

# Seeker 1.0 GNC Flight Performance

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# Why Are We Here?

- We like space
- Accelerate spaceflight
- Share our experience with rapid development and operation of small satellites for inspection/proximity operations
- Create partnerships to advance the state of free-flying extravehicular inspectors





# Content



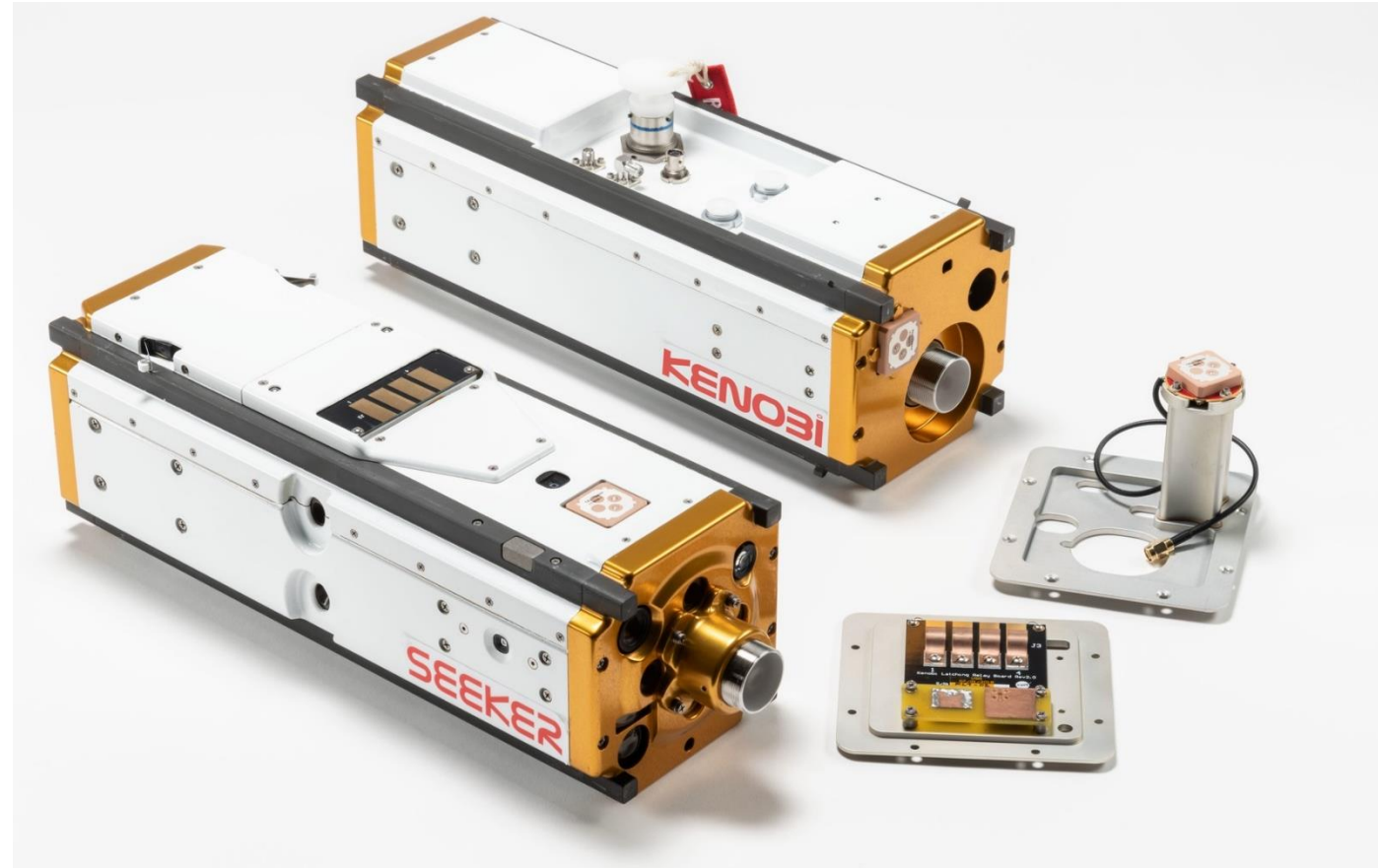
- Seeker System Review**
- Seeker Mission Review**
- On-console Observations**
- GNC Performance**
- Success and Failure Overview**
- Forward Plan**



# Seeker Project



- ❑ First step of evolutionary free-flying inspector design
- ❑ ISS “X-by” Project (Class 1E)
- ❑ Flew onboard NG-11
- ❑ ATP 7/2017, delivery 10/2018, \$1.8M
- ❑ Early-career focused
- ❑ **Goals:**
  - Demonstrate safe operation around target spacecraft
  - Demonstrate core inspection capabilities
  - Establish “rules of the road”

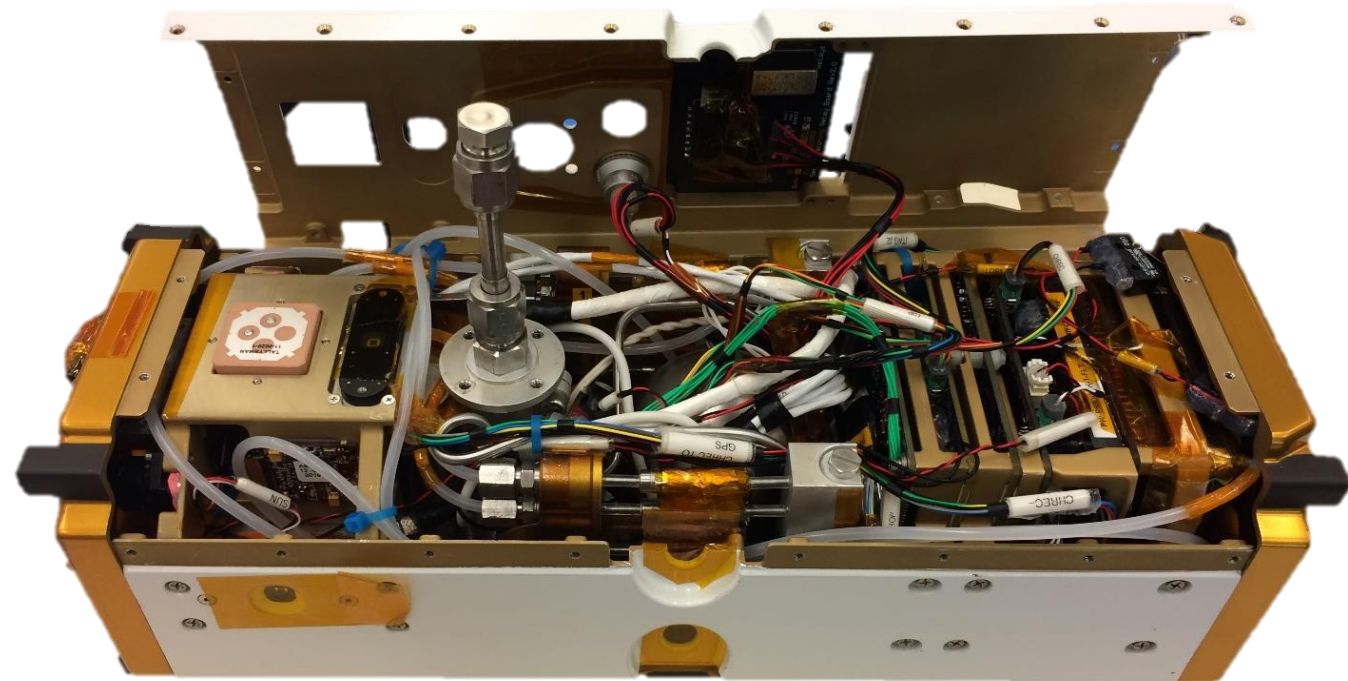
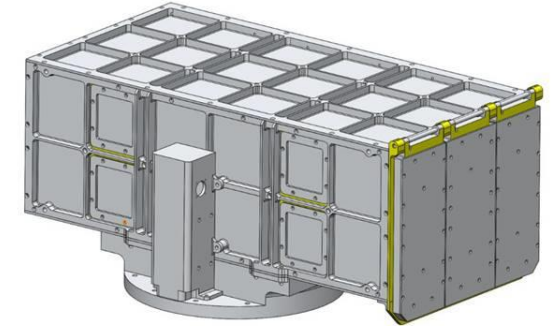
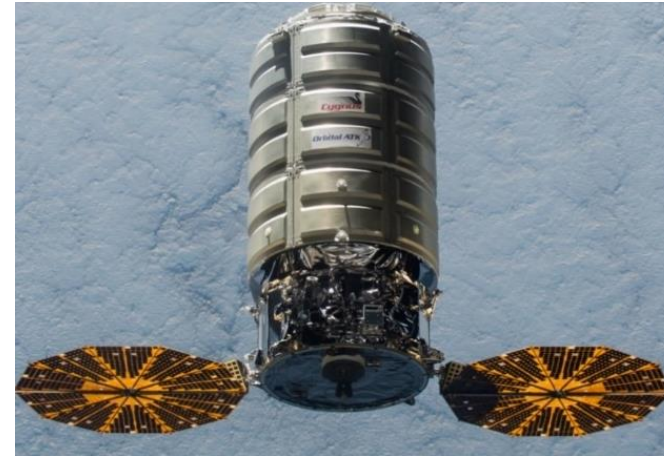




# Seeker Hardware



- ❑ **Cygnus, NG-11 (Northrop Grumman)**
  - Target vehicle
- ❑ **External NanoRacks CubeSat Deployer, e-NRCSD (NanoRacks)**
  - CubeSat deployer
  - Special mods to accommodate Seeker
- ❑ **Seeker (NASA JSC)**
  - Chaser vehicle
  - 3U form-factor (10x10x30 cm), ~6 kg
  - 6 DOF via 12 cold-gas (GN<sub>2</sub>) thrusters
  - Communicates w/ Kenobi via 5 GHz Wi-Fi
  - 2 Cameras (Navigation & Inspection)
- ❑ **Kenobi (NASA JSC)**
  - Data relay box mounted directly on Cygnus
  - Derivative of Seeker design (3U, ~4kg)
  - Communicates w/ Cygnus via RS422
  - 1 Camera to record Seeker motion





# Seeker Sensors

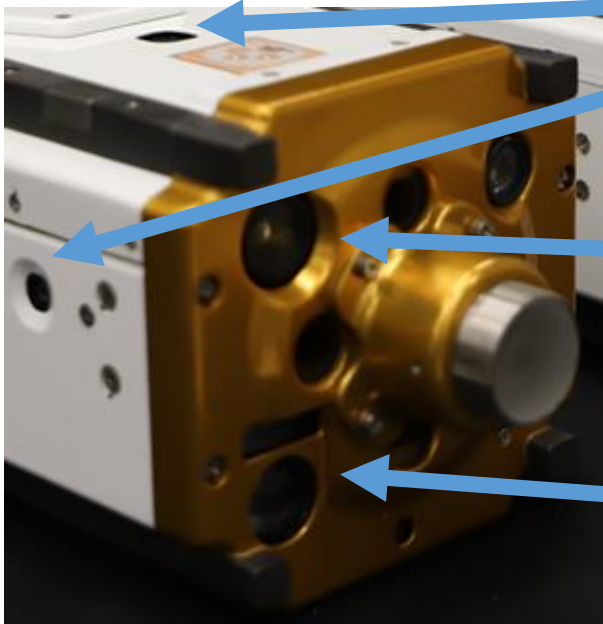


## ❑ COTS:

- Sony FCB-MA130 camera
- DLEM-SR laser rangefinder (LRF)
- STIM300 inertial measurement unit (IMU)

## ❑ Space-rated COTS:

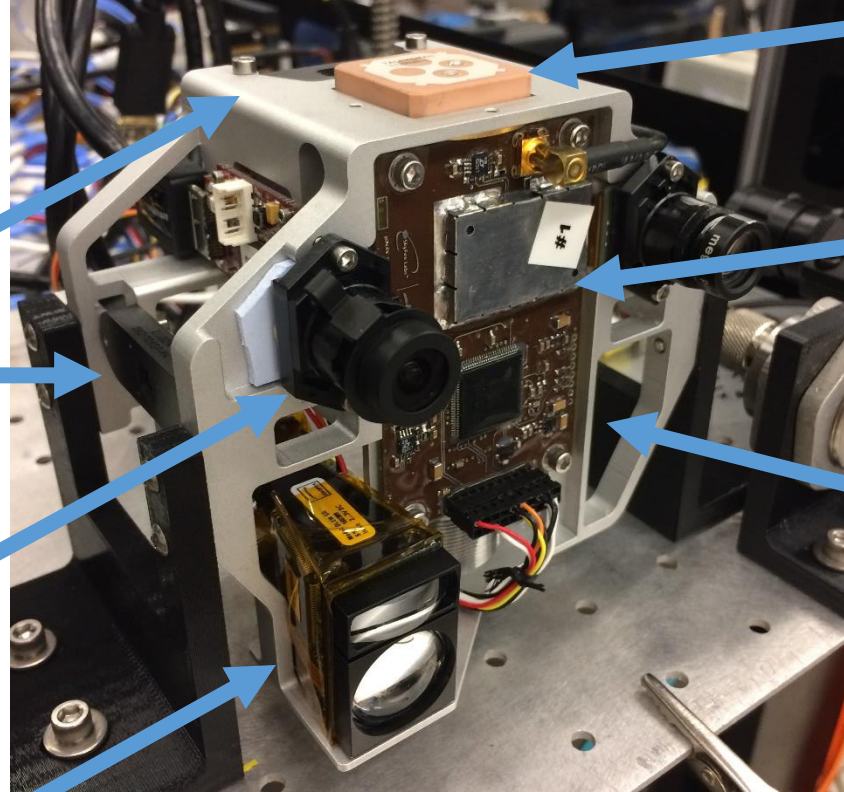
- nanoSSOC-D60 sun sensors
- piNav-NG GPS



Sun sensors

Navigation camera

LRF



GPS antenna

GPS receiver

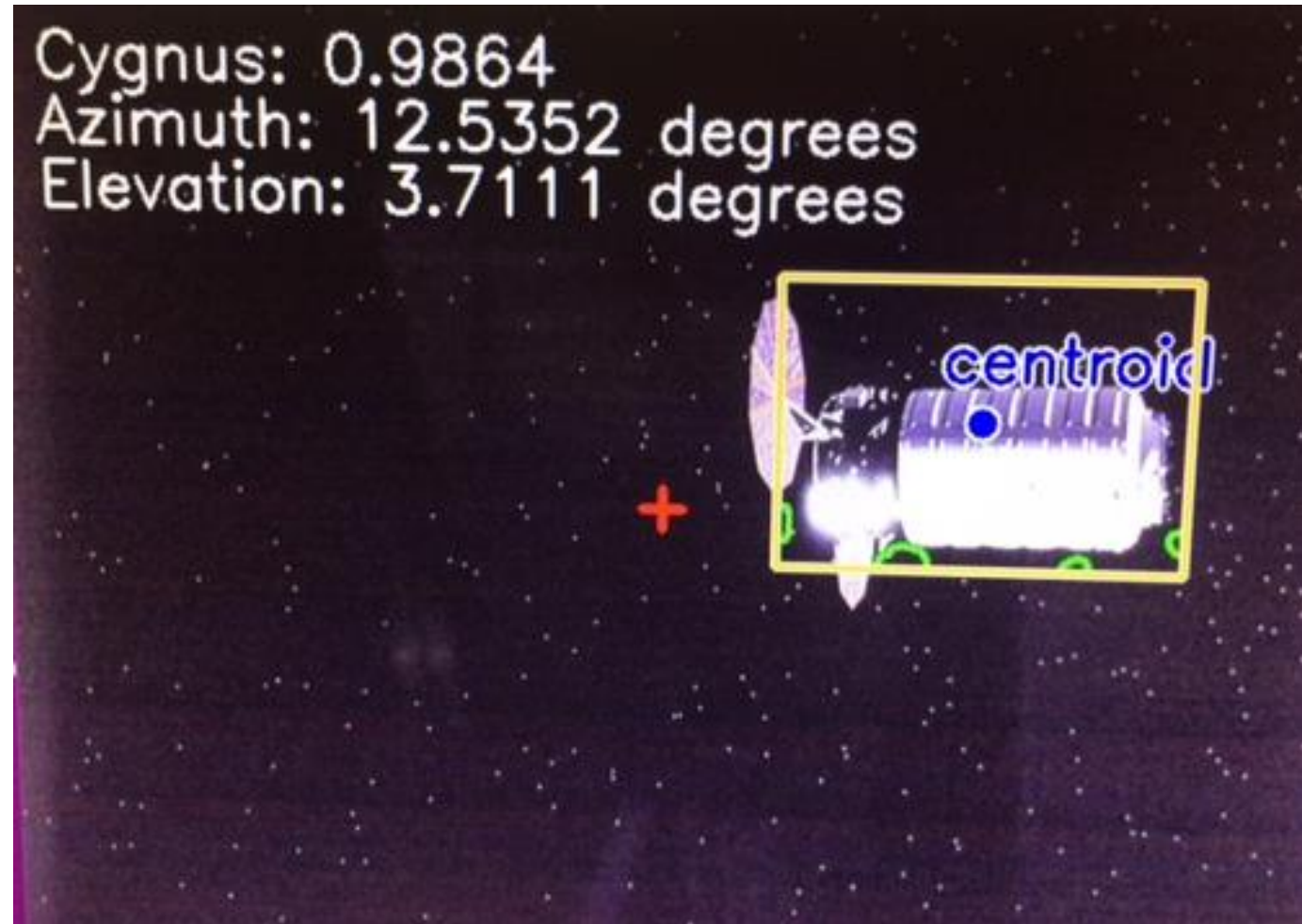
IMU (occluded)



# Vision-based Navigation



- ❑ Developed by UT-Austin
- ❑ Convolutional neural network w/ traditional contouring
  - Detects Cygnus (bounds)
  - Attempts to outline within bounds using contouring approaches
  - Calculates centroid of resulting area
- ❑ Outputs bearing to target
- ❑ Testing shows lighting robustness and low false positives
- ❑ Runs on Intel Joule 570x





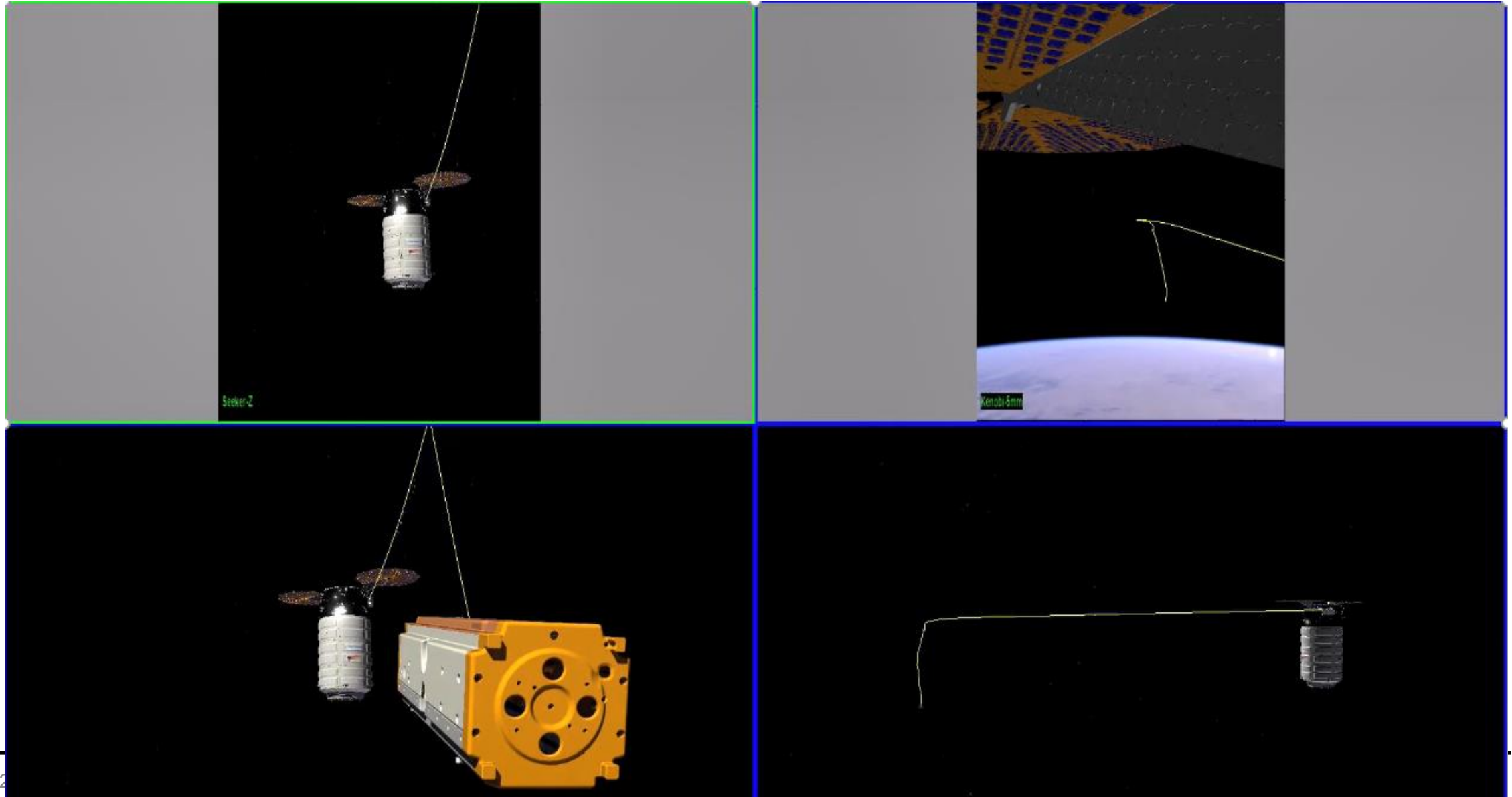
# Seeker GNC Algorithms



- ❑ **All running onboard the vehicle in Core Flight System (CFS) software**
- ❑ **Automated Flight Manager (AFM) (5 Hz)**
  - (mostly) linear state machine that configures vehicle
  - Allows vehicle to be operated with only three ground commands (“next,” “disable,” and “leave”)
- ❑ **Navigation**
  - 24 states covering inertial, relative, and biases
  - Multiplicative Extended Kalman Filter running at 5Hz
  - Dynamics/IMU propagator at 50Hz
- ❑ **Guidance (5 Hz)**
  - Enforces keep-out zone and speed limit
  - Able to do waypoint seeking, position hold, attitude hold, and target tracking
- ❑ **Control (5 Hz)**
  - Phase plane for rotation, P-I for translation
  - Thruster selection accounts for vehicle limitations



# Nominal Trajectory





# (January 2019's) Forward Plan



- ❑ **March 2019—Deliver**
- ❑ **April 2019—Launch**
- ❑ **July 2019—Flight operations**
- ❑ **August 2019—Data analysis, BET creation**
- ❑ **Early 2020—share results?**
- ❑ **Mid 2020—start Seeker 2.0?**
  
- ❑ **Potential upgrades for the next flight:**
  - Improve vision-based navigation to provide pose
  - Swap DLEM-SR for DLEM20
  - Change NAV filter from inertial-relative to kinematic
  - Add LiDAR for DTO
  - Upgrade guidance to potential field
  - Upgrade control to be optimization based
  - Enhance AFM capability
  - Explore adding reaction wheels





**3/19/2019**

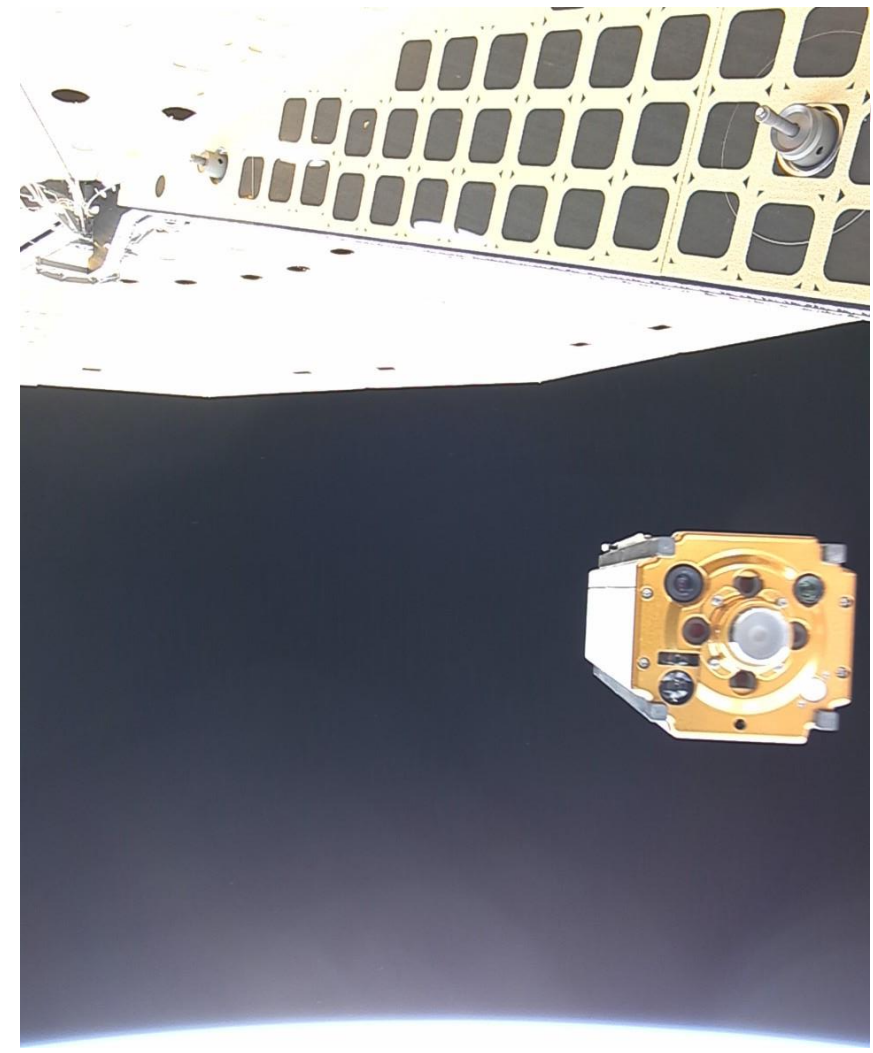
Deployer Integration

## 2019 Actual



**4/17/2019**

Launch



**9/16/2019**

Operations

- **October-present:** data analysis
- **February:** discussion on next steps



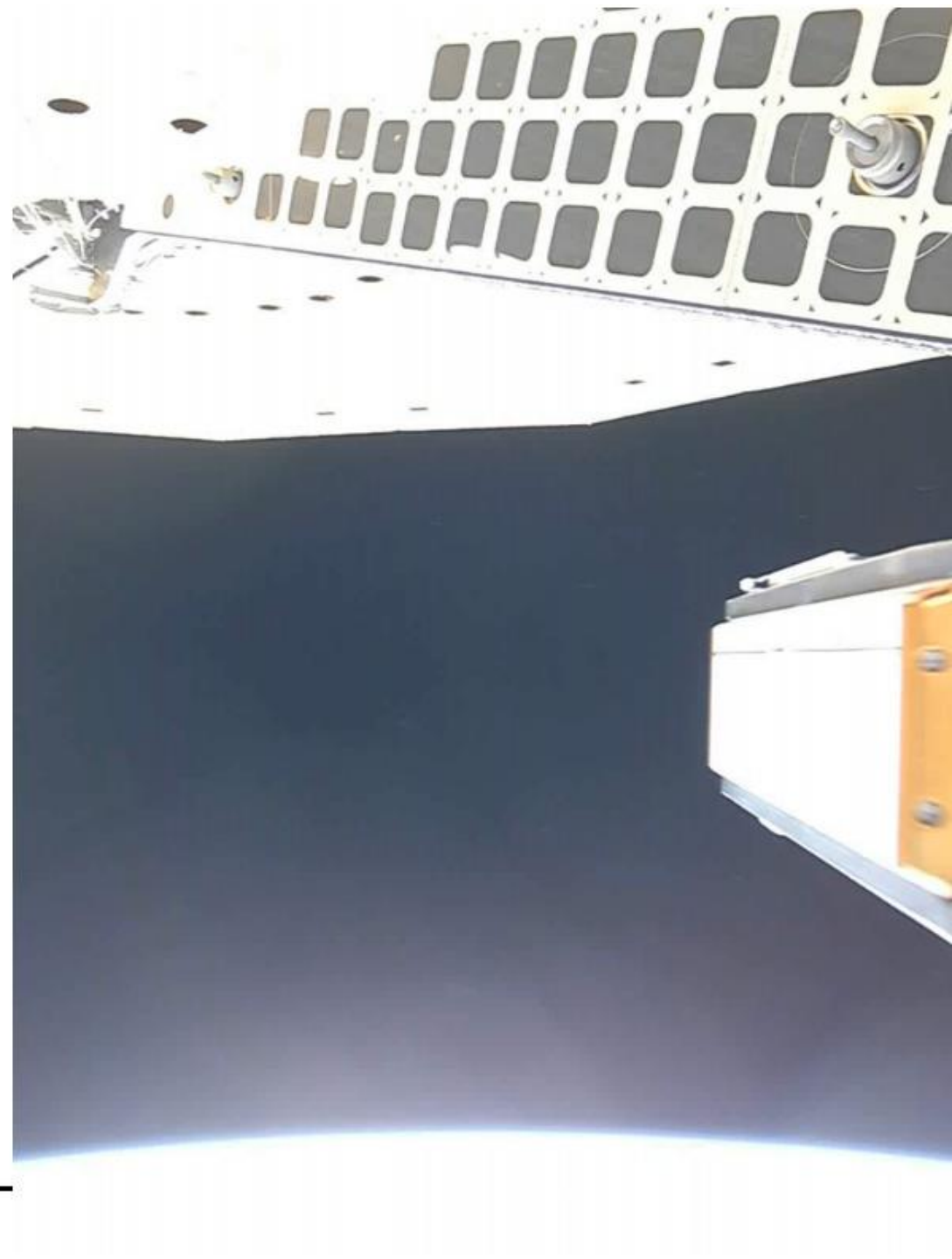
# Mission Operations Timeline



**Seeker deployed at 1900 GMT on 2019-09-16**

- Deploy-6 days: Kenobi power-up and checkout, looks good (no GPS)**
- Deploy-1hr: Kenobi power-up and checkout, looks good (no GPS)**
- Deploy-15min: Seeker power-up and checkout, looks good**
  - Good prop, battery, comm, thermal
- Deploy: Things look as expected**
- Deploy+30s: LRF stops returning measurements, position closer than expected**
- Deploy+60s: some brief LRF returns**
- Deploy+75s: Large, unexpected roll**
- Deploy+130s: communication lost with vehicle**
- Deploy+150s: communication reacquired**
- Deploy+155s: communication lost with the vehicle, inhibit command sent**

# Flight Videos





# Visible Anomalies



## ❑ T+33s: Seeker points off-target

- Likely poor gyro bias estimation, recovers with other sensor measurements

## ❑ T+68s: Seeker begins uncontrolled roll

- Due to insufficient current to command any arbitrary combination of jets, control system prioritizes the channel with the greatest error
- At this time, the system has a very large downrange error– the vehicle believes it has stopped short of its target point and guidance changes modes to accelerate away from Cygnus
- **Uncommanded accelerations apparent in all data** (nav, sensors, BET, etc.)



# GNC Performance

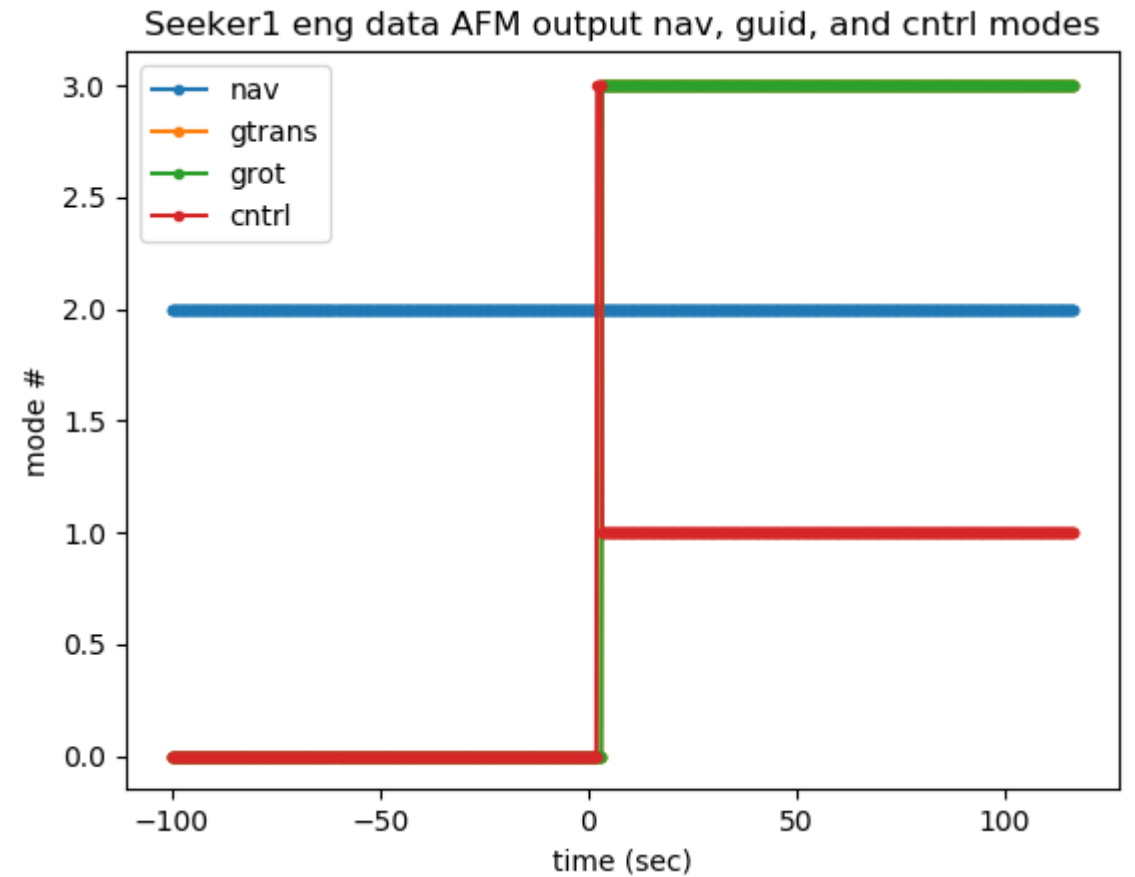
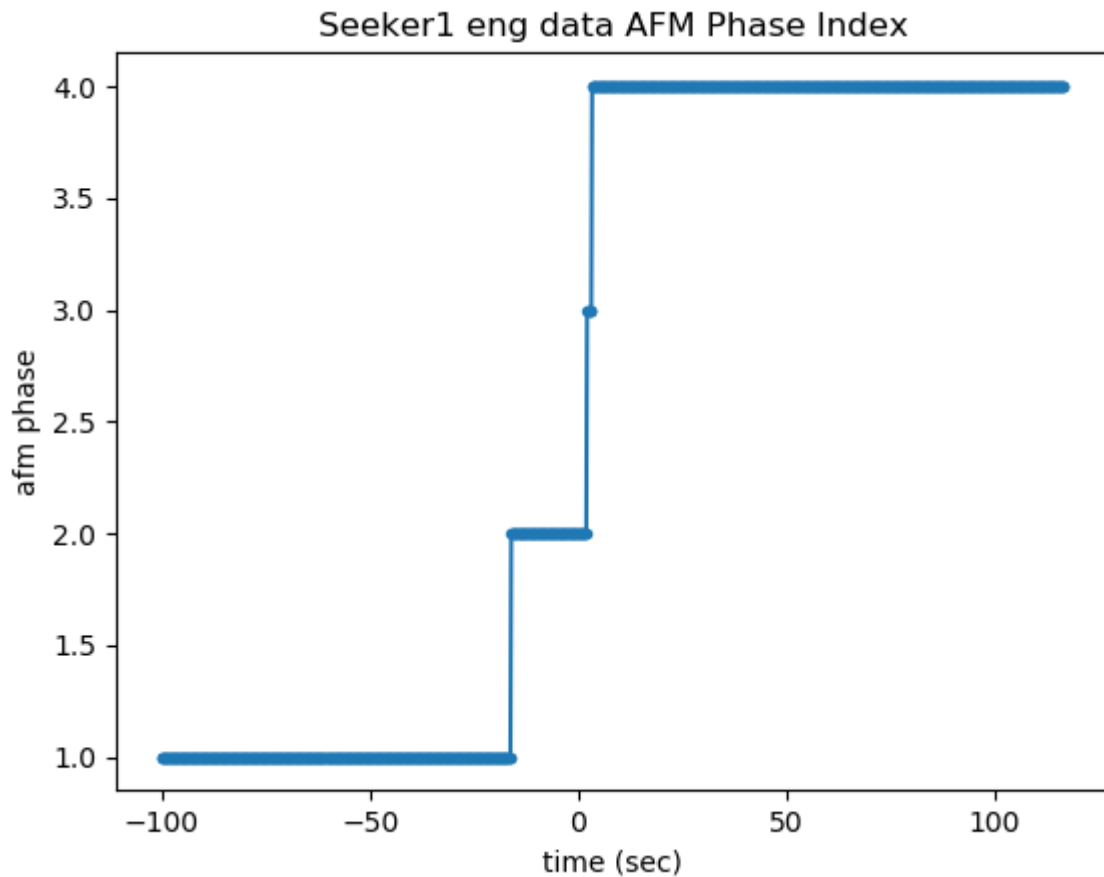




# GNC Performance: AFM



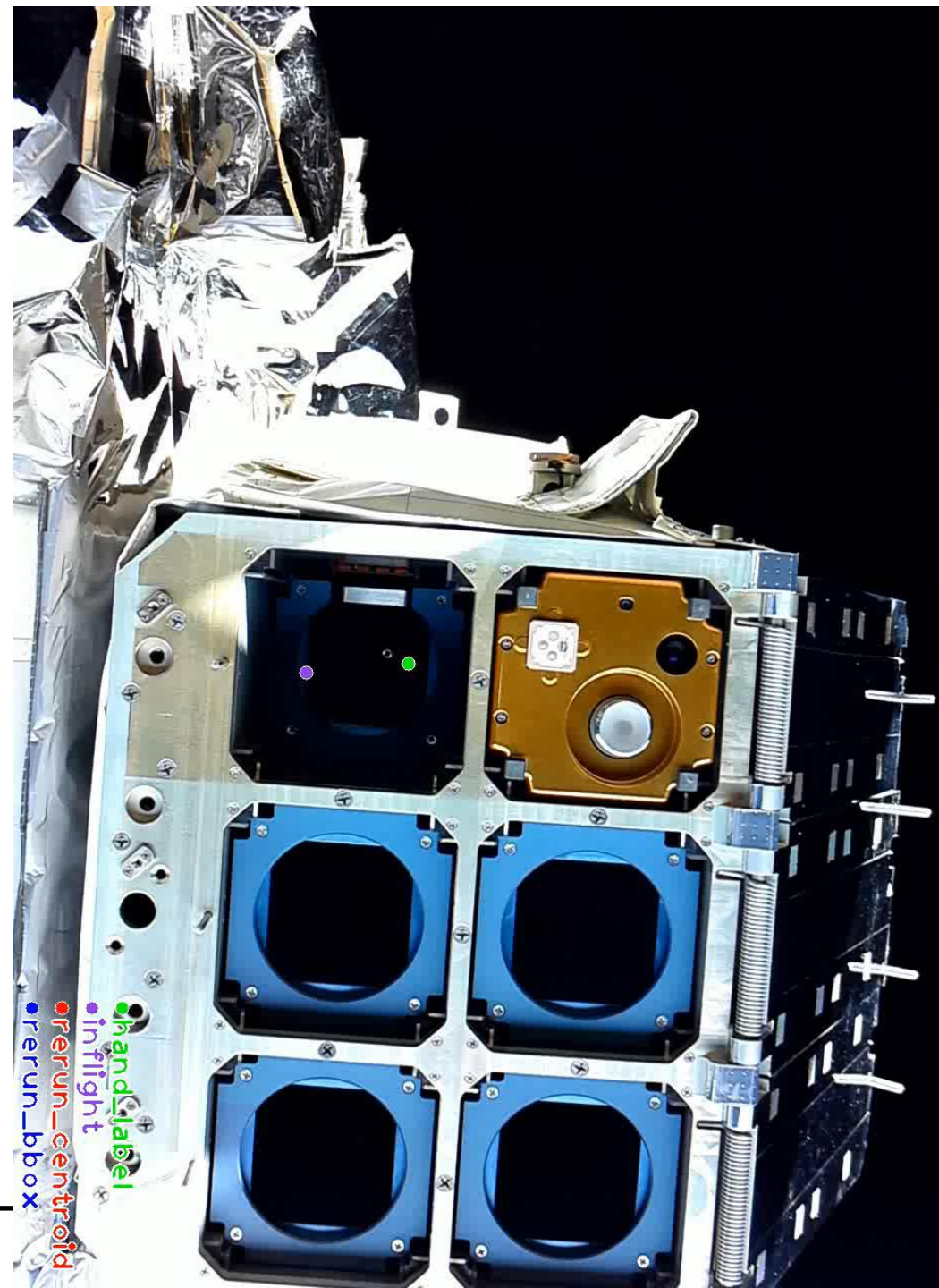
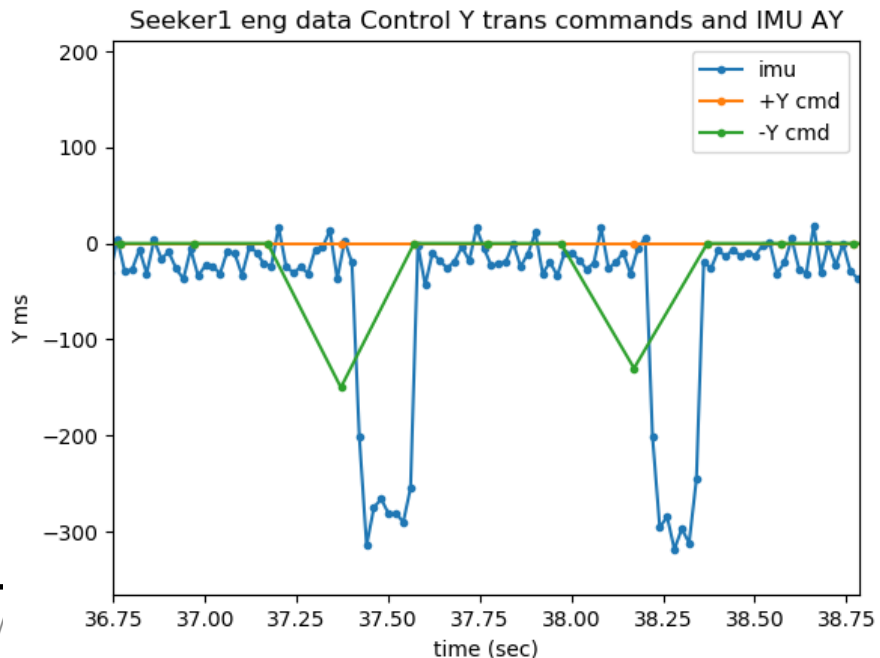
- ❑ Detected deployment as expected
- ❑ Moded vehicle as expected





# GNC Performance: Sensors

- GPS: no acquisition**
  - expected from ground testing and EMI issues
- LRF: worked well**
- IMU: worked well**
- VizNav: worked well**
  - especially given poor camera gain
- Sun sensors: worked fairly well**

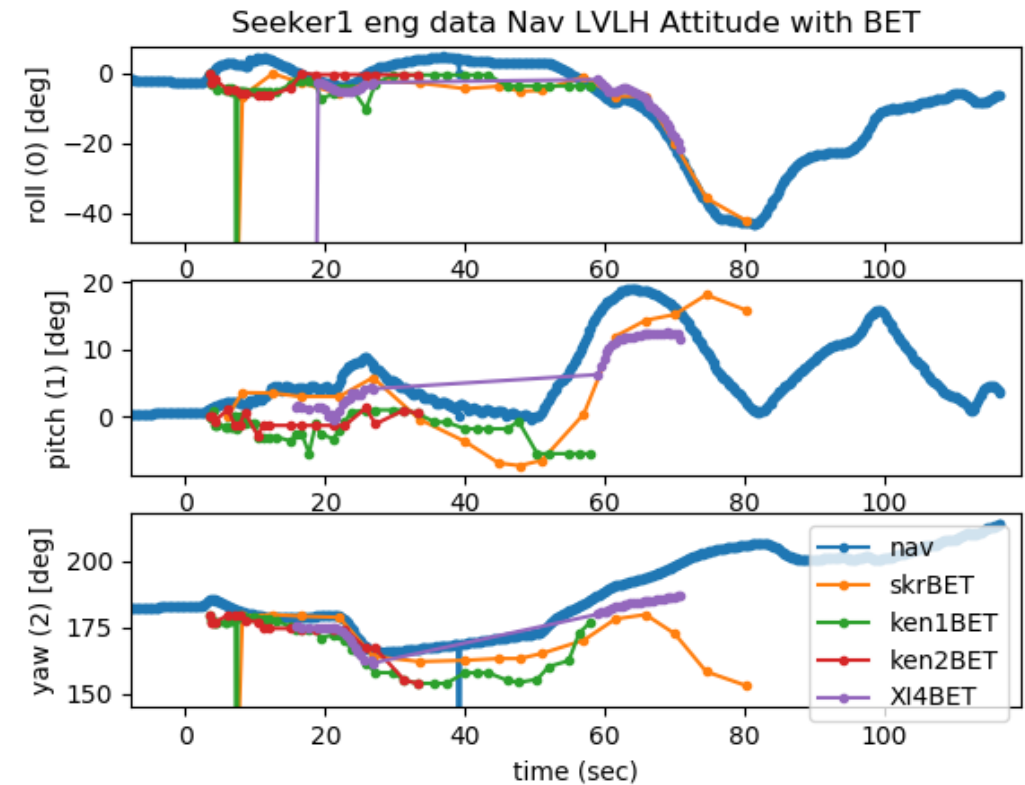
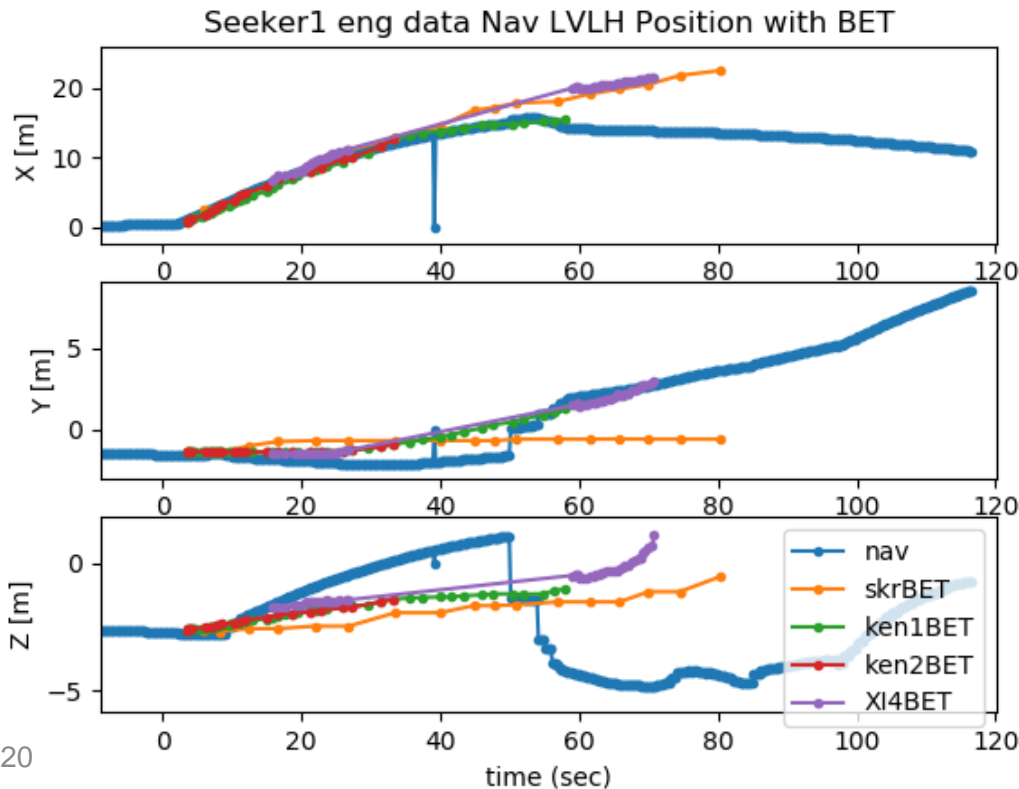




# GNC Performance: Navigation



- ❑ **Poor gyro bias estimation**
  - seen on the ground, missed handoff of bias between propagator and filter
- ❑ **Good agreements with BETs**
  - Within 5 degrees and 5m per axis
- ❑ **VizNav measurement erroneously incorporated into downrange state**

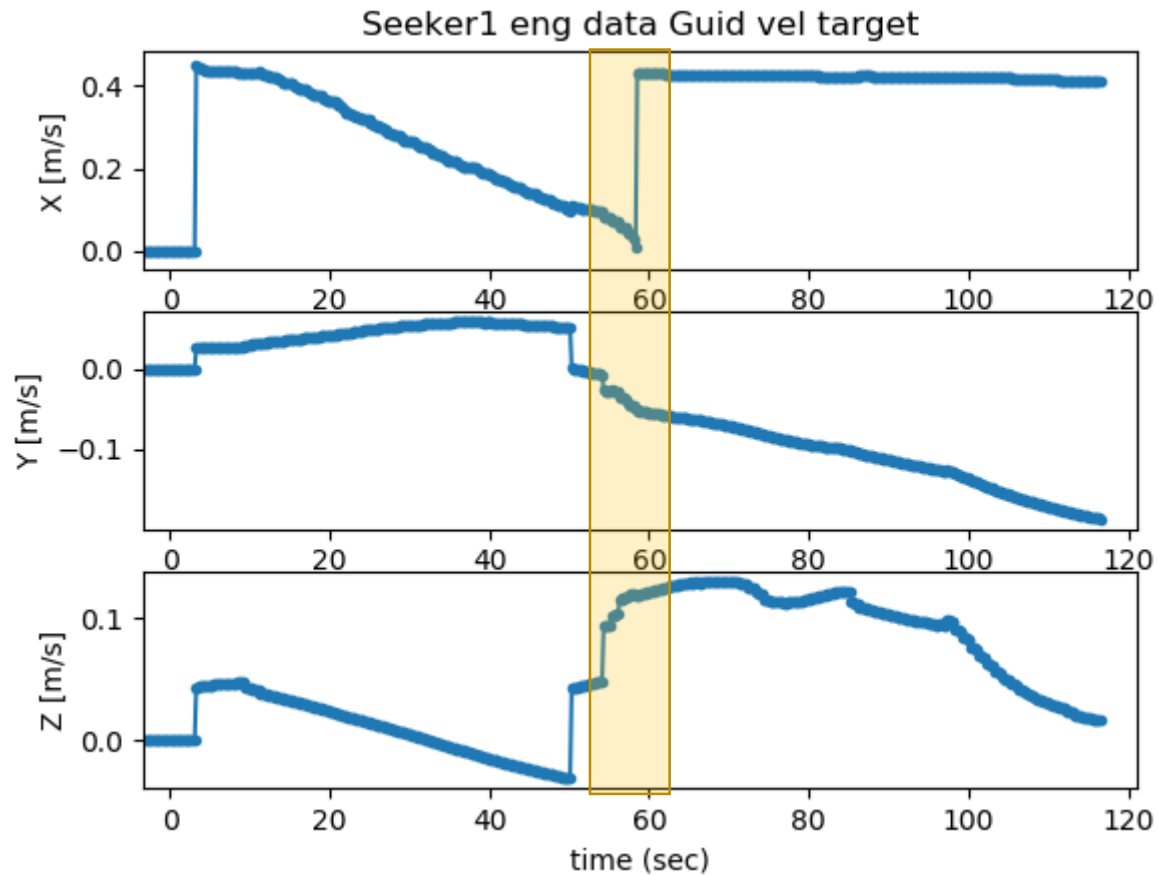




# GNC Performance: Guidance



- ❑ Outputs as expected based on navigation inputs
- ❑ Mode changes as expected
  - Translational mode change at approximately 55 seconds

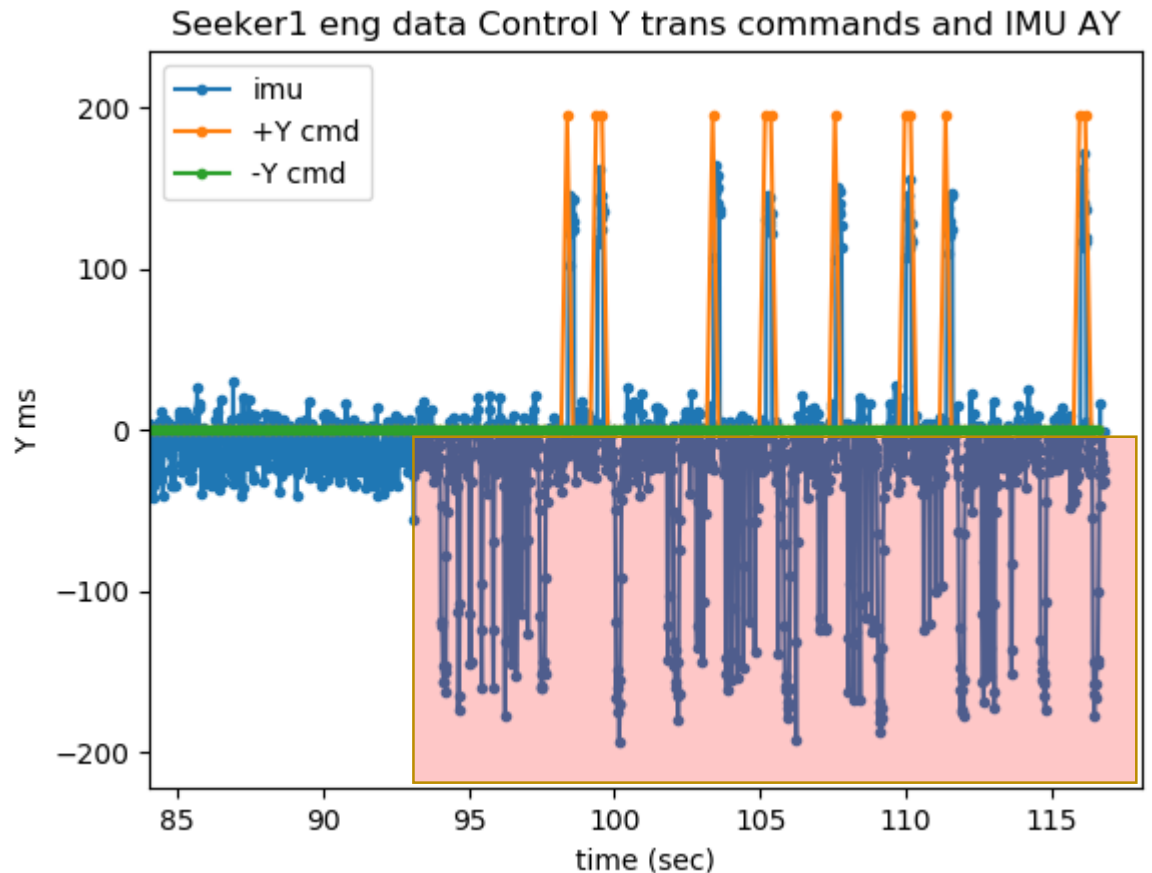
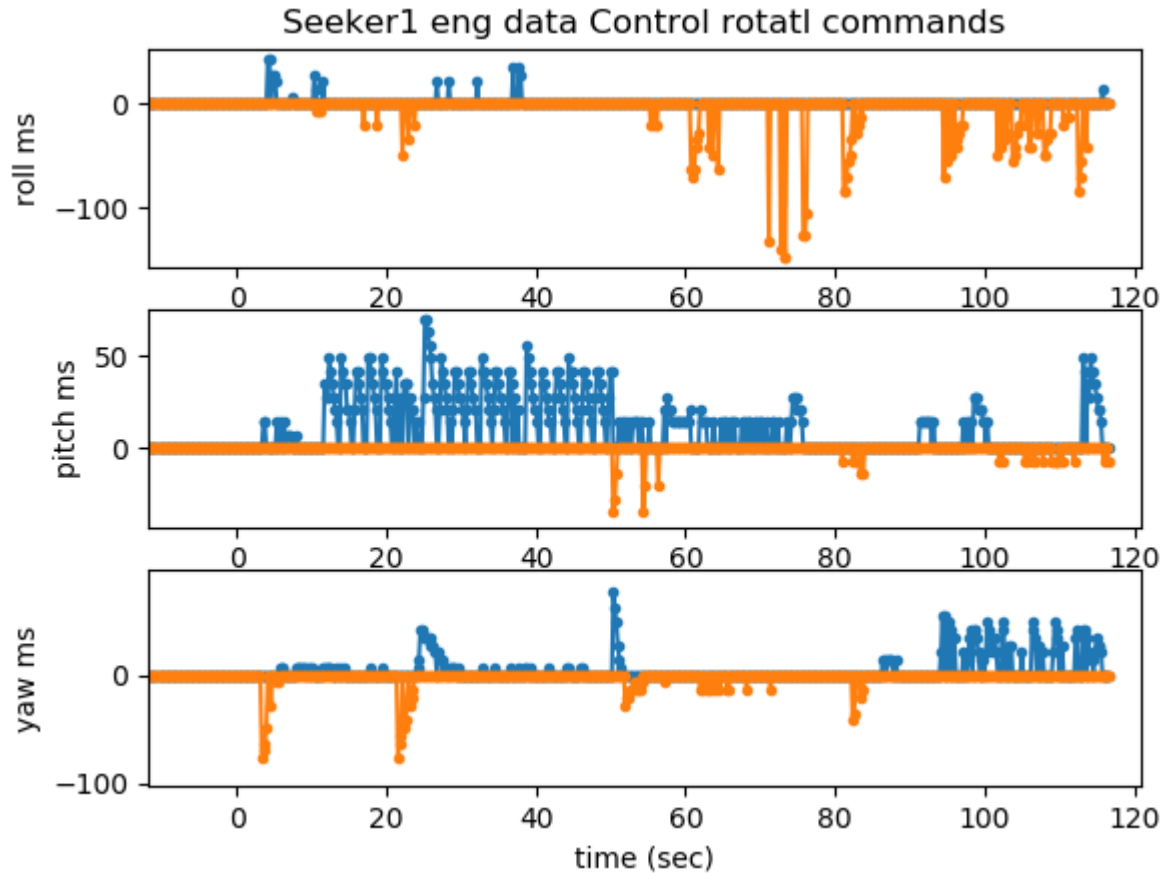




# GNC Performance: Control

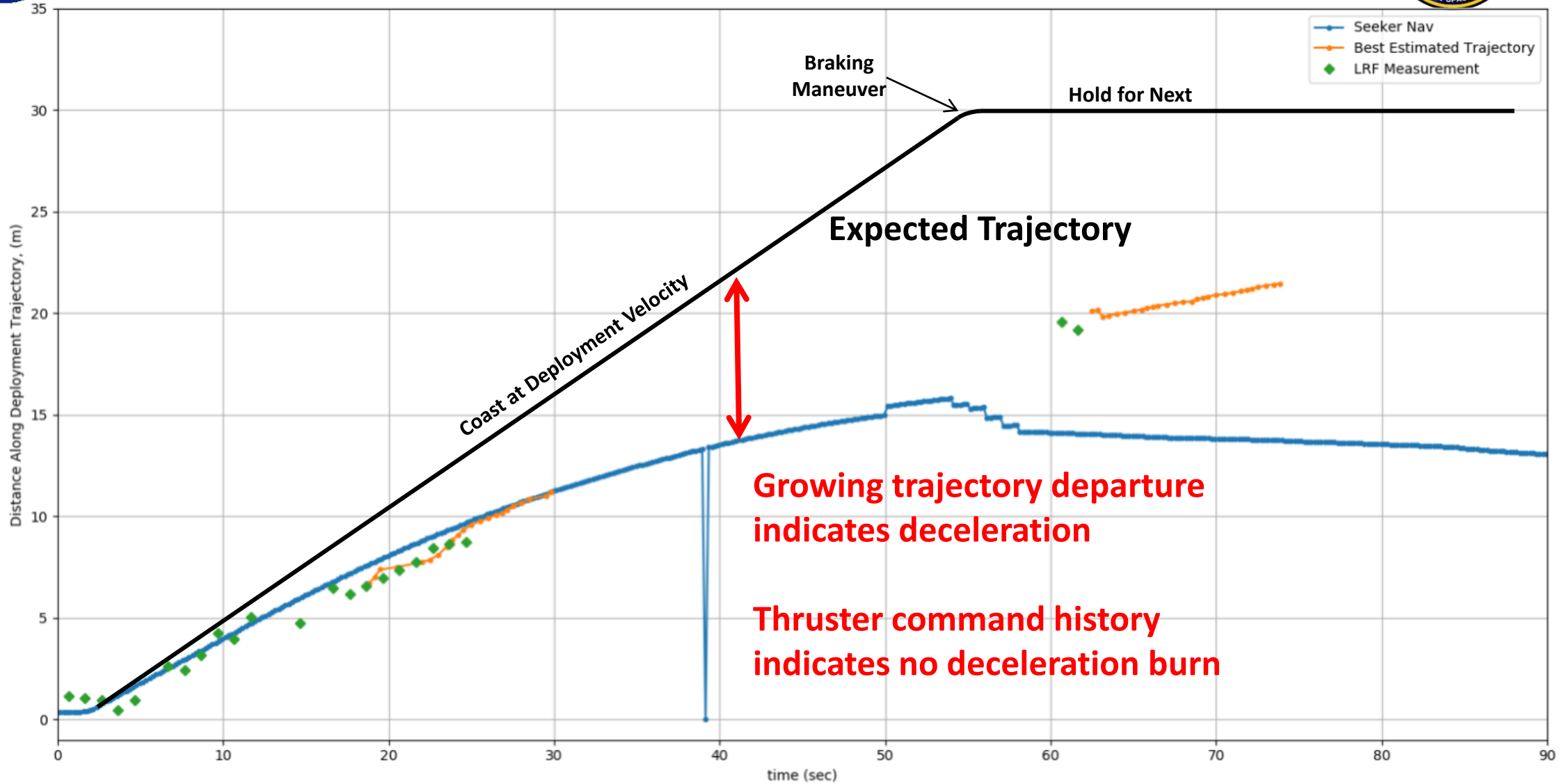


- ❑ Commands all within expected limits
- ❑ Commands as expected based on guidance inputs
- ❑ Some sensed accelerations are uncorrelated to their respective commands





# Uncommanded Deceleration

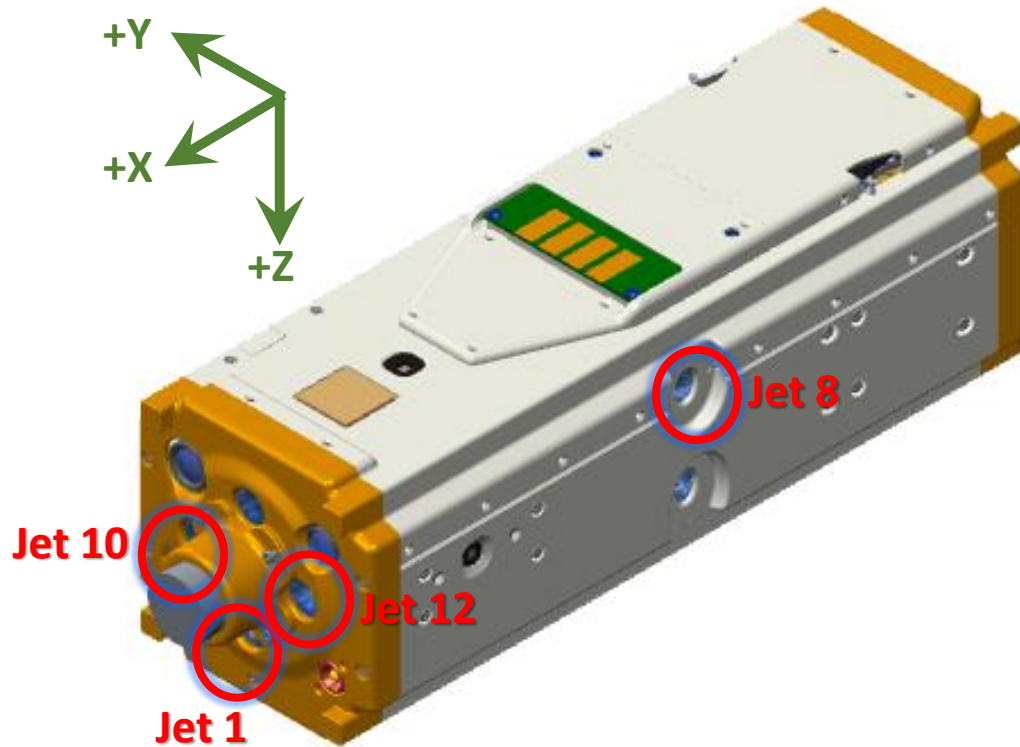




# Fatal Issue – Loss of Vehicle Control



- ❑ Uncommanded accelerations obvious in IMU data
- ❑ Accelerations correlate to intermittent/failed-off thrusters 1, 8, 10, and 12
  - Vehicle could not thrust as designed in 5 axes and could not thrust at all in 1 side of 1 axis



THRUSTER MAP					
TRANSLATION			ROTATION		
Axis	Thrusters		Thrusters		Axis
+ X	9	11	6	7	+ Roll
- X	10	12	5	8	- Roll
+ Y	7	8	1	4	+ Pitch
- Y	5	6	2	3	- Pitch
+ Z	2	4	9	12	+ Yaw
- Z	1	3	10	11	- Yaw
Impaired Axis			Dead Jet		
Dead Axis			Intermittent Jet		



# The Good, the Bad, and the Ugly



## Things that went right

- With the exception of the loss of control, just about everything worked as expected...
- Kenobi powered up with no (unexpected) issues
- Seeker powered up with no issues (plenty of prop/battery and good comm)
- Deploy went smoothly and appears to have been as-advertised
- Vehicle moded exactly as designed
- System captured and downlinked hundreds of pictures and 100MB+ of data
- Delivered on-time
- Great on-console execution

## Things that went wrong

- Did not achieve our advertised 'minimum success'
  - Loss of control

## Easy things we should clean up

- Improve gyro bias estimation
- Acquire hi-res images sooner
- Relocate GPS antennas and address EMI
- Clean up VizNav algorithm
- Record more data
- Time stamp images



# Forward Plan



- ❑ February 2020– Complete analysis and present to stakeholders
- ❑ March 2020– Start Seeker 1.1?
- ❑ Late 2020– Launch onboard NG14?

## ❑ Seeker 1.1

*Fix what broke, clean up what you can, minimize cost and schedule*

- **Big things** (likely root cause)
  - Build prop/avionics qual unit to verify environmental survivability
  - Add 3DOF air bearing demo for jet pair verification
- **Little things** (nice to haves)
  - Update navigation system to properly estimate gyro bias
  - Relocate GPS antennas and shield USB3 connections
  - Remove contouring from VizNav algorithm
  - Timestamp images
  - Record propulsion data onboard at high rate
  - Upgrade camera
  - Update control/prop controller to reduce rejected commands
  - Fix 1Hz telemetry packet timing



# Acknowledgments



**Special thanks to:**

- The ISS Program**
- Northrop Grumman**
- NanoRacks**
- Draper Laboratory**
- The UT-Austin vision-based navigation team**

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**And many more!**



# Backup

