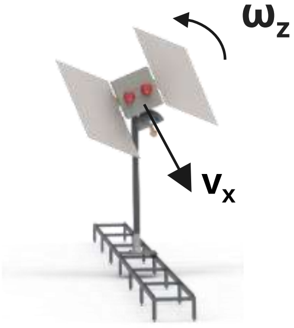
1. SCOPE set to position at **0 [m]**.
2. Track ends **90 [m]** away from SCOPE, starting at **105 [m]**.
3. Accurate pointing calibration achieved with digital level laser beam.
4. SCOPE's sensors are activated.



Detect

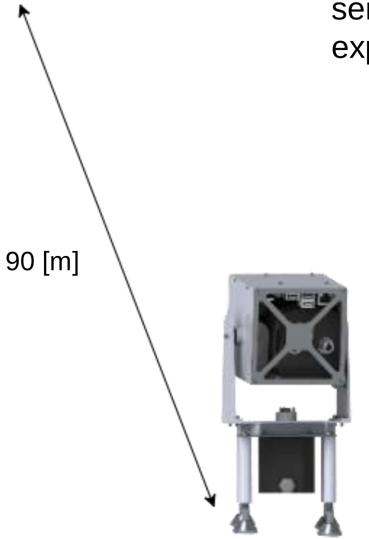
1. Winch drives target at **0.1 [m/s]**
2. Sensor test stand is turned manually.
3. Digital level displays truth angles **[θ,ψ]**
4. Algorithm outputs angles needed to center target in FOV

Test 1: Acquire and Track



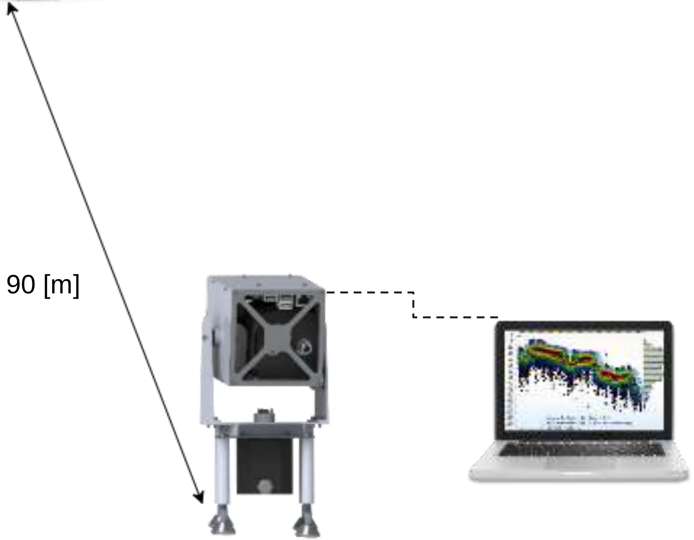
Track

1. Target continues to move in-line
2. Track ends at position **90 [m]**
3. Ensure software and sensors transitioned as expected

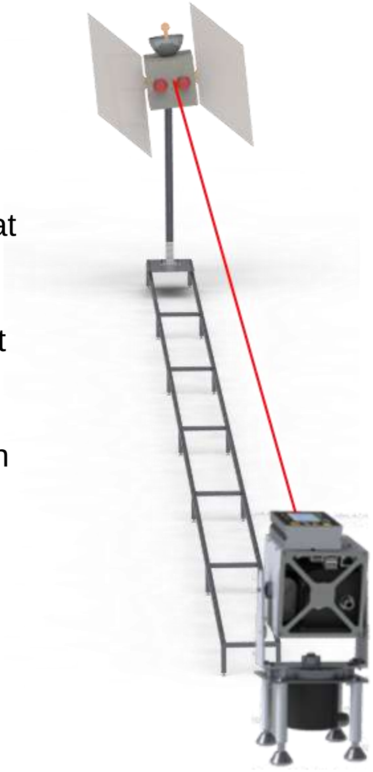


Data Acquisition

1. Motors turned off
2. Analyze data in Matlab
3. Restart test with different motor speeds



Test 2 : Track and Orientation



Setup/Calibration

1. SCOPE set to position at **0 [m]**.
2. Track ends **1 [m]** away from SCOPE, starting at **16 [m]**.
3. Accurate pointing calibration achieved with laser beam.
4. SCOPE’s sensors are activated.

Initialization

1. Loud clap signal start of test and allow for data synchronization.
2. Target motor spinning at desired rotational rate.
3. Winch motor pulling at desired velocity.

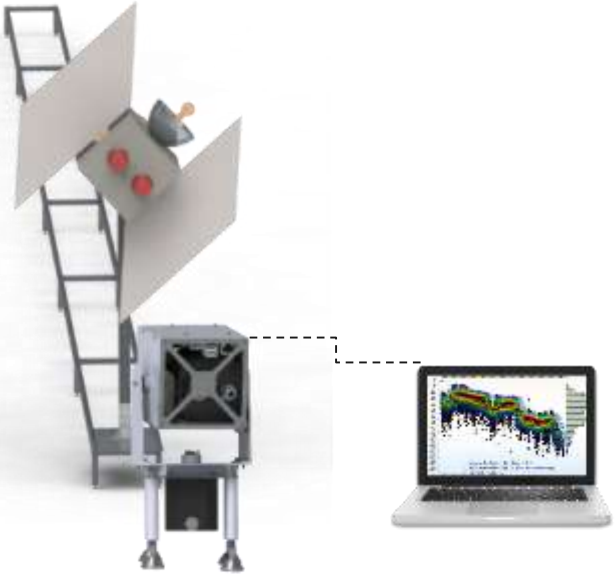
Test 2: Track and Orientation

Transition

1. Monitor sensors to make sure transition happens flawlessly.

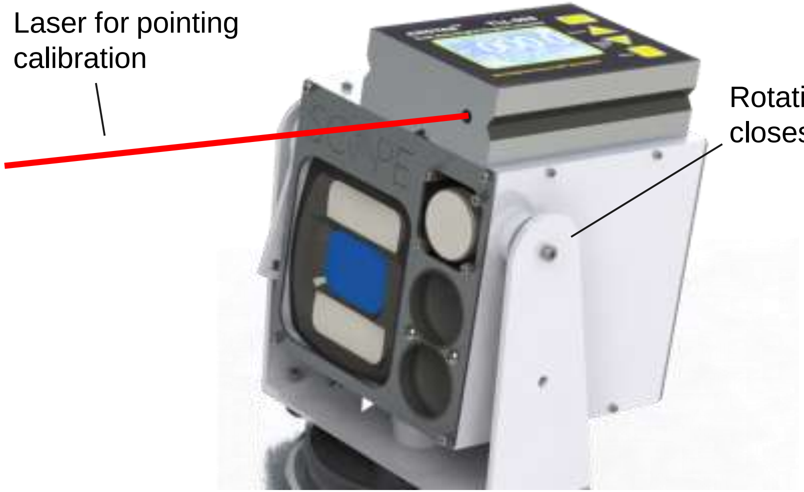
Data Acquisition

1. Turn off motors.
2. Analyze data in matlab.
3. Restart test with different input voltages to motors.



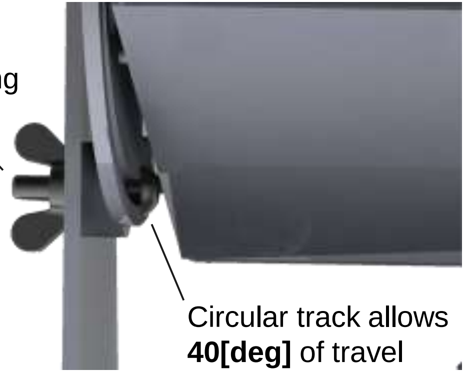
The Sensor Package Test Stand

Laser for pointing calibration



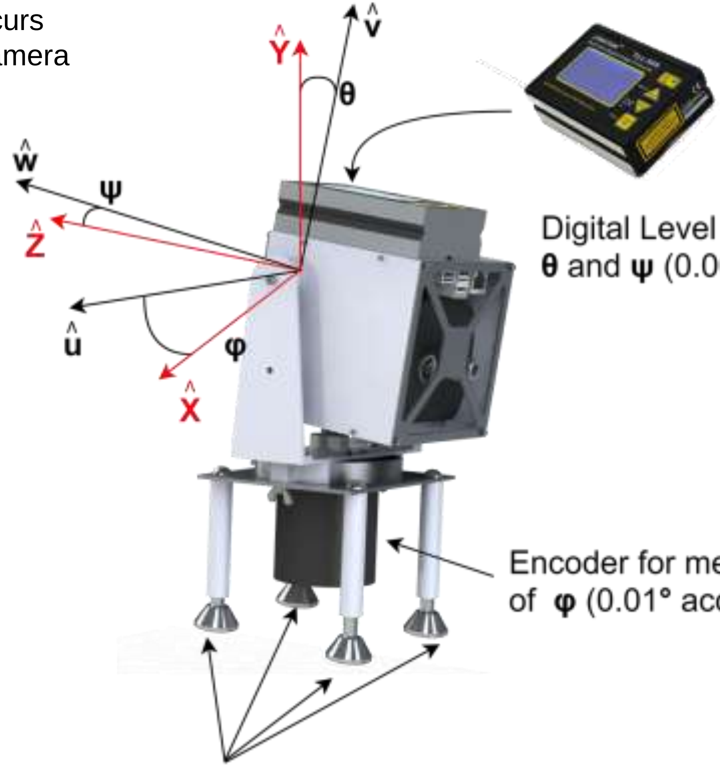
Rotation occurs closest to camera

Wingnut for manual tightening



Circular track allows **40[deg]** of travel

Inertial and **Body** Frame Representation



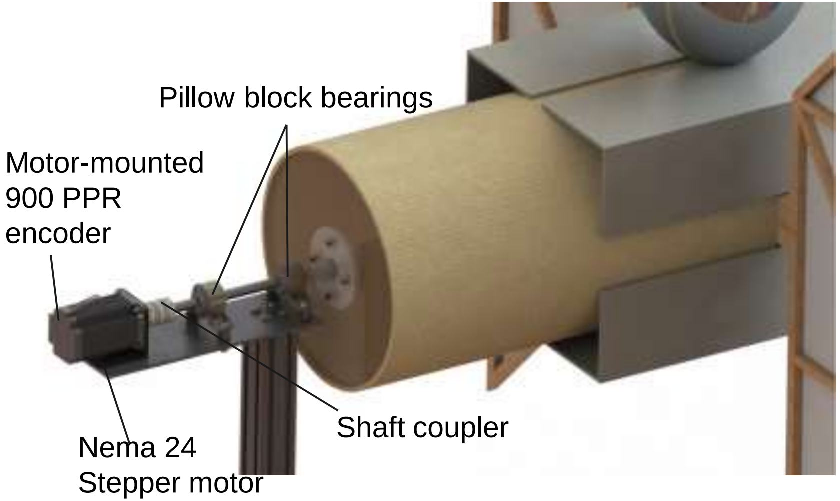
Digital Level measures **θ** and **ψ** (0.005° accuracy)

Encoder for measurement of **φ** (0.01° accuracy)

Leveling Feet

Target test stand & winch

Inline wheel and track system ensures proper pointing with translation



Requirement Tested	Test Stand Capability
DR 2.1,2: Output target's relative position and velocity with an error of less than **1%** up until a relative position of **1[m].**	500 PPR winch encoder gives accuracy in distance to **1[cm]**.
DR 4.2: Output the target satellite's relative orientation with an error of less than **1[deg]**.	3600 PPR encoder gives rotation position at an accuracy of **0.1[deg]**.
DR 5.2: Detect target satellite rotation rates between **1[deg/s] and 5[deg/s]**	Nema 23 Stepper motor provides enough torque to rotate target satellite at constant rotational rate.
DR 5.1: The error of the sensor package's relative rotation rate output shall be less than **1[deg/s].**	Instantaneous roll rate can be calculated from encoder to an accuracy of **0.1[deg/s]**.

Test Plan

Acquire and Track Test

↓

-Dependancies-
ITLL Hallway Lighting

↓

-Schedule-
3/5/18 to 3/19/18

Track and Orientation Test

↓

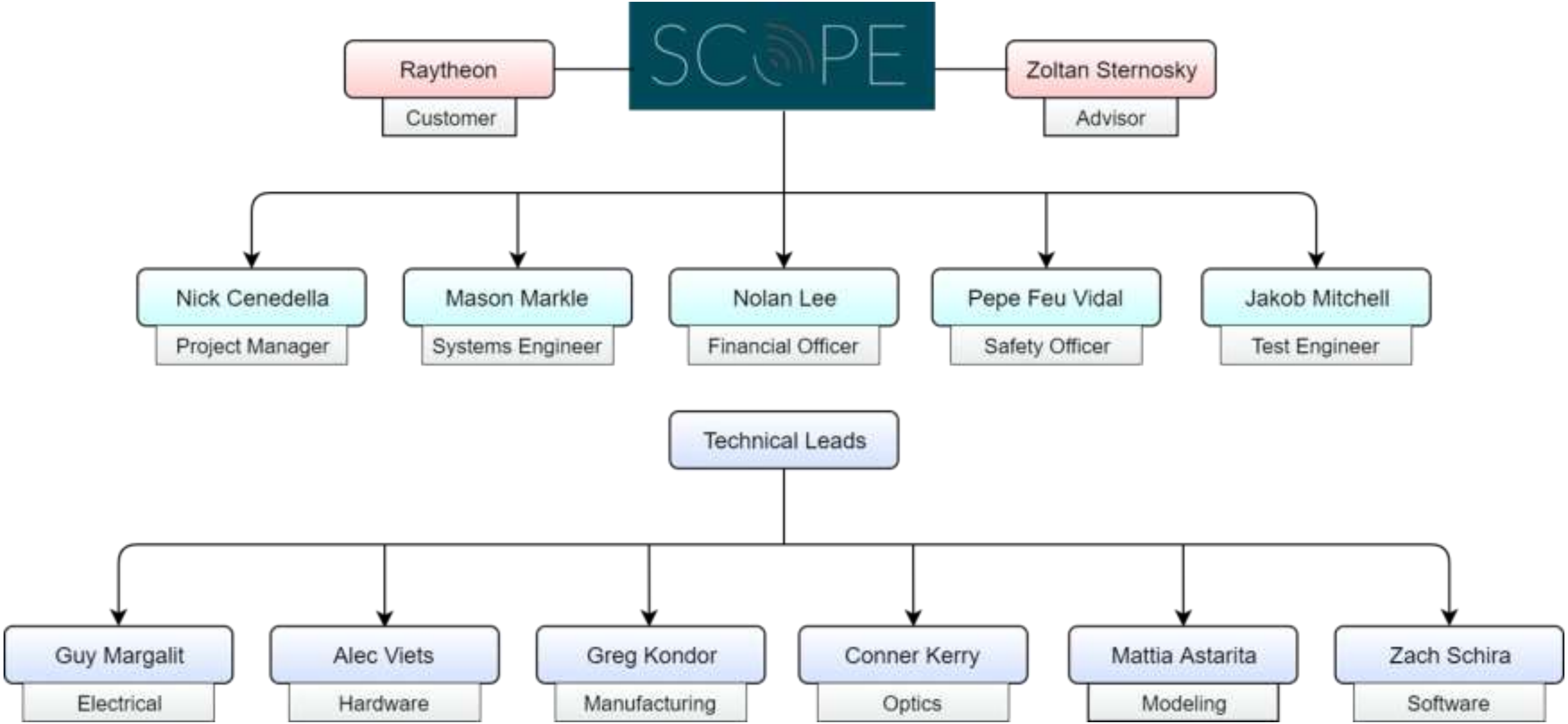
-Dependancies-
ITLL Hallway Lighting

↓

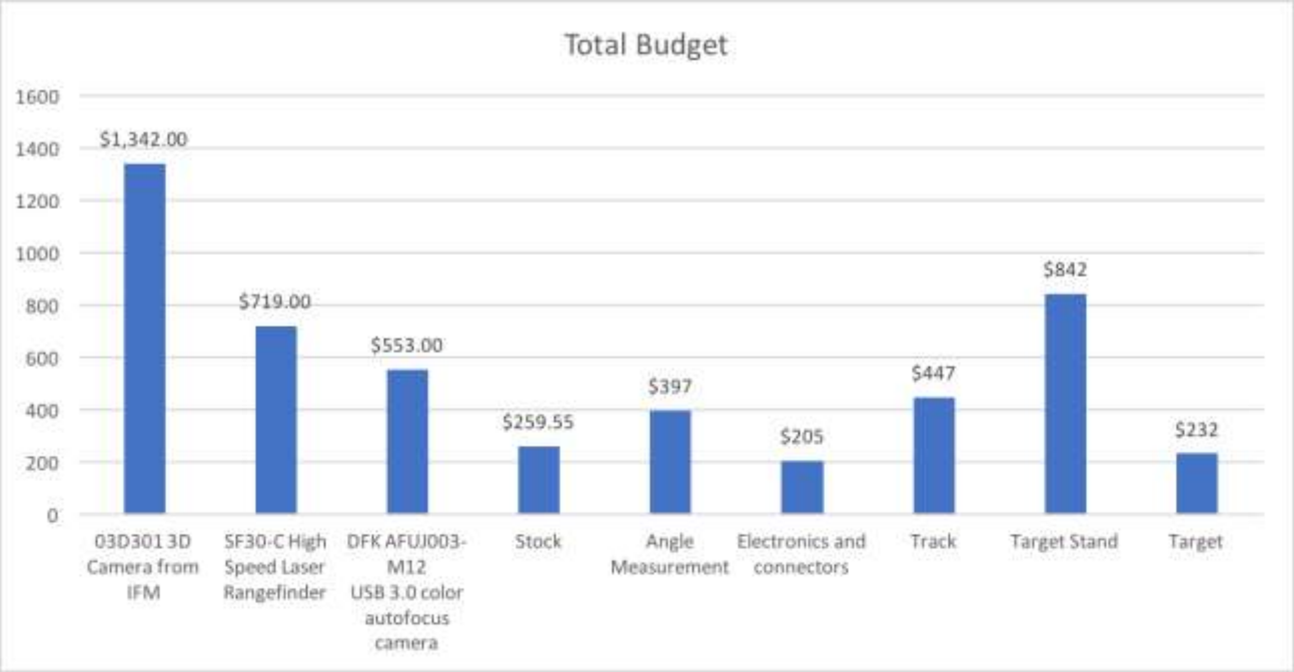
-Schedule-
3/19/18 to 4/2/18

Project Planning

Organizational Chart



Cost Plan



Category	**Total Price**
Hardware	$3,475.45
Testing	$1,521
Total	**$4,996.45**
Margin	0.0652%

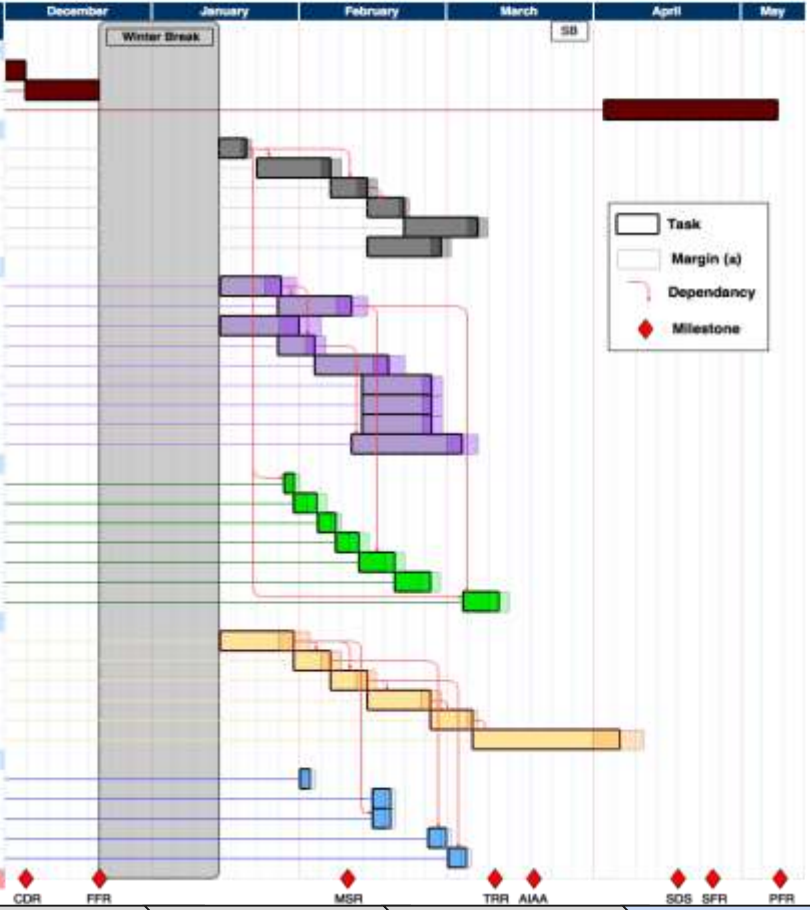
Work Breakdown Structure

Items to be completed in Spring 2018:

Electrical	Software	Testing
• Order Materials • Configure and Integrate Components • Debug Integrated Algorithms	• Produce/Modify Algorithms and Drivers • Configure and Integrate Components • Debug Integrated Algorithms	• Order Materials • Configure and Integrate Components • Manufacture Necessary Hardware Components • Conduct System Tests
Hardware	**Systems**	
• Order Materials • Configure and Integrate Components	• Determine Statistical Significance of Testing Results	

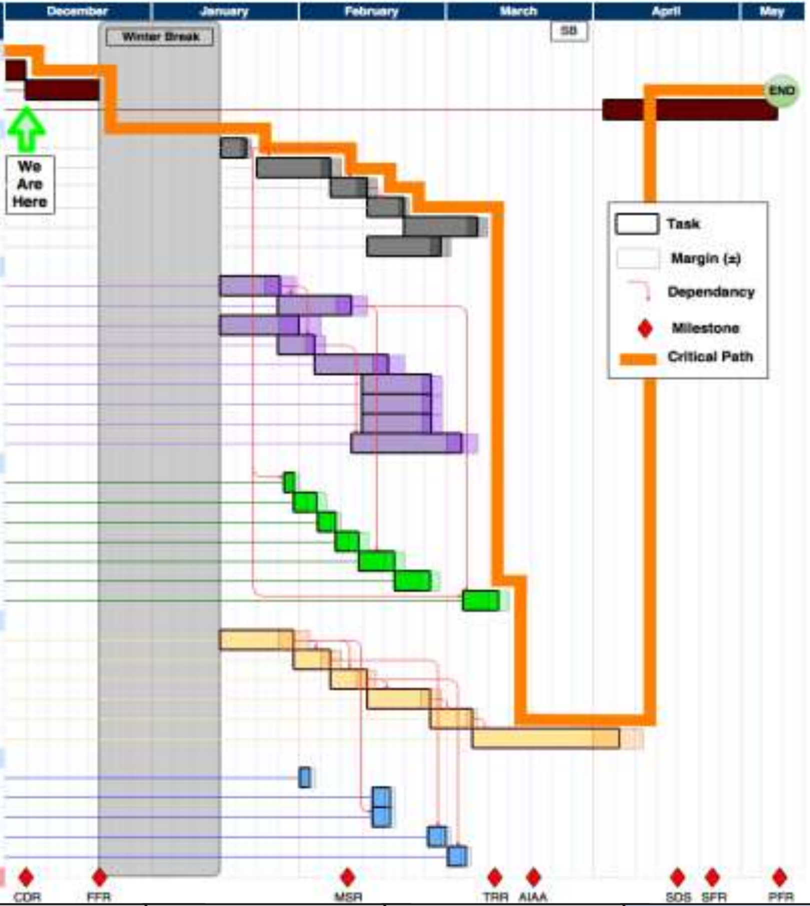
Work Plan

	SCOPE Project Task Timeline	Duration	Start	End	Margin (a)
	Miscellaneous				
1	Critical Design Review	4 days	12/01/17	12/05/17	0 days
2	Fall Final Report	13 days	12/05/17	12/18/17	0 days
3	Spring Reporting	5.2 wk	04/02/18	05/10/18	0 days
	Hardware				
4	Order Stock Material	3 days	01/16/18	01/19/18	1 day
5	Machine sensor package shell	2 wk	01/22/18	02/05/18	2 days
6	Machine sensor mounting face	1 wk	02/05/18	02/12/18	2 days
7	Interface Sensors	1 wk	02/12/18	02/19/18	1 day
8	Manufacture sensor test stand	2 wk	02/19/18	03/05/18	2 days
9	Manufacture target test bed	2 wk	2/12/18	2/26/18	2 days
	Software				
10	Move acquire to C/C++	1.5 wk	01/16/18	01/26/18	3 days
11	Acquire Unit Tests	2 wk	01/26/18	02/09/18	3 days
12	Orientation Unit Tests	2 wk	01/16/18	01/30/18	4 days
13	Test algorithms on rock-64	1 wk	01/26/18	02/02/18	2 days
14	Improve orientation at close range	2 wk	02/02/18	02/16/18	3 days
15	Develop/Integrate camera driver	2 wk	02/12/18	02/26/18	2 days
16	Develop/Integrate lrf driver	2 wk	02/12/18	02/26/18	2 days
17	Develop/Integrate flash lidar driver	2 wk	02/12/18	02/26/18	2 days
18	Develop/Integrate overall driver	3 wk	02/10/18	03/03/18	3 days
	Electrical				
19	Configure Rock64	2 days	01/27/17	01/29/18	1 day
20	Configure visual camera connection to Rock64	4 days	01/30/18	02/03/18	2 days
21	Configure LRF with Rock64	3 days	02/04/18	02/07/18	1 day
22	Configure LiDar sensor	4 days	02/08/18	02/12/17	2 days
23	Debug Acquire/Track algorithm on Rock64	6 days	02/13/17	02/19/17	2 days
24	Debug Orientation Algorithm on Rock64	6 days	02/20/17	02/26/17	2 days
25	Finalize Test of Overall Algorithm on Rock64	6 days	03/04/17	03/10/17	2 days
	Testing				
26	Acquire Test Materials	2 wk	01/16/18	01/26/18	3 days
27	Build Test Track	1 wk	01/28/18	02/04/18	2 days
28	Machine Test Cart Base	1 wk	02/04/18	02/11/18	2 days
29	Manufacture Test Cart	2 wk	02/12/18	02/26/18	2 days
30	Finalize test setup and Schedule testing time	1 wk	02/26/18	03/05/18	1 day
31	Conduct testing	4 wk	03/05/18	04/02/18	5 days
	Systems				
32	Run Error Analysis of Manufacturing	2 days	02/01/18	02/03/18	1 day
33	Statistical significance of Track Testing	3 days	02/15/18	02/18/18	1 day
34	Statistical significance of Acquire Testing	3 days	02/15/18	02/18/18	1 day
35	Statistical significance of Orientation Testing	3 days	02/26/18	02/29/18	1 day
36	Statistical significance of Overall Testing	3 days	03/01/18	03/04/18	1 day
	Milestones				



Critical Path

	SCOPE Project Task Timeline	Duration	Start	End	Margin (±)
	Miscellaneous				
1	Critical Design Review	4 days	12/01/17	12/05/17	0 days
2	Fall Final Report	13 days	12/05/17	12/18/17	0 days
3	Spring Reporting	5.2 wk	04/02/18	05/10/18	0 days
	Hardware				
4	Order Stock Material	3 days	01/16/18	01/19/18	1 day
5	Machine sensor package shell	2 wk	01/22/18	02/05/18	2 days
6	Machine sensor mounting face	1 wk	02/05/18	02/12/18	2 days
7	Interface Sensors	1 wk	02/12/18	02/19/18	1 day
8	Manufacture sensor test stand	2 wk	02/19/18	03/05/18	2 days
9	Manufacture target test bed	2 wk	2/12/18	2/26/18	2 days
	Software				
10	Move acquire to C/C++	1.5 wk	01/16/18	01/26/18	3 days
11	Acquire Unit Tests	2 wk	01/26/18	02/09/18	3 days
12	Orientation Unit Tests	2 wk	01/16/18	01/30/18	4 days
13	Test algorithms on rock-64	1 wk	01/26/18	02/02/18	2 days
14	Improve orientation at close range	2 wk	02/02/18	02/16/18	3 days
15	Develop/integrate camera driver	2 wk	02/12/18	02/26/18	2 days
16	Develop/integrate lrf driver	2 wk	02/12/18	02/26/18	2 days
17	Develop/integrate flash lidar driver	2 wk	02/12/18	02/26/18	2 days
18	Develop/integrate overall driver	3 wk	02/10/18	03/03/18	3 days
	Electrical				
19	Configure Rock64	2 days	01/27/17	01/29/18	1 day
20	Configure visual camera connection to Rock64	4 days	01/30/18	02/03/18	2 days
21	Configure LRF with Rock64	3 days	02/04/18	02/07/18	1 day
22	Configure LiDar sensor	4 days	02/08/18	02/12/17	2 days
23	Debug Acquire/Track algorithm on Rock64	6 days	02/13/17	02/19/17	2 days
24	Debug Orientation Algorithm on Rock64	6 days	02/20/17	02/26/17	2 days
25	Finalize Test of Overall Algorithm on Rock64	6 days	03/04/17	03/10/17	2 days
	Testing				
26	Acquire Test Materials	2 wk	01/16/18	01/28/18	3 days
27	Build Test Track	1 wk	01/28/18	02/04/18	2 days
28	Machine Test Cart Base	1 wk	02/04/18	02/11/18	2 days
29	Manufacture Test Cart	2 wk	02/12/18	02/26/18	2 days
30	Finalize test setup and Schedule testing time	1 wk	02/26/18	03/05/18	1 day
31	Conduct testing	4 wk	03/05/18	04/02/18	5 days
	Systems				
32	Run Error Analysis of Manufacturing	2 days	02/01/18	02/03/18	1 day
33	Statistical significance of Track Testing	3 days	02/15/18	02/18/18	1 day
34	Statistical significance of Acquire Testing	3 days	02/15/18	02/18/18	1 day
35	Statistical significance of Orientation Testing	3 days	02/26/18	02/29/18	1 day
36	Statistical significance of Overall Testing	3 days	03/01/18	03/04/18	1 day
	Milestones				



Acknowledgments

We would like to thank **Trudy Schwartz, Bobby Hodgkinson**, and **Matt Rhode** for their guidance with the testing design.

We would also like to thank **Zoltan Sternovsky** for general project guidance.

Thank you to **Lee** and **Tim** for presentation practice help and feedback.

Thank you for your support!

Questions?

References

Users.auth.gr. N. p., 2017. Web. 15 Oct. 2017."DFK AFUJ003-M12." The Imaging Source, www.theimagingsource.com/products/autofocus-cameras/usb-3.0-color/dfkafuj003m12/.

Brown, Gary. "How Autofocus Cameras Work." HowStuffWorks, 1 Apr. 2000, electronics.howstuffworks.com/autofocus3.htm.

"Depth of Field, Angle & Field of View, & Equivalent Lens Calculator." Points in Focus Photography, 31 Aug. 2017, www.pointsinfocus.com/tools/depth-of-field-and-equivalent-lens-calculator/#{"c":[{"av":"8","fl":16,"d":100000}],"m":1}.

"Infrastructure," *Research and Engineering Center for Unmanned Vehicles* Available: http://www.colorado.edu/recuv/facilities/infrastructure

"OpenCV: Open Source Computer Vision." https://docs.opencv.org/3.3.0

"Advanced Scientific Concepts Inc." *Advancedscientificconcepts.com*. N. p., 2017. Web. 16 Oct. 2017.

SF11/C. "SF11/C (120 M) - Lightware Optoelectronics (Pty) Ltd." *LightWare Optoelectronics (Pty) Ltd*. N. p., 2017. Web. 16 Oct. 2017.

References

Rusinkiewicz, Szymon; Marc Levoy (2001). Efficient Variants of the ICP Algorithm. Proceedings Third International Conference on 3-D Digital Imaging and Modeling. Quebec City, Quebec, Canada. pp. 145–152.

M. Attia Y. Slama M. A. Kamoun "On performance evaluation of registration algorithms for 3d point clouds" Computer Graphics Imaging and Visualization (CGiV) 2016 13th International Conference pp. 45-50 2016.

Libretexts. “Propagation of Error.” *Chemistry LibreTexts*, Libretexts, 14 Mar. 2017, chem.libretexts.org/Core/Analytical_Chemistry/Quantifying_Nature/Significant_Digits/Propagation_of_Error.

“Normal Distributions: Definition, Word Problems.” Statistics How To, www.statisticshowto.com/probability-and-statistics/normal-distributions/

Corcoran, Jem. “Intro the Mathematical Statistics.” APPM Lecture. 2017, Boulder, CU Boulder.

Jackson, Jelliffe. “Uncertainty Analysis.” ASEN Lecture. 2015, Boulder, CU Boulder.

“Monte Carlo Simulation.” Monte Carlo Simulation: What Is It and How Does It Work? - Palisade, www.palisade.com/risk/monte_carlo_simulation.asp

"O3D301 - 3D Camera - Eclass: 27310205 / 27-31-02-05." *Ifm.com*. N. p., 2017. Web. 16 Oct. 2017.

References

http://1.bp.blogspot.com/_SjnNZeKhheo/TTWSPzsI1nI/AAAAAAAAAnI/SpCXSVeDfFU/s1600/Cygnus+approaching+the+ISS.jpg

https://imgur.com/gallery/WNG2Iqq - Soyuz docking with ISS GIF

https://www.theimagingsource.com/products/autofocus-cameras/usb-3.0-color/dfkafuj003m12/

https://www.aico-lens.com/product/f-25mm-f-2-10mp-4k-m12-far-field-board-lens-achf2520fm/

http://robotsforroboticists.com/kalman-filtering/

Backup Slide Index

Testing	Simulations	Derivation	Software	Error
Functional Requirements fulfilled	Thermal conditions	Sensor Calibration	Autofocus capabilities	Blender
Test Plan	Power Outputs	Error in offset turning	Flash LiDAR resolution	Distribution of LRF mean
Test 1	Operational temperatures	Minimum pointing accuracy	FLOOD explained	Use of Kalman filers
Testing Hardware Flowchart	Static load analysis	Sensor face offset	KD tree	Position Error Propagation
The Target Satellite		Error in offset rotation	FLOOD timing	Mean central limit theorem
Encoder Quadrature		Error due to face offset		OPC w/ background subtraction
		1km infeasibility		
		Motor/encoder requirements		

Fulfilling Functional Requirements

Functional Requirements	Test
FR 1	Transition Test 1
FR 2	Transition Test 1
FR 3	Transition Test 1
FR 4	Transition Test 2
FR 5	Transition Test 2
FR 6	Inspection
FR 7	Inspection

Test Plan

- **Acquire and Track Test**
  - Dependencies
    - ITLL/Engineering Center hallway availability - Already talked to Dean and outlined test plan.
    - Lighting - Received approval and ability to control lighting
  - Schedule
    - Currently Acquire and Track testing is scheduled for 3/5/18 to 3/19/18.
      - Enough time to be flexible
- **Track and Orientation Testing**
  - Dependencies
    - ITLL/Engineering Center Hallway availability and Lighting
  - Schedule
    - Track and Orientation testing is scheduled for 3/19/18 to 4/2/18
      - Orientation testing can be conducted prior than this to account for Spring Break

Test 1

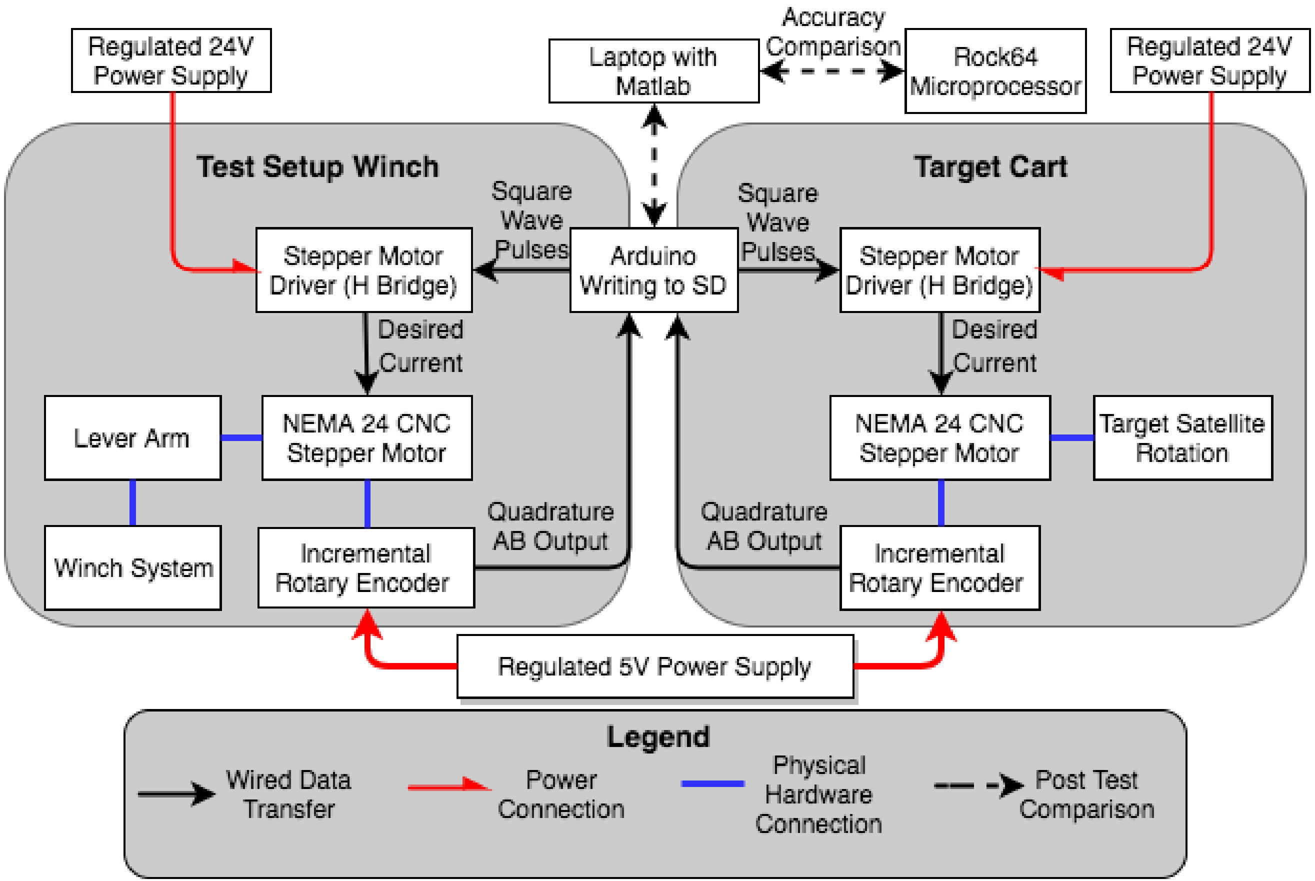
Assumptions:

- The rail system allows the cart to move perfectly straight:
  - i.e the side to side motion is constrained and can be assumed to be so small that it is negligible
- The motor does not fluctuate:
  - i.e the motor pulls at a constant angular velocity and there is no noise or fluctuations in this velocity
- The target satellite will be moving at a constant rate of .1 m/s during the “Acquire phase” and then speed up to testing speeds for the remainder of the test

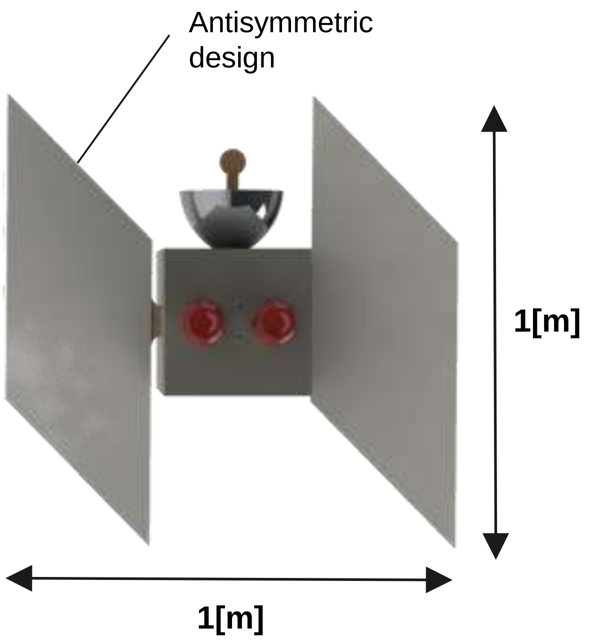
Phases:

- Set SCOPE at origin, 0 m
- Use a tape measure, (EC class 1) to set the rail at a distance that will cover 90m - 105m from SCOPE
- Turn on SCOPE and position it down the line of sight from the target
- Set the first 60s of target movement to .1 m/s and the remainder of the test to .1 m/s
- Turn on the motor/microcontroller setup
- Repeat steps 4 and 5 with varying remainder of test velocities from .1 m/s to 1 m/s.

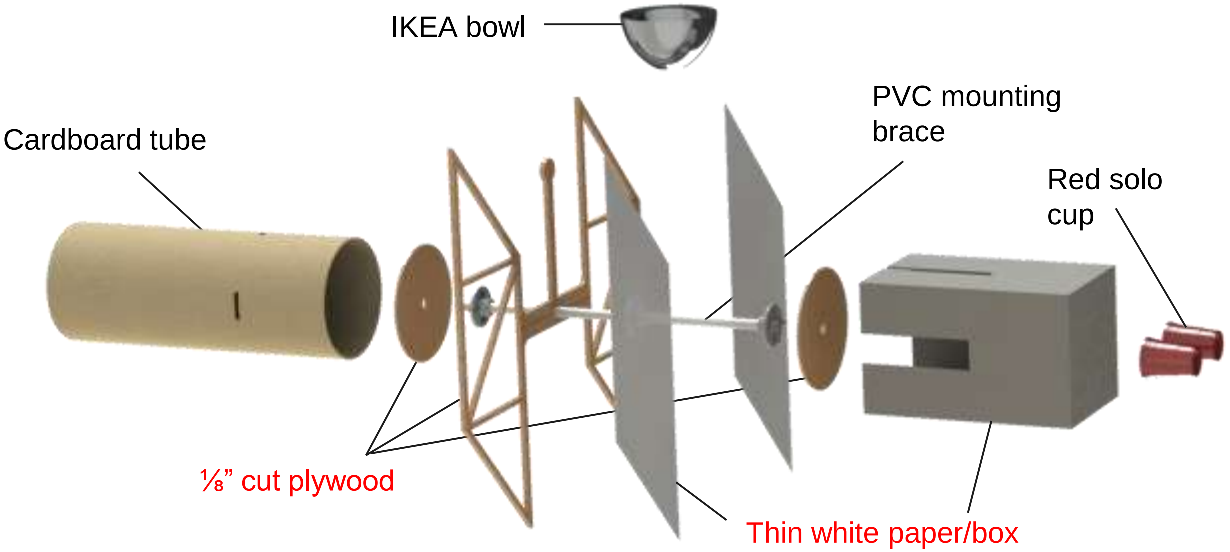
Testing Hardware Flow Chart



The Target Satellite



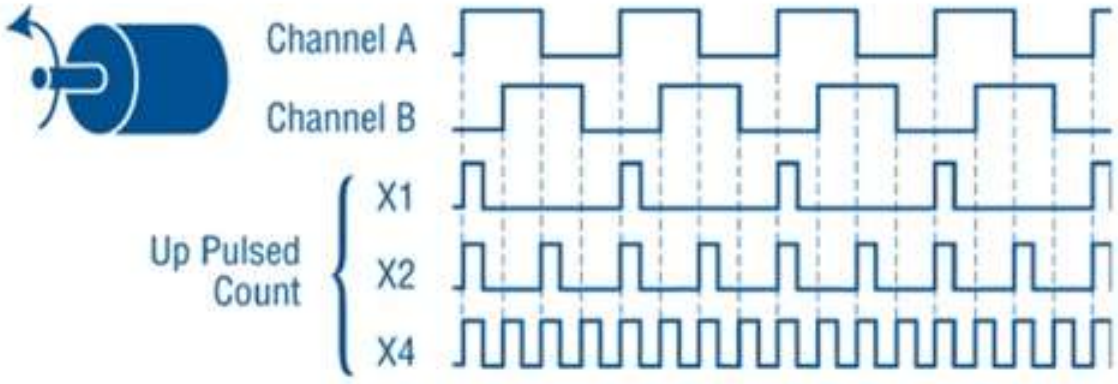
Mass = **3.3[kg]**

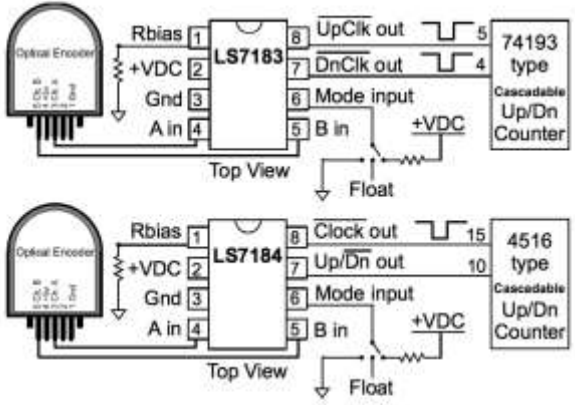


Driving Requirements
DR 1.1: The sensor shall be able to detect a target satellite with volumetric dimensions between 20x20x30 [cm] and 1x1x1 [m].
DR 1.4: The sensor shall be able to detect a target satellite under favorable lighting conditions

Encoder Quadrature

- Utilize encoders with AB Quadrature output along with an **LS7184 encoder chip**
  - This allows for the group to quadruple the effective pulses per revolution
  - Could help mitigate our current budget situation
- Chip allows for 4x normal PPR values because it counts the leading and trailing edges of both channels of the quadrature encoder’s pulse train. (see image below)





FEA Mesh and Parameters (thermal)

<u>All bodies have constant material properties:</u>

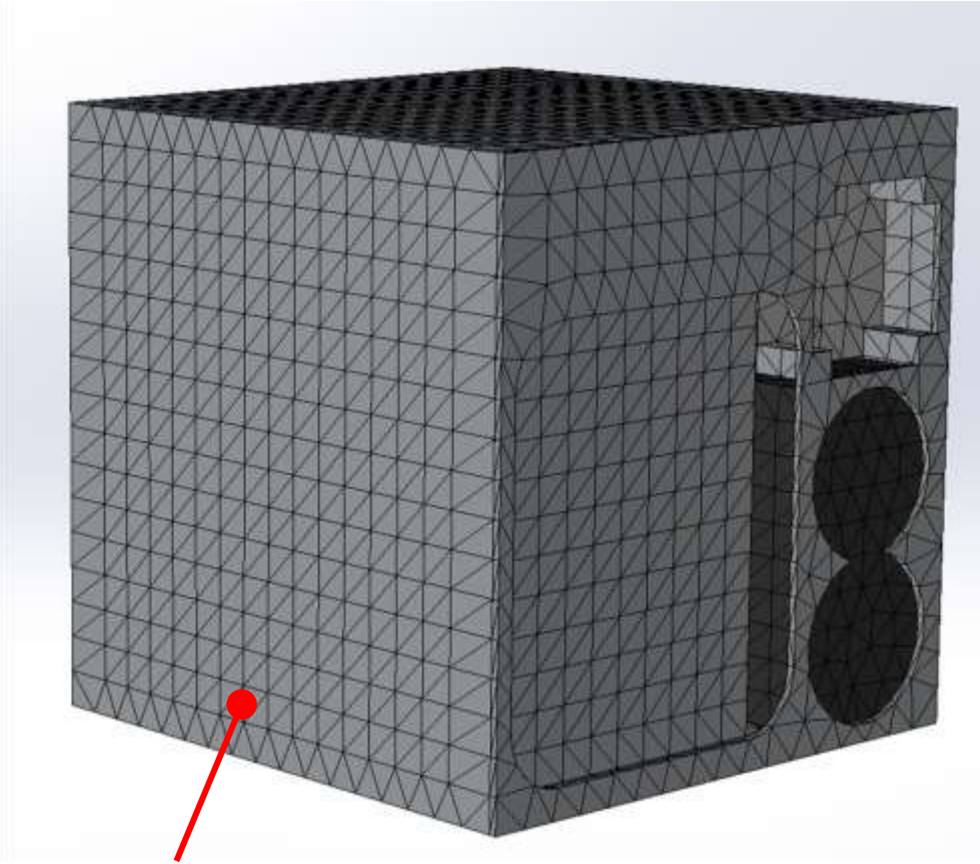
Component(s): Shell
Material: 6061 Aluminum Alloy
Thermal Conductivity: 170 W/(m*K)

Component(s): Laser Rangefinder
Material: ABS PC
Thermal Conductivity: 0.2618 W/(m*K)

Component(s): Rock64 Board
Material: Non-conductive PCB Substrate
Thermal Conductivity: 0.2256 W/(m*K)

Component(s): Visual Camera, 03D301 LiDAR
Material: ABS PC/6061 Aluminum
Thermal Conductivity: 85 W/(m*K)

Contact Resistance: 2.5x10^-4 W*m^2/K



Triangular based mesh

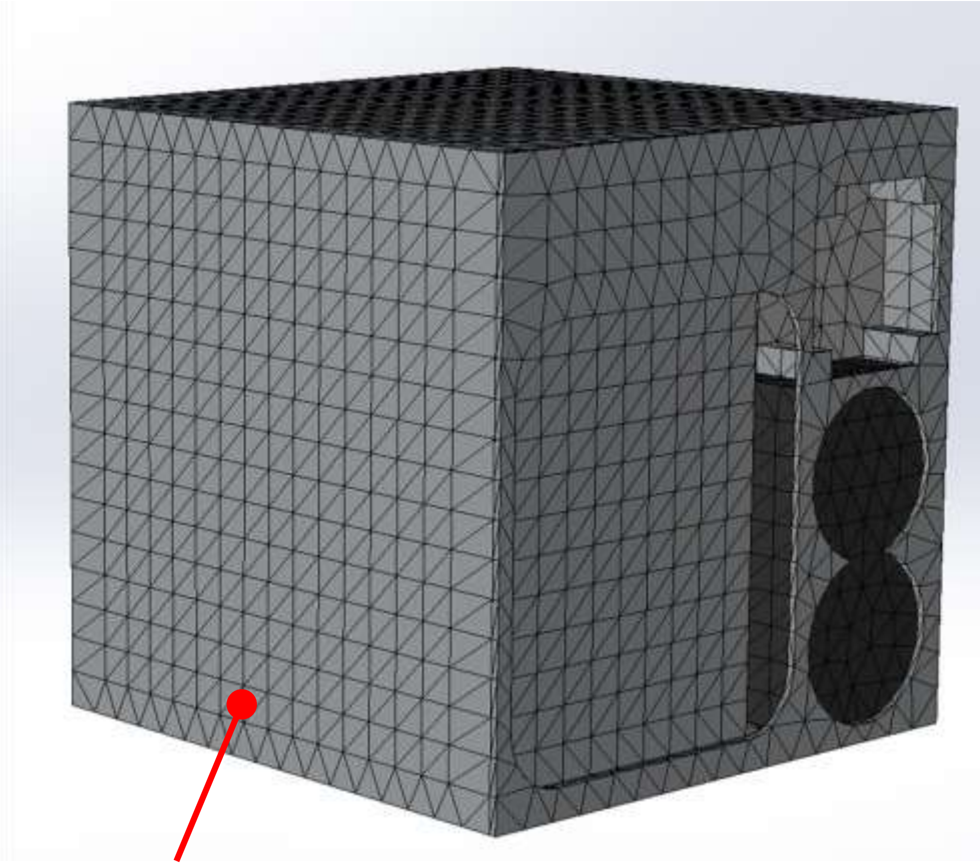
FEA Mesh and Parameters (thermal)

<u>Model uses the following conditions:</u>

Ambient Temperature: 290K

Thermal Emissivity: 0.12

Contact Resistance: 2.5x10^-4 W*m^2/K



Triangular based mesh

Various Power Outputs

Component	Low Power	Peak Power	Mean Power
Rock64 Media Board	1.25W	10W	**2.5W**
IFM 03D301 Flash LiDAR	5W	48W	**10W**
DFK AFUJ003-M12	n/a	5W	**1.25W**
SC30-C Laser Rangefinder	n/a	5W	**1.25W**

<u>Sources</u>
Rock64: https://forum.pine64.org/showthread.php?tid=1220
AFUJ003: https://www.theimagingsource.com/products/autofocus-cameras/usb-3.0-color/dfkafuj003m12/
SC30-C: https://www.parallax.com/product/28058
03D301: https://www.ifm.com/hu/en/product/O3D301

Various Operational Temperatures

Component	Peak Operational Temperature	Maximum Predicted Temperature
Rock64 Media Board	65°C	42°C
IFM 03D301 Flash LiDAR	50°C	30°C
DFK AFUJ003-M12	45°C	27°C
SC30-C Laser Rangefinder	40°C	26°C

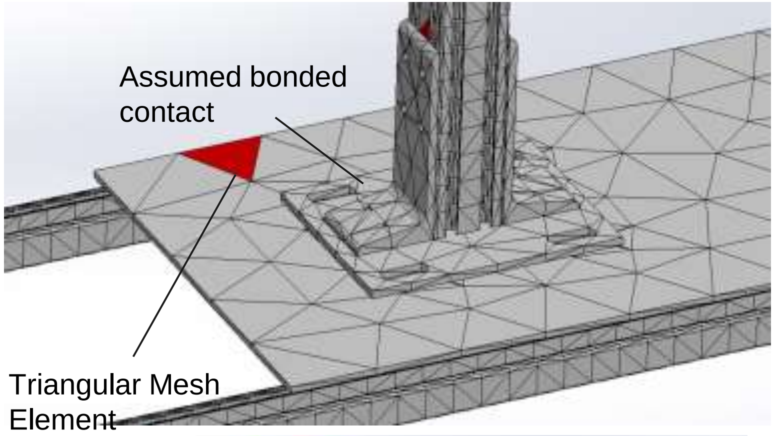
Sources
Rock64: https://forum.pine64.org/showthread.php?tid=1220
AFUJ003: https://www.theimagingsource.com/products/autofocus-cameras/usb -3.0-color/dfkafuj003m12/
SC30-C: https://www.parallax.com/product/28058
03D301: https://www.ifm.com/hu/en/product/O3D301

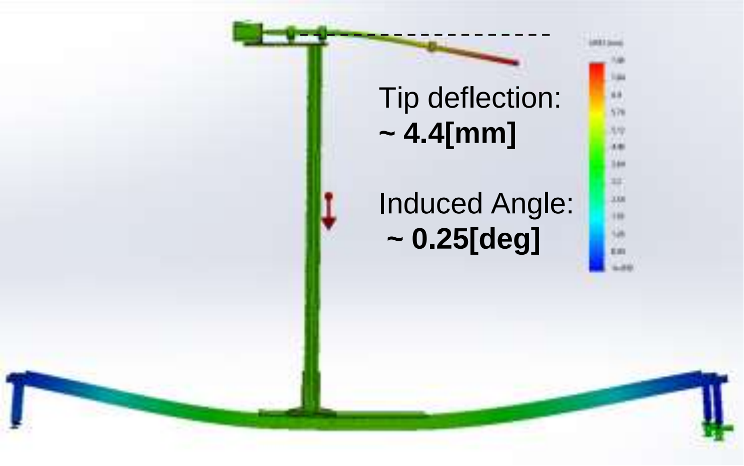
Static Loads Analysis

Conclusions:

1. The test stand will withstand loads during test 1 and test 2.

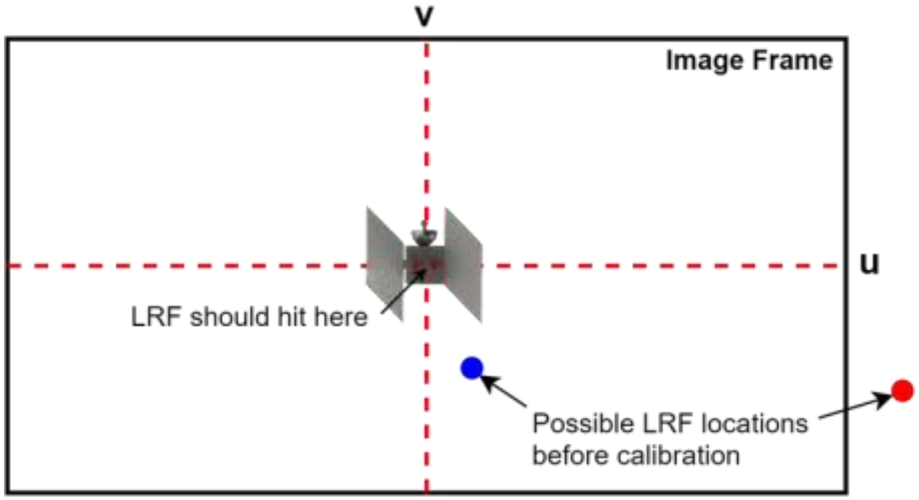
2. Calibration will take into account for the **0.25[deg]** angle deflection.





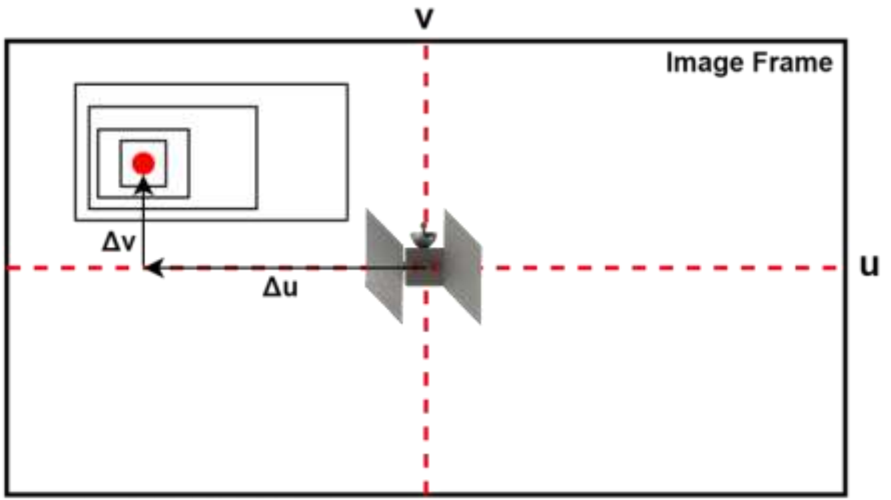
Maximum dip: **~ 4.28[mm]**

Sensor Calibration



If ●, then the origin of the image frame can be moved to that point.

If ●, then mechanical techniques can adjust camera pointing.



1. Localize offset point with cardboard, decreasing in size.
2. Measure the distance offset and apply correction.

These calibration methods can be used for both the laser rangefinder and the flash LiDAR.

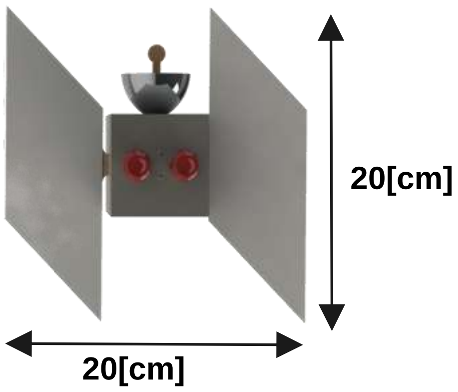
Minimum Pointing Accuracy

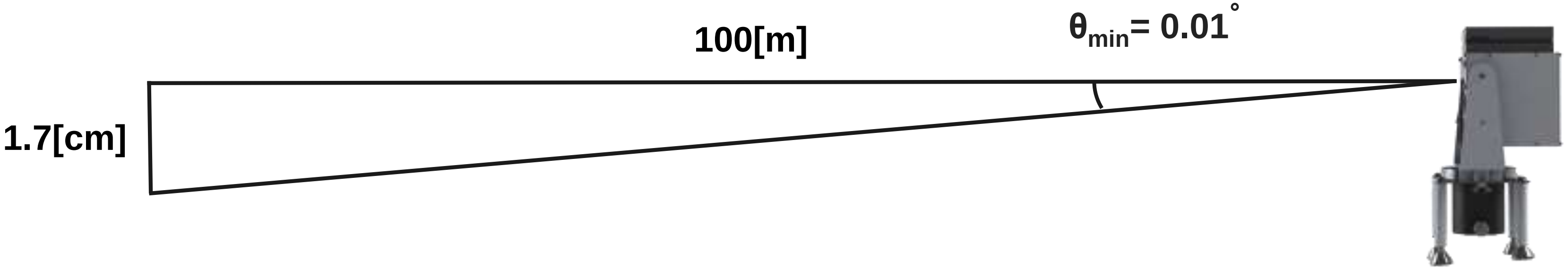
The minimum sized model defines the pointing accuracy to be required as a **20[cm]** vertical and horizontal resolution.

This means that the sensor package must be able to rotate at **0.115[deg]** per step.

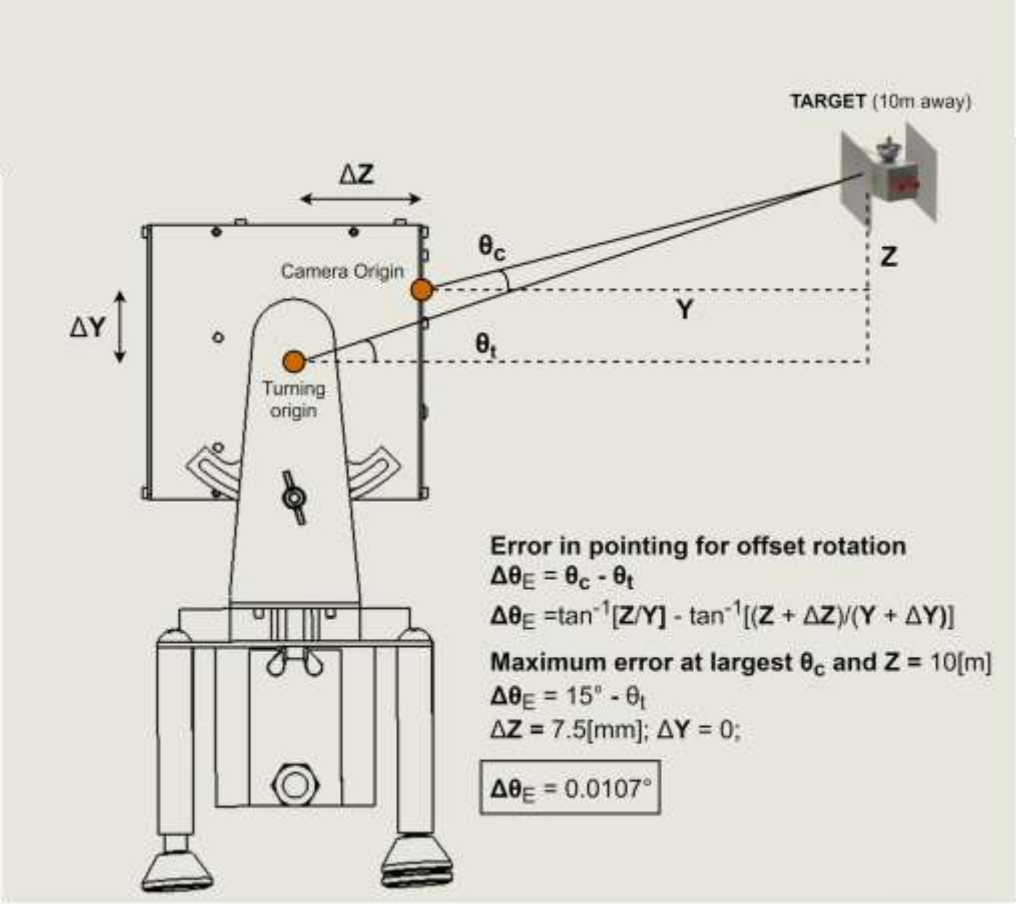
The resolution of our **sensor test stand encoders and digital level** give a resolution of **0.01[deg].**

Therefore, we can measure up to **1.7[cm]** per step

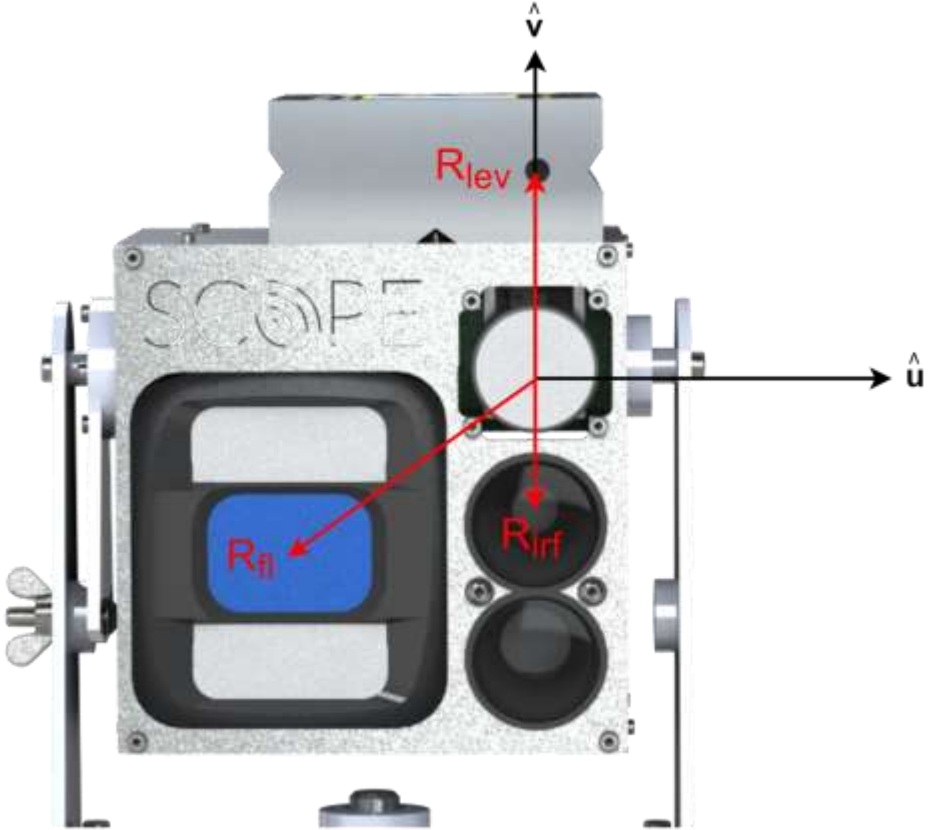




Error in Offset Turning



Sensor Face Offset



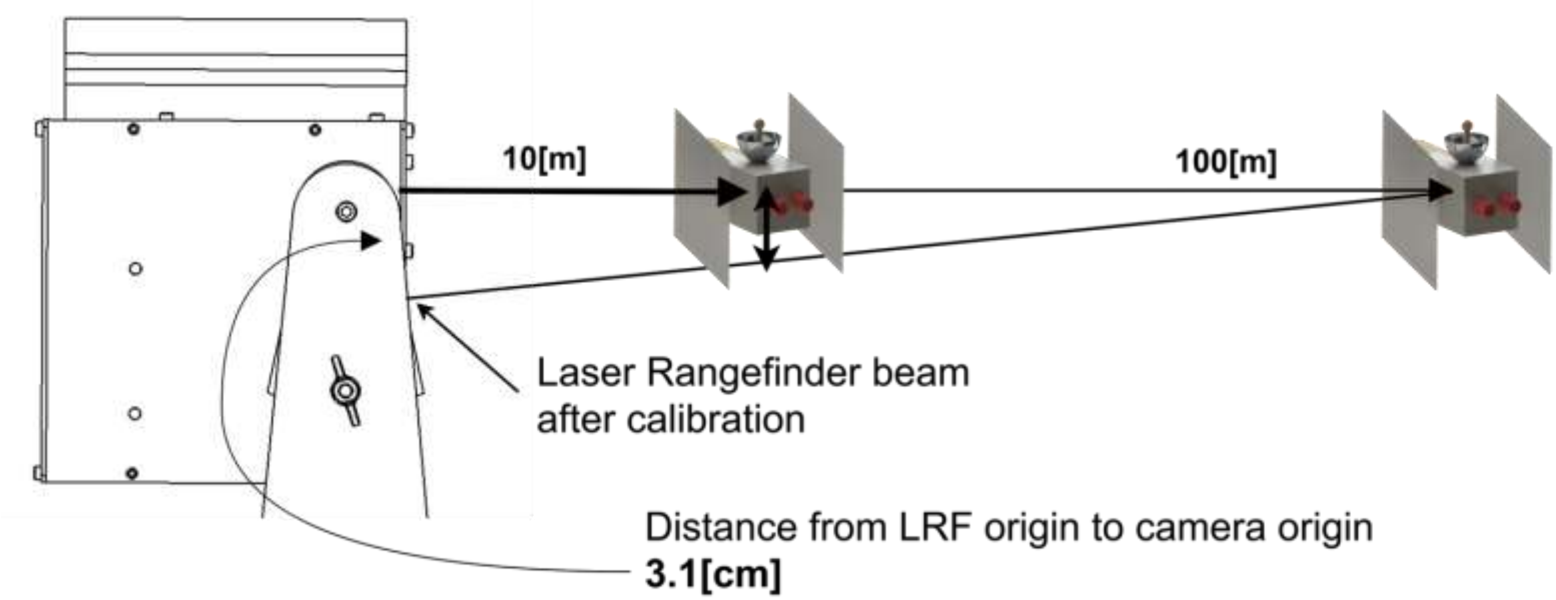
All offsets are accounted for in software

R_{lev} = <0,38,0> [mm]

R_{lrf} = <0,-31,0> [mm]

R_{fl} = <-49,-35,0> [mm]

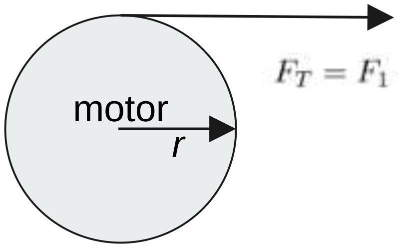
Error Due to Face Offset



This offset causes error in pointing as the object gets closer.

At **10[m]**, the closest position in which the laser rangefinder is used, this error (vertical offset) is **2.79[cm].**

Track Motor math



$$F_T = F_1 + F_2$$

Givens:

$$r = 5\ cm$$
$$F_1 = 20\ N$$
$$\sigma = 1.5$$

Analysis:

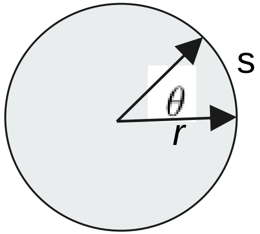
$$a = 1.5\ m/s^2$$
$$m = F_1/a = 2.040\ kg$$
$$F_2 = ma = 3.06\ N$$
$$F_T = F_1 + F_2 = 23.06\ N$$
$$T = F_T r = 1.153\ Nm$$
$$\boxed{T_F = T\sigma = 1.7295\ Nm}$$
$$\boxed{P_F = F v_{max}\sigma = 34.59\ W}$$
$$\boxed{\omega_{max} = v_{max}/r = 12.5\ rad/s = 190.98\ RPM}$$
$$\boxed{\omega_{min} = v_{max}/r = 12.5\ rad/s = 19.09\ RPM}$$

Conclusions:

Need pullout torque at least 2 Nm between ~19 RPM and 190 RPM
Need 34.59 W for power

Track Encoder math

encoder



Analysis:

$$\boxed{ppr = 2\pi/\theta = 314.159}$$

$$\boxed{f_{max} = \omega_{max}/\theta = 1000Hz}$$

$$\boxed{f_{min} = \omega_{min}/\theta = 100Hz}$$

Givens:

Choose s = 1 mm (accuracy at 1 m) one order of magnitude greater than Functional requirement

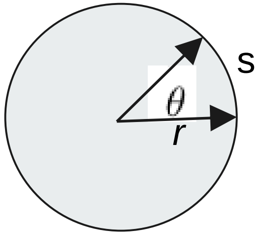
$$r = 5\ cm$$
$$\theta = s/r = 0.02\ rad$$
$$\omega_{max} = 190.98\ RPM$$
$$\omega_{min} = 19.09\ RPM$$

Conclusions:

- Need at least 314 pulses per rev
- Need a min frequency of 1000 Hz

Orientation Encoder math

encoder



Givens:

$$r = 5\ cm$$
$$\omega_{max} = 5\ deg/s$$
$$\omega_{min} = 1\ deg/s$$

Analysis:

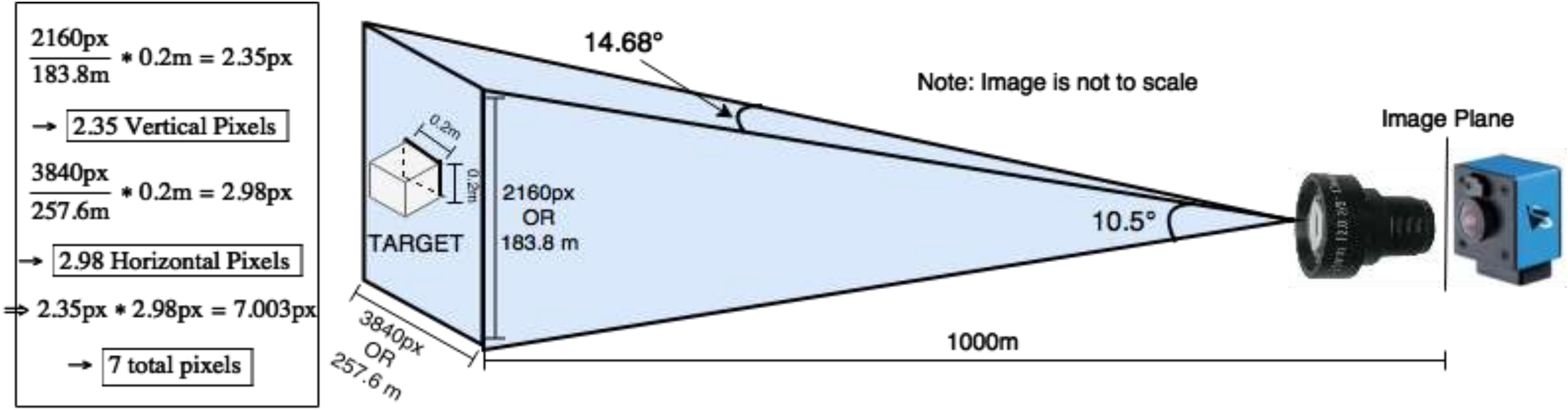
Choose detection angle to be 0.1 deg (one order of magnitude greater than functional requirement)

$$\theta = 0.1\ deg$$
$$\boxed{ppr = 360deg/\theta = 3600}$$
$$\boxed{f_{max} = \omega_{max}/\theta = 50\ Hz}$$
$$\boxed{f_{min} = \omega_{min}/\theta = 10\ Hz}$$

Conclusions:

- Need at least 3600 pulses per rev
- Need a min frequency of 50 Hz

1km Infeasibility



Allowable pixel error for background subtraction: 7px

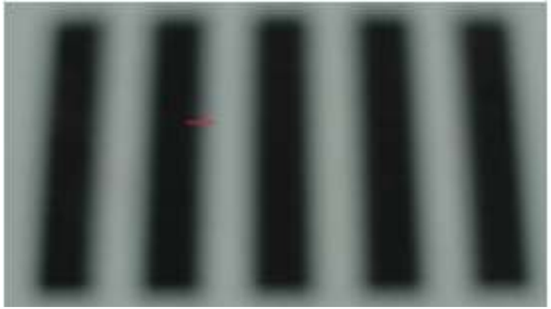
Autofocus capabilities

Two types: Passive and Active

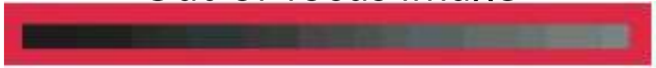
1. Active uses SONAR or IR
2. Passive uses pixel comparison and computer analysis

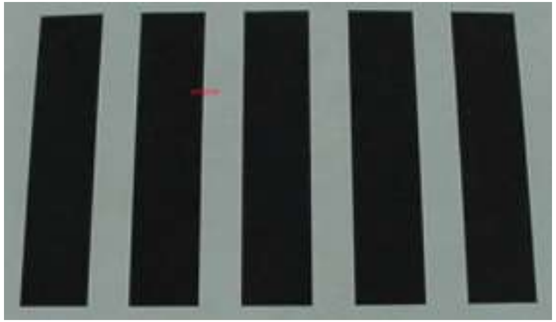
Passive: Determines blurriness of image → adjusts to find min. Blurriness

- Determines blurriness by contrast of edge pixels



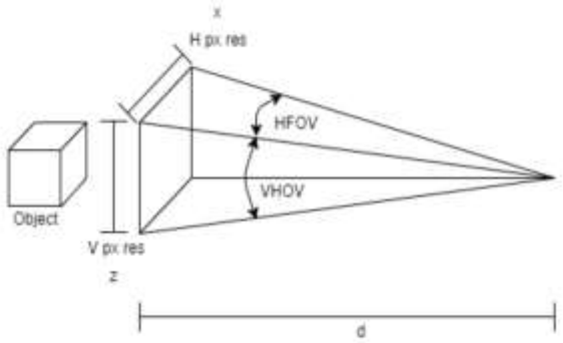
Out-of-focus image





In-focus image

Flash LiDAR Resolution



$$x = 2d\tan\left(\frac{hfov}{2}\right)$$

$$z = 2d\tan\left(\frac{vfov}{2}\right)$$

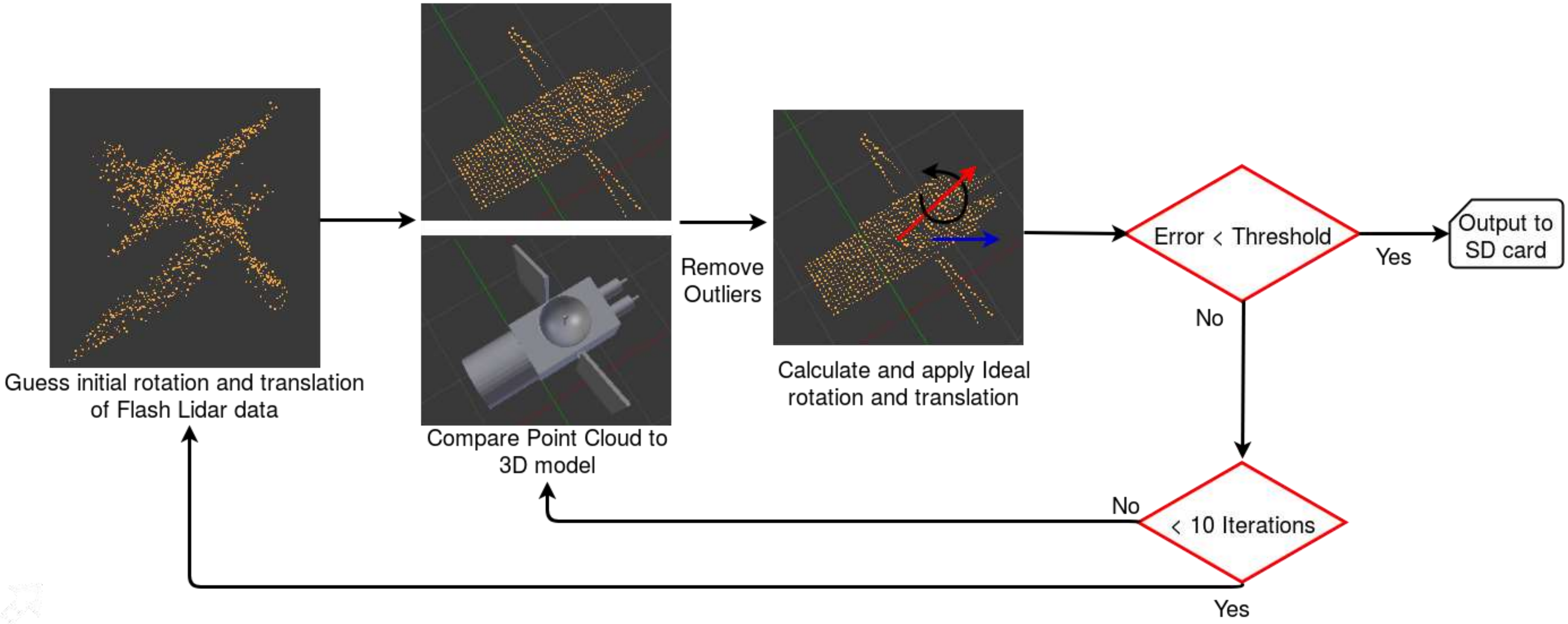
$$horizontalpix/m = \frac{HpxRes}{x}$$

$$verticalpix/m = \frac{VpxRes}{x}$$

$$\frac{TotalPixelRes}{m^2} = horizontalpix/m * verticalpix/m$$

IFM O3D301	FOV:40X30	RES:176X132	20 x 20 cm	1 x 1 m
Distance (m)	total (px/m^2)	(cm^2/pixel)	Pixel per object	Pixel per object
11	492	20.32	20	492
10	596	16.79	24	596
9	735	13.60	29	735
8	931	10.75	37	931
7	1215	8.23	49	1215
6	1654	6.04	66	1654
5	2382	4.20	95	2382
4	3722	2.69	149	3722
3	6617	1.51	265	6617
2	14888	0.67	596	14888
1	59554	0.17	2382	59554

FLOOD Explained



FLOOD Explained

Given the two point cloud sets M and D, where D is the set produced by the LiDAR scan, and M is the set derived from the model. For each point $d_i \in \mathbb{R}^3$ in D, and a rotation R and translation t, there is a point c_i such that.

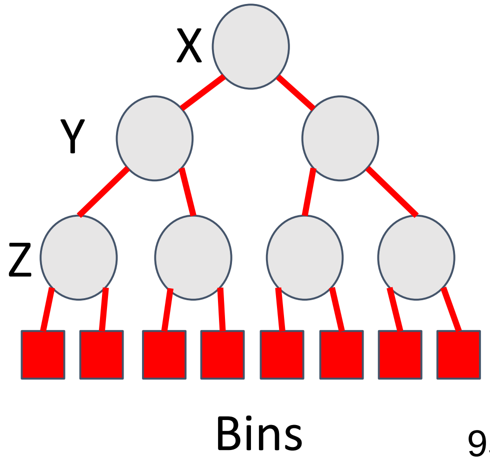
$$c_i = arg \min_{c_k \in M} \parallel (Rd_i + t) - c_k \parallel, \qquad \forall i = 1...m \tag{1}$$

t and R are then calculated using the following error function.

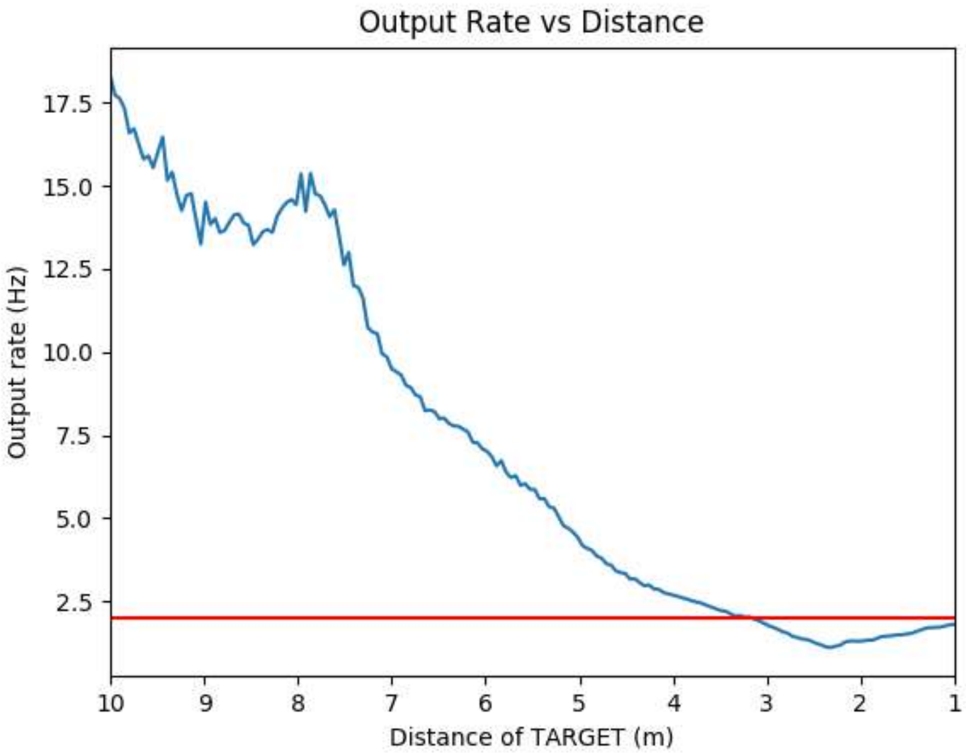
$$\epsilon = \frac{1}{m} \min_{t,R} \sum_{i=1}^{m} \parallel Rd_i + t - c_i \parallel^2 \tag{2}$$

