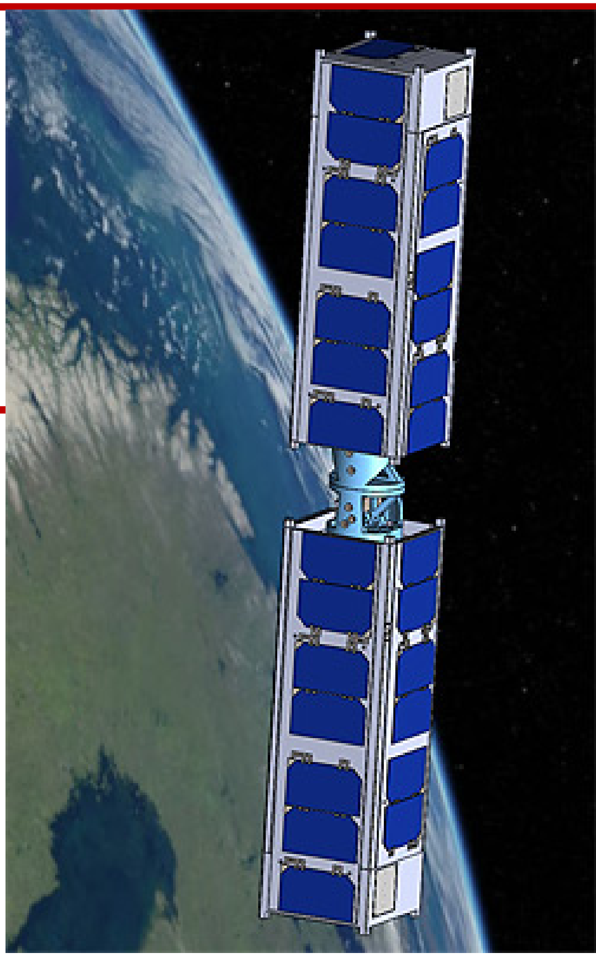
CornellEngineering
Sibley School of Mechanical and Aerospace Engineering

Pathfinder for Autonomous Navigation:
Flight Demonstration of Commercial Off-the-Shelf Technologies for Spacecraft Rendezvous and Docking



Mason Peck

May 10, 2023

Adapted and Updated from
Stewart Aslan, Kyle Krol, and Mason Peck
AIAA SciTech Forum
January 2021

23* Grand Challenges in Space Robotics

- In a future where **in-situ resources**, **in-orbit manufacturing**, and virtually **unlimited processing** and memory capabilities are commonplace, what does space robotics look like?

- A vision for space robotics in this future brings together **trusted autonomy** and spacecraft architectures for a **sustainable presence** beyond Earth orbit. It embraces the opportunities and challenges that will arise when we cut the cord that ties robotic spacecraft to the Earth and come to depend almost entirely upon resources from the lunar surface, asteroids, and beyond.

* *cf*. David Hilbert, *Mathematical Problems*, Lecture delivered before the International Congress of Mathematicians at Paris in 1900 in BULLETIN (New Series) OF THE AMERICAN MATHEMATICAL SOCIETY Volume 37, Number 4, pp 407–436 S 0273-0979(00)00881-8

23* Grand Challenges in Space Robotics

- These 23 challenges are framed in terms of open questions, but a candidate "moonshot" solution is also offered, around which technology development might coalesce.
- I.e., the text in this list is formatted as "**open research area** *: tech demo opportunity*"

Electromechanical

1) **High Torque, High Agility**: *CMG Robotics*
2) **Bioinspired Locomotion and Energy Scavenging**: *Soft Robotics for Planetary Exploration*
3) **Eliminate sliding and rolling contacts**: *Compliant Mechanisms for Long Life*
4) **Power Resilience**: *Modular, Embedded Power*
5) **Low Power Robotics**: *Gyroscopic Actuation*
6) **Reduce or Eliminate Integration and Test on the Ground**: *Self-Healing Space Robotics*

Algorithmic

7) **Trusted Robotic Space Autