University of Colorado Boulder

ASEN 4018 Senior Projects, Fall 2018
Preliminary Design Review (PDR)

CCAR

VANTAGE

Visual **A**pproximation of **N**anosat **T**rajectories to **A**ugment **G**round-based **E**stimation

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Customer: *Prof. Penina Axelrad (CCAR), John Gaebler (CCAR)*

Advisor: *Prof. Marcus Holzinger*

Presenters

Project Description	Lara
Sensor System Feasibility	Sean
Software Feasibility	Justin
Avionics Feasibility	Jerry
Testing Feasibility	Zach
Status Summary	Nick

Project Description

Project Objectives

Motivation:

With the constant increase in CubeSat launches, space traffic is becoming a real concern. Due to the limitations inherent to ground-based tracking systems, **tracking data for SmallSats is often not available until several minutes to several hours after SmallSat deployment**. The VANTAGE project's use-case will significantly reduce delays in obtaining orbital tracks by **associating relative trajectory measurements with specific CubeSats at close-range immediately after deployment**. These close-range measurements are of special interest to regulatory bodies like the FAA and JSpOC, both of which aim to better understand and regulate space traffic.

Mission Statement:

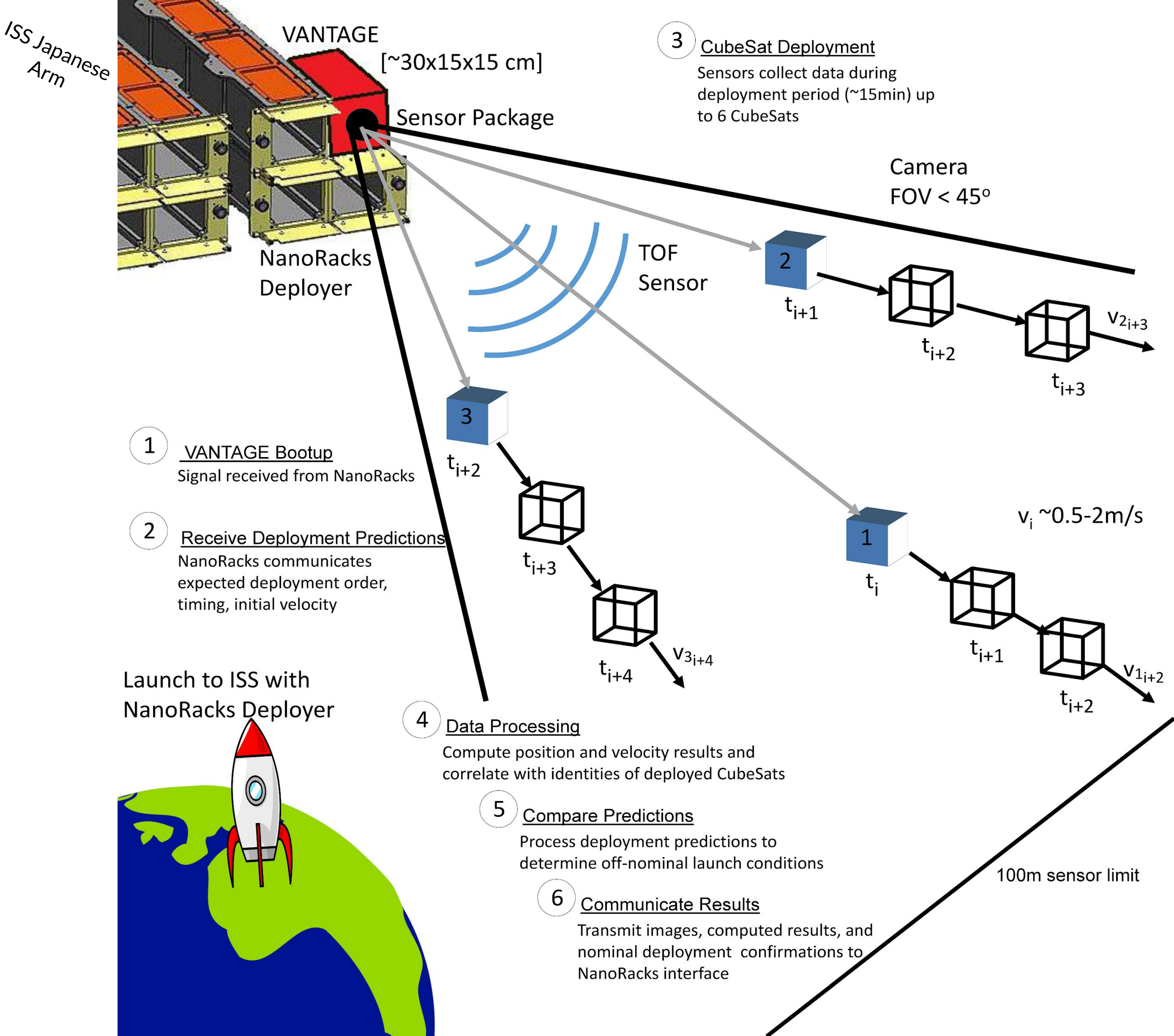
The **long term vision** of this project is to augment existing, ground-based CubeSat Space Situational Awareness (SSA) by observing CubeSat deployments from the perspective of the space-based deployer. **This year's** VANTAGE team will produce a **proof of concept** for this mission by developing a **ground based prototype** which will be tested using a simulated CubeSat deployment in a laboratory environment.

Project Stakeholders:

- Customer: Prof. Axelrad and John Gaebler
- Associated Company: NanoRacks

Concept of Operations

Multi-Year Vision



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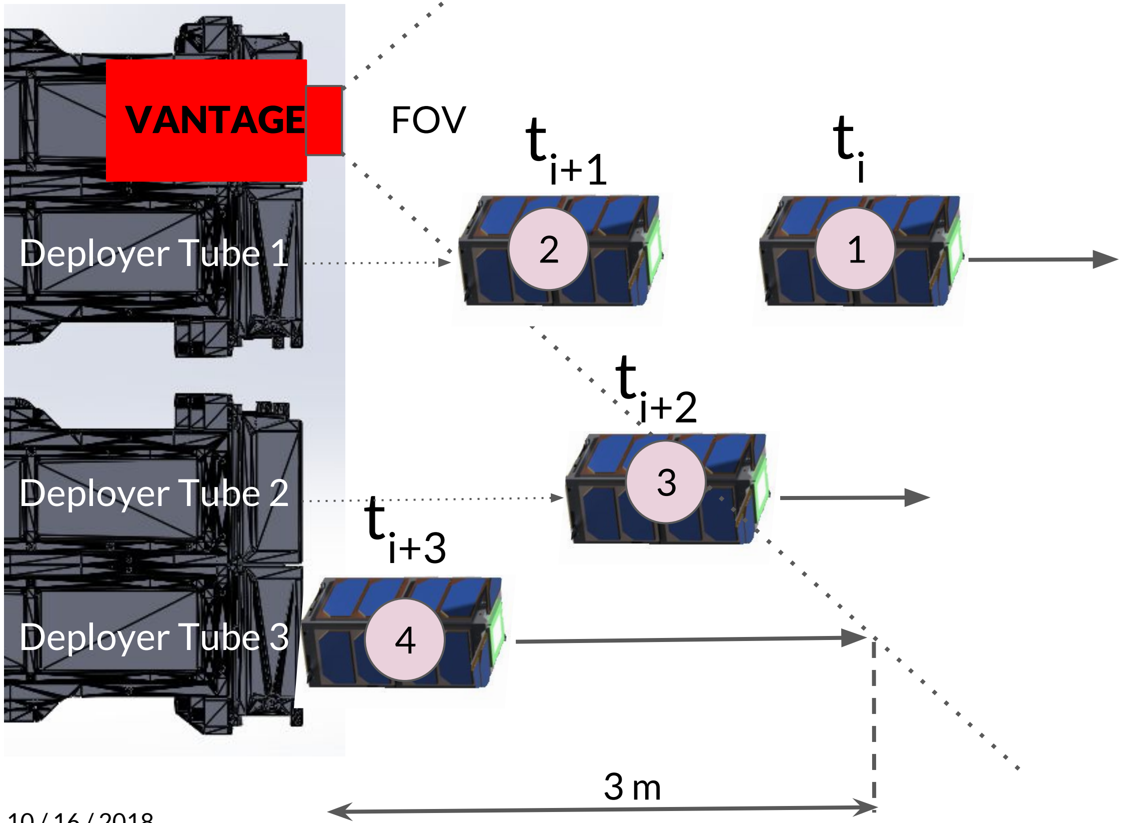
Vision for VANTAGE Use-Case FOV



Deployment Predictions

- Expected Deployer Tube
- Expected Velocity
- *Commanded* Launch Time

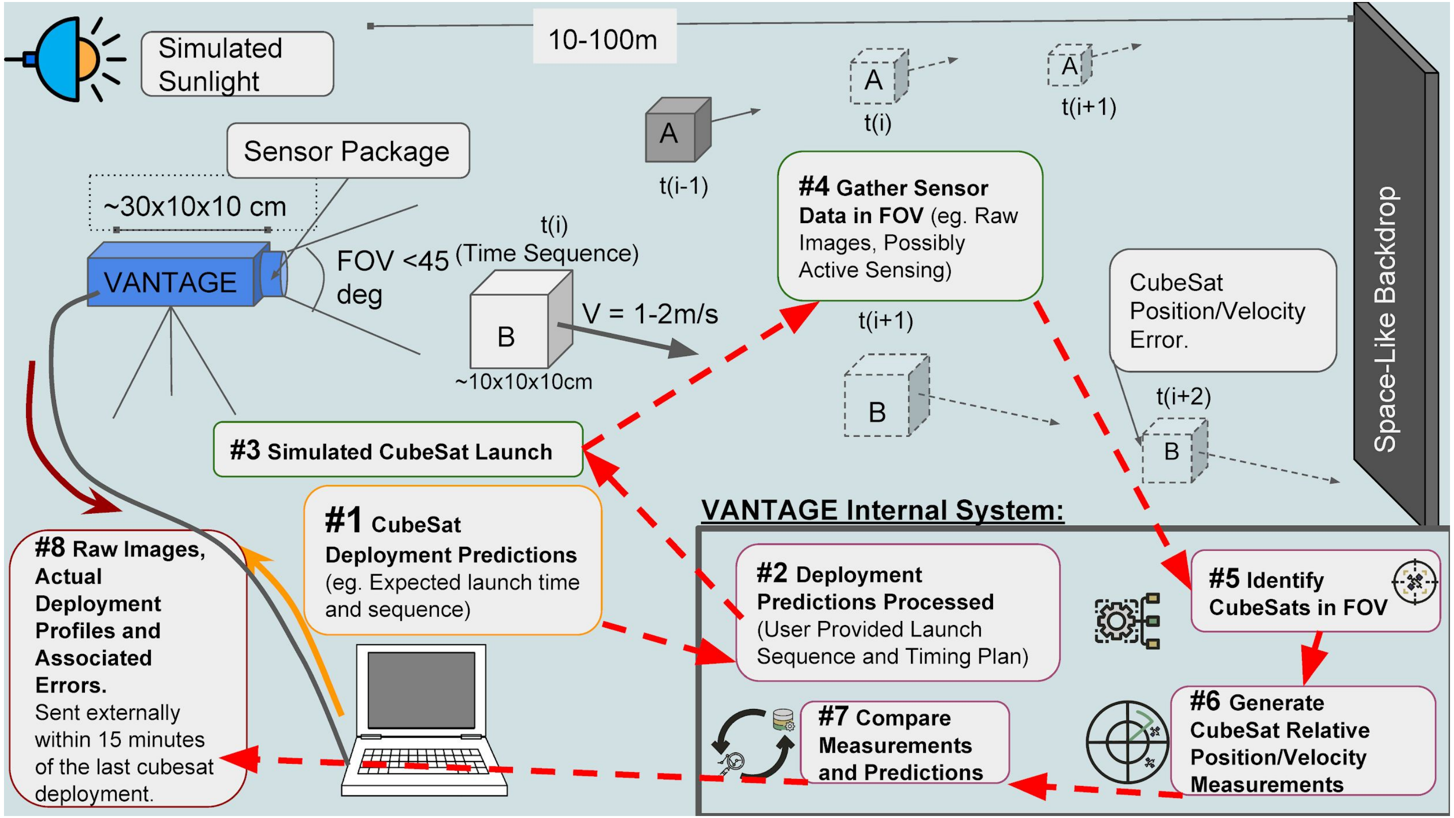
Measured Data

- Measured Positions
- Calculated Velocity
- *Calculated* Launch Time

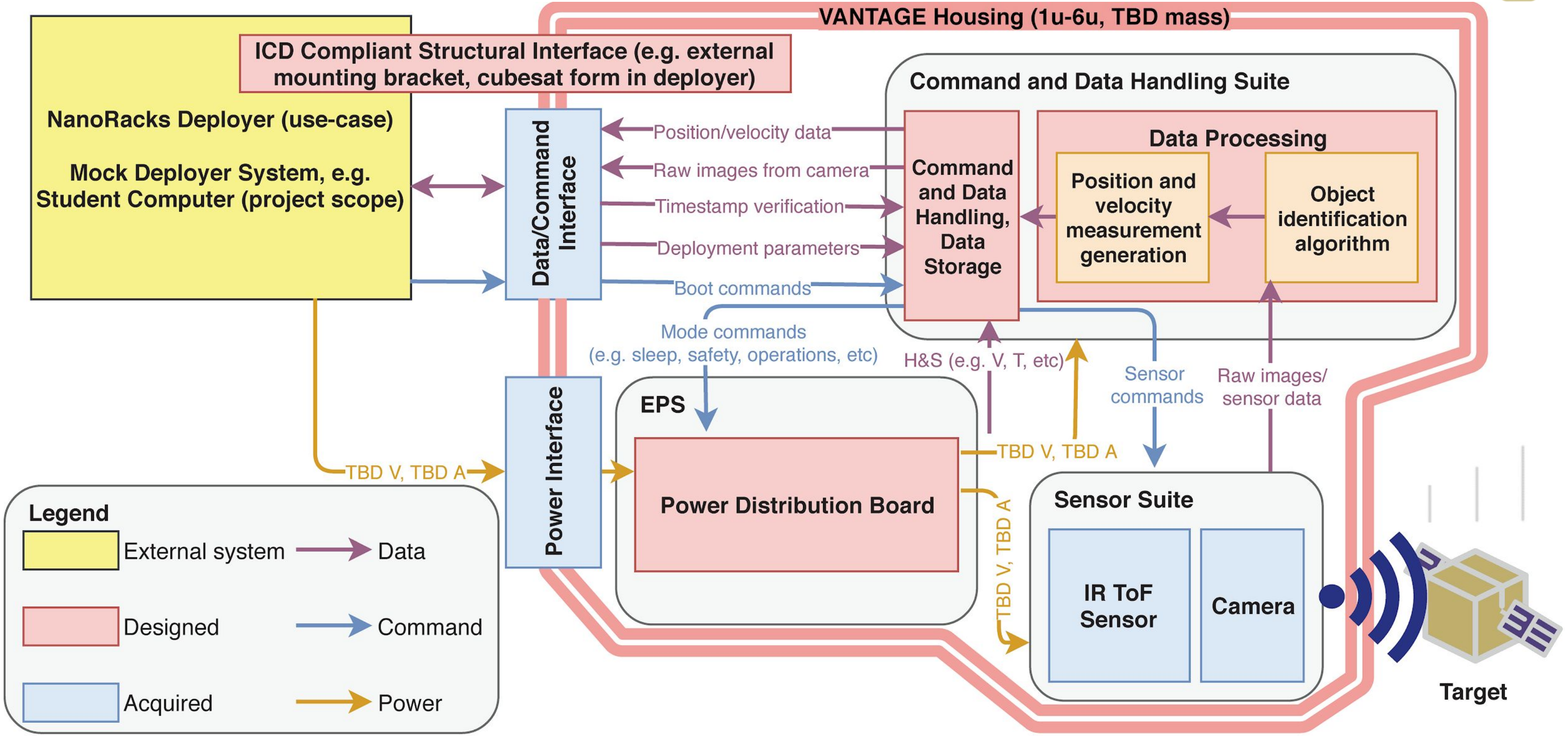
NanoRacks System Verification

- Compare measured data to deployment predictions and report results.

Concept of Operations: This Year



Functional Block Diagram

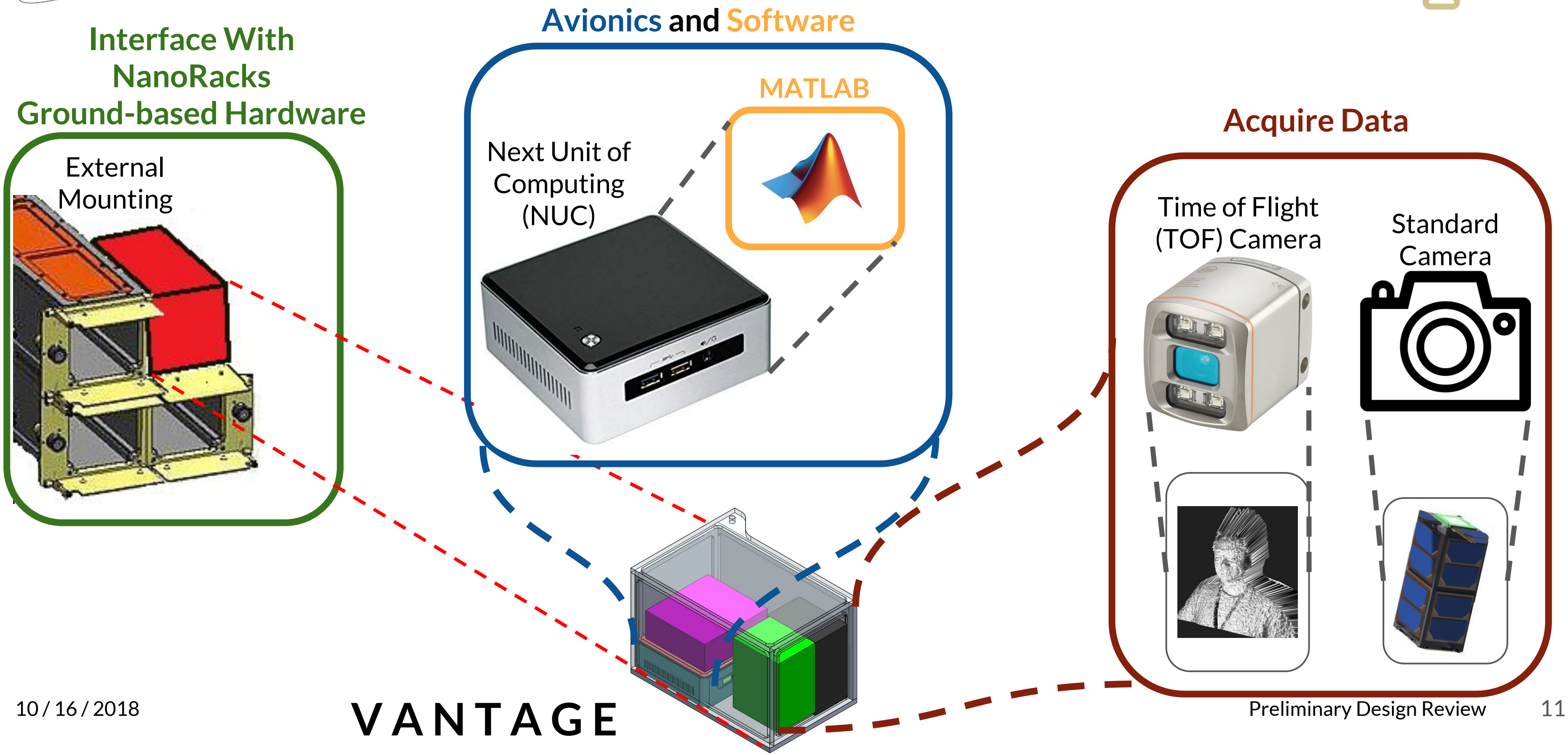


Functional Requirements

Req.	Description
FR.1	The system shall support in-focus imaging of at most 6 mock 1U CubeSats at some range between 3 and 100 meters from the VANTAGE payload.
FR.2	The system shall receive and interpret commands and the deployment manifest from a PC which simulates the NanoRacks use-case system.
FR.3	The system shall accept power analogous to that which is available from the NanoRacks use-case system.
FR.4	The system shall integrate mechanically with a structural interface which simulates the NanoRacks use-case system.
FR.5	The system shall uniquely detect and track up to 6 mock 1U-3U CubeSats while they remain between 3 and 100 m of the VANTAGE payload.
FR.6	The system shall estimate the position and velocity vectors of CubeSats between a distance of 3 and 100 m.
FR.7	The system shall recognize off-nominal deployment cases, which shall include off-nominal relative initial velocities and off-nominal deployment times from the test system.
FR.8	The system shall report position/velocity vector measurements, off-nominal deployment cases, and raw images from the current mock deployment to the PC which simulates the NanoRacks use-case system before the next NanoRacks CubeSat Deployer (NRCSD) tube deployment would normally occur in the use-case.

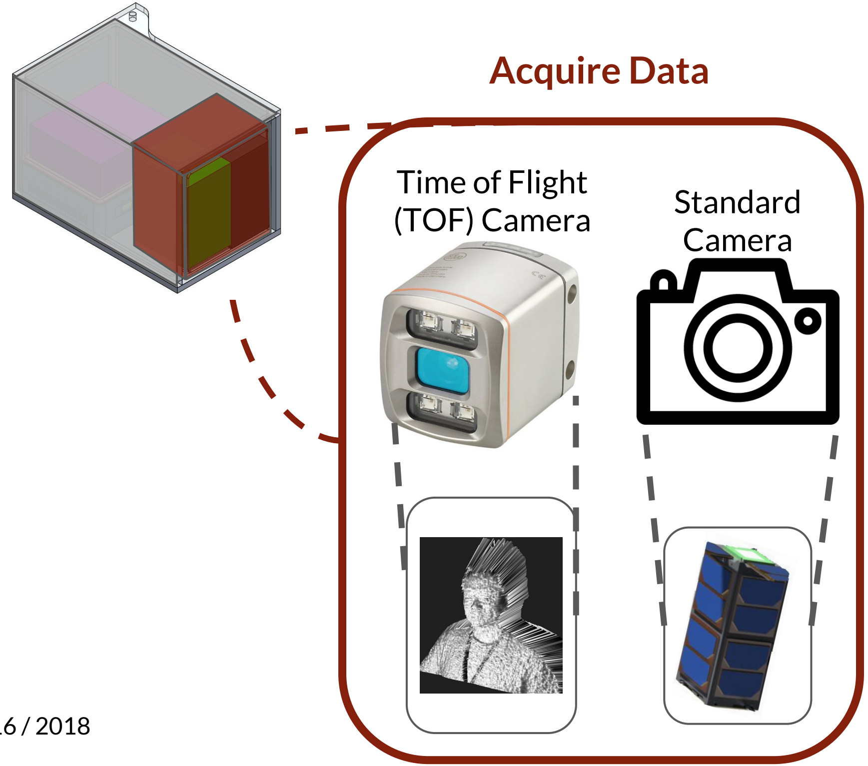
Baseline Design

Baseline Design Overview



Baseline Design - Sensors

VANTAGE



TOF Primary Function:
Range Measurement

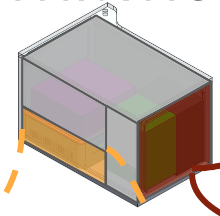
- IFM O3D313 IR Time of Flight (ToF) Camera
- $1460
- 60° x 45° FOV
- 352 x 264 Resolution
- 8m Maximum Range
- 25 fps capability
- +/- 20mm range accuracy at 8 m range

Standard Camera Primary Function:
Cross-Range Measurement

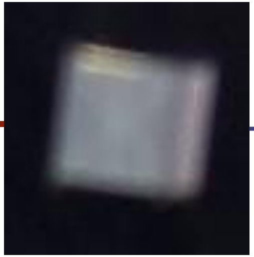
- Canon EOS 80D DSLR
- ~$1200 for Camera+Lens
- 6000 x 4000 Resolution
- 7 fps capability

Baseline Design - Software

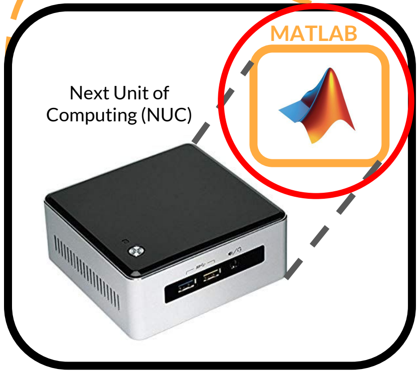
VANTAGE

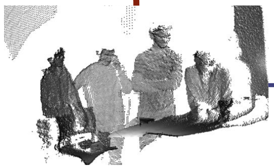


Images

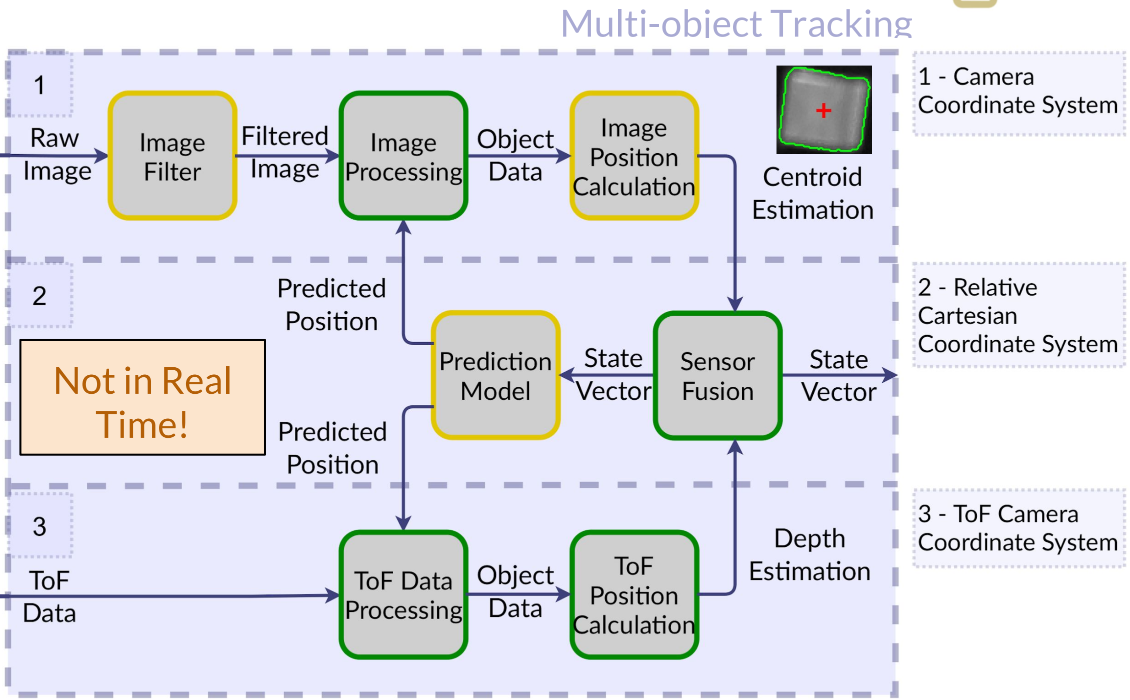


Software





TOF Sensor Output

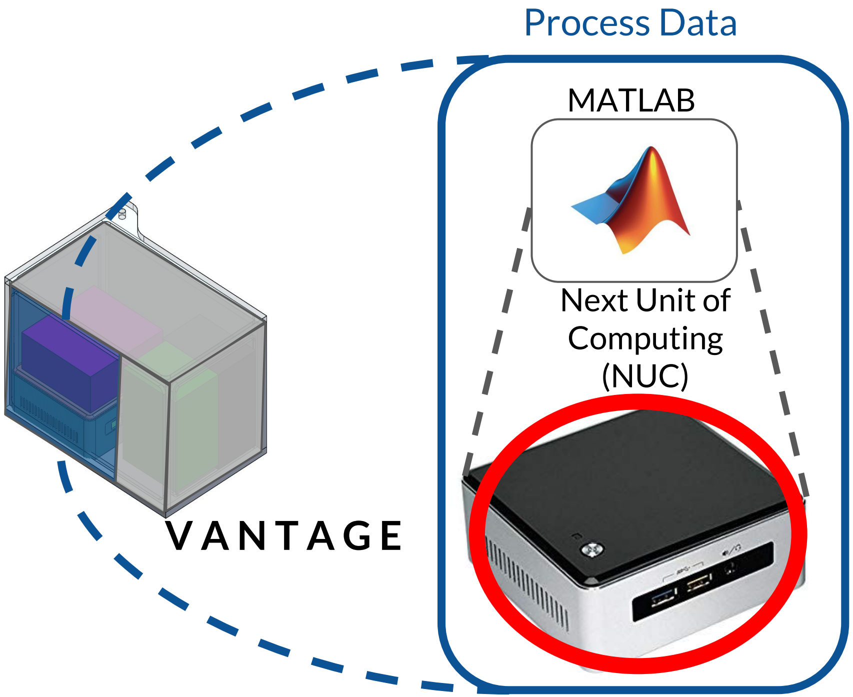


Legend

Relative Straight-Forward Implementation

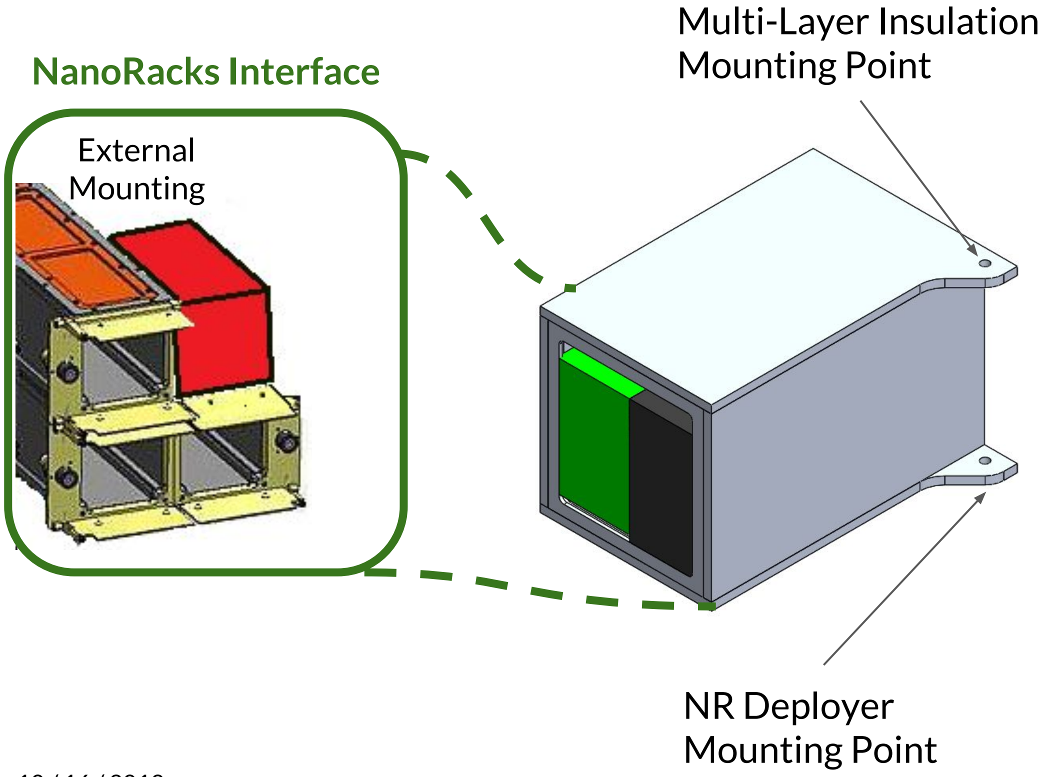
Relatively Complex, Iterative Implementation

Baseline Design - Avionics



NUC Component	Description
CPU	Intel Core I7 or Intel Core I5
RAM	Up to 32GB
Disk Memory	Up to 5TB
Interface	USB 3.0
Max Power	65 W
OS	Linux , Windows
Dimensions	11.5 x 11.1 x 0.51 cm
Cost	~$770.00

Baseline Design - Structural Interface



- 6 panel design
  - Based on QB50 satellite design
- Uses #4-40 fasteners for panel and internal component mounting
- Interface mounting to NR NRCSD using a single ¼”-28 bolt
- Has ¼”-28 threaded hole for MLI blanket mounting
- Front plate has sensor window
- Space remains internally for mounting bulkheads
- Limited forces expected in use case
  - NRCSDs are only connected with two fasteners
  - VANTAGE is ⅓ size of NRCSD
    - 5.43in x 5.67in x 8.66in
- Cost: ~$100.00

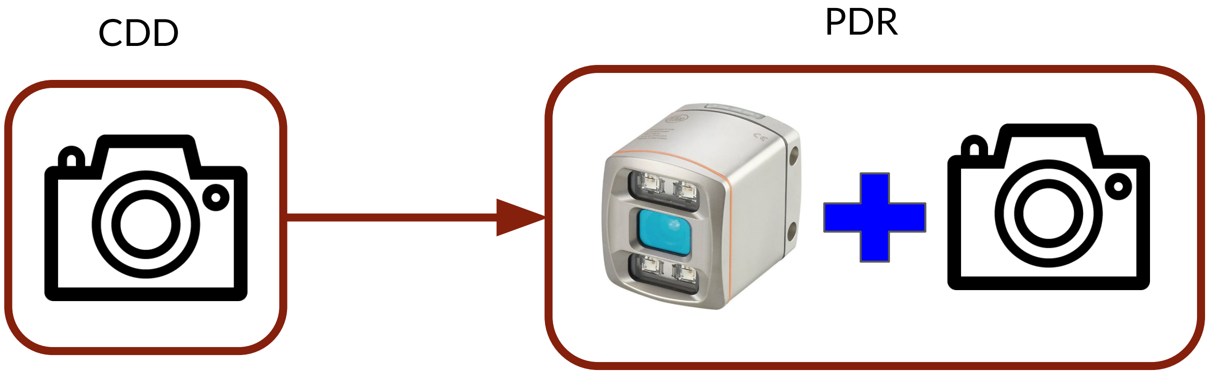
Project Changes Since CDD

Baseline Design Sensor Change

- VANTAGE has made the decision to go with a Time of Flight (TOF) camera paired with an optical camera instead of just using an optical camera.

Reasons For the Change

- The TOF + Camera option scored second highest to the single camera option.
- TOF provides more easily obtained range measurements.
- Single camera range measurements are difficult to compute and require significant computation for accurate results.



Evidence of Feasibility

Critical Project Elements

Sensors

- Error in position / velocity measurements as a function of range

Software

- Object Recognition
- Multi-object Tracking

Avionics

- Can we store, process and report on all of our data within 15 minutes?

Test Rig

- Creating the proper test environment
- Mock CubeSats Deployments properly simulate real CubeSats
- Truth data for position / velocity is sufficiently accurate

Sensors Feasibility

Overview

Sensors Feasibility Overview

Position and Velocity Accuracy

Subsystem CPEs	Governing Requirement(s)	Parent Functional Requirements	CPE Justification
Error in Position and Velocity Measurements	DR 6.1, 6.2	FR.6	Sensors record sensor data, and choosing the right ones will help us meet requirements.

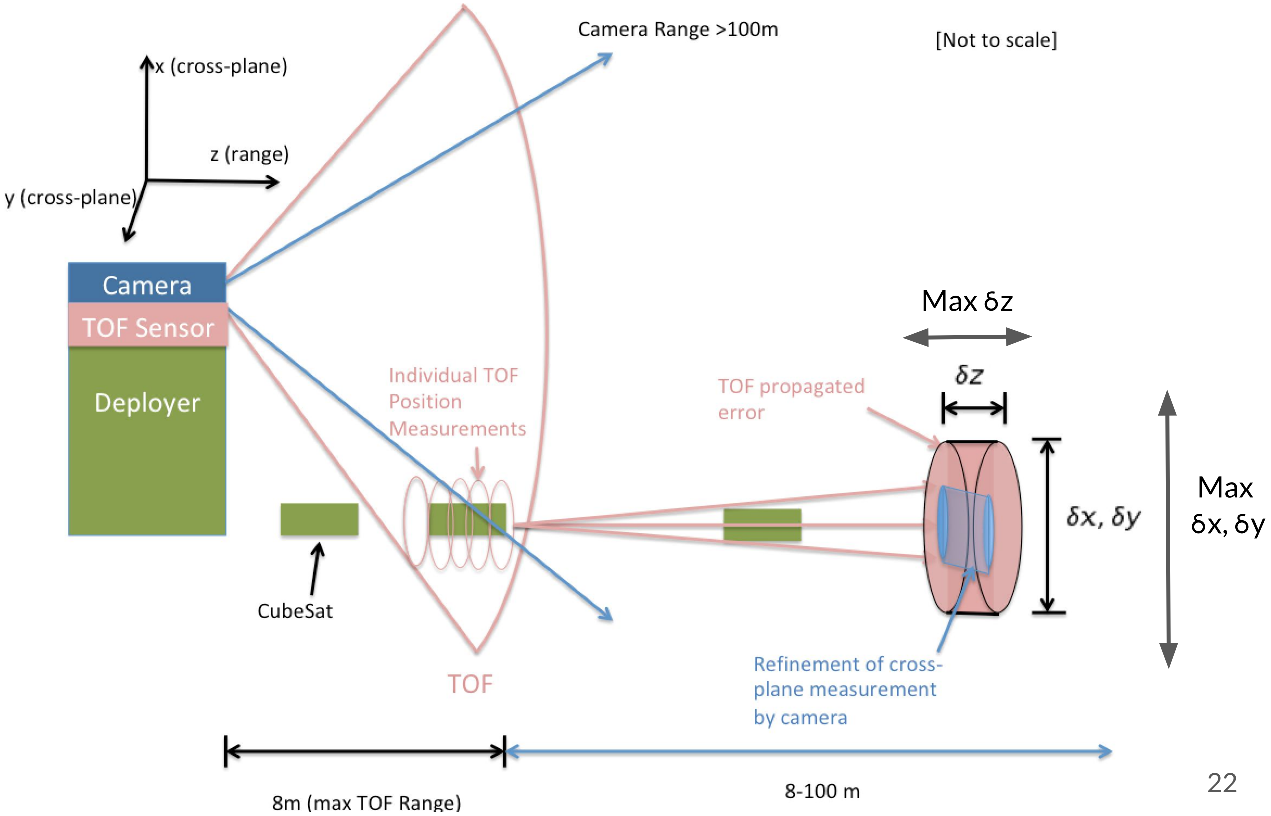
Req.	Summary	Link to Slide(s)
DR 6.1	Position Accuracy (10 cm for 3-10m ,10% of range to 100 m)	DR 6.1
DR 6.2	Velocity Accuracy (1 cm/s to 10 m , 10cm/s to 100m)	DR 6.2

Sensors Feasibility

Error in Position and Velocity Measurements

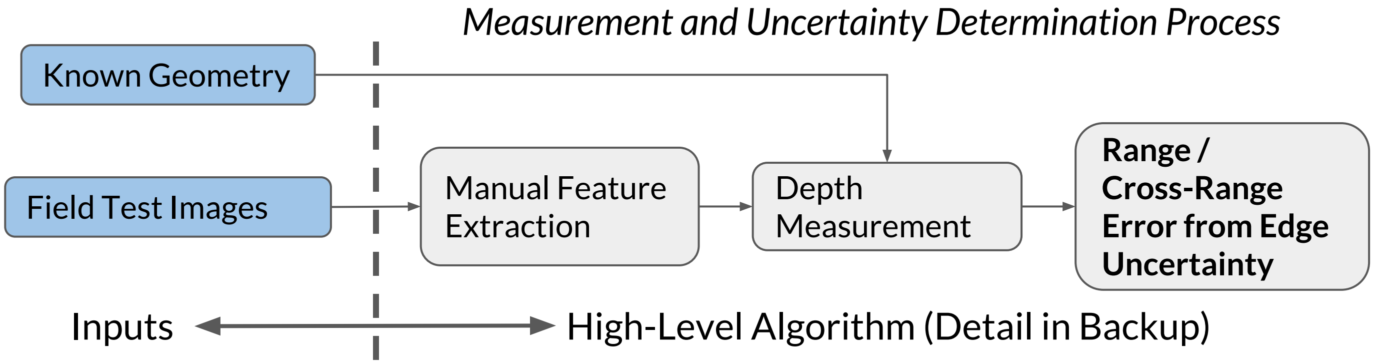
Sensor Fusion: High-Level Error Depiction

- TOF is extremely accurate in depth (z) at short range
- TOF measurements are propagated to 100 m
- Cross-plane measurements (x,y) are refined over full range using camera



Camera-Only Accuracy Feasibility

Image from field test



Actual Range	Measured Range	Range Uncertainty (1σ)	Cross-Range Uncertainty	Error + Uncertainty
5.0m	5.12m	0.30m	0.22 cm	42 cm > 10cm
100.0m	94.33m	4.76m	0.24 m	10.43 m >10 m

A camera alone does not satisfy position measurement requirements

Req.	Summary
DR 6.1	Position Accuracy (10 cm for 3-10m ,10% of range to 100 m)

TOF Camera: Error Analysis

TOF Sensor Error Figures
(from Data Sheet)

Range	Depth Error
>3m	7 mm
3-5 m	10 mm
5-7 m	15 mm
7-8 m	20 mm

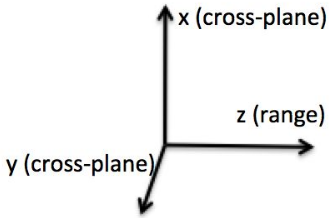
$$v = \frac{\Delta x}{\Delta t}$$

$$\delta v = \sqrt{\delta x^2 + \delta t^2}$$

Electronic timing of measurements assumed to be very accurate. ⇨ $\delta t << \delta x$

Assuming constant velocity, the velocity estimate is refined by each position measurement.

$$\delta v_{refined} \propto \frac{\delta v}{\sqrt{N}}$$



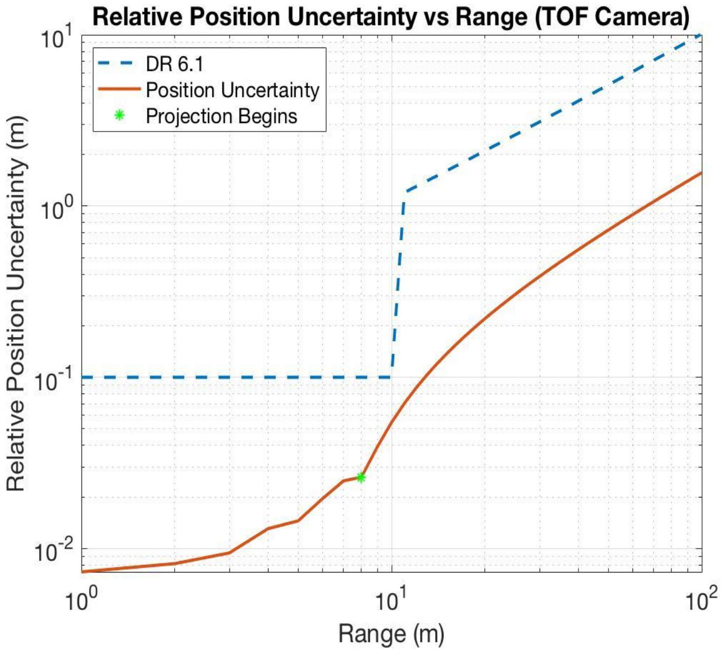
Cross-plane accuracy approach: Assumed sensor can measure geometric center to ½ pixel.

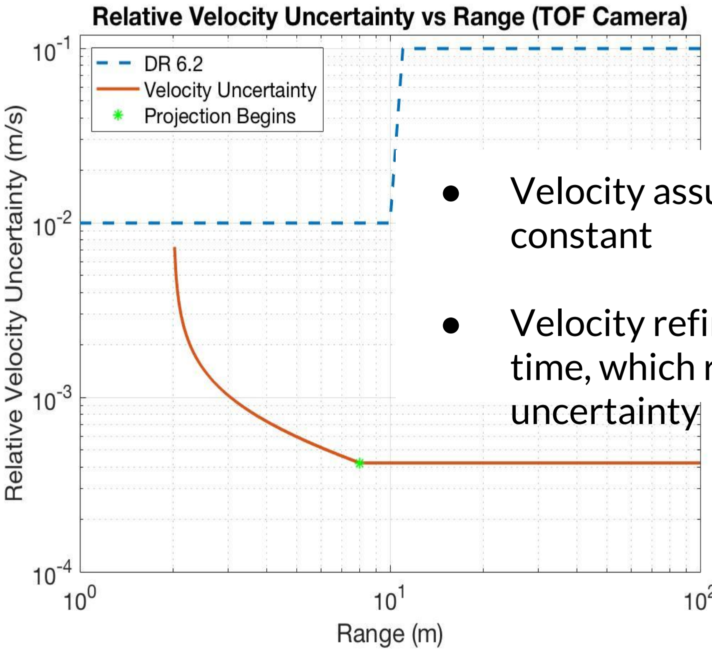
N = Number of TOF Position Measurements - 1

Assumed conservative TOF measurement rate of 12 fps (max TOF FPS = 25 FPS)

TOF Camera: Position/Velocity Accuracy

DR 6.1 and DR 6.2 Feasible? Yes:





- Velocity assumed constant
- Velocity refined over time, which reduces uncertainty

Req.	Summary
DR 6.1	Position Accuracy (10 cm for 3-10 10m ,10% of range to 100 m)
DR 6.2	Velocity Accuracy (1 cm/s to 10 m , 10cm/s to 100m)

Software Feasibility

Overview

Software Feasibility Overview

Subsystem CPEs	Governing Requirement(s)	Parent Project Objective(s)	CPE Justification
Object Recognition	DR 5.2	FR.5	If the software is unable to identify mock CubeSats, it will be unable to measure and associate their trajectories.
Multi-object Tracking	DR 5.2, FR 1	FR.1, FR.5	CubeSats are deployed in clusters. VANTAGE will be unable to provide sufficient tracking in the use-case if it cannot track multiple objects in the FOV.

Req.	Summary	Link to Slide(s)
DR 5.2	Software shall detect mock CubeSats within FOV at a distance of 3-100m	DR 5.2

Software Feasibility

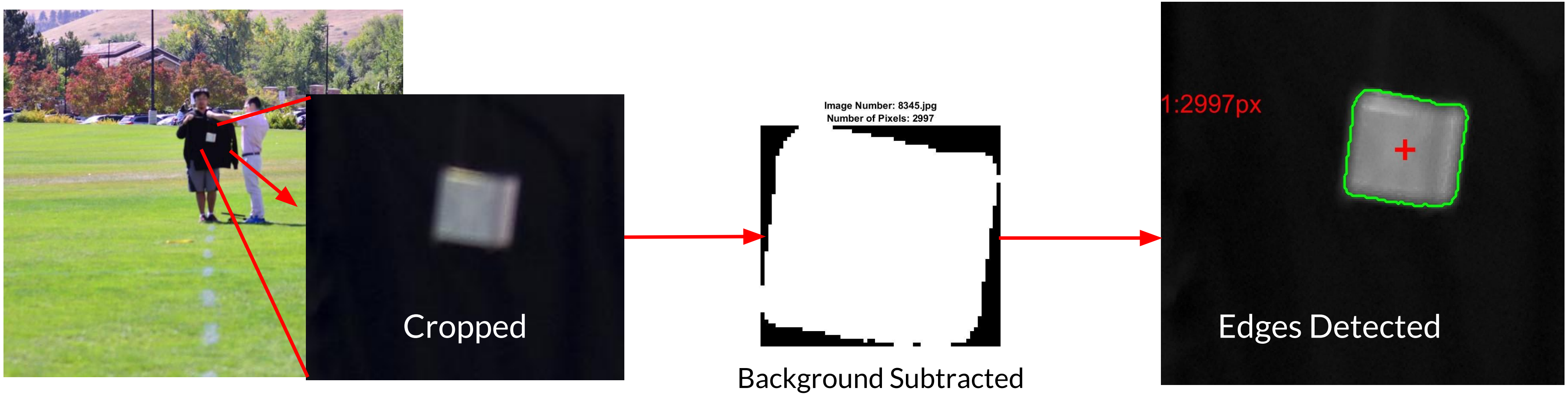
Object Recognition

Camera Object Recognition

Feasible? Yes:

- *Test Details*: Nikon D800, 7360x4912, FOV 28.8°x19.5°, focal length 100 m
- Real mock CubeSat image at a range of 30 m, tests over full range given in backup

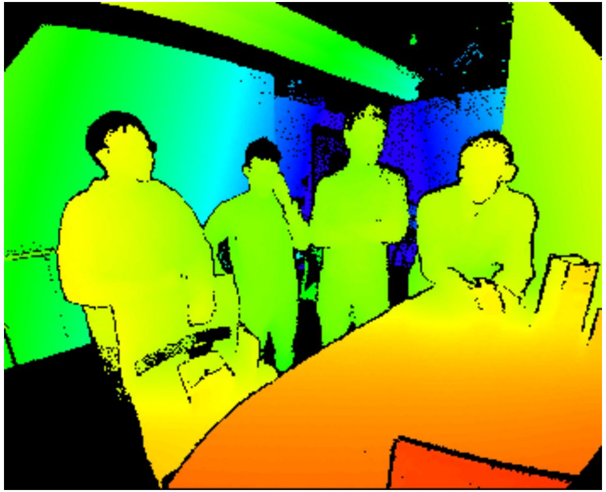
Resulting data includes centroid, pixel count, and object boundary pixels



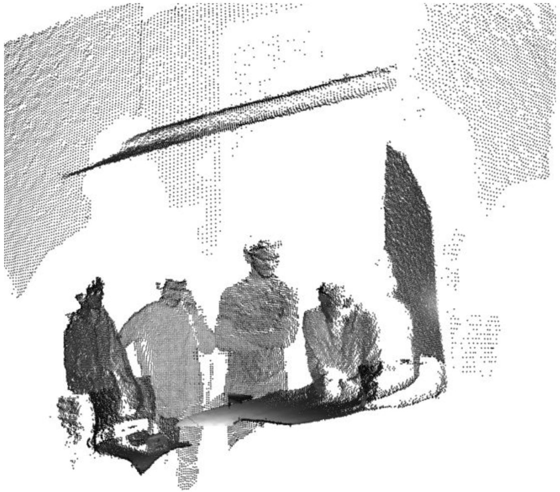
Req.	Summary
DR 5.2	Software shall detect mock CubeSats within FOV at a distance of 3-100m

TOF Camera Feasibility Progress

Prof. McMahon's TOF Camera Sensor Measurements (2D left, 3D right)



2D image from TOF Software Package



- TOF sensor provides depth measurements of all objects within its FOV at short range
- Images demonstrate team's ability to work with output from a TOF camera
- Path forward:
  - Perform open field-testing of object recognition with mock CubeSat
  - Not yet performed due to schedule constraints and limited access to the on-campus TOF camera

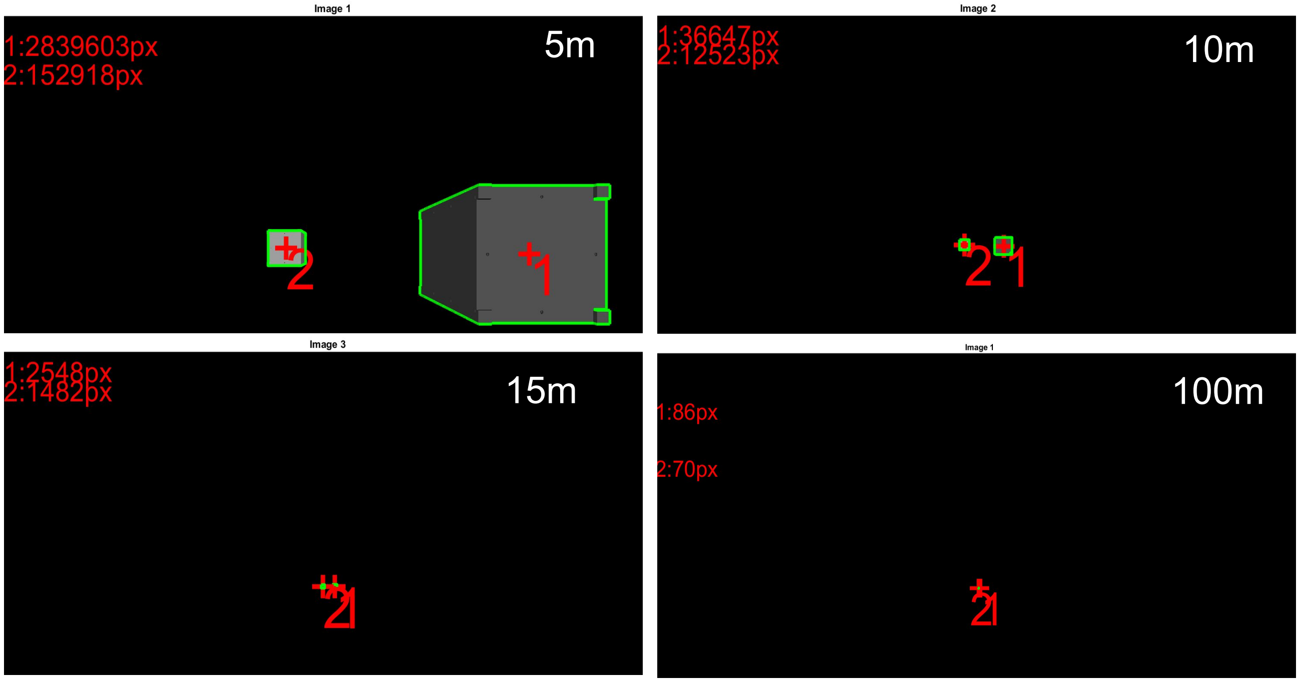
Software Feasibility

Multi-object Tracking

Multi-object Tracking Simulation

- Simulation done with a 3D graphics software
  - Cinema 4D R20
- Camera FOV seen is FOV 28.8°x19.5°
  - This is what what we use in real photo test. (Validate simulation work)
- Video is real time but cut
  - Expected deployment velocities are 1-2m/s (general NanoRacks predictions)
  - From start to finish expected to take between 50-100s for the full range test

Multi-object Tracking



Simplified analysis for determining feasibility:

- Rectilinear Motion
- Equal linear velocities for 1 and 2
- Thus the initially larger pixel cluster will always be larger through images
- Shows feasibility of differentiating realistic objects up to 100 m
- Can be extended to six objects for clear visibility (see backup)

Req.	Description
FR.5	The system shall uniquely detect and track up to 6 mock 1U-3U CubeSats while they remain between 3 and 100 m of the VANTAGE payload.

Avionics Feasibility

Avionics Feasibility Overview

Subsystem CPEs	Governing Requirement(s)	Functional Requirements	CPE Justification
Data Storage and Processing Data	DR.8.1-EL DR.8.2-EL	FR.8	The selected avionics will limit VANTAGE's processing speed and maximum storage capacity, so these factors must be taken into account when selecting hardware.

Req. Label	Summary	Links to Slide(s)
DR 8.1 EL	The electronics subsystem shall transmit results within 15 minutes of final mock CubeSat deployment.	DR.8.1
DR 8.2 EL	The system shall store all images, sensor data, and estimates within an onboard data storage device.	DR.8.2

Data Storage and Processing Data

DR 8.1 and DR 8.2 Feasible? Yes:

Process	Time*
Data import from camera (USB3.0)	115.6 Sec
Processing Camera Necessary RAW Footage	300 Sec
Image Recognition	2.38 Sec
Estimate velocity and position	100 Sec
Output to Use-Case-System (USB2.0)	52 Sec
Total	**569 Sec = 9.5Min**

- Compatible with standard SSD drives (up to 5 TB possible, 64* GB is more than enough)
  - *Support for these numbers in Backup

NUC Image Processing Time Estimates

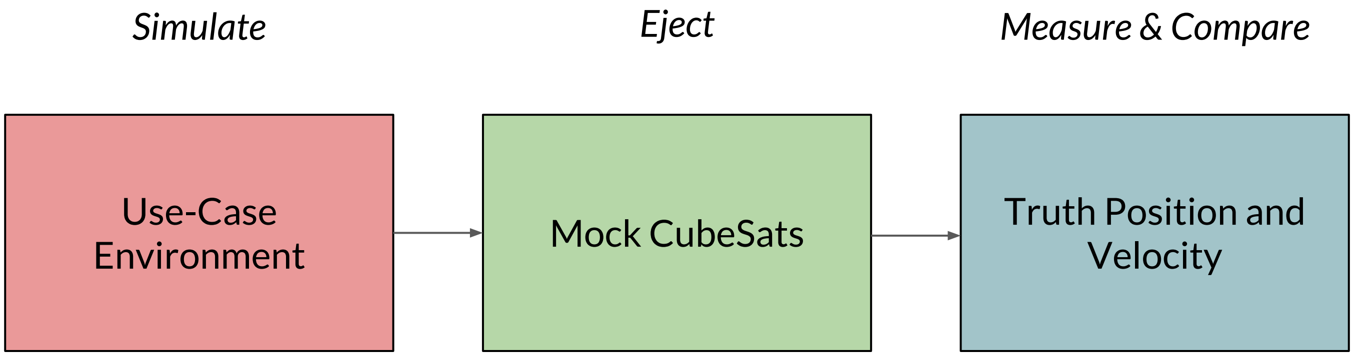
- Data input through and write from USB3.0
  - 25MB/s
- Processing CR2.RAW-DNG
  - 5 Min based on experience
- Image Recognition
  - 0.0238 sec per image
- Estimate Velocity and Position
  - 1 sec per image
- Output USE-CASE two raw footage(500MB)
  - 10MB/S

Req.	Summary
DR 8.1	The electronics subsystem shall transmit results within 15 minutes of final mock CubeSat deployment.
DR 8.2	The system shall store all images, sensor data, and estimates within an onboard data storage device.

Testing Feasibility

Overview

Testing Feasibility CPEs



Testing Feasibility

100m Full-Scale Test

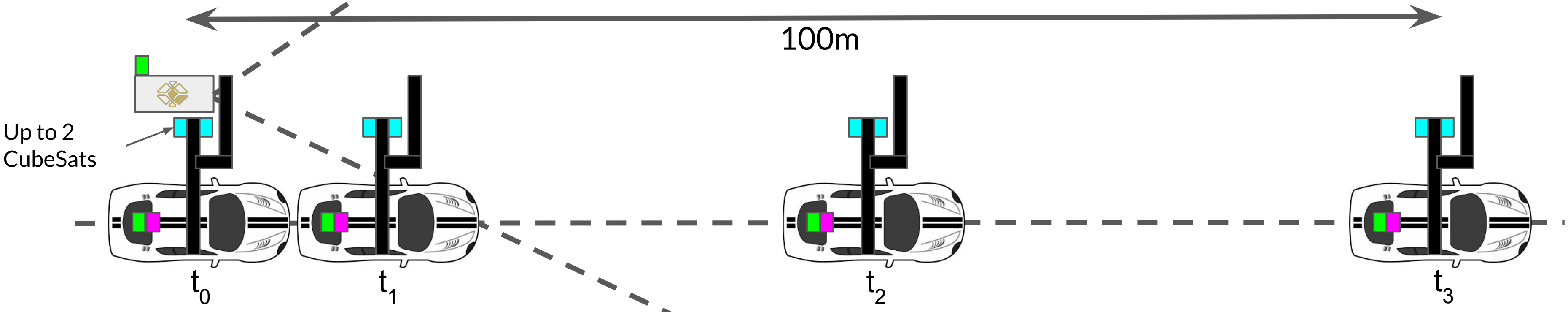
100m Full Scale Test

Subsystem CPEs	Testable Requirement(s)	Parent Functional Requirements	CPE Justification
Testing & Verification	DR.3.1 DR.6.1 DR.6.2	FR.3, FR.6	The VANTAGE system must be tested in order to verify requirements. As a technology and concept ground based demonstration it is important to simulate the use case of the system accurately so that system requirements can be verified.

Testable Requirements

Req. Label	Summary
DR.3.1	The system shall operate with up to 120 VDC with a ripple voltage of 3Vpp and less than 5 A, which simulates the power available from the NanoRacks use-case system.
DR.6.1	Software subsystem shall produce relative position vector estimates accurate up to 10 cm 1σ to a distance of 10 m, changing to an accuracy of at least a tenth of the range 1σ up to a distance of 100 m.
DR.6.2	Software subsystem shall provide relative velocity vector estimates accurate up to 1 cm/s 1σ to a distance of 10 m, changing to an accuracy of 10 cm/s 1σ up to a distance of 100 m.

100 m Full Scale Test - Layout



- Mock cubeSat
- Mounting Boom and Dark Screen
- RTK GPS
- High Precision IMU

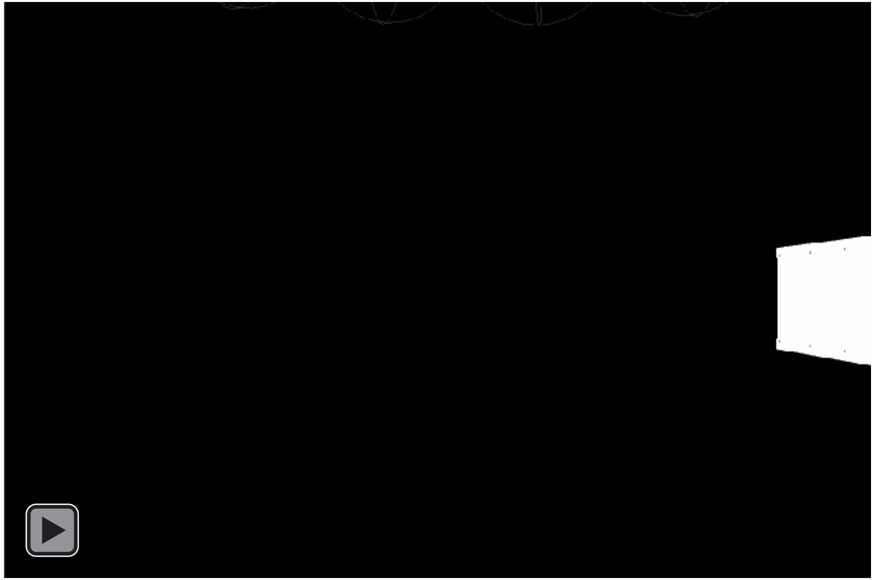
Legend

Truth Data	Test Data
RTK GPS	Vantage Sensor Subsystem
High Precision IMU	

- Scale model also considered but presents additional challenges
    - TOF and Camera sensor cannot be scaled down to generate similar area/pixel density at scaled range
- Full scale test gives opportunity to demonstrate complete system functionality

100m Full Scale Test Simulation

- Simulation done with a 3D graphics software
  - Cinema 4D R20
- Camera FOV seen is 20°x20°
  - This is what we expect to see with the current FOV used in the baseline design
- Video is accelerated
  - Expected deployment velocities are 1-2m/s (general NanoRacks predictions)
  - From start to finish, expected to take between 50-100s for the full range test



100 m Test System - Feasibility

- **Possible Locations**
  - Boulder Airport Taxiway, Big parking lots (flatirons mall, etc.)
  - Expect limited traffic at night at both locations

- **Manufacturing**
  - Expect cutting and welding pipe to fabricate boom for mock cubesats
    - Personal welding resources available over Winter Break and at aero machine shop upon start of Spring semester
    - Less competition for welding resources than for milling

- Iteration and Modularity details in backup

100m Test Accuracy Feasibility

- Must measure velocity accurate up to 1 cm/s (DR 6.2), position up to 10 cm (DR 6.1)

GPS RTK (ublox C94-M8P) Receiver

Property	Description
Velocity Accuracy	0.05m/s
Timing Accuracy	5 Hz update rate
Position Accuracy	0.025m
Size	15.9mm x 12.1mm x 2.2mm
Availability	Dr. Akos has the full C94-M8P package that he would be willing to lend to us for testing


Image Credit: ublox

Analog Devices 3-axis IMU (ADIS16405BMLZ)

Property	Description
Accelerometer Accuracy	3.33 mg/LSB
Gyroscope Accuracy	0.0125 deg/s/LSB
Acceleration Accuracy	0.0000333 m/s^2
Size	31..9mm x 22.9mm x 23.5mm
Availability	Has been checked out from Trudy

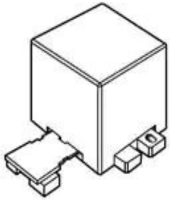


Image Credit: Analog Devices

Testing Feasibility

Modular Test System

Modular Test System

Subsystem CPEs	Testable Requirement(s)	Parent Functional Requirements	CPE Justification
Testing & Verification	DR.1.3; DR.1.4 DR.6.1; DR.6.2 DR.7.2; DR.7.3	FR.1 FR.6 FR.7	The VANTAGE system must be tested in order to verify requirements. As a technology and concept ground based demonstration it is important to simulate the use case of the system accurately so that system requirements can be verified.

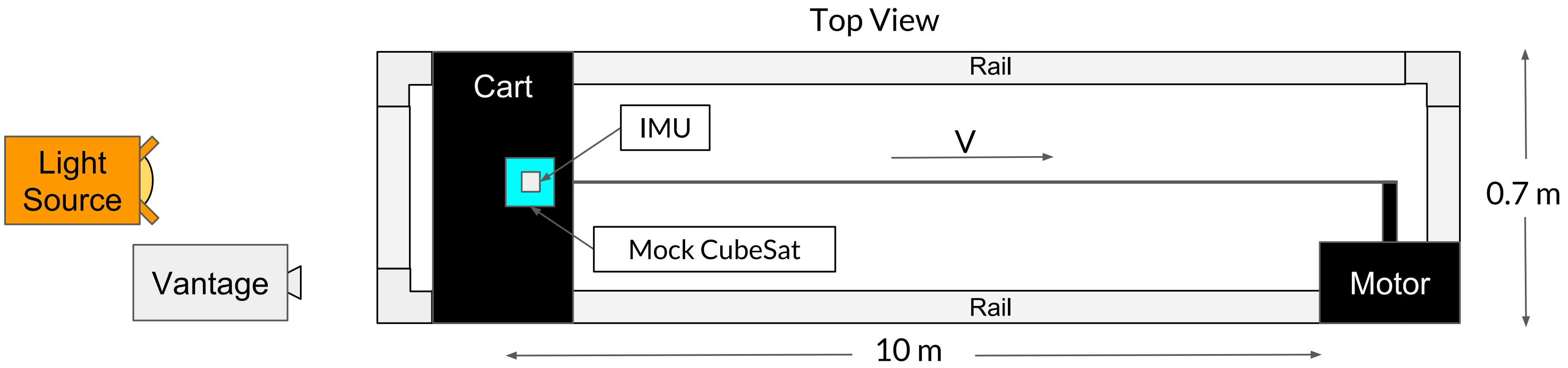
Testable Requirements

Req. Label	Summary
DR.1.3	Imaging subsystem shall produce at least 2 images of each mock CubeSat deployed by the test system.
DR.1.4	Imaging subsystem shall produce in-focus images of mock CubeSats
DR.6.1	Software subsystem shall produce relative position vector estimates accurate up to 10 cm 1σ to a distance of 10 m, changing to an accuracy of at least a tenth of the range 1σ up to a distance of 100 m.
DR.6.2	Software subsystem shall provide relative velocity vector estimates accurate up to 1 cm/s 1σ to a distance of 10 m, changing to an accuracy of 10 cm/s 1σ up to a distance of 100 m.
DR.7.2	Software subsystem shall recognize if mock CubeSats exit the test system greater than 3 seconds before/after predicted with a tolerance of 0.5 seconds 3σ.
DR.7.3	Software subsystem shall recognize if initial relative velocities are less than 0.5m/s or greater than 2.0m/s with a tolerance of 0.1m/s 3σ.

Modular Test System - Layout

Truth Data	Test Data
High Precision IMU	Vantage Sensor Subsystem

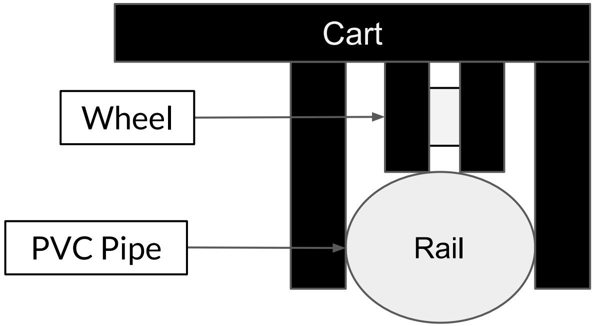
- 10 m PVC pipe track
- Mock CubeSat mounted to cart
- Cart moves along track on wheels, pulled by motor (see next slide)
- High accuracy IMU (see 100m test) used for truth position measurements



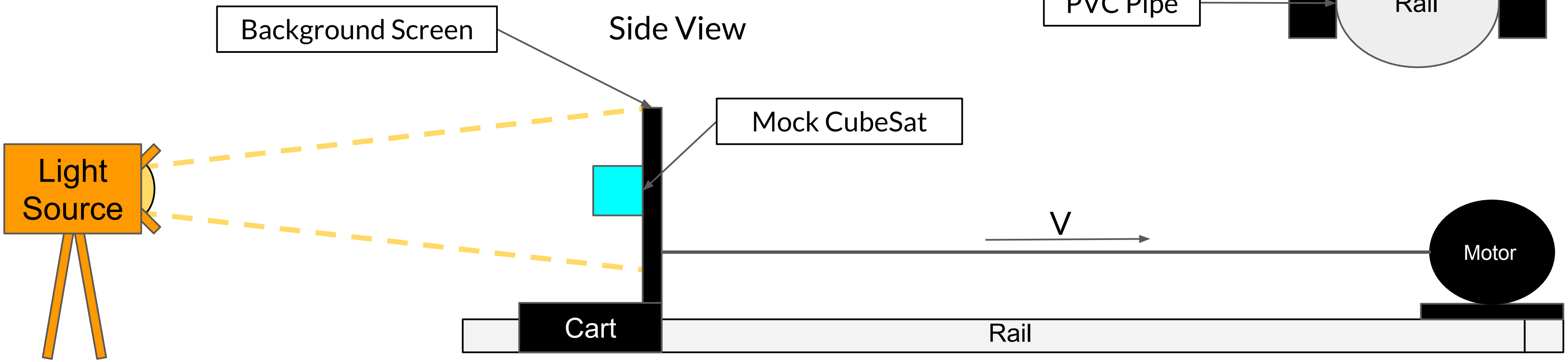
Modular Test System - Layout

- 2 Wheels mounted to each side of cart
- Mock CubeSat mounted to black non-reflective background
- Light source illuminates Mock CubeSat

Wheel Mounting
(Front View)



Side View



Modular Test System - Feasibility

- **Possible Locations**
  - For 100m of testing (10 separate test iterations)
    - Balch Fieldhouse, Indoor Practice Facility
    - Precedent exists for Senior Projects groups to access
  - For test workmanship and short range only
    - EC hallways are generally free of people after business hours
    - Set is designed to be easily broken down into components which can be stored in the Grad Projects work room
- **Manufacturing**
  - PVC Pipe and Acrylic will need to be cut
    - Bandsaw availability
- **Ability to Iterate**
  - Assembly necessary at beginning of each test
  - Location will need to be reserved, likely only at night
  - To mitigate risks several sessions will be planned in advance
- **Modularity of Test**
  - Each requirement can be verified individually

Project Status Summary

Baseline Design Feasibility

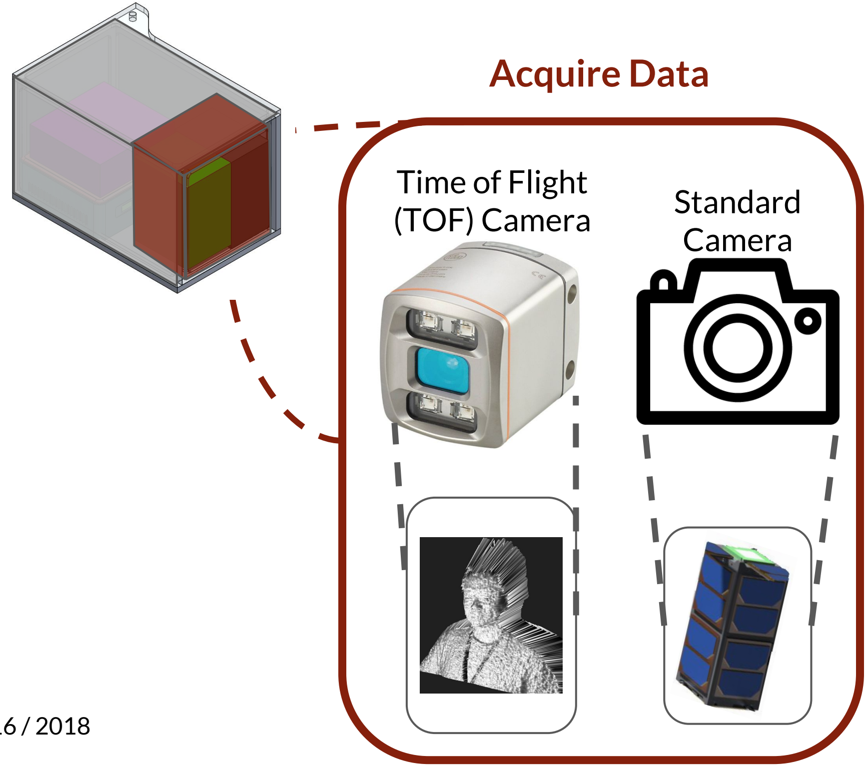
System Summaries

CCAR

Summary of Sensors

VANTAGE

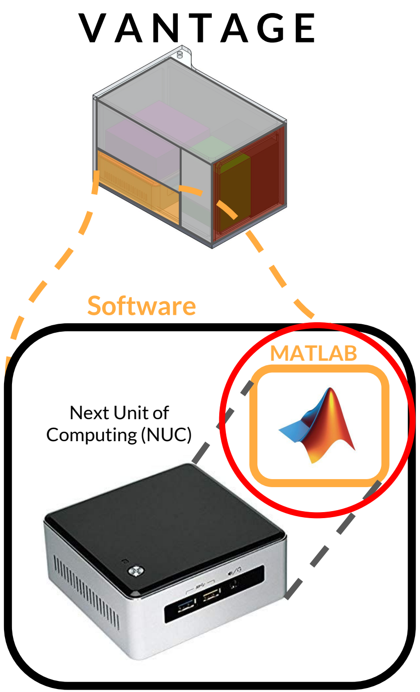
VANTAGE



- TOF Camera & Standard Camera **both work in tandem**
- Enable position / velocity measurements **within required precision**
- Provide adequate ability to **sense and track CubeSats from 3-100m**
- Planning on conducting **more field tests with Prof. McMahon's ToF Camera** to get field data w/ our mock CubeSat models

System	Feasibility
Sensors	**FEASIBLE**
Software	
Avionics	
Testing	

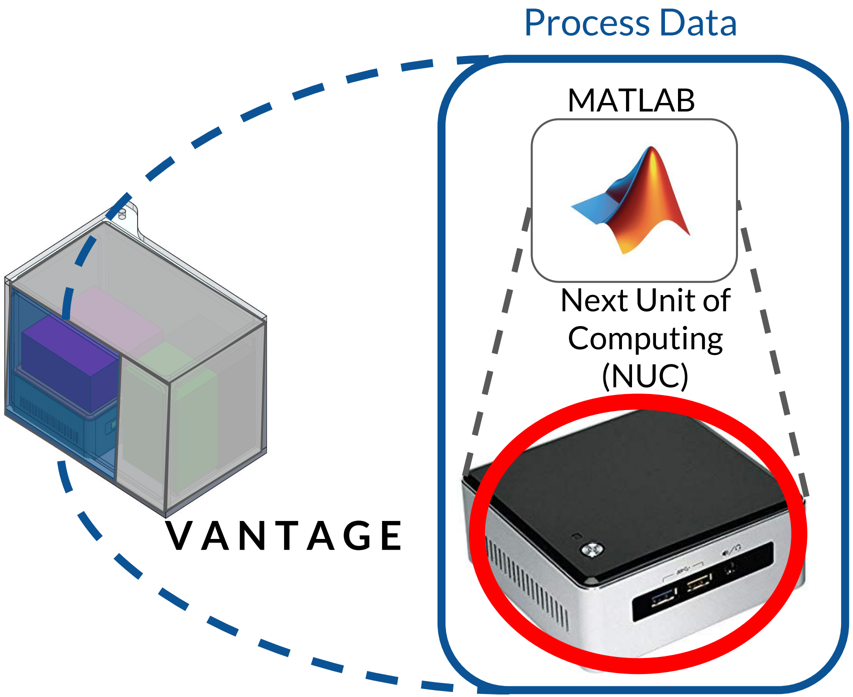
Summary of Software



- Edge detection algorithm **recognizes individual objects**
- Sensor data **can related to individual CubeSat position & velocity**
- Heuristic multi-object tracking algorithms **keeps track of object identity**

System	Feasibility
Sensors	**FEASIBLE**
Software	**FEASIBLE**
Avionics	
Testing	

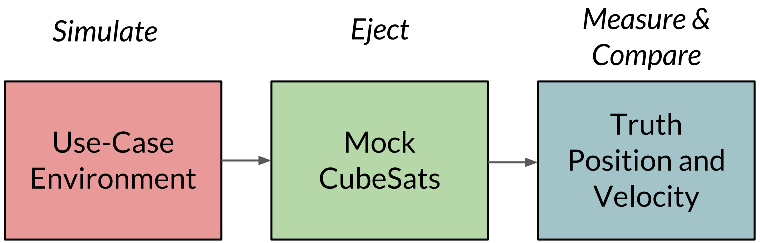
Summary of Avionics



- Avionics system **meets data storage requirements**
- NUC **processes data** generated **within required time limit**

System	Feasibility
Sensors	**FEASIBLE**
Software	**FEASIBLE**
Avionics	**FEASIBLE**
Testing	

Summary of Testing



- Provides simulated interface **power and data to VANTAGE**
- Completely Simulates CubeSat Deployment Conditions
- 100m Full Scale Test provides high precision data over **full use-case range** with slow iteration
- Modular Test System provides high accuracy, precise **close range data** with rapid iteration

System	Feasibility
Sensors	**FEASIBLE**
Software	**FEASIBLE**
Avionics	**FEASIBLE**
Testing	**FEASIBLE**

Project Budget

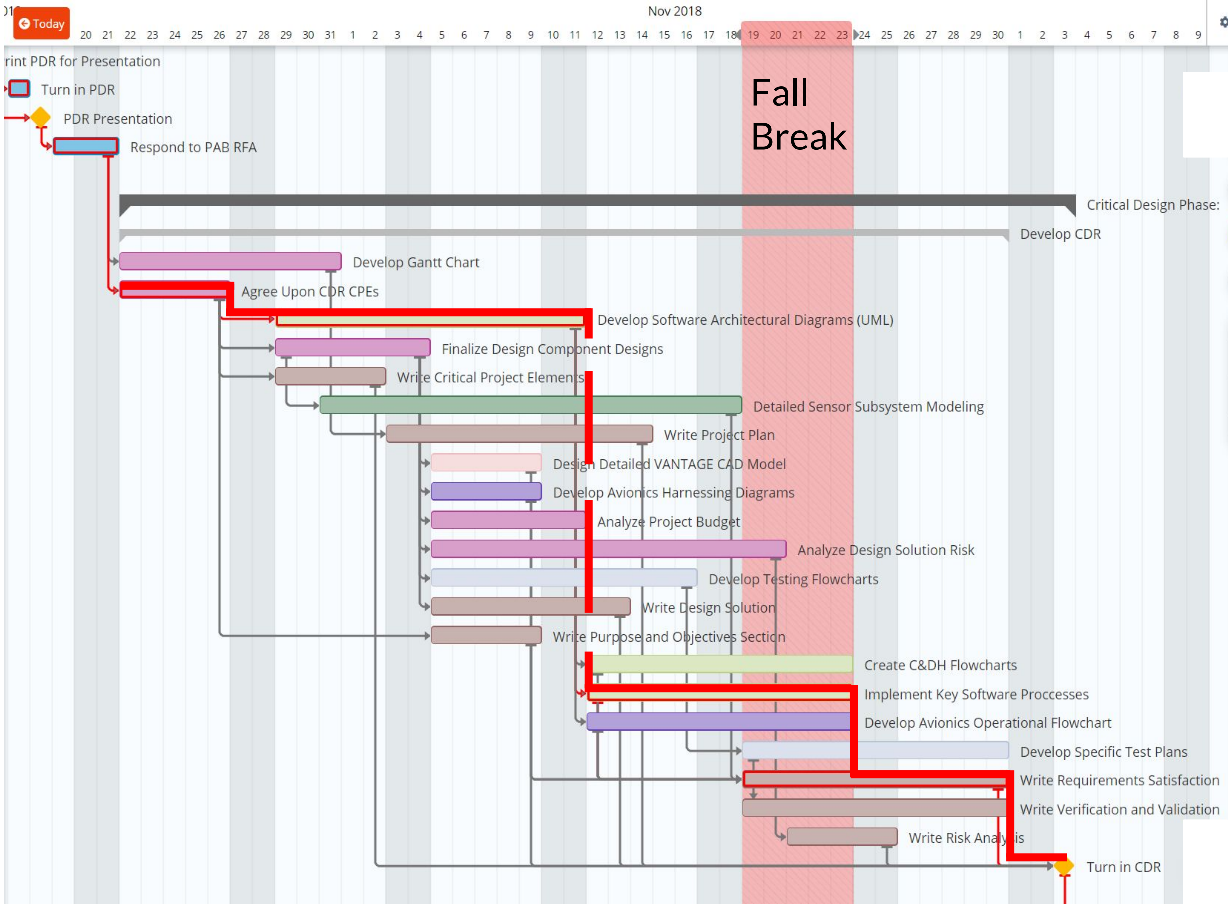
Subsystems:	Structures	Sensors	Software	Electronics	Testing	Total
Total Cost:	$102.44	$2,660.00	$0.00	$769.28	$284.64	$3,713.92

Base Plate	1	$14.74
Left Plate	1	$14.74
Right Plate	1	$14.74
Top Plate	1	$14.74
Front Plate	1	$8.04
Back Plate	1	$8.04
18-8 Stainless Steel Socket Head Screw 1/4"-28 Thread Size, 5/8"	40	$10.72
18-8 Stainless Steel Helical Insert, 4-40 Right-Hand Thread, 0.168" Long	40	$16.68
O3D313 IR ToF Camera	1	$1,460.00
Canon EOS 80D DSLR	1	$1,200.00
MATLAB License	1	$0.00
Various external packages	1	$0.00
INTEL® NUC KIT NUC8I7BEH	1	$484.30
500GB Solid State Drive	1	$86.99
16 GB RAM	1	$99.99
DC/DC CONVERTER 24V 120W	1	$63.00
DC DC CONVERTER 3.3-24V 250W	1	$35.00

3in OD PVC Pipe for track	80	$139.28
3in PVC Elbow 90 degree	4	$10.64
Clear Cast Acrylic Sheet 24" x 48" x 1/8"	1	$44.74
Black spray paint	1	$3.97
Pololu 12V, 100:1 Gear Motor w/ 64 CPR Encoder	1	$39.95
Rubber Wheel 3" Diameter x 1-1/4" Wide, 270 lb. Capacity	4	$10.12
3in PVC Coupling Slip Inside	6	$35.94
14 Inch Long, 1/8 Inch Diameter, Steel Alloy, Arc Welding Electrode	1	$21.36
1 in. x 10 ft. Electric Metallic Tube (EMT) Conduit	6	$62.40
18-8 Stainless Steel Socket Head Screw M4 x 0.7 mm Thread, 20 mm Long	25	$8.24
Zinc-Plated Steel Hex Nut Medium-Strength, Class 8, M4 x 0.7 mm Thread	25	$2.35

Project Schedule

CDR Project Schedule



- **All Tasks have built in 10% approximate margin**
- **Software** is on the critical path
- Detailed **Sensor Analysis** is also expected to take a long time

LEGEND

- *Critical Path*
- SysE / PM / Finance
- Avionics
- Software
- Sensors
- Structures
- Testing
- Document Creation

Questions?

Table of Contents

Backup Table of Contents

Requirements Feasibility Table

Requirements Feasibility Table

Req.	Full Description	Link to Slide(s)
FR.1	The system shall support in-focus imaging of at most 6 mock 1U CubeSats at some range between 3 and 100 meters from the VANTAGE payload.	Supported by DRs
DR.1.1	The system shall use a camera to capture images of mock CubeSats.	DR.1.1
DR.1.2	Imaging subsystem shall have a FOV greater than 20°x20°.	DR.1.2
DR.1.3	Imaging subsystem shall produce at least 2 images of each mock CubeSat deployed by the test system.	DR.1.3
DR.1.4	Imaging subsystem shall produce in-focus images of mock CubeSats.	DR.1.4
FR.2	The system shall receive and interpret commands and the deployment manifest from a PC which simulates the NanoRacks use-case system.	Supported by DRs
DR.2.1	The electronics subsystem shall interface with the PC which simulates the NanoRacks use-case system via a USB2.0 Port for all data communication needs.	DR.2.1
DR.2.2	Software subsystem shall interpret a deployment manifest file sent from the PC which simulates the NanoRacks use-case system.	DR.2.2

Requirements Feasibility Table

Req.	Full Description	Link to Slide(s)
FR.3	The system shall accept power analogous to that which is available from the NanoRacks use-case system.	Supported by DRs
DR.3.1	The system shall operate with up to 120 VDC with a ripple voltage of 3Vpp and less than 5 A, which simulates the power available from the NanoRacks use-case system.	DR.3.1
DR.3.2	The system shall draw less than 520 Watts.	DR.3.2
DR.3.3	The electronics subsystem shall enter a low power mode when not performing any operations (i.e. before a final test has been started, after a final test has been completed and all post-processing and communications have completed).	DR.3.3
FR.4	The system shall integrate mechanically with a structural interface which simulates the NanoRacks use-case system.	Supported by DRs
DR.4.1	The system shall meet the structural requirements listed in NanoRacks Interface Control Documents.	DR.4.1
DR.4.2	The VANTAGE team shall build a structural interface that simulates the NanoRacks Deployer structural interface use-case system accurate up to 0.005 in.	DR.4.2

Requirements Feasibility Table

Req.	Full Description	Link to Slide(s)
FR.5	The system shall uniquely detect and track up to 6 mock 1U-3U CubeSats while they remain between 3 and 100 m of the VANTAGE payload.	Supported by DRs
DR.5.1	Sensor subsystem shall have a sensing FOV of at least 20°x20°.	DR 5.1
DR.5.2	The system shall detect whether a mock CubeSat is within its FOV 99% of the time while the mock cubesat remains between 3 and 100 m of the VANTAGE payload.	DR 5.2 Backup
FR.6	The system shall estimate the position and velocity vectors of CubeSats between a distance of 3 and 100 m.	Supported by DRs
DR.6.1	Software subsystem shall produce relative position vector estimates accurate up to 10 cm 1σ to a distance of 10 m, changing to an accuracy of at least a tenth of the range 1σ up to a distance of 100 m.	DR.6.1 Backup
DR.6.2	Software subsystem shall provide relative velocity vector estimates accurate up to 1 cm/s 1σ to a distance of 10 m, changing to an accuracy of 10 cm/s 1σ up to a distance of 100 m.	DR.6.2

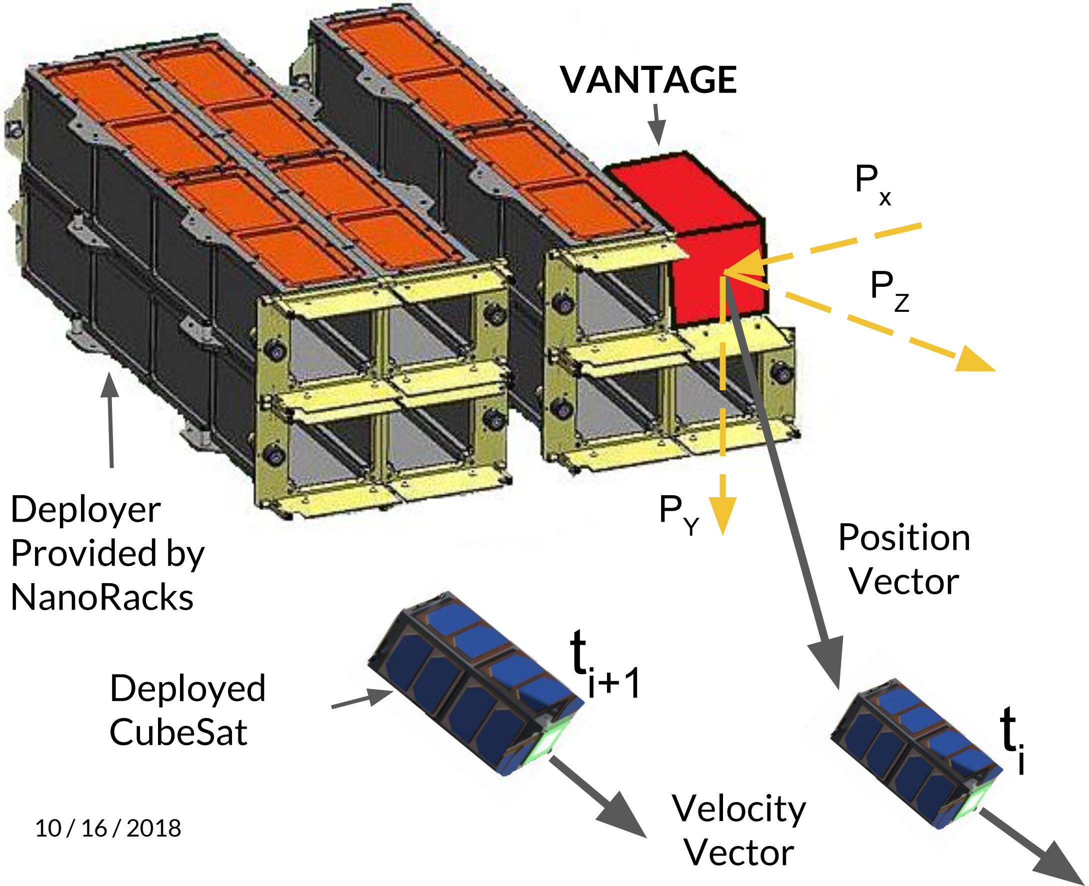
Requirements Feasibility Table

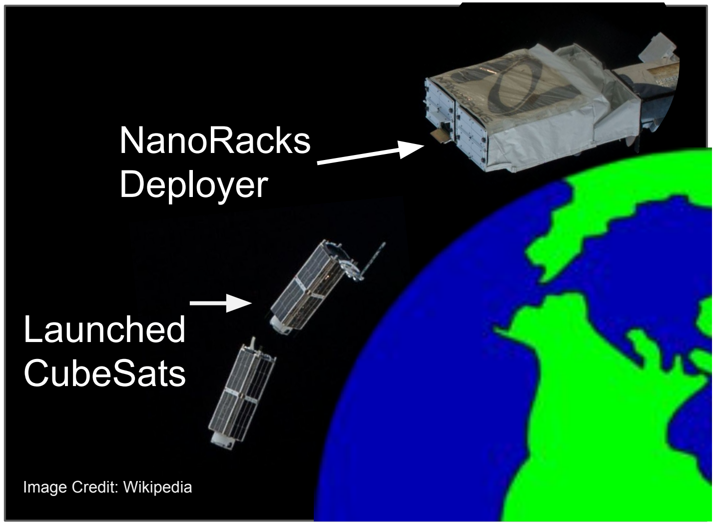
Req.	Full Description	Link to Slide(s)
FR.7	The system shall recognize off-nominal deployment cases, which shall include off-nominal relative initial velocities and off-nominal deployment times from the test system.	Supported by DRs
DR.7.1	Software subsystem shall maintain current time, synchronized with global time UTC, from the PC which simulates the NanoRacks use-case system with an accuracy of at least ±1 ms.	DR.7.1
DR.7.2	Software subsystem shall recognize if mock CubeSats exit the test system greater than 3 seconds before/after predicted with a tolerance of 0.5 seconds 3σ.	DR.7.2
DR.7.3	Software subsystem shall recognize if initial relative velocities of mock CubeSats are less than 0.5m/s or greater than 2.0m/s with a tolerance of 0.1m/s 3σ.	DR.7.3
FR.8	The system shall report position/velocity vector measurements, off-nominal deployment cases, and raw images from the current mock deployment to the PC which simulates the NanoRacks use-case system before the next NanoRacks CubeSat Deployer (NRCSD) tube deployment would normally occur in the use-case.	Supported by DRs
DR.8.1	The electronics subsystem shall transmit all relative position and velocity vector estimates and uncertainties, as well as mock CubeSat deployment images back to the PC which simulates the NanoRacks use-case system within 15 minutes of final mock CubeSat deployment.	DR.8.1 Backup
DR.8.2	The system shall store all images, sensor data, and estimates within an onboard data storage device.	DR.8.2 Backup

Backup Slides

Backup Project Description

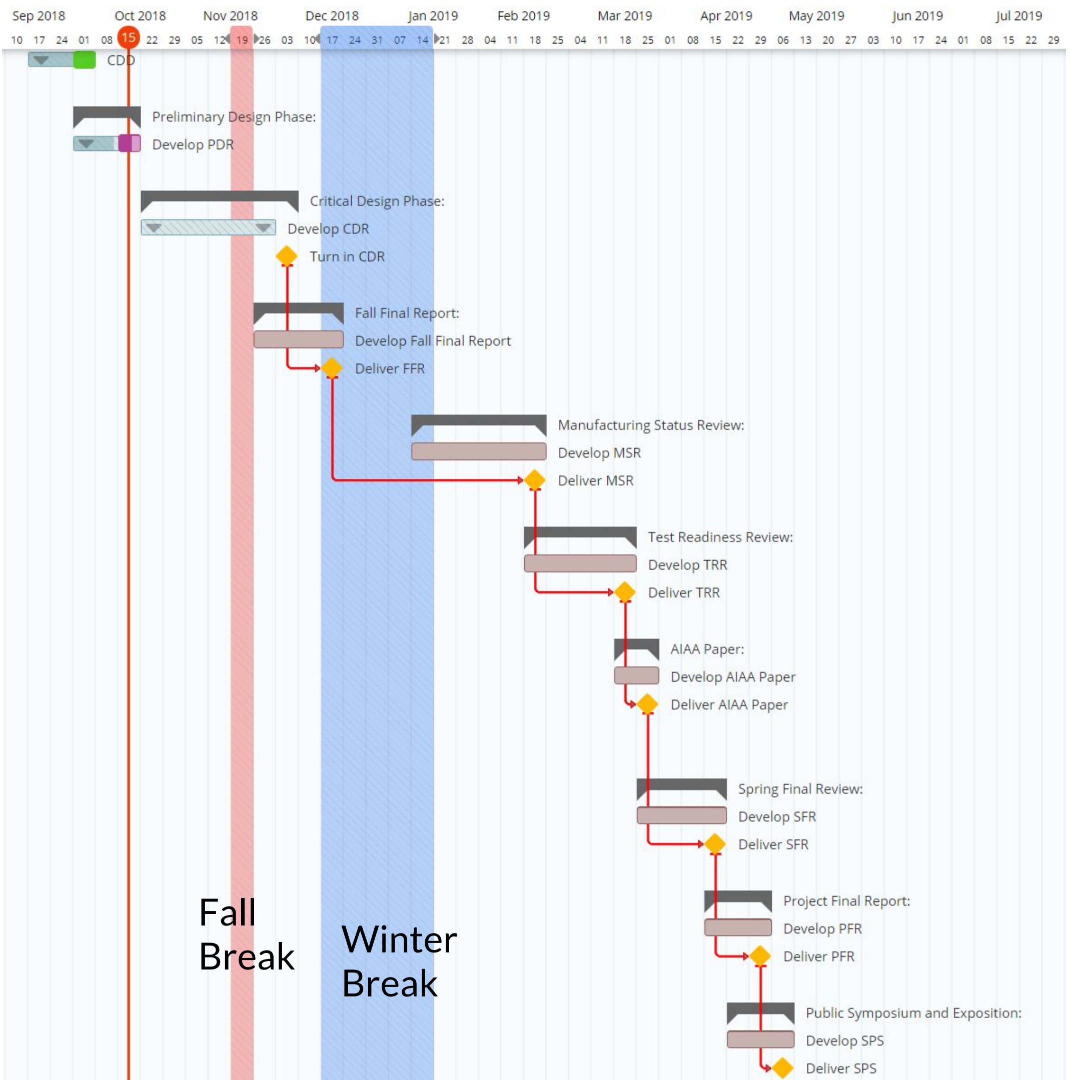
Vision for NanoRacks Interface





Backup Budget

Subsystems:	Structure	Sensors	Software	Electronics	Testing	Total	
Total Cost:	$102.44	$2,660.00	$0.00	$769.28	$284.64	$3,713.92	
Verified By:							
Item Description	**Quantity**	**Quantity per Pl**	**Pkg Req**	**Cost per Pkg**	**Total Cost**	**Extra Notes**	**Link**
Base Plate	1	1	1	$14.74	$14.74		https://www.mcmaster.com/8975k561
Left Plate	1	1	1	$14.74	$14.74		https://www.mcmaster.com/8975k561
Right Plate	1	1	1	$14.74	$14.74		https://www.mcmaster.com/8975k561
Top Plate	1	1	1	$14.74	$14.74		https://www.mcmaster.com/8975k561
Front Plate	1	1	1	$8.04	$8.04		https://www.mcmaster.com/8975k436
Back Plate	1	1	1	$8.04	$8.04		https://www.mcmaster.com/8975k437
18-8 Stainless Steel Socket Head Screw 1/4"-28 Thread Size, 5/8"	40	50	1	$10.72	$10.72		https://www.mcmaster.com/92196a319
18-8 Stainless Steel Helical Insert, 4-40 Right-Hand Thread, 0.168" Long	40	10	4	$4.17	$16.68	Expected to need about 40. We may need slightly more	https://www.mcmaster.com/91732a285
O3D313 IR ToF Camera	1	1	1	$1,460.00	$1,460.00		https://www.ifm.com/us/en/product/O3D313
Canon EOS 80D DSLR	1	1	1	$1,200.00	$1,200.00	Expected to need different lense cost slightly more	
MATLAB License	1	1	1	$0.00	$0.00		https://oit.colorado.edu/software-hardware/software-downloads-and-licensing/matlab
Various external packages	1	1	1	$0.00	$0.00		https://oit.colorado.edu/software-hardware/software-downloads-and-licensing/matlab
INTEL® NUC KIT NUC8I7BEH	1	1	1	$484.30	$484.30		https://www.intel.com/content/www/us/en/products/boards-kits/nuc/kits/nuc8i7beh.html
500GB Solid State Drive	1	1	1	$86.99	$86.99		https://www.amazon.com/Samsung-500GB-Internal-MZ-76E500B-AM/dp/B0781Z7Y3S/ref=sr_1_3/141-8500920-922514
16 GB RAM	1	1	1	$99.99	$99.99		https://www.newegg.com/Product/Product.aspx?Item=N82E16820231489&ignorebbr=1&nm_mc=KNC-GoogleAdwords-P
DC/DC CONVERTER 24V 120W	1	1	1	$63.00	$63.00		https://www.digikey.com/products/en?keywords=1866-5036-nd
DC DC CONVERTER 3.3-24V 250W	1	1	1	$35.00	$35.00		https://www.digikey.com/product-detail/en/tdk-lambda-americas-inc/I6A24014A033V-002-R/285-2857-ND/5604255
3in OD PVC Pipe for track	80	10	8	$17.41	$139.28		https://www.homedepot.com/p/JM-eagle-3-in-x-10-ft-PVC-Schedule-40-DWV-Plain-End-Pipe-531095/100161921
3in PVC Elbow 90 degree	4	1	4	$2.66	$10.64		https://www.homedepot.com/p/3-in-PVC-DWV-90-Degree-Hub-x-Hub-Elbow-C4807HD3/100346018
Clear Cast Acrylic Sheet 24" x 48" x 1/8"	1	1	1	$44.74	$44.74		https://www.mcmaster.com/8560k262
Black spray paint	1	2	1	$3.97	$3.97		https://www.homedepot.com/p/Rust-Oleum-Painter-s-Touch-2X-12-oz-Semi-Gloss-Black-General-Purpose-Spray-Paint-2
Pololu 12V, 100:1 Gear Motor w/ 64 CPR Encoder	1	1	1	$39.95	$39.95		https://www.robotshop.com/en/pololu-12v-1001-gear-motor-64-cpr-encoder.html?gclid=EAIaIQobChMI68SRjruB3gIVhjpp
Rubber Wheel 3" Diameter x 1-1/4" Wide, 270 lb. Capacity	4	1	4	$2.53	$10.12		https://www.mcmaster.com/2337t13
3in PVC Coupling Slip Inside	6	1	6	$5.99	$35.94		https://www.acehardware.com/departments/plumbing/pipe-fittings/plastic-fittings/4512331?x429=true&utm_source=googl
14 Inch Long, 1/8 Inch Diameter, Steel Alloy, Arc Welding Electrode	1	1	1	$21.36	$21.36		https://www.mscdirect.com/browse/tnpla/59803999?cid=ppc-google-New+-+Welding+%26+Soldering+-+PLA_sqHmEEE
1 in. x 10 ft. Electric Metallic Tube (EMT) Conduit	6	1	6	$10.40	$62.40		https://www.homedepot.com/p/1-in-x-10-ft-Electric-Metallic-Tube-EMT-Conduit-101568/100400409?MERCH=REC-_-PIP
18-8 Stainless Steel Socket Head Screw M4 x 0.7 mm Thread, 20 mm Long	25	100	1	$8.24	$8.24		https://www.mcmaster.com/91292a121
Zinc-Plated Steel Hex Nut Medium-Strength, Class 8, M4 x 0.7 mm Thread	25	100	1	$2.35	$2.35		https://www.mcmaster.com/90591a255


Sep 2018
Oct 2018
Nov 2018
Dec 2018
Jan 2019
Feb 2019
Mar 2019
Apr 2019
May 2019
Jun 2019
Jul 2019
CDD
Preliminary Design Phase:
Develop PDR
Critical Design Phase:
Develop CDR
Turn in CDR
Fall Final Report:
Develop Fall Final Report
Deliver FFR
Manufacturing Status Review:
Develop MSR
Deliver MSR
Test Readiness Review:
Develop TRR
Deliver TRR
AIAA Paper:
Develop AIAA Paper
Deliver AIAA Paper
Spring Final Review:
Develop SFR
Deliver SFR
Project Final Report:
Develop PFR
Deliver PFR
Public Symposium and Exposition:
Develop SPS
Deliver SPS
Fall Break
Winter Break

Backup Software

Flowchart

Software Functional Flowchart

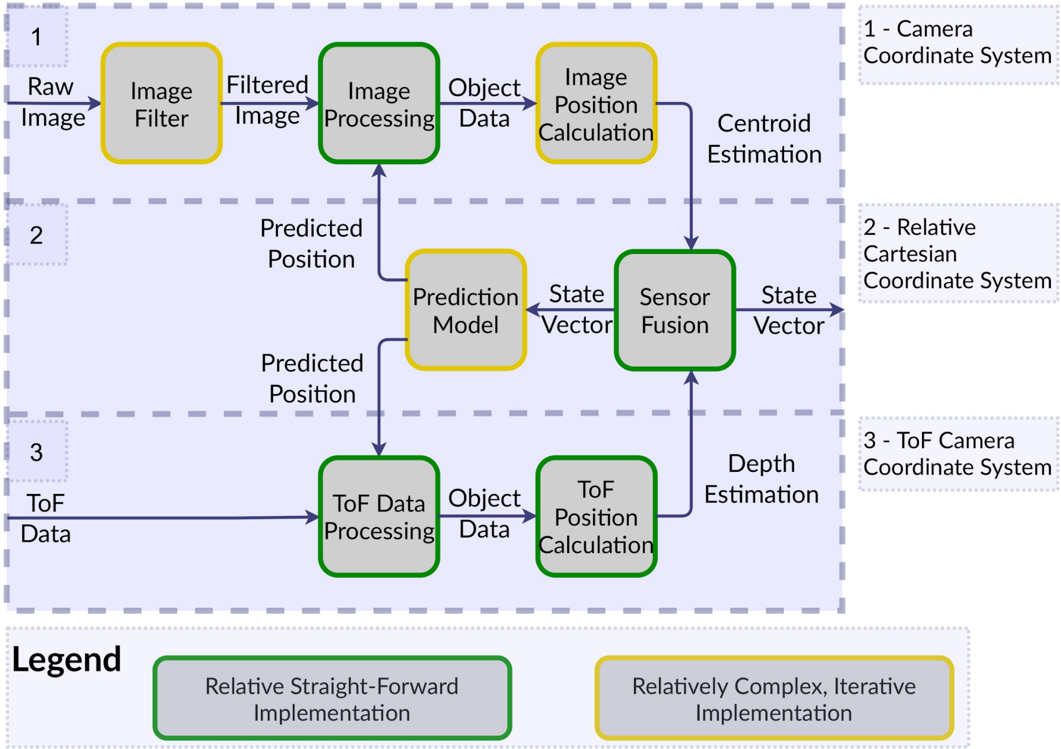


Image Filter
Input a raw image
Filter the image
Output filtered image

Image Processing
Input a filtered image
Detect image object in image
Isolate image object region
Extract image object features
Output image object features

Image Position Calculation
Input image object features
Calculate centroid position region
Output centroid position region
(Convert Optical to Cartesian)

Prediction Model
Input state vector
Predict Future Position region for next expected time step
Output predicted position region
(Convert cartesian to image)
(Convert cartesian to ToF)

ToF Processing
Input ToF data
Detect ToF object in ToF data
Isolate ToF object region
Extract ToF object features
Output ToF object features

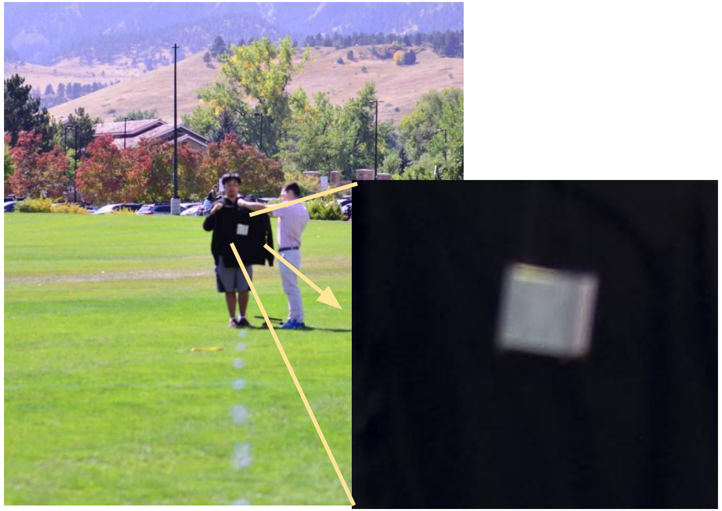
ToF Position Calculation
Input ToF object features
Calculate depth position region
Output Depth position region
(Convert Polar to Cartesian)

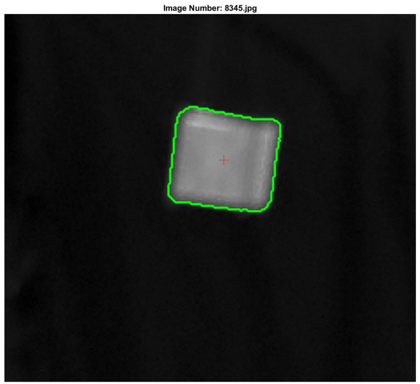
Sensor Fusion
Input Centroid and Depth position regions
Interpolate ToF Depth position regions over time
Synchronize relative time of image and ToF to same absolute time frame
Estimate Cartesian position
Estimate Cartesian velocity
Output state vector

Backup Object Recognition

Algorithm for the PDR

Object Recognition Algorithm





- Binarize image to define exact pixels as object border

- Trace exterior boundaries of objects
- Determine boundaries corresponding to object edge
- Count pixels within boundary to determine object properties

Binarization Filter

- Takes in a grayscale image
- Checks the shade of each pixel
- Compares each shade value to a threshold value
- Values above this ➝ 1
- Values below this ➝ 0
- Outputs logical matrix

Image Source: Mathworks Imbinarize documentation

Edge Detection Algorithm

- Takes in a binarized image
- Detects transitions from 0 to 1
- Marks adjacent transitions as edge
- Ignores transitions contained by complete edges
- Returns separate lists of complete edges as well as the corresponding body pixels

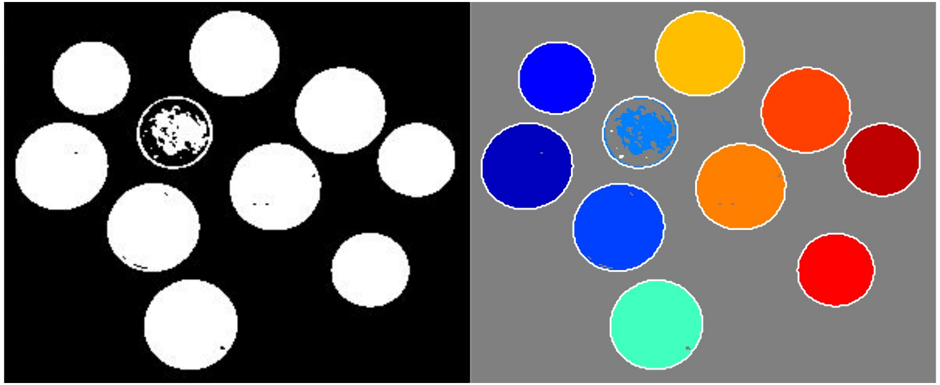
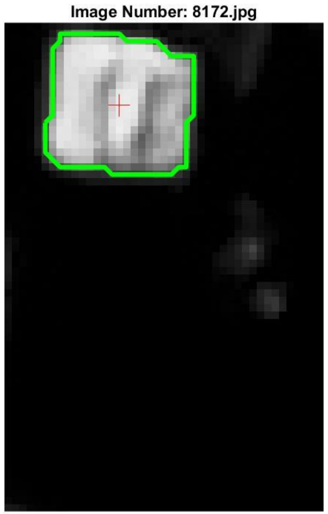


Image Source: Mathworks Imbinarize documentation

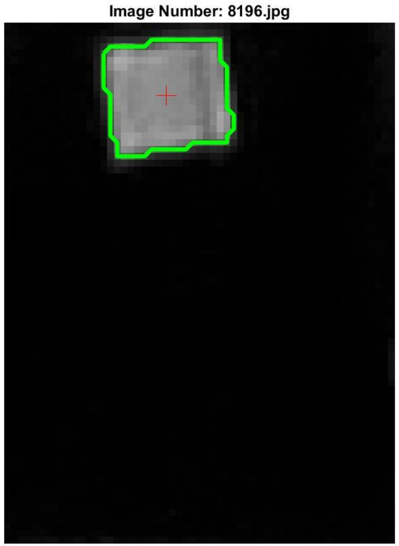
Backup Object Recognition

Detection of mock CubeSats in real images over the full range

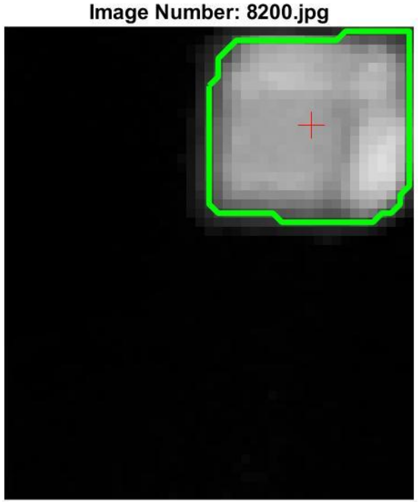
Full Range Object Recognition



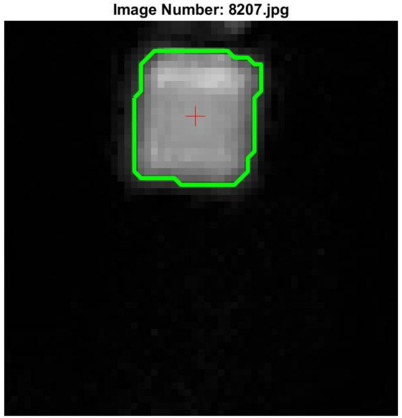
100 m



95 m



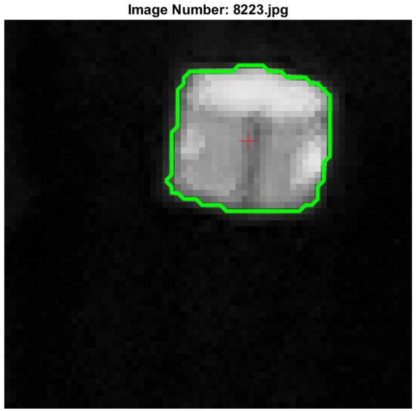
90 m

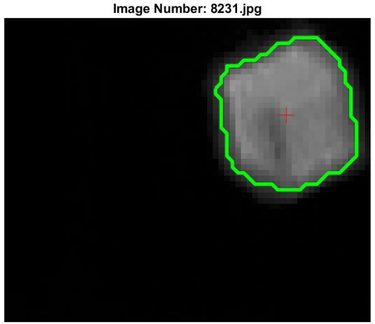


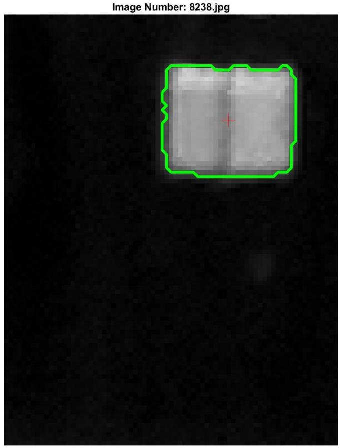
90 m

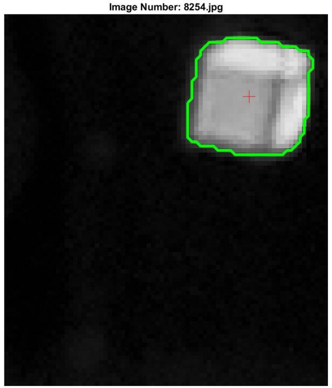
Nikon D800, 7360x4912, FOV 28.8°x19.5°, focal length 100 m

Full Range Object Recognition





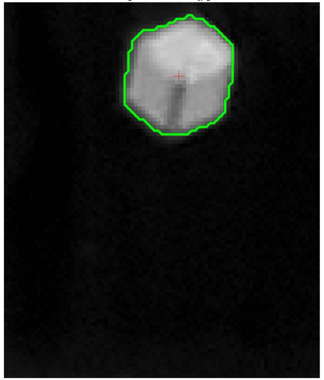


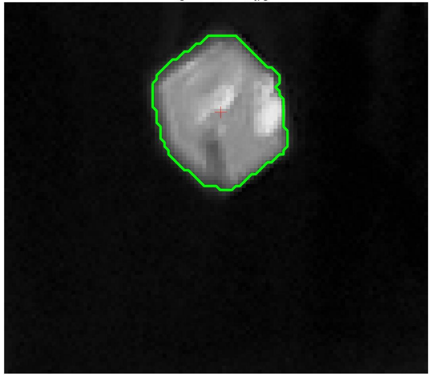


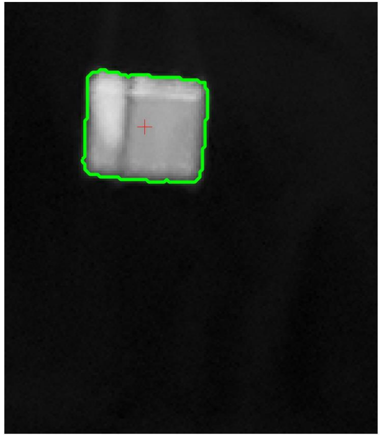
80 m 80 m 70 m 70 m

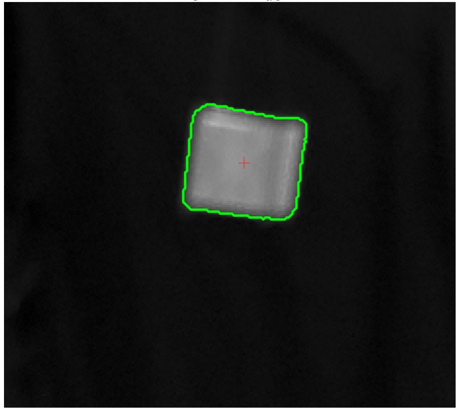
Nikon D800, 7360x4912, FOV 28.8°x19.5°, focal length 100 m

Full Range Object Recognition





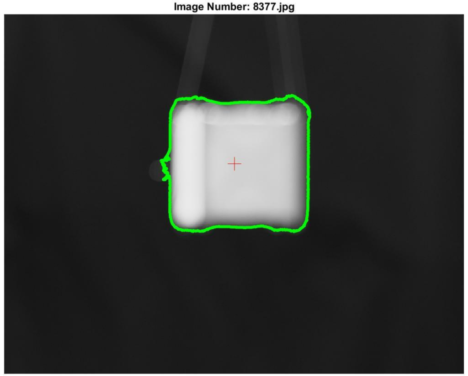


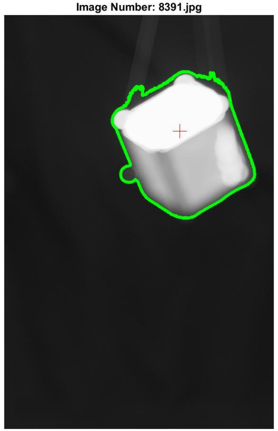


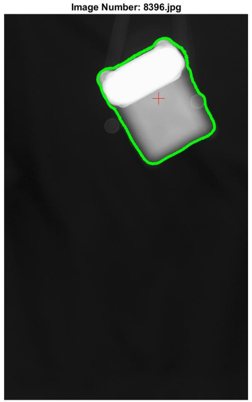
70 m | 60 m | 40 m | 30 m

Nikon D800, 7360x4912, FOV 28.8°x19.5°, focal length 100 m

Full Range Object Recognition







5 m 5 m 5 m

Nikon D800, 7360x4912, FOV 28.8°x19.5°, focal length 100 m

Backup Multi-object Tracking

Algorithm

CCAR

Multi-object Tracking Algorithm

VANTAGE

1. Perform image processing, binarization, and edge detection algorithm

2. Set a boundary pixel count threshold based on the largest boundary
   a. Assumption made here is that the largest boundary will always pertain to a CubeSat

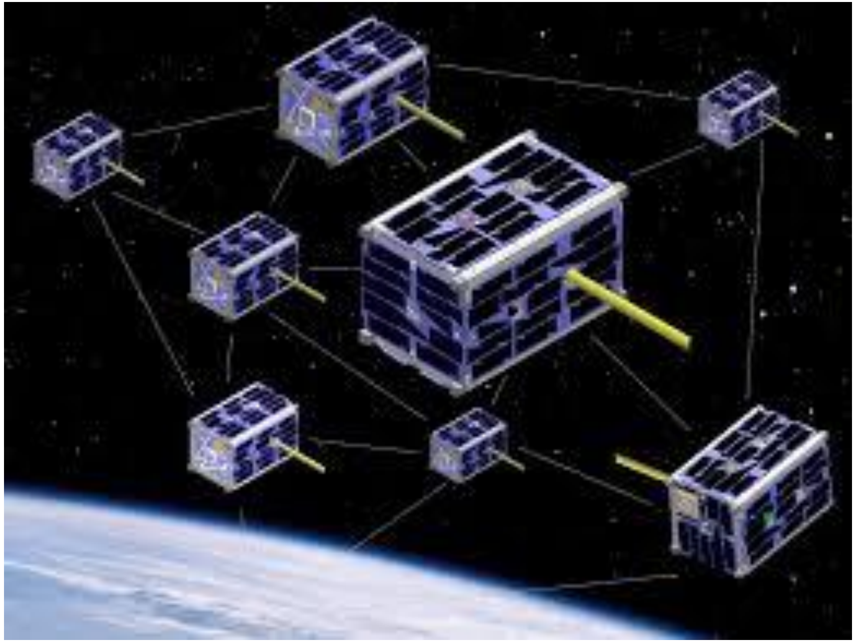
3. Iterate through each boundary, if the boundary size exceeds the pixel count threshold, consider that object as a CubeSat
   a. Assumption made here is that objects within the FOV will be primarily CubeSats, with small noise-related boundaries scattered throughout

4. Perform analysis on objects that pass the threshold check

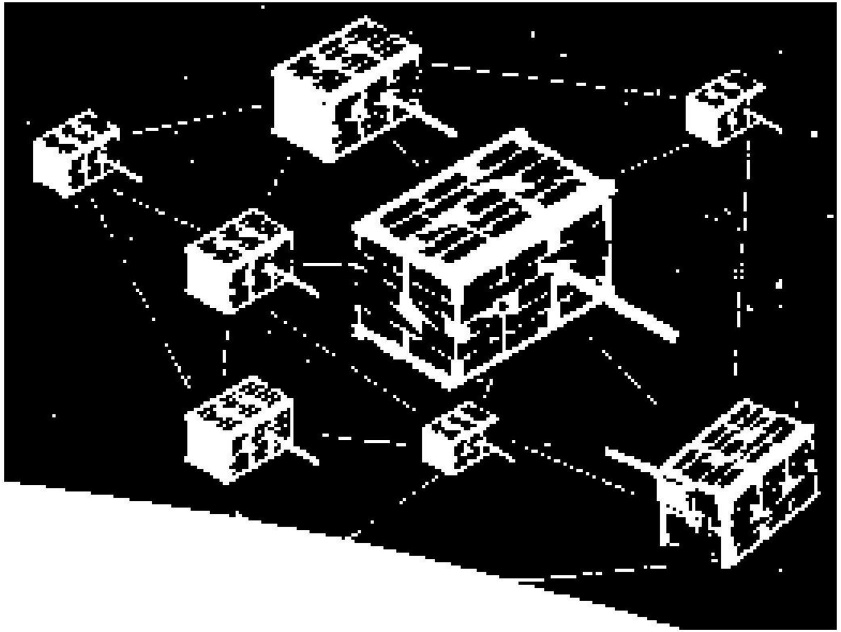
Backup Multi-object Tracking

Close-objects Identification

Close-object Identification



Petro, A., “Small Spacecraft Technology”

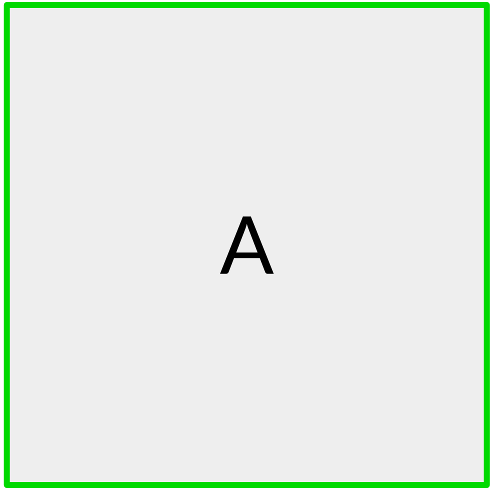


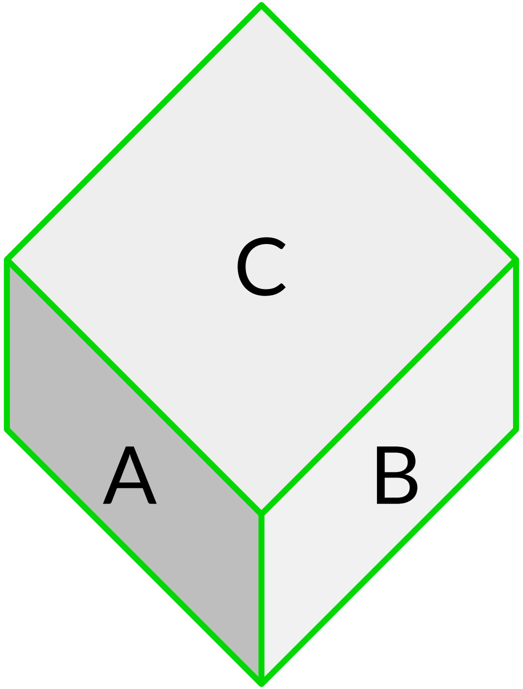
- Feasible with more development on edge detection

Backup Satellite Tumbling

Geometry Identification

Geometry Identification

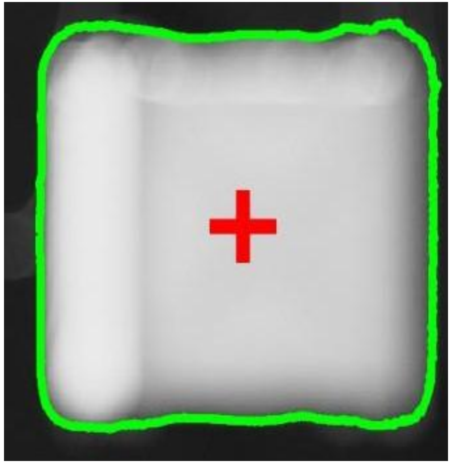


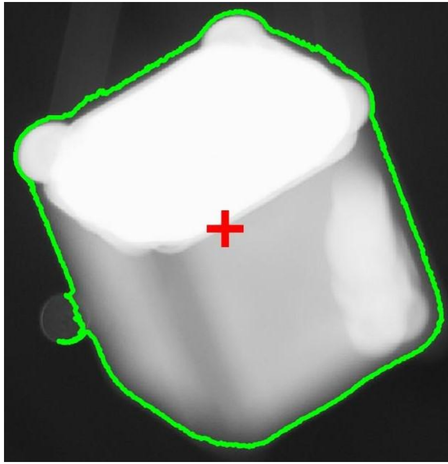


Geometry Identification

- Borders will have clear geometric distinctions in straight-on vs. tumbling images
  - Cube edges within border may be inferred based on outside border angle

- Visual magnitude across the image will vary grayscale values for each visible side
  - With further grayscale processing, edges within border may be detected based on sharp gradient between cube sides





Backup Software

Satisfying Requirements

Feasibility of DR 2.2

Req.	Full Description
DR.2.2	Software subsystem shall interpret a deployment manifest file sent from the PC which simulates the NanoRacks use-case system.

Feasible? Yes:

- The team possesses a great deal of experience in parsing text files with complex formats.
- NanoRacks has informed the team that VANTAGE will largely be able to define the format of this manifest text file, further making the requirement feasible.

Feasibility of DR 7.1

Req.	Full Description
DR.7.1	Software subsystem shall maintain current time, synchronized with global time UTC, from the PC which simulates the NanoRacks use-case system with an accuracy of at least ±1 ms.

Feasible? Yes:

- Team PC will be synchronized to UTC over the internet and used as the baseline time, since in the use-case the NR deployer time will be treated as exact
- The PC will be connected to the VANTAGE NUC over USB 2.0, which can be used to synchronize the NUC internal clock with the PC's time
- The NUC processor will be either an Intel I5 or I7, whose clocks do not lose 1 ms over a 90 minute period (maximum full test duration)

Feasibility of DR 7.2 and 7.3

- **DR 7.2 Feasible? Yes:**
  - Time before launch, $t = \frac{r_z}{v_z}$ for r_z, v_z at the same point, so $\delta t = t\left(\frac{\delta r_z}{|r_z|} + \frac{\delta v_z}{|v_z|}\right)$
  - Ex (with maximum allowable errors):

t (s)	r_z (m)	v_z (m/s)	δr_z (m)	δv_z (m/s)	δt (s)
5	10	2	0.1	0.01	0.06 < 0.5

  - If calculated launch time (±0.5 sec 3σ) is greater than 3 seconds off of predicted launch time, it is off-nominal as defined by team requirements.

- **DR 7.3 Feasible? Yes:**
  - If calculated mock CubeSat speed is less than 0.5 m/s or greater than 2.0 m/s, it is off-nominal as defined by NanoRacks CubeSat ICD.

Req.	Summary
DR 7.2	Software shall recognize if mock CubeSats exit test system at abnormal time (with a tolerance of 0.5 seconds 3σ)
DR 7.3	Software shall recognize if mock CubeSats exit test system at abnormal velocity (within a tolerance of velocity accuracy requirements: DR 6.2)

Backup Software

Miscellaneous

Software Trade Study

Table 4. Programming Languages Trade Study

	Weight	Python	C++	C	MATLAB
Quality and Availability of Packages/Libraries	55%	1	1	1	1
Implementation Difficulty (Learning, Manhours)	30%	2	2	3	1
Speed/Runtime	15%	3	3	3	2
Total/Result	100%	1.6	1.6	1.9	1.15

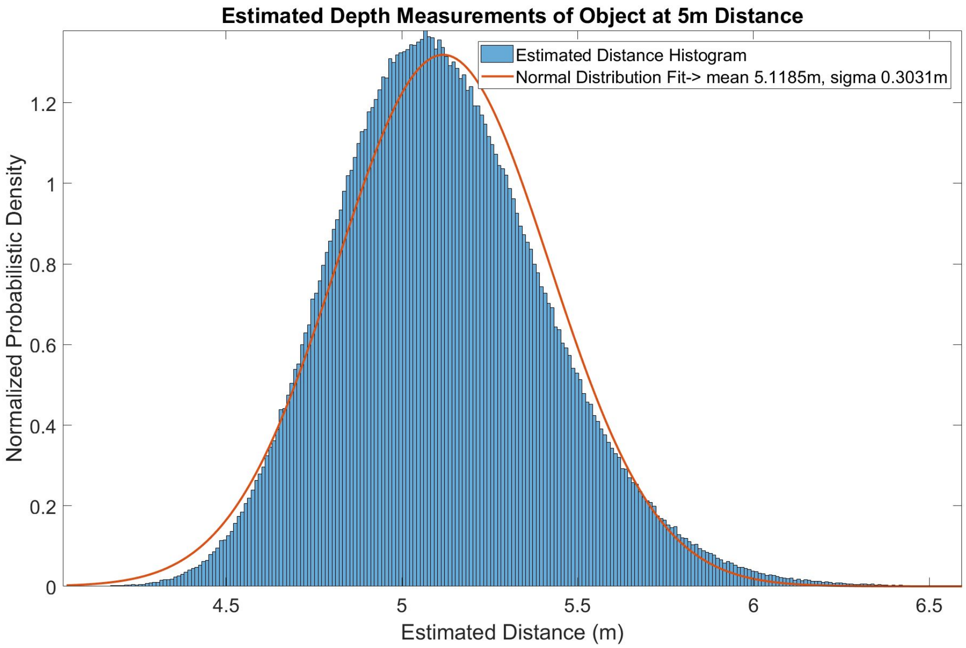
Calculating Uncertainty for Camera Estimation

Using the field test images, we found the general region of pixels that the mock Cubesat edge could actually exist in.

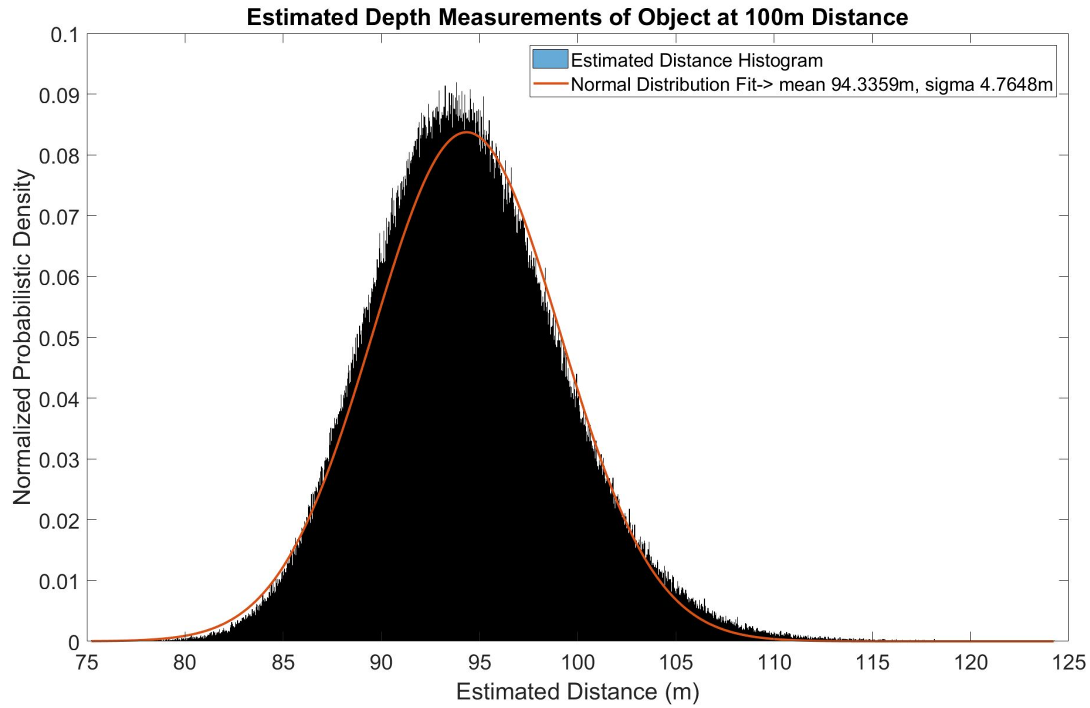
This region is assumed to be caused by the lack of focus the camera has for the mock Cubesat in the images. These values were manually extracted, to demonstrate a rough approximation of the Camera's limitation, before any software error is introduced.

Assuming that this region is normally distributed, with a 1 σ being half the maximum distance of the blurry region, we propagate the pixel edge uncertainty outwards to derive depth estimation uncertainty.

Using a Monte Carlo simulation where the variance comes from the uncertainty in the location of the edges of the mock Cubesat, we simulate 10^6 trials and assume a normal distribution for the result.



Calculating Uncertainty for Camera Estimation



We used a pinhole camera first order approximation model to convert the image pixels into a depth estimation model.

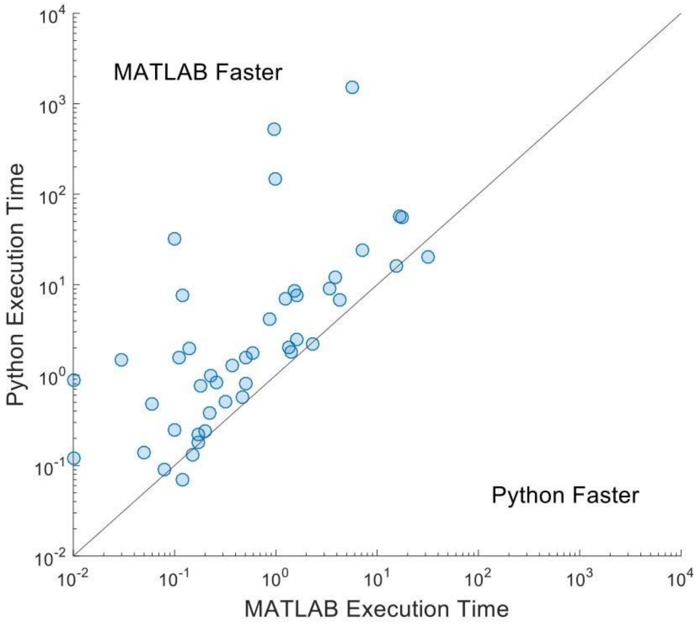
At 100m, using these assumptions, the mean of the simulation was found to be around 94m, with a standard deviation of around 5m.

Given that the data used to calculate these rough approximations were ideal images with a 10cm square pointing directly to the camera lens, these results were treated as a best case camera uncertainty bound.

These results lead us to look into using another sensor for depth measurements.

MATLAB vs. Python

MATLAB Performance over Python	Average	Best
Engineering	3.2x	64x
Statistics	2.7x	52x
Graphics	31x	540x
Nested for loops	64x	64x



Backup Structures

Structure Requirements (DR 4.1 and DR 4.2)

Req.	Description
DR.4.1-STR	The system shall meet the structural requirements listed in NanoRacks Interface Control Documents.
DR.4.2-STR	The VANTAGE team shall build a structural interface that simulates the NanoRacks Deployer structural interface use-case system accurate up to 0.005 in.

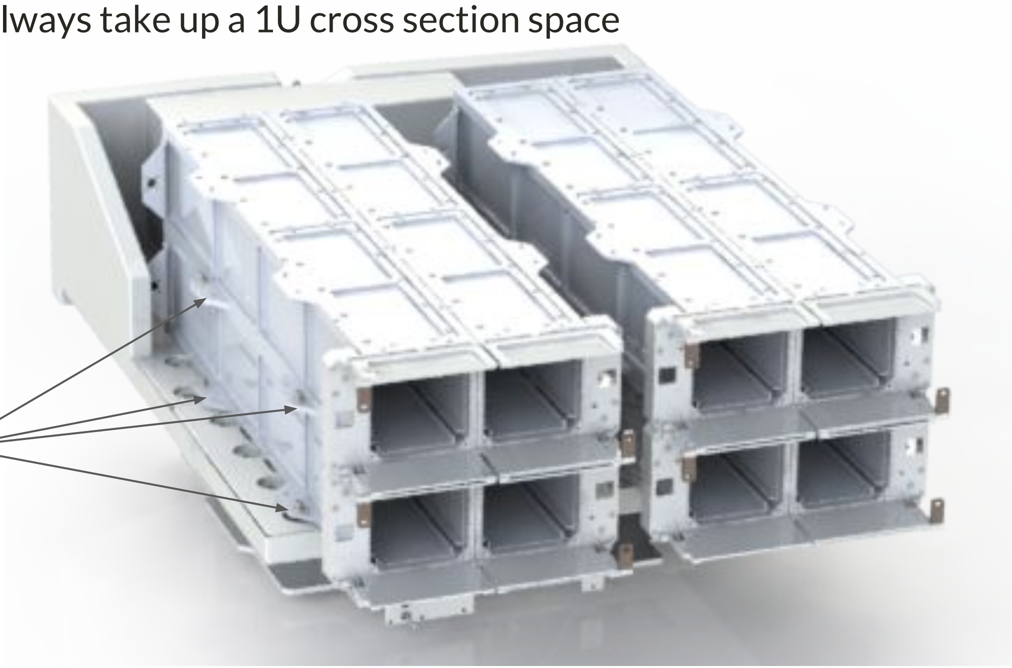
- No CPEs associated with the VANTAGE structure
- Considered non-critical for the project
  - Does not serve a critical purpose
  - Primary level of success does is a flat-sat system demonstration so no hardware integration needed
- Feasibility? YES
  - Similar requirements designed for and met on MAXWELL and CUE3 projects
  - Plenty of contact with NR to be able to confirm interface by CDR

VANTAGE Structure Overview

- Traded three interface options: Internal w/ Payloads, Internal Alone, and External
    - External configuration settled on based on trade study conducted
- External configuration replaces a single NRCSD tube in the NR deployer assembly
    - Configuration can be used in NR launch cases with ≤ 42U of payloads
        - Takes one 6U payload tube out of the NR deployer assembly
        - Approximately 50% of launches based on conversation with NR
- External configuration uses same mounting scheme as the NRCSD
    - Based on CAD of the NR deployment assembly this is a single bolt interface
    - Held in place by ¼”*28 bolt and fits snugly against other NRCSDs
- External configuration needs to include interface for NR MLI blanket
    - A single ¼”-28 threaded hole will need to be positioned to emulate current interface on the NRCSD

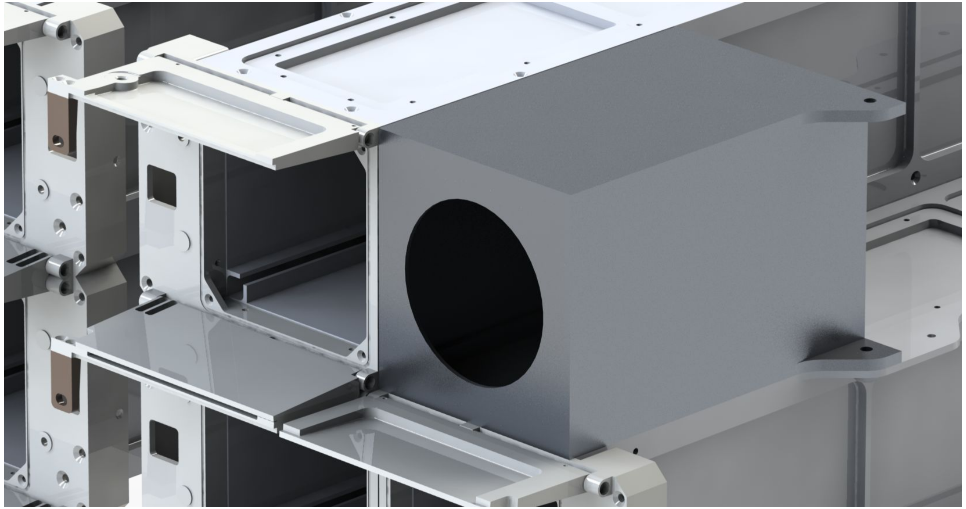
NR Deployment Assembly

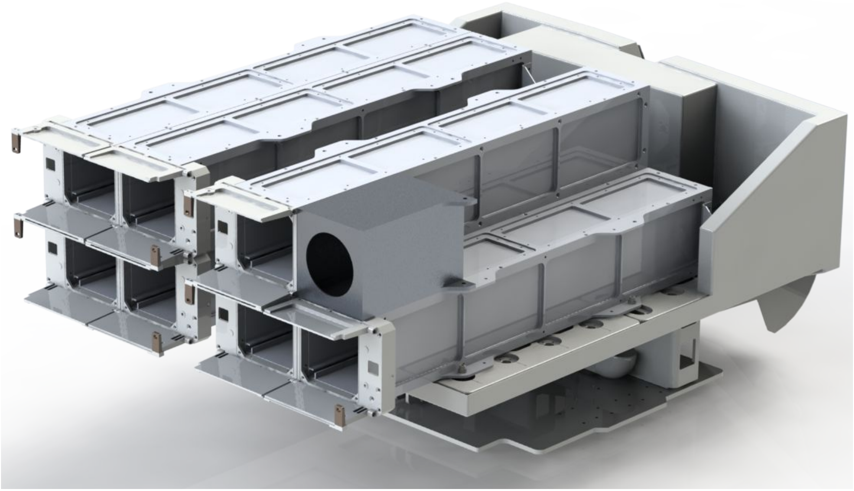
- Exists in multiple configurations
  - 8x1U; 6x1U+1x2U; 4x1U+2x2U; 2x1U+3x2U; 4x2U
- VANTAGE will always take up a 1U cross section space



NR NRCSD
Mounting Points

VANTAGE CAD





- Feasible? Yes
  - Interfacing is trivial
  - Will be able to identify sizes required of space ready components that exist or need to be developed

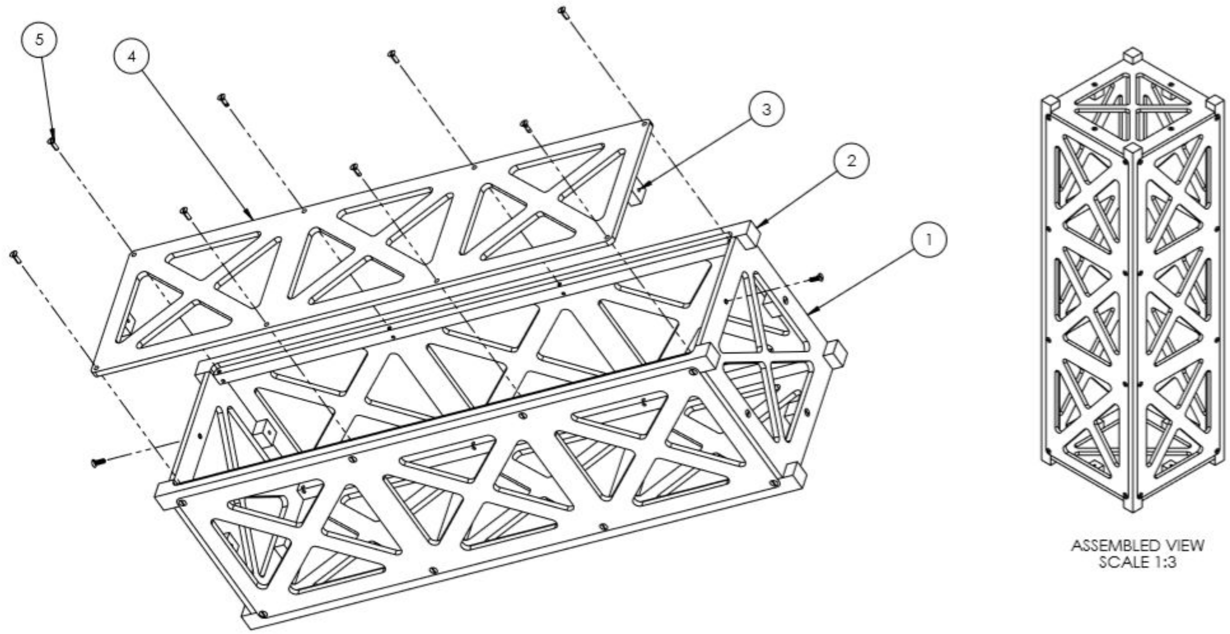
Structures Trade Study

Table 13. Structural Interface Trade Study

	Weight	Inside NRCSD Behind CubeSats	Inside NRCSD Alone	External to NRCSD
Algorithm Implications	60%	4	3	3
Development Time	20%	3	5	5
Cost	10%	3	3	4
Available Volume	5%	5	3	1
Maximum Tolerance	5%	5	5	1
Total/Result	100%	3.80	3.50	3.30

NOTES:
ANCHORS ARE SECURED WITH STAKING

REVISIONS			
REV.	DESCRIPTION	DATE	APPROVED
A	3U ASSEMBLY - INITIAL RELEASE	10/6/2018	10/6/2018



ASSEMBLED VIEW
SCALE 1:3

BOM Table			
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	1U Face - Open		2
2	3U Rail		4
3	Anchor		8
4	Side - Open		4
5	91781A078		40

VANTAGE

UNIVERSITY OF COLORADO
1111 ENGINEERING DRIVE
BOULDER, CO 80309-0427

Tolerances Unless Noted: X.X ±.05, X.XX ±.01, X.XXX ±.005, ANGLES ±0°30'
Units: INCHES

INTERPRET DRAWING PER ASME Y14.5M-1994.
MACHINE ALL SURFACES TO A 63 MICROINCH FINISH OR BETTER.
FILLETS .015 MAX .003 MIN.
BREAK ALL EDGES.

DESCRIPTION: 3U ASSEMBLY
MATERIAL: ACRYLIC & Al 6061

PART NUMBER	REV	SCALE	SHEET
X	A	1:2	1 OF 1

ENGINEER: ABOAF
DRAWN BY: ABOAF
APPROVED: ABOAF

NOTES:
ANCHORS ARE SECURED WITH STAKING

REVISIONS			
REV.	DESCRIPTION	DATE	APPROVED
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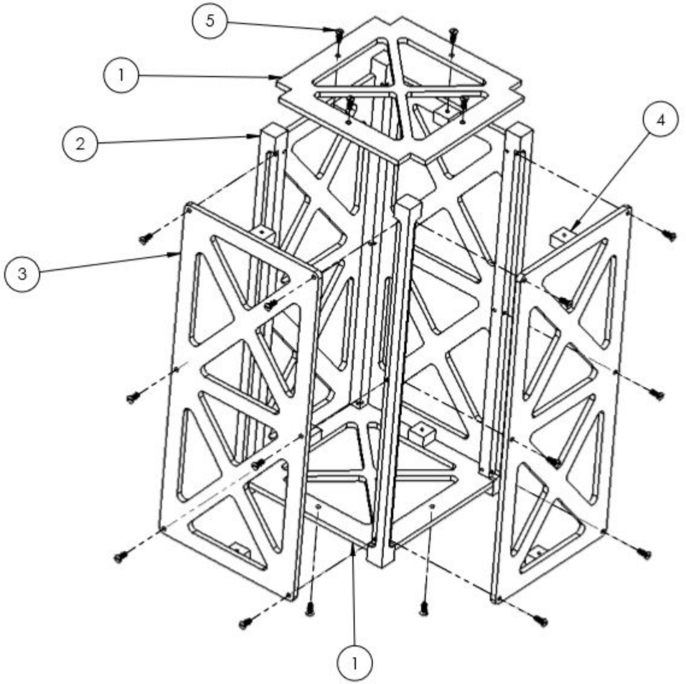

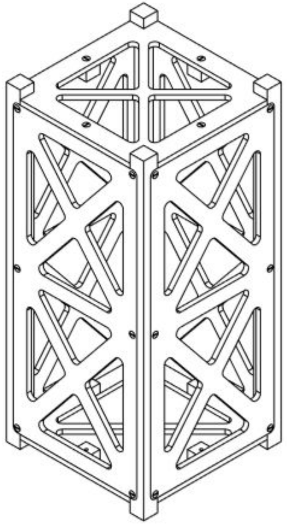

ASSEMBLED VIEW

BOM Table			
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	1U Face - Open		2
2	2U Rail		4
3	Side - Open		4
4	Anchor		8
5	91781A078		32

VANTAGE

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1111 ENGINEERING DRIVE
BOULDER, CO 80309-0427

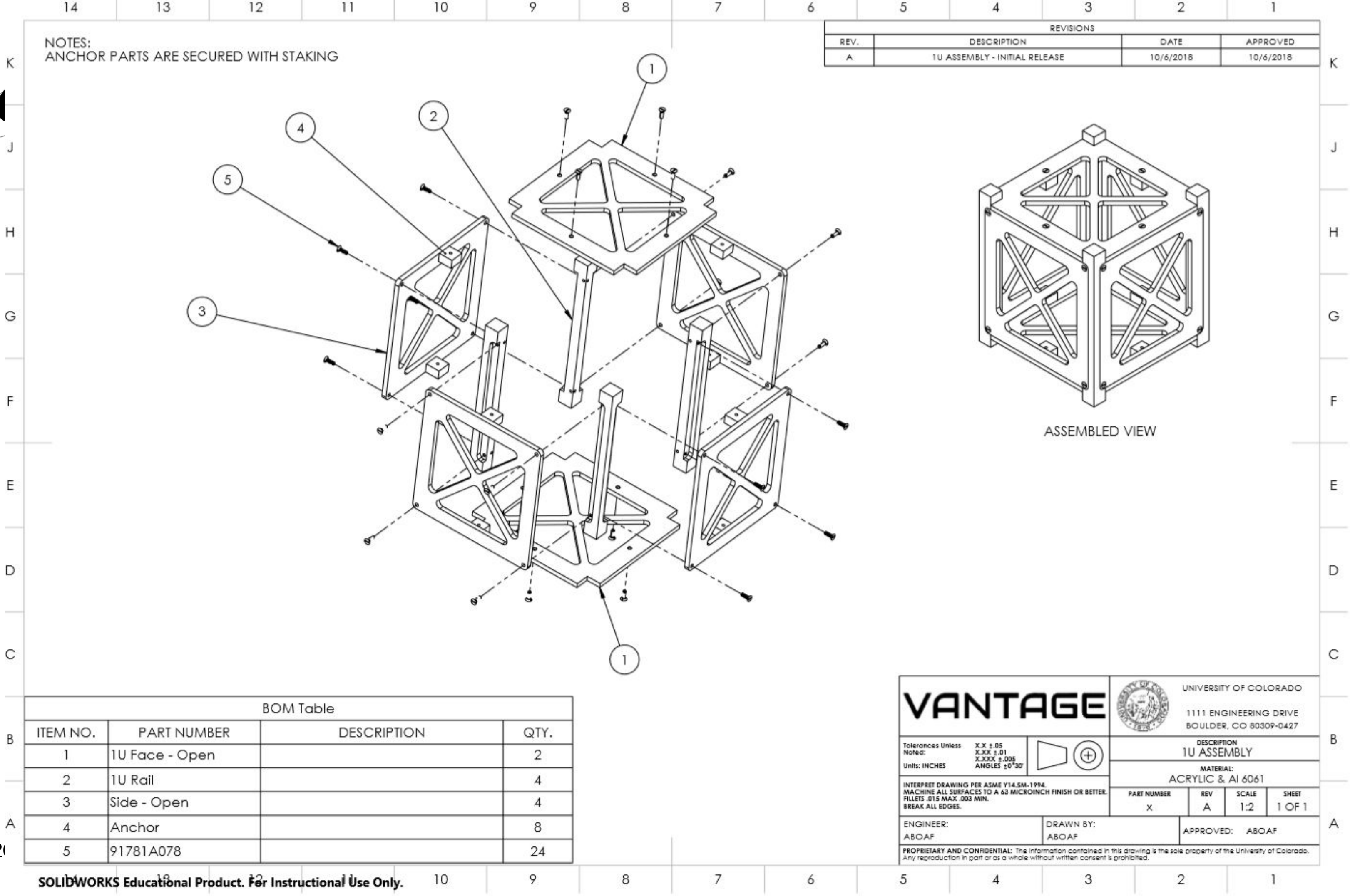
Tolerances Unless Noted: X.X ±.05 X.XX ±.01 X.XXX ±.005
Units: INCHES ANGLES ±0°30'

INTERPRET DRAWING PER ASME Y14.5M-1994.
MACHINE ALL SURFACES TO A 63 MICROINCH FINISH OR BETTER.
FILLETS .015 MAX .003 MIN.
BREAK ALL EDGES.

DESCRIPTION: 2U ASSEMBLY
MATERIAL: ACRYLIC & Al 6061

PART NUMBER	REV	SCALE	SHEET
x	A	1:2	1 OF 1

ENGINEER: ABOAF
DRAWN BY: ABOAF
APPROVED: ABOAF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REVISIONS
REV. | DESCRIPTION | DATE | APPROVED
A | 1U ASSEMBLY - INITIAL RELEASE | 10/6/2018 | 10/6/2018
ASSEMBLED VIEW
BOM Table
ITEM NO. | PART NUMBER | DESCRIPTION | QTY.
1 | 1U Face - Open | | 2
2 | 1U Rail | | 4
3 | Side - Open | | 4
4 | Anchor | | 8
5 | 91781A078 | | 24
VANTAGE
UNIVERSITY OF COLORADO
1111 ENGINEERING DRIVE
BOULDER, CO 80309-0427
Tolerances Unless Noted: X.X ±.05 X.XX ±.01 X.XXX ±.005 ANGLES ±0°30'
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BREAK ALL EDGES.
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MATERIAL:
ACRYLIC & Al 6061
PART NUMBER x
REV A
SCALE 1:2
SHEET 1 OF 1
ENGINEER: ABOAF
DRAWN BY: ABOAF
APPROVED: ABOAF
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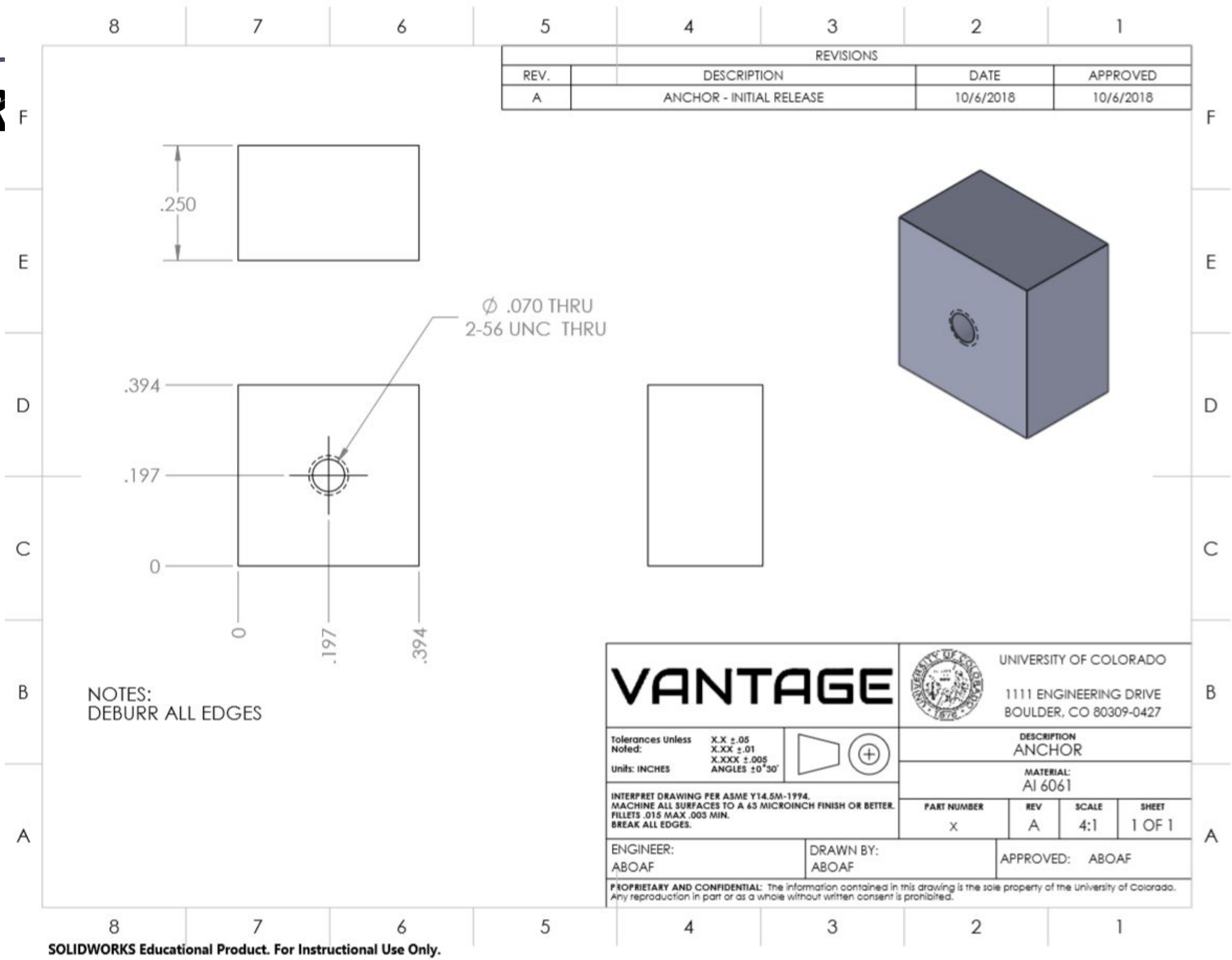
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UNIVERSITY OF COLORADO
1111 ENGINEERING DRIVE
BOULDER, CO 80309-0427
Tolerances Unless Noted:
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SCALE
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SHEET
1 OF 1
ENGINEER:
ABOAF
DRAWN BY:
ABOAF
APPROVED: ABOAF
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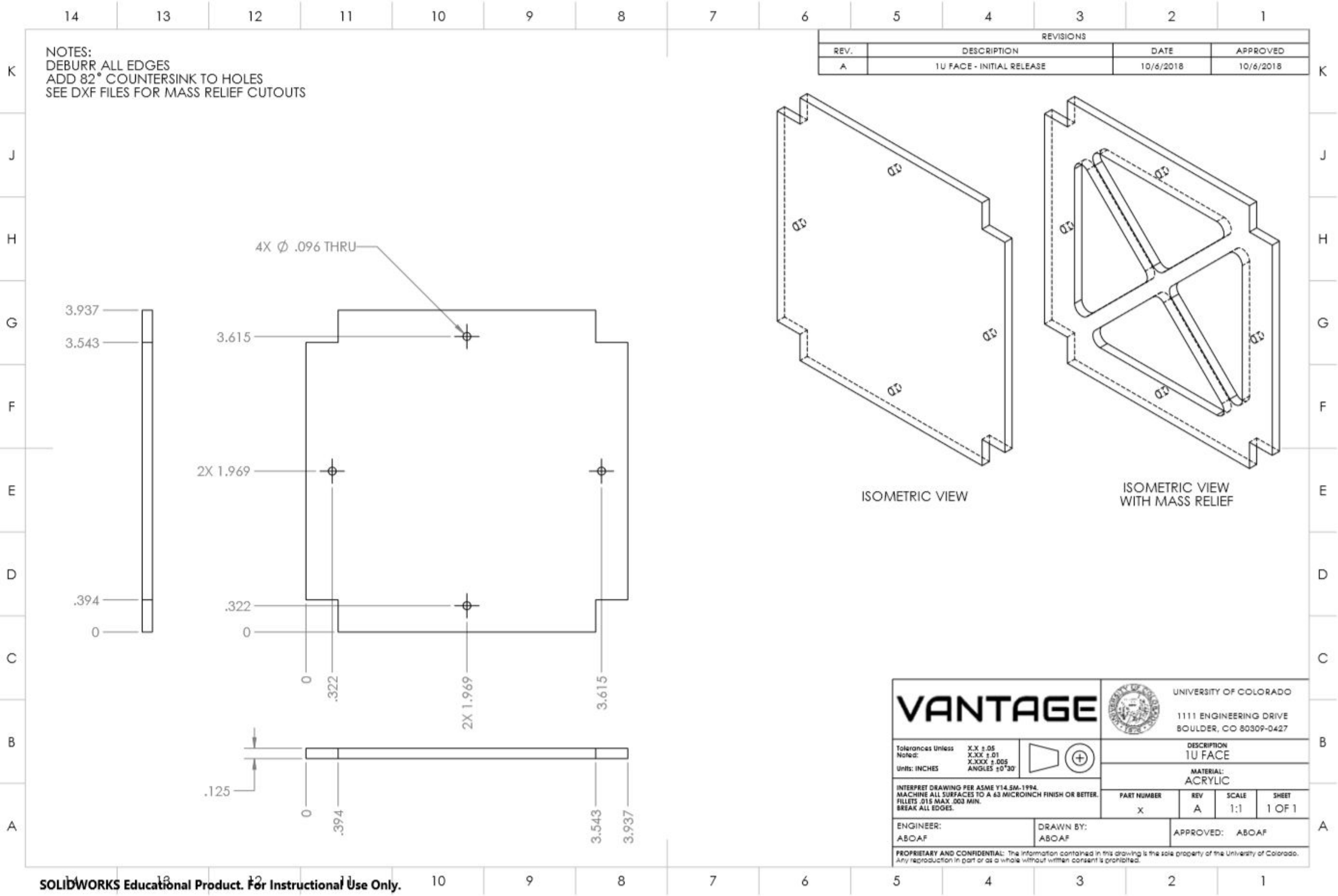
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ADD 82° COUNTERSINK TO HOLES
SEE DXF FILES FOR MASS RELIEF CUTOUTS
REVISIONS
REV.
DESCRIPTION
DATE
APPROVED
A
1U FACE - INITIAL RELEASE
10/6/2018
10/6/2018
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3.543
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3.615
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3.937
ISOMETRIC VIEW
ISOMETRIC VIEW
WITH MASS RELIEF
VANTAGE
UNIVERSITY OF COLORADO
1111 ENGINEERING DRIVE
BOULDER, CO 80309-0427
Tolerances Unless Noted:
Units: INCHES
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X.XXX ±.005
ANGLES ±0°30'
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1U FACE
MATERIAL:
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MACHINE ALL SURFACES TO A 63 MICROINCH FINISH OR BETTER.
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BREAK ALL EDGES.
PART NUMBER
x
REV
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SCALE
1:1
SHEET
1 OF 1
ENGINEER:
ABOAF
DRAWN BY:
ABOAF
APPROVED: ABOAF
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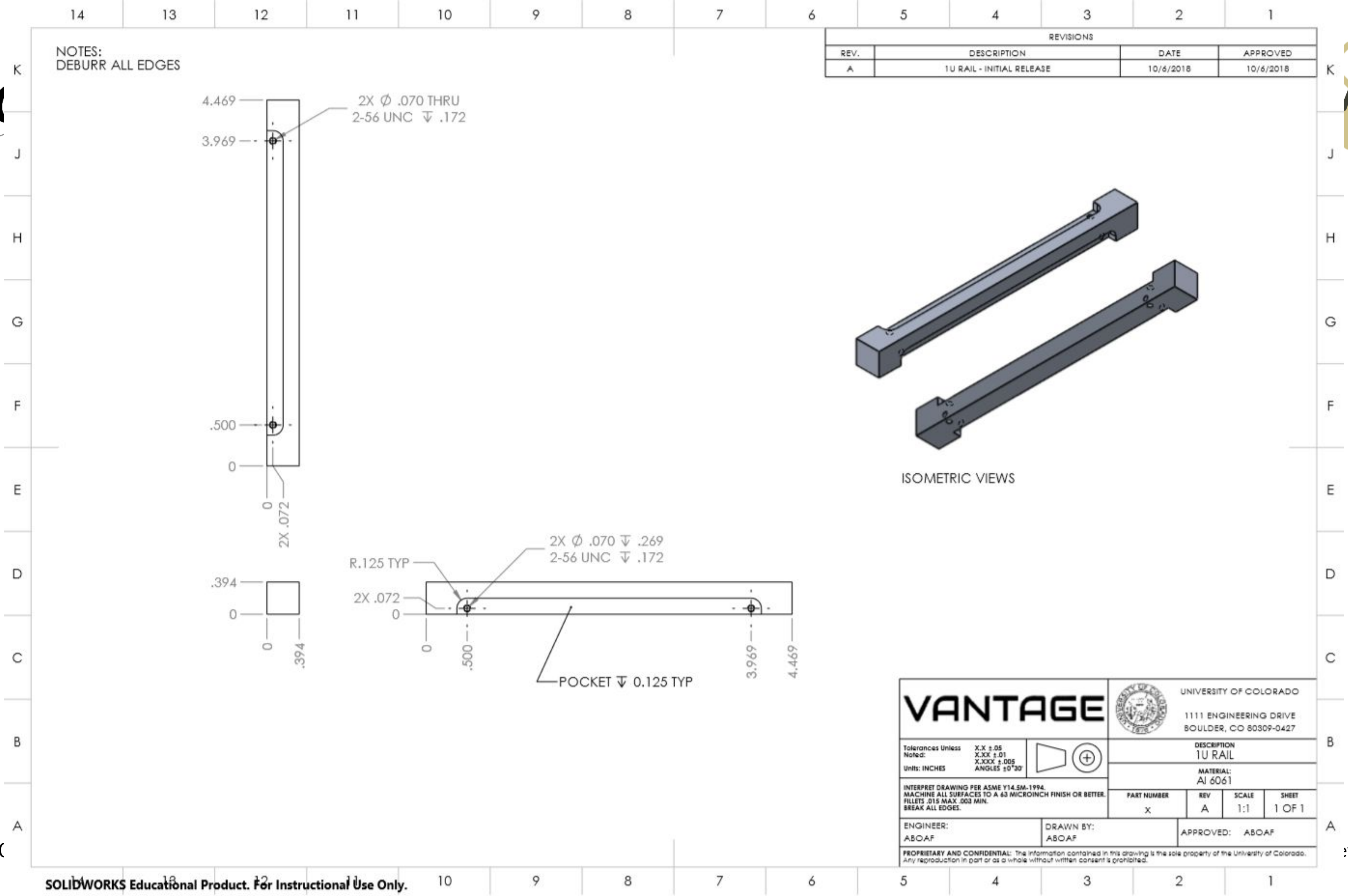
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.394
R.125 TYP
2X ∅ .070 ↧ .269
2-56 UNC ↧ .172
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ISOMETRIC VIEWS
VANTAGE
UNIVERSITY OF COLORADO
1111 ENGINEERING DRIVE
BOULDER, CO 80309-0427
Tolerances Unless Noted:
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X.XXX ±.005
ANGLES ±0°30'
Units: INCHES
INTERPRET DRAWING PER ASME Y14.5M-1994.
MACHINE ALL SURFACES TO A 63 MICROINCH FINISH OR BETTER.
FILLETS .015 MAX .003 MIN.
BREAK ALL EDGES.
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MATERIAL:
Al 6061
PART NUMBER
x
REV
A
SCALE
1:1
SHEET
1 OF 1
ENGINEER:
ABOAF
DRAWN BY:
ABOAF
APPROVED: ABOAF
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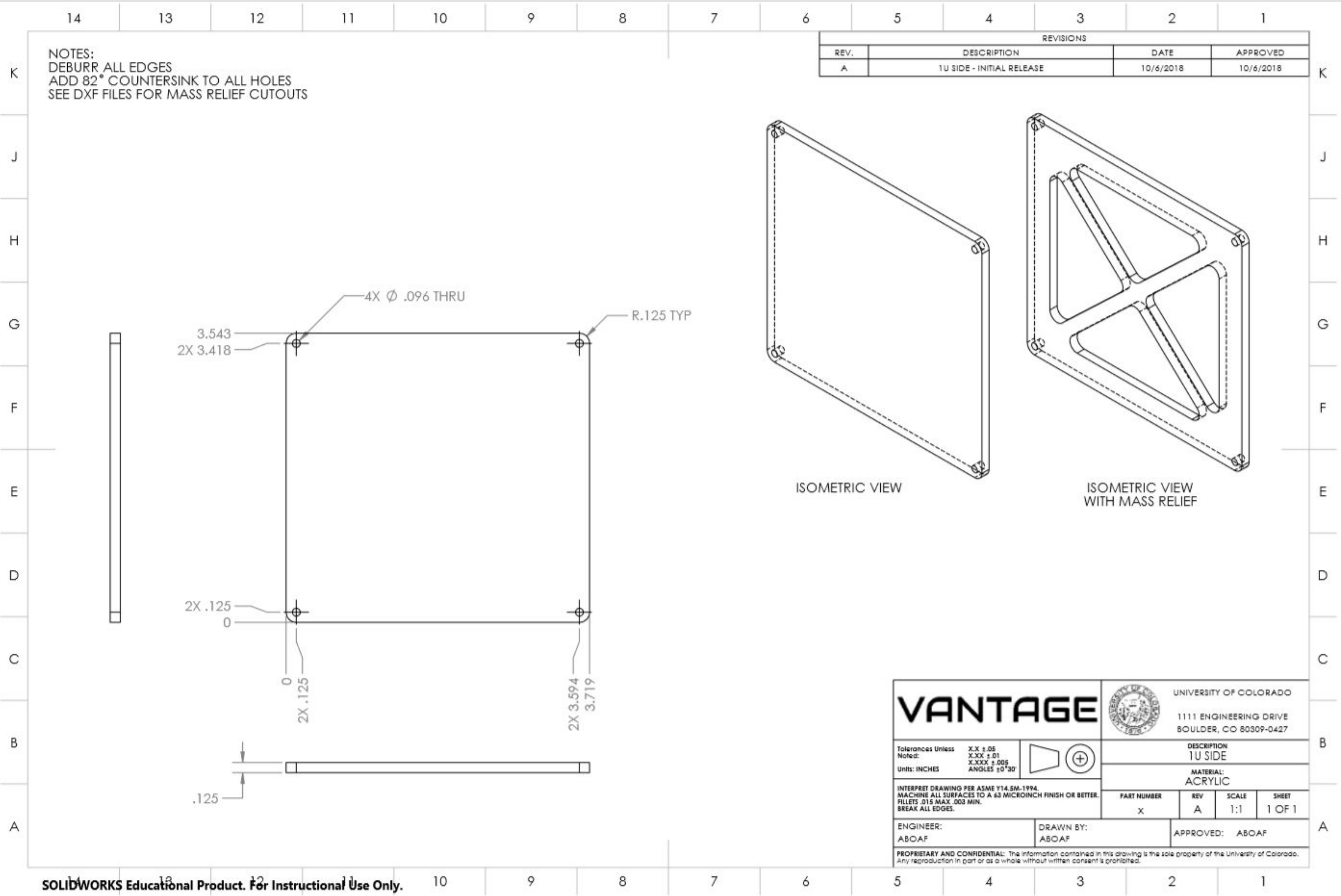
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ADD 82° COUNTERSINK TO ALL HOLES
SEE DXF FILES FOR MASS RELIEF CUTOUTS
REVISIONS
REV. | DESCRIPTION | DATE | APPROVED
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R.125 TYP
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2X .125
2X 3.594
3.719
.125
ISOMETRIC VIEW
ISOMETRIC VIEW
WITH MASS RELIEF
VANTAGE
UNIVERSITY OF COLORADO
1111 ENGINEERING DRIVE
BOULDER, CO 80309-0427
DESCRIPTION
1U SIDE
MATERIAL:
ACRYLIC
PART NUMBER
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REV
A
SCALE
1:1
SHEET
1 OF 1
ENGINEER:
ABOAF
DRAWN BY:
ABOAF
APPROVED: ABOAF
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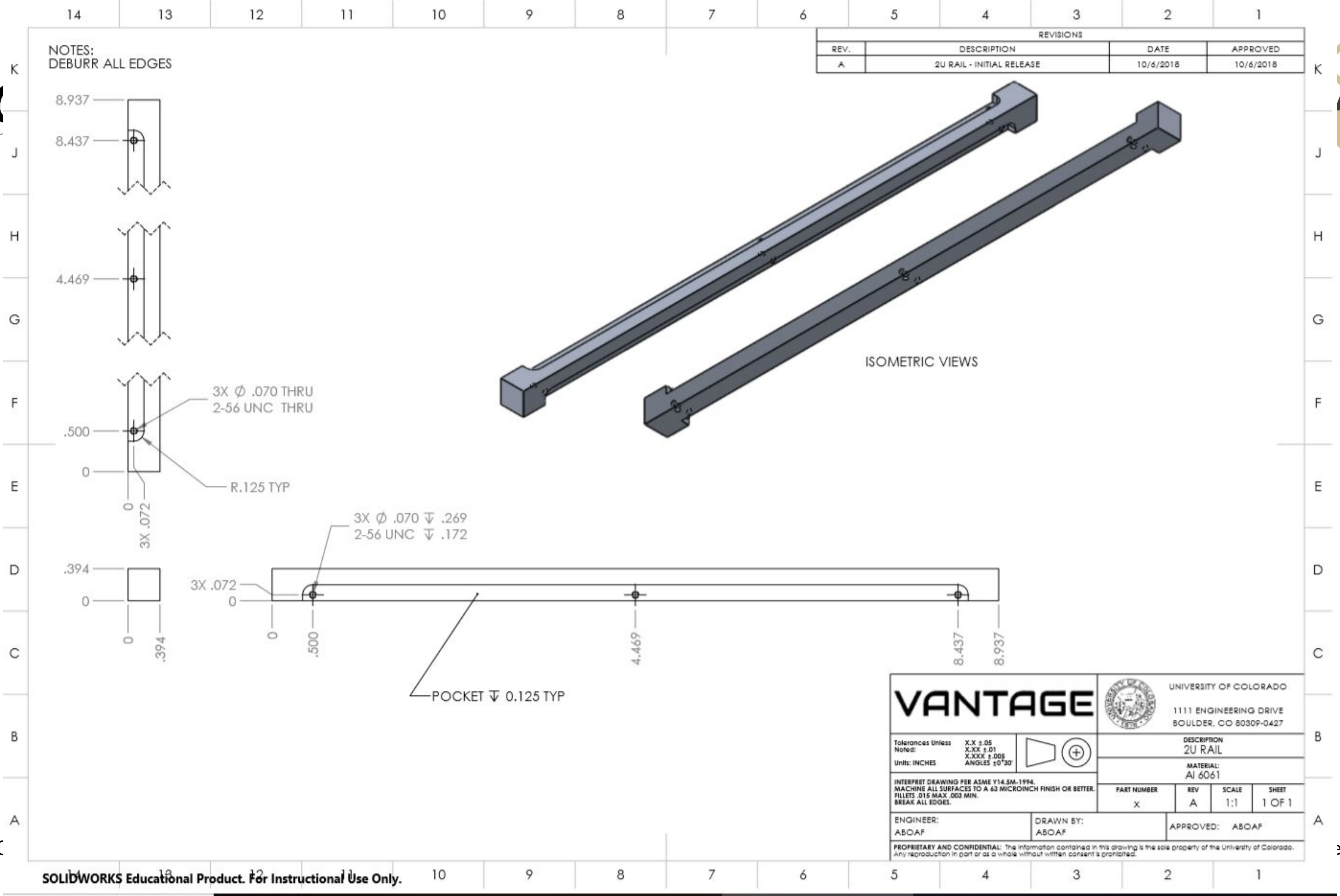
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REVISIONS
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R.125 TYP
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.500
4.469
8.437
8.937
POCKET ↧ 0.125 TYP
ISOMETRIC VIEWS
VANTAGE
UNIVERSITY OF COLORADO
1111 ENGINEERING DRIVE
BOULDER, CO 80309-0427
Tolerances Unless Noted: X.X ±.05 X.XX ±.01 X.XXX ±.005 ANGLES ±0°30'
Units: INCHES
INTERPRET DRAWING PER ASME Y14.5M-1994.
MACHINE ALL SURFACES TO A 63 MICROINCH FINISH OR BETTER.
FILLETS .015 MAX .003 MIN.
BREAK ALL EDGES.
DESCRIPTION
2U RAIL
MATERIAL:
Al 6061
PART NUMBER x
REV A
SCALE 1:1
SHEET 1 OF 1
ENGINEER: ABOAF
DRAWN BY: ABOAF
APPROVED: ABOAF
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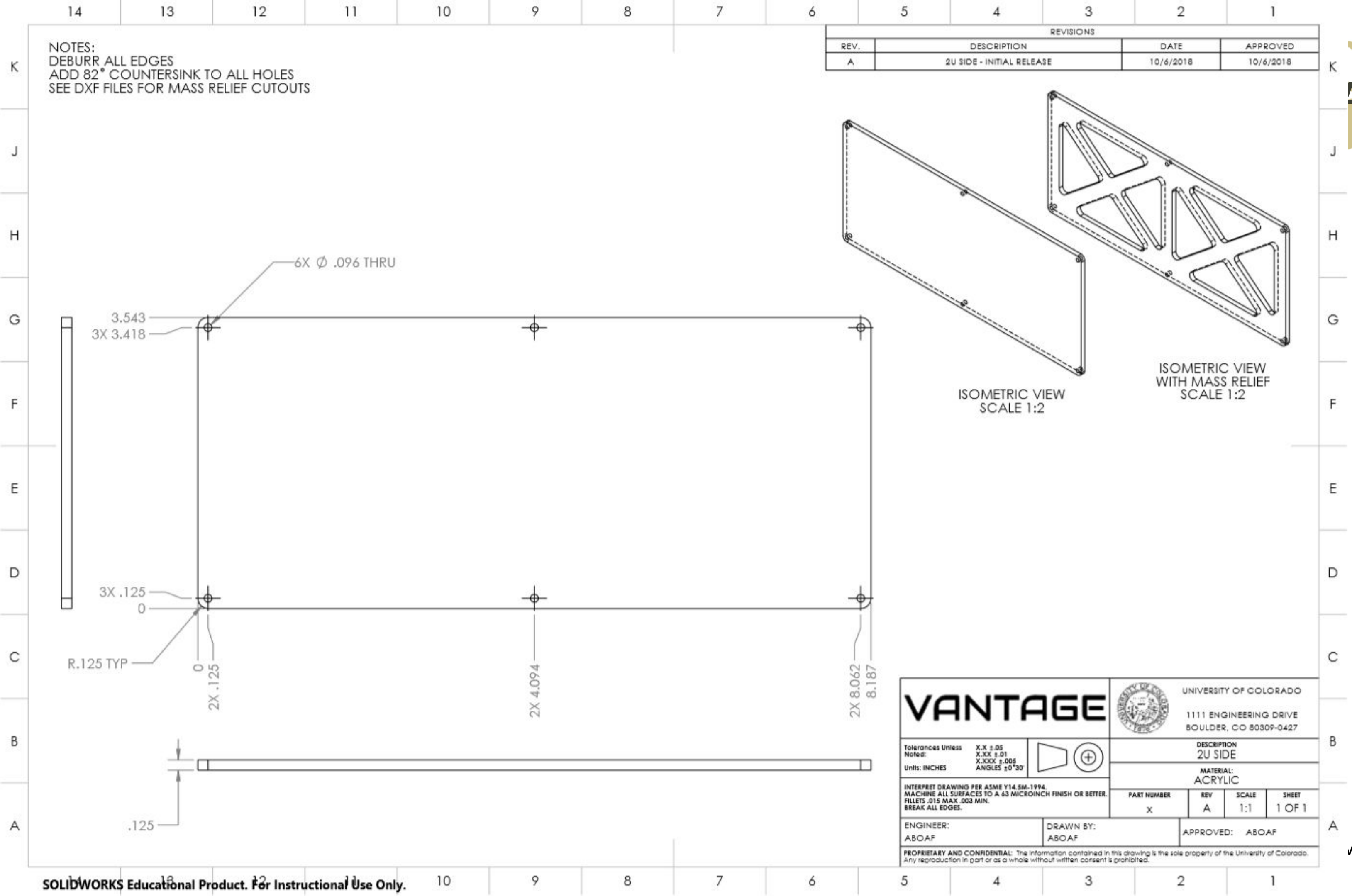
NOTES:
DEBURR ALL EDGES
ADD 82° COUNTERSINK TO ALL HOLES
SEE DXF FILES FOR MASS RELIEF CUTOUTS
REVISIONS
REV. | DESCRIPTION | DATE | APPROVED
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6X ∅ .096 THRU
3.543
3X 3.418
3X .125
0
R.125 TYP
0
2X .125
2X 4.094
2X 8.062
8.187
.125
ISOMETRIC VIEW
SCALE 1:2
ISOMETRIC VIEW
WITH MASS RELIEF
SCALE 1:2
VANTAGE
UNIVERSITY OF COLORADO
1111 ENGINEERING DRIVE
BOULDER, CO 80309-0427
Tolerances Unless Noted: X.X ±.05 X.XX ±.01 X.XXX ±.005 ANGLES ±0°30'
Units: INCHES
INTERPRET DRAWING PER ASME Y14.5M-1994.
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BREAK ALL EDGES.
DESCRIPTION
2U SIDE
MATERIAL:
ACRYLIC
PART NUMBER x
REV A
SCALE 1:1
SHEET 1 OF 1
ENGINEER: ABOAF
DRAWN BY: ABOAF
APPROVED: ABOAF
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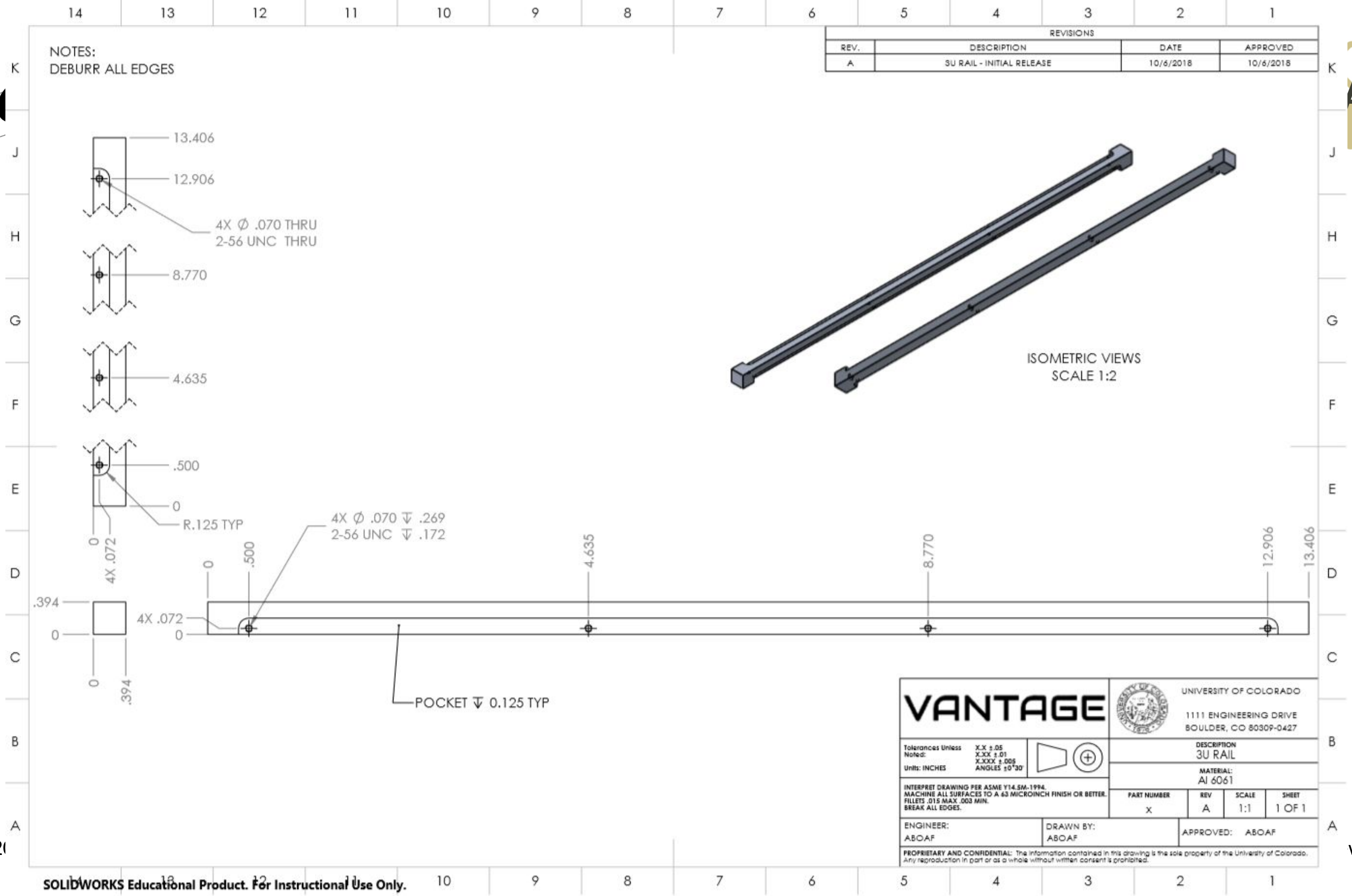
NOTES:
DEBURR ALL EDGES
REVISIONS
REV. | DESCRIPTION | DATE | APPROVED
A | 3U RAIL - INITIAL RELEASE | 10/6/2018 | 10/6/2018
13.406
12.906
4X Ø .070 THRU
2-56 UNC THRU
8.770
4.635
.500
0
R.125 TYP
4X .072
.394
4X Ø .070 ↧ .269
2-56 UNC ↧ .172
POCKET ↧ 0.125 TYP
ISOMETRIC VIEWS
SCALE 1:2
VANTAGE
UNIVERSITY OF COLORADO
1111 ENGINEERING DRIVE
BOULDER, CO 80309-0427
Tolerances Unless Noted: X.X ±.05 X.XX ±.01 X.XXX ±.005 ANGLES ±0°30'
Units: INCHES
INTERPRET DRAWING PER ASME Y14.5M-1994.
MACHINE ALL SURFACES TO A 63 MICROINCH FINISH OR BETTER.
FILLETS .015 MAX .003 MIN.
BREAK ALL EDGES.
DESCRIPTION 3U RAIL
MATERIAL: Al 6061
PART NUMBER x
REV A
SCALE 1:1
SHEET 1 OF 1
ENGINEER: ABOAF
DRAWN BY: ABOAF
APPROVED: ABOAF
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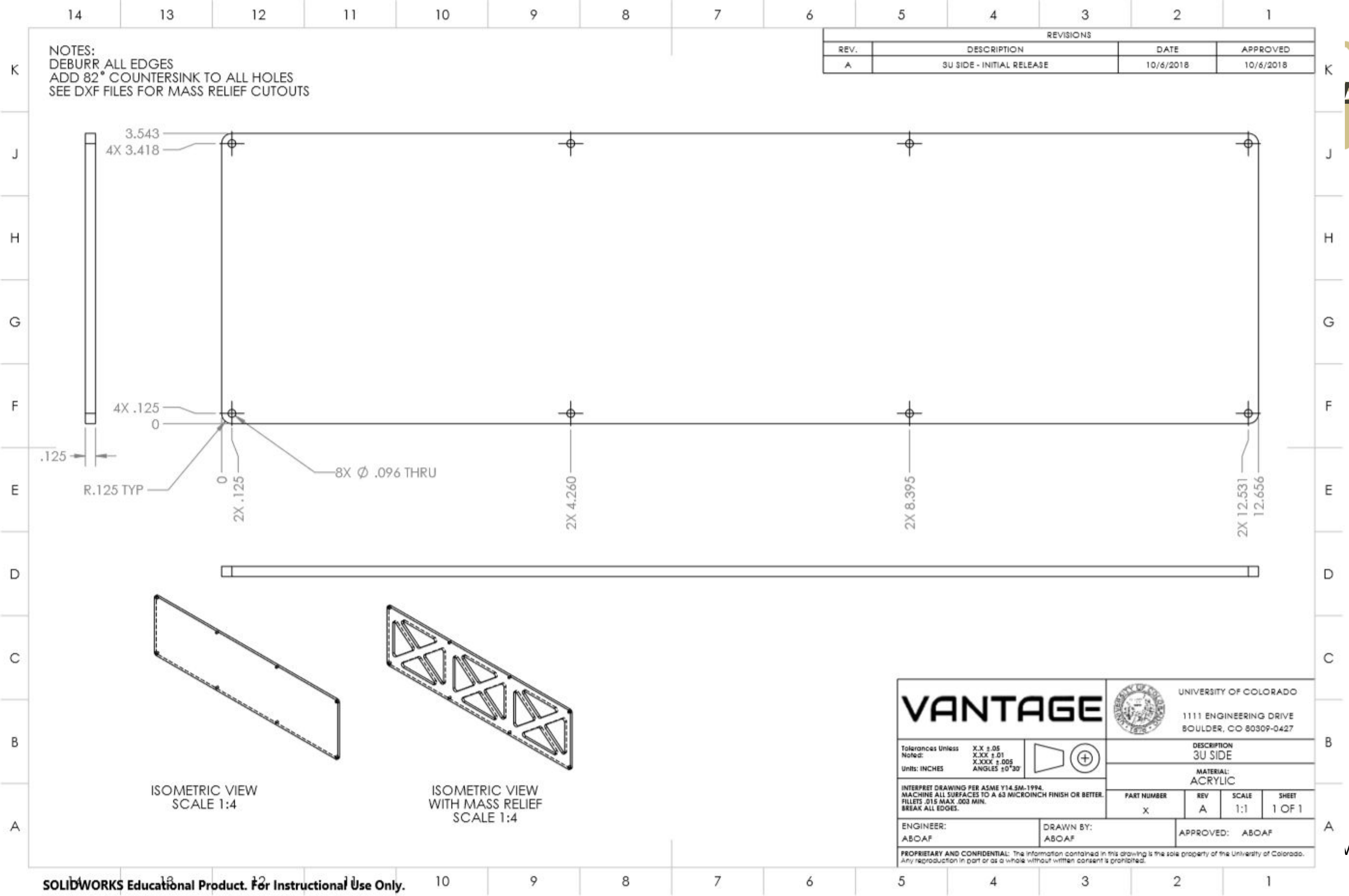
NOTES:
DEBURR ALL EDGES
ADD 82° COUNTERSINK TO ALL HOLES
SEE DXF FILES FOR MASS RELIEF CUTOUTS
REVISIONS
REV. | DESCRIPTION | DATE | APPROVED
A | 3U SIDE - INITIAL RELEASE | 10/6/2018 | 10/6/2018
3.543
4X 3.418
4X .125
0
.125
R.125 TYP
8X Ø .096 THRU
0
2X .125
2X 4.260
2X 8.395
2X 12.531
12.656
ISOMETRIC VIEW
SCALE 1:4
ISOMETRIC VIEW
WITH MASS RELIEF
SCALE 1:4
VANTAGE
UNIVERSITY OF COLORADO
1111 ENGINEERING DRIVE
BOULDER, CO 80309-0427
Tolerances Unless Noted: X.X ±.05 X.XX ±.01 X.XXX ±.005 ANGLES ±0°30'
Units: INCHES
DESCRIPTION
3U SIDE
MATERIAL:
ACRYLIC
INTERPRET DRAWING PER ASME Y14.5M-1994.
MACHINE ALL SURFACES TO A 63 MICROINCH FINISH OR BETTER.
FILLETS .015 MAX .003 MIN.
BREAK ALL EDGES.
PART NUMBER x
REV A
SCALE 1:1
SHEET 1 OF 1
ENGINEER: ABOAF
DRAWN BY: ABOAF
APPROVED: ABOAF
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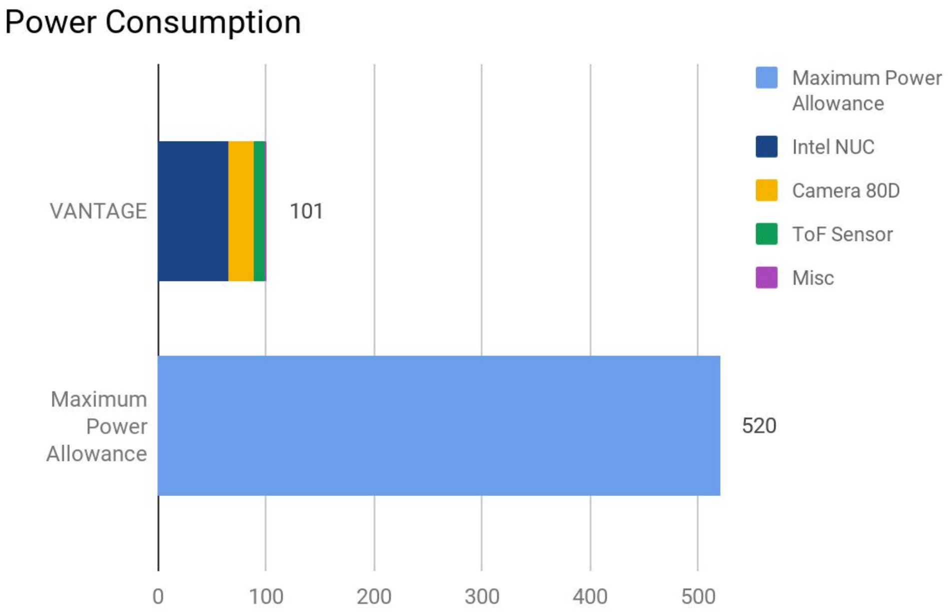
Backup Avionics

Avionics - Power Consumption (DR 3.2)

Feasible? Yes

- *VANTAGE power usage below maximum power allowance*
- *Power Break Down*
  - *NUC MAX - 60W*
  - *Camera Canon 80D MAX - 24W*
  - *ToF Sensor MAX - 10W*
  - *Misc (Power Up signal) - 2W*
  - *Total - 101W*



Req.	Summary
DR 3.2	The system shall draw less than 520 Watts.

Power Budget Reference

Material	Link
Intel Nuc	https://www.intel.com/content/dam/www/public/us/en/documents/guides/one-pagers-nuc-specs-guide.pdf
Camera Canon 80D	https://www.adorama.com/icadre6.html?gclid=CjwKCAjwjIHeBRAnEiwAhYT2h2ynNb9OFtxuG8hJu1of5e92HTI2wYU0qvLgK4ekX-dQWfHsHA4EWRoCD88QAvD_BwE
ToF sensor	https://www.acehardware.com/departments/plumbing/pipe-fittings/plastic-fittings/4512331?x429=true&utm_source=google&utm_medium=cpc&gclid=CjwKCAjwjIHeBRAnEiwAhYT2h9GIKj3KliNmM9DI6pKYmgw8BpviMn5Z7QXAz4J7MAXcVI2DVcuefBoCaZQQAvD_BwE https://www.ifm.com/cn/en/product/O3D313
Arduino board	https://www.homedepot.com/s/black%2520spray%2520paint?NCNI-5

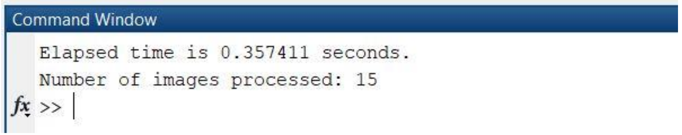
Backup Avionics DR 2.1

Req.	Summary
DR 2.1	The electronics subsystem shall interface with the PC which simulates the NanoRacks use-case system via a USB2.0 Port for all data communication needs.

Feasible? Yes, NUC is USB 2.0 compatible.

Data Processing Time Calculations (DR 8.1)

- Calculation back up
  - 100 raw footage taken (1 m/s CubeSat)   Total Image Size - > 2890 MB
- Data import from camera (USB3.0)
  - 2890 MB footage use USB3.0 (base on experience 25MB /Sec average write speed) -> 115.6 Sec -> 2MIN
- Processing Camera Necessary RAW Footage   CR2.RAW -> DNG
  - MATLAB can't read CR2.RAW footage it need process to DNG file. (base on DXO non correction export 100 images roughly take up 300Sec)
- Image Recognition
  - Base on the code one image need average 0.0238 sec to process.
- Estimate velocity and position
  - 1 sec per picture
- Output to Use-Case-System (USB2.0)
  - 2 RAW footage (520MB) with 10MB/S read time 52 Sec write time



Req.	Summary	Addressed in Slide(s)
DR 8.1	VANTAGE shall have ability to store and processing large amount data in 15 Min	

Data Storage Calculations (DR 8.2)

	Normal Size	Number of useage	Total
Camera CR2 footage	28.9 MB	100	2890 MB
DNG raw footage	250 MB	100	25000 MB
Windows Size	20GB	1	20480 MB
Matlab Size	6GB	1	6144 MB
Total			**55014 MB = 53.7GB**

Feasible? Yes

Req.	Summary
DR 8.2	The system shall store all images, sensor data, and estimates within an onboard data storage device.

CCAR

Avionics - Sleep mode (DR 3.3)

VANTAGE

Feasible? Yes:

- Avionics will enter a low power mode when not performing any operations
- An Arduino UNO (0.35 W power draw) will be capable of awaiting power-on command from controller PC and sending boot up signal to NUC.

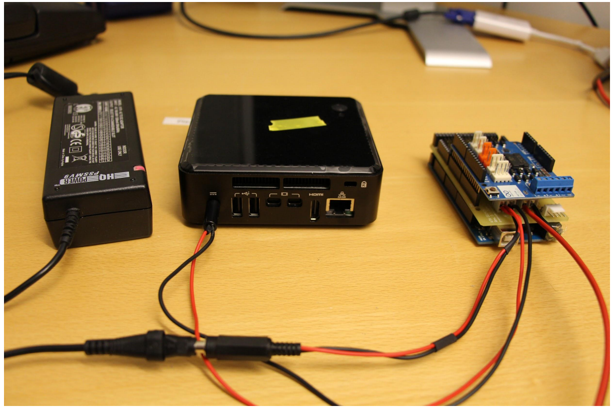


Image Credit: http://anywiki.csc.

Req. Label	Summary
DR.3.3-EL	The electronics subsystem shall enter a low power mode when not performing any operations (i.e. before a final test has been started, after a final test has been completed and all post-processing and communications have completed).

Avionics-Power Supply (DR 3.1)

Feasible? Yes:

- Need ability to step down 120VDC to 24VDC and 19VDC

- 120V to 24V DCDC Converter
  - MEAN WELL USA Inc. 1866-5036-ND
    - $63.00
    - 120W max (~20 W more than expected max power draw)

- 24 V to 19 V DCDC Converter
  - TDK-Lambda Americas Inc. 285-2857-ND
    - $35.00
    - 250W max

Image Credit: DigiKey

Req. Label	Summary
DR.3.1-EL	The system shall operate with up to 120 VDC with a ripple voltage of 3Vpp and less than 5 A, which simulates the power available from the NanoRacks use-case system.

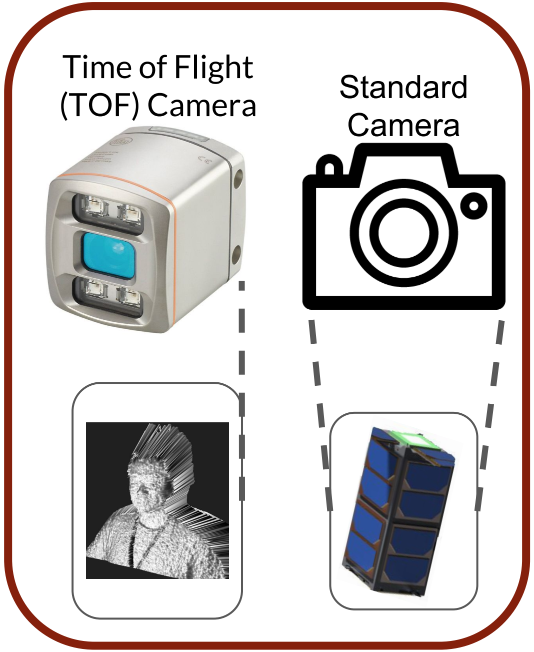
Avionics Trade Study

	Weight	MPSoC	SoC	Cell Phone	NUC	Raspberry Pi
Space Certifiable	30%	1	1	4	3	2
Performance*	30%	2	3.3*	1.7*	1	3.3*
Processor Memory (RAM)	N/A	1	3	3	1	4
Data Memory Size (ROM)		1	4	1	1	2
Processor Speed		1	3	1	1	5
Supported Languages		5	3	2	1	2
Development Time	25%	5	5	1	1	3
Cost	10%	4	3	3	3	1
Power	5%	2	1	1	3	1
Total/Result	100%	2.65	2.88	2.32	1.90	2.48

Backup Sensors

Baseline Design (Sensor Package)

Acquire Data



	Weight	1 Camera	Stereoscopic	Cam+IR ToF	Cam + Diffuse LIDAR	Cam+Scan LIDAR
Accuracy	23%	5	4	1	4	3
Software Development Time	20%	2	5	3	3	4
Cost	18%	2	5	4	4	4
Power	16%	1	2	4	3	3
Hardware Development Time	13%	2	3	3	2	4
Size	10%	1	2	4	3	4
Total/Result	100%	1.46	2.76	1.95	2.24	2.64

Satisfaction of Other Reqs

DR 1.1- *System shall use a camera to capture images of CubeSats*

- We chose a camera as part of the baseline design.

DR 1.2- *Imaging subsystem shall have a FOV greater than 20°x20°*

- TOF Sensor has FOV of 60°x45°, Camera Lens will be selected such that there is a FOV greater than 20°x20°

DR 1.3- *Imaging subsystem shall produce at least 2 images of each mock CubeSat deployed by the test system*

- The Camera can take pictures at a rate of 7 fps, so this will be easily satisfied.

DR 1.4- *Imaging subsystem shall produce in-focus images of mock CubeSats.*

- Camera will be focused at a relatively close range so that high-quality, in focus images can be produced.

DR 5.1 (same as 1.2)

Backup Sensors

Calculations

Cross-Range Accuracy

Given a sensor with a FOV (x and y) and resolution(nx,ny), we can estimate the angular resolution by:

$$\alpha = \frac{FOV_x}{n_x}$$

Assumes square pixels

The cross-plane dimension a of a certain pixel at a distance d, where alpha is in radians:

$$a = d\alpha$$

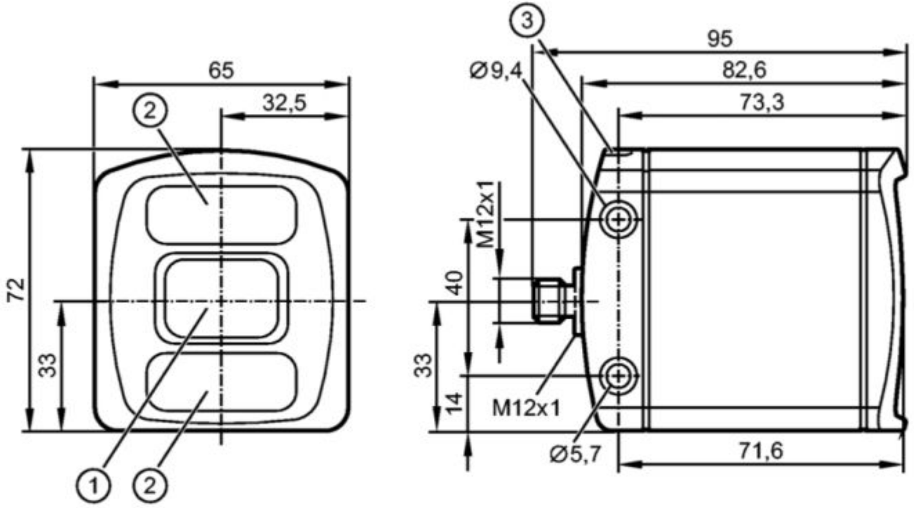
And the dimensional accuracy of a measurement can be given as an accuracy in pixels, r:

$$Accuracy = dr\alpha$$

Sub-pixel precision is typically possible for objects that take up as little as 10 pixels. ½ pixel accuracy was chosen as a conservative estimate of the possible precision

Composition of Total Errors

$$E_{total} = \sqrt{E_x^2 + E_y^2 + E_z^2}$$



dt << dx

$$V_z = \frac{z_2 - z_1}{t_2 - t_1}, \qquad \Delta t = t_2 - t_1, \qquad \Delta z = z_2 - z_1$$

$$\delta_{V_z} = \sqrt{\left(\frac{\partial V_z}{\partial z_2}\delta_{z_2}\right)^2 + \left(\frac{\partial V_z}{\partial z_1}\delta_{z_1}\right)^2 + \left(\frac{\partial V_z}{\partial t_2}\delta_{t_2}\right)^2 + \left(\frac{\partial V_z}{\partial t_1}\delta_{t_1}\right)^2}$$

$$\delta_{V_z} = \sqrt{\left(\frac{1 - z_1}{\Delta t}\delta_z\right)^2 + \left(\frac{z_2 - 1}{\Delta t}\delta_z\right)^2 + \left(\frac{\Delta z}{\Delta t^2}\delta_t\right)^2 + \left(\frac{\Delta z}{\Delta t^2}\delta_t\right)^2}$$

Using: $\Delta t = 0.05s\ (20Hz)$, $\Delta z = V\Delta t = 0.1m$, $z_1 = 3m$, $z_2 = 3.1m$

With uncertainties: $\delta z = 10mm$, $\delta t = 0.002ms$

$$\delta_{V_z} = \sqrt{\left(-0.04\right)^2 + \left(0.042\right)^2 + \left(6.4 \times 10^{-9}\right)^2 + \left(-6.4 \times 10^{-9}\right)^2}$$

Determination of N

N is the total number of position measurements made

$$\delta v_{refine} = \frac{\delta v}{\sqrt{N}}$$

Detailed Analysis Steps

- Determining when a CubeSat will enter the FOV
    - Assuming worst case
        - VANTAGE set up as far away as possible
        - CubeSat Moving at max. (Expected velocity of 2 m/s)

- Determine when the CubeSat leaves the effective range of the TOF sensor

- (Multiply the difference by the fps of the measurement)-1=N

FPS Conservatively chosen to be 5 fps, resolution and range tend to worsen with high fps. *The max for this sensor is 25 fps.*

Relative Motion Model

$$x(t) = \frac{\dot{x}_o}{\omega}\text{SIN}(\omega t) - \left(3x_o + \frac{2\dot{y}_o}{\omega}\right)\text{COS}(\omega t) + \left(4x_o + \frac{2\dot{y}_o}{\omega}\right)$$

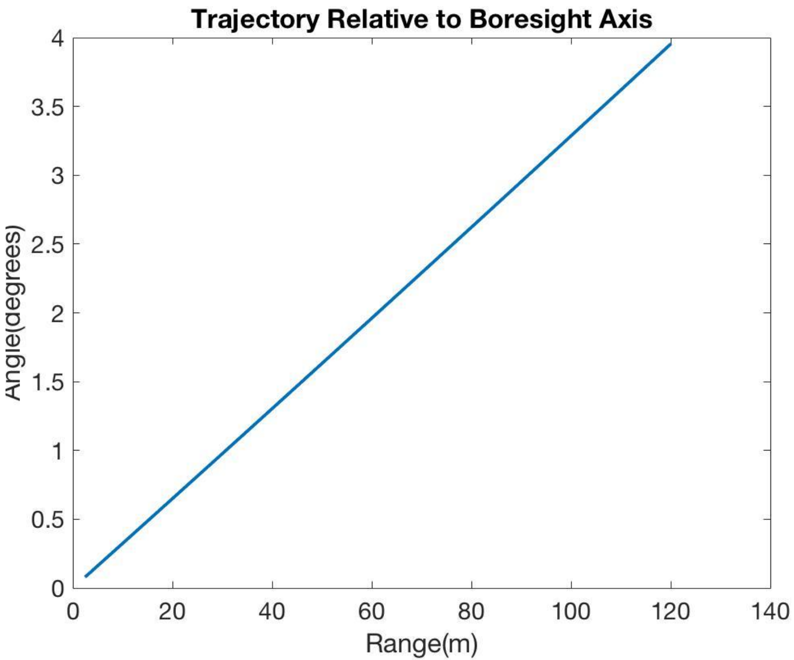
$$y(t) = \left(6x_o + \frac{4\dot{y}_o}{\omega}\right)\text{SIN}(\omega t) + \frac{2\dot{x}_o}{\omega}\text{COS}(\omega t) - (6\omega x_o + 3\dot{y}_o)t + \left(y_o - \frac{2\dot{x}_o}{\omega}\right)$$

$$z(t) = z_o\text{COS}(\omega t) + \frac{\dot{z}_o}{\omega}\text{SIN}(\omega t)$$

$$\dot{x}(t) = \dot{x}_o\text{COS}(\omega t) + (3\omega x_o + 2\dot{y}_o)\text{SIN}(\omega t)$$

$$\dot{y}(t) = (6\omega x_o + 4\dot{y}_o)\text{COS}(\omega t) - 2\dot{x}_o\text{SIN}(\omega t) - (6\omega x_o + 3\dot{y}_o)$$

$$\dot{z}(t) = -z_o\omega\text{SIN}(\omega t) + \dot{z}_o\text{COS}(\omega t)$$

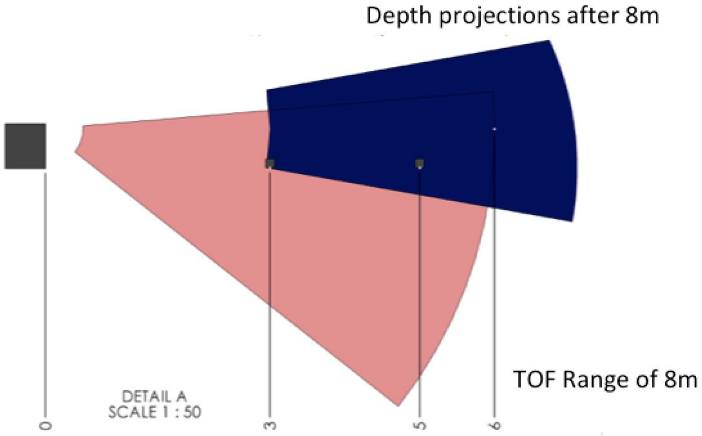


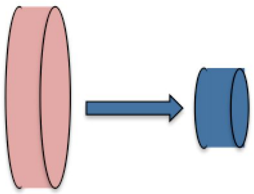
Position and Velocity errors will propagate similarly to a rectilinear assumption (x,y,z,xdot,ydot, zdot all to first power)

Backup Sensors

Miscellaneous

Backup Sensor Fusion





Refinement of TOF Predictions by Camera

Backup Testing

100 m Test

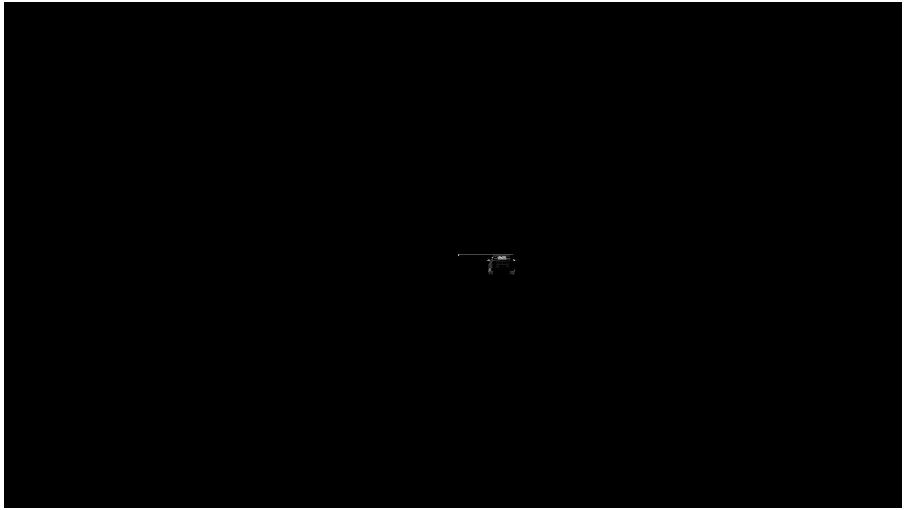
100 m Test System - Layout

Start of ejection sequence Time t_0: Mock cubesats are not in view

Time t_1:mock cubesat comes into view for the first time

100 m Test System - Layout

Time t_2: mock cubesats are midway down range (~50m)



Time t_3: mock cubesats are at end of range (~100m)

100 m Test System - Materials

<table>
<tr><th>Material</th><th>Link</th></tr>
<tr><td>Welding Rods</td><td>https://www.mscdirect.com/browse/tnpla/59803999?cid=ppc-google-New+-+Welding+%26+Soldering+-+PLA_sqHmEEE1d___164124449405_c_S&mkwid=sqHmEEE1d|dc&pcrid=164124449405&rd=k&product_id=59803999&gclid=Cj0KCQjwl9zdBRDgARIsAL5Nyn0Y5Zi0HIlPsANID-Acp1AI-pzSXkmXILU9ipiw27O-nHhQlt-BvloaAnsEEALw_wcB</td></tr>
<tr><td>Steel Tubing</td><td>https://www.homedepot.com/s/electric%2520metallic%2520tubing?NCNI-5</td></tr>
<tr><td>Mounting & Fasteners</td><td>https://www.mcmaster.com/standard-socket-head-screws</td></tr>
<tr><td>Black Spray Paint</td><td>https://www.homedepot.com/s/black%2520spray%2520paint?NCNI-5</td></tr>
</table>

100 m Test System - Feasibility

- Ability to Iterate
  - Some difficulty to iterate full system test
    - Requires logistics to arrange test timing with VANTAGE team and location
    - Planning for multiple test windows on the front end should mitigate this risk
  - Will be a quick build which can even be done over winter break so that testing can begin early in Spring
    - Estimate 1 full days to cut material to required lengths
    - Estimate 2 full days to weld in shop
- Concept Modularity
  - Can test various parts of system independently before moving to full scale test
    - Boom and car mechanical validation
    - Cubesats and car
    - RTK GPS & IMU with car and portable power systems
    - Vantage power and functionality bench tests with portable power system

100m Full Scale Test Simulation

- Simulation done with a 3D graphics software
  - Cinema 4D R20
- Boom will be painted black
- Black screen behind payloads is not visible on the render
- Light source will shine on payloads from car

100m Test Accuracy Feasibility

GPS RTK Alternative (OEM729)

- Velocity Accuracy: 0.03 m/s RMS
- Timing Accuracy: 20 ns RMS
- Position Accuracy: 1 cm
- Availability: Dr. Axelrad (VANTAGE Customer) is willing to lend this device to the team for testing purposes. Dr. Akos is willing to lend another OEM6 receiver to pair with what Dr. Axelrad has.
- Data Sheet: https://www.novatel.com/assets/Documents/Papers/OEM729-Product-Sheet.pdf

Analog Devices 3-axis IMU and magnetometer (ADIS16405BMLZ):

- Sensor accuracy: 0.0125 deg/s/LSB
- Sensor availability: Has been checked out from Trudy.
- Data Sheet: http://www.analog.com/media/en/technical-documentation/data-sheets/ADIS16400_16405.pdf

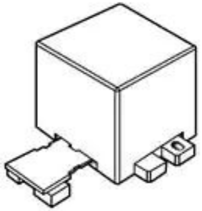


Image Credit: Analog Devices

Backup Testing

Modular Test

Modular Test System - Motor

1. Assumptions:

$$\rho_{acrylic} = 1180\ [kg/m^3]$$
$$\rho_{cardboard} = 700\ [kg/m^3]$$
$$V_{acrylic} = 0.00277\ [m^3]$$
$$V_{cardboard} = 0.000249\ [m^3]$$
$$m_{cubesat} = 0.2\ [kg]$$
$$m_{wheels} = 0.4\ [kg]$$
$$\mu_{plastic} = 0.4\ R_{motor} = 0.0075\ [m]$$

2. Total mass of the cart :

$$m_i = \rho_i V_i$$
$$m_{total} = \sum m_i = 5.12\ [kg]$$

3. Maximum frictional force acting on the cart :

$$F_{friction} \leq \mu_{plastic} F_N = \mu_{plastic} M_{total} g = 22.033\ [N]$$

4. Initially will need to accelerate to 0.5-2 m/s in 3m :

$$a_{max} = \frac{{V_{max}}^2}{2} = 0.667\ [m/s^2]$$

5. Requiring a force from the motor :

$$\sum F = m_{total} a_{max} = F_{motor} - F_{friction}$$
$$F_{motor} = 25.779\ [N]$$

6. With a corresponding torque :

$$T_{motor} = R_{motor} \times F_{motor} = 0.193\ [N \cdot m]$$

This is a reasonable max torque value, as the current selected motor has a stall torque of 1.024 [N*m]

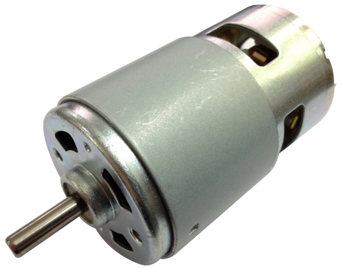
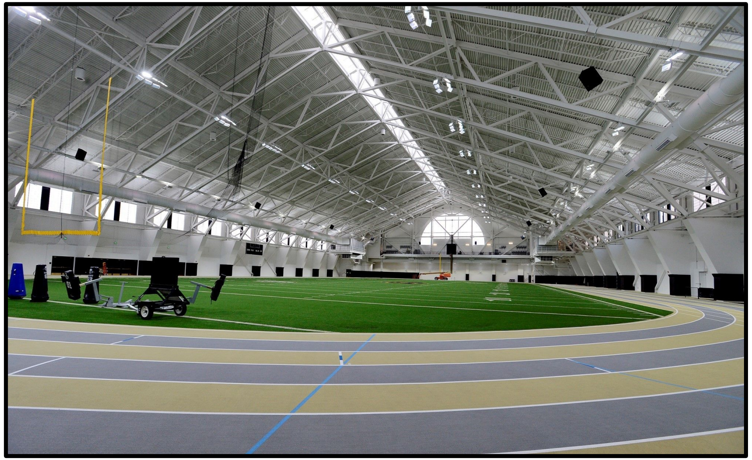


Image Credit: BEMONOC

CCAR

Modular Test System - Locations

VANTAGE



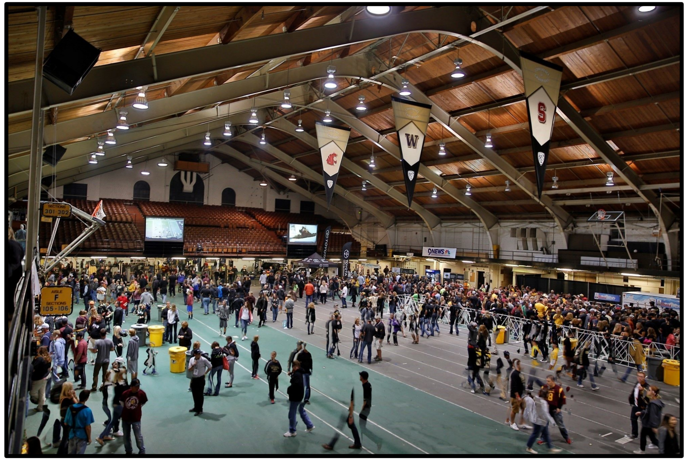


Image Credit: Colorado Buffaloes

- Indoor Practice Facility
  - 108,000 sq. ft.
  - Football team uses year round
  - Feasible to gain access
  - Testing will occur at night
- Balch Fieldhouse
  - 37,050 sq. ft.
  - Used for storage in Spring
  - Easy to gain access
  - Testing will occur at night

Modular Test System - Materials

Material	Link
PVC Pipe	https://www.homedepot.com/p/JM-eagle-3-in-x-10-ft-PVC-Schedule-40-DWV-Plain-End-Pipe-531095/100161921
PVC Corner Piece	https://www.homedepot.com/p/3-in-PVC-DWV-90-Degree-Hub-x-Hub-Elbow-C4807HD3/100346018
PVC Pipe Inside Connector	https://www.acehardware.com/departments/plumbing/pipe-fittings/plastic-fittings/4512331?x429=true&utm_source=google&utm_medium=cpc&gclid=CjwKCAjwjIHeBRAnEiwAhYT2h9GIKj3KIiNmM9DI6pKYmgw8BpviMn5Z7QXAz4J7MAXcVI2DVcuefBoCaZQQAvD_BwE
Black Spray Paint	https://www.homedepot.com/s/black%2520spray%2520paint?NCNI-5
Acrylic Sheet	https://www.mcmaster.com/acrylic
Wheels	https://www.amazon.com/Rolland-Office-Chair-Caster-Replacement/dp/B002TTR74M
Motor	https://www.amazon.com/BEMONOC-Small-DC-Motor-Torque/dp/B01DVHAW6A/ref=pd_sim_60_5?_encoding=UTF8&pd_rd_i=B01DVHAW6A&pd_rd_r=f32f3091-ce7d-11e8-9a8b-017d633f01ef&pd_rd_w=8VaY6&pd_rd_wg=rpF90&pf_rd_i=desktop-dp-sims&pf_rd_m=ATVPDKIKX0DER&pf_rd_p=18bb0b78-4200-49b9-ac91-f141d61a1780&pf_rd_r=TF7KYV628BAKE08FAPEE&pf_rd_s=desktop-dp-sims&pf_rd_t=40701&psc=1&refRID=TF7KYV628BAKE08FAPEE