FLOOD Explained- K-D Search

1. Faces from 3D model are stored in bins in a k-d tree data structure
   a. Each bin represents a 3D box
2. For each point from our Lidar scan traverse down to bin containing that point
3. Check the distance from point to each face contained in bin
4. Repeat step 3 for neighboring bins if the distance to the edge of that bin is less than the current minimum found distance

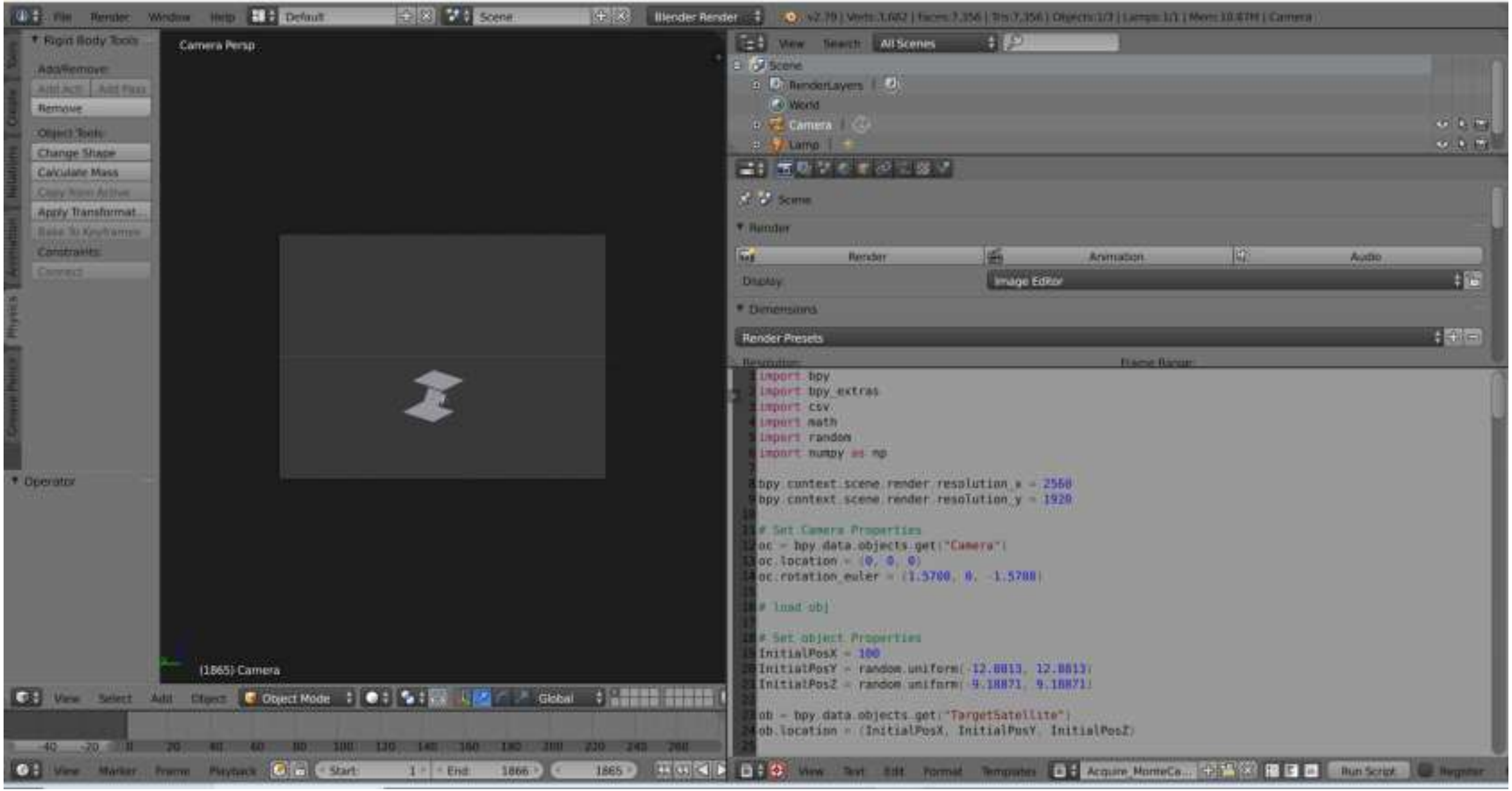


FLOOD Timing



- Almost always above 2 Hz minimum
- Add in maximum number of points so algorithm does not have to process 10’s of thousands of points

Blender



Camera Persp
(1865) Camera
Object Mode
Global
Scene
RenderLayers
World
Camera
Lamp
Render
Animation
Audio
Display:
Image Editor
Dimensions
Render Presets
import bpy
import bpy_extras
import csv
import math
import random
import numpy as np
bpy.context.scene.render.resolution_x = 2560
bpy.context.scene.render.resolution_y = 1920
# Set Camera Properties
oc = bpy.data.objects.get("Camera")
oc.location = (0, 0, 0)
oc.rotation_euler = (1.5700, 0, -1.5700)
# load obj
# Set object Properties
InitialPosX = 100
InitialPosY = random.uniform(-12.0013, 12.0013)
InitialPosZ = random.uniform(-9.18871, 9.18871)
ob = bpy.data.objects.get("TargetSatellite")
ob.location = (InitialPosX, InitialPosY, InitialPosZ)
Run Script

Distribution of LRF Mean

n= number of LRF returns per every system data output
σ = standard deviation of normal distribution for single LRF data output
$\bar{X}$ = the mean of all LRF data over the coarse of half a second. It should be noted the the expected value of the mean is the actual distance.
CI = Confidence Interval
$Z_{\alpha/2}$ = Normal Distribution Critical value

Important to note that the standard deviation of the mean is $\frac{\sigma}{\sqrt{n}}$

Normal distribution of mean of LRF data:

$$CI : \bar{X} \pm Z_{\alpha/2}\frac{\sigma}{\sqrt{n}} \rightarrow Z_{\alpha/2}\frac{\sigma}{\sqrt{n}} \leq 0.01\bar{X}$$

For a 99% confidence interval that the LRF is returning data with in one percent of actual distance, $Z_{\alpha/2} = 2.575$.

$$(2.575)\frac{\sigma}{\sqrt{n}} \leq 0.01\bar{X} \rightarrow \sigma \leq 0.003883d$$

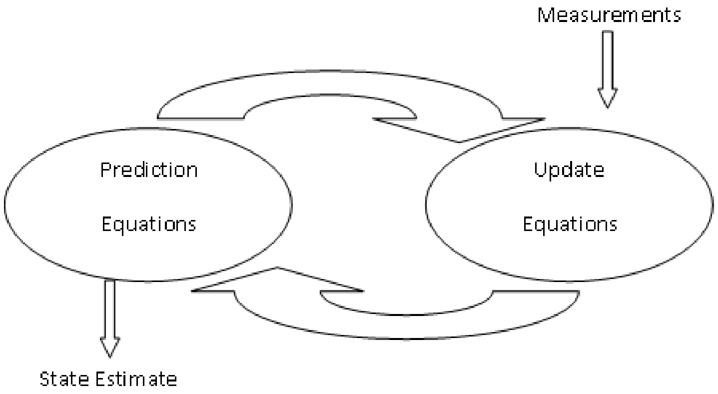
Use of Kalman Filtering

Means to use data from multiple sources in order to create a joint probability distribution that can then be used to more accurately predict the correct data parameters.

Our Date Sources:

- Laser Range Finder
- Optical Camera
- LiDar

Our goal using a Kalman filter: to optimize estimation of the state of the TARGET satellite in the Orientation Phase.



Position Error Propagation

Using the standard deviation of the position the standard deviation of the velocity can be calculated with the following equation:

$$x = a + b - c \quad \sigma_x = \sqrt{\sigma_a^2 + \sigma_b^2 + \sigma_c^2}$$

For velocity error propagation ($\sigma_{pos1} = \sigma_{pos}$):

$$vel = pos2 - pos1 \quad \sigma_{vel} = \sqrt{\sigma_{pos1}^2 + \sigma_{pos2}^2} = \sqrt{2\sigma_{pos1}^2} = \sqrt{2}\sigma_{pos}$$

Based on the velocity error propagation, the standard deviation of the laser range finder needs to be the following to satisfy 1% accuracy. The worst case is at 10m with 10 data returns per half second.

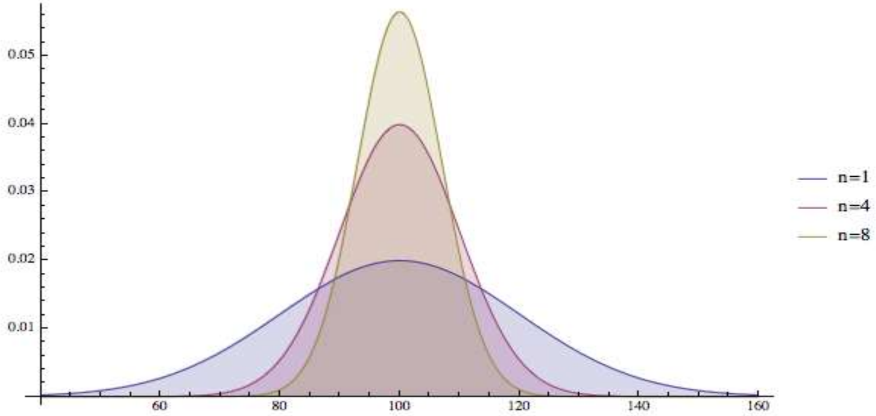
$$\sqrt{2}\sigma_{pos} \leq \sqrt{n}(0.003883)d \rightarrow \sigma_{pos} \leq \sqrt{n/2}(0.003883)d = \sqrt{5}(0.03883) = 0.0868$$

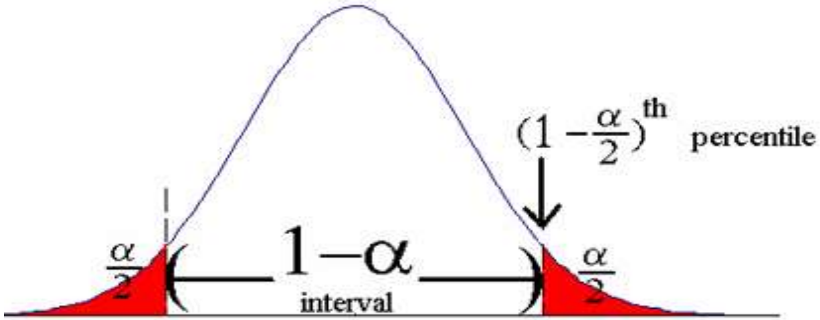
Therefore the 99% confidence interval can be calculated.

$$Z_{\alpha/2}\frac{\sigma}{\sqrt{n}} = (2.575)(0.0868/\sqrt{1}) = \pm 0.224m$$

Behavior of STD of Sample Mean-Central Limit Thm

Important to note that the standard deviation of the mean is $\frac{\sigma}{\sqrt{n}}$





OpC w/ Background subtraction

σ_n = standard deviation of vertical pointing off center in number of pixels
σ_ψ = standard deviation of horizontal pointing off center in meters
σ_θ = standard deviation of vertical pointing off center in meters
d = distance away from camera

α = horizontal full angle
β = vertical full angle
m = number of pixels in horizontal direction
n = number of pixels in vertical direction
σ_m = standard deviation of horizontal pointing off center in number of pixels

To calculate the standard deviation in terms of meters.

$$\sigma_\psi = \frac{2dtan(\frac{\alpha}{2})}{m}(\sigma_m) \quad \sigma_\theta = \frac{2dtan(\frac{\beta}{2})}{n}(\sigma_n)$$

A smaller field of view is beneficial, the alpha and beta of the hard found that is the smallest but can still fit the larger possible target in the FOV at the minimum distance of 10 m with a 25mm focal length is $\alpha = 14.68$ and $\beta = 10.5deg$

The expected value for the distance returned from the center of the object is zero so in order to construct the normal distributions for horizontal and vertical pointing.

$$\theta = \sigma_\theta Z \quad \psi = \sigma_\psi Z$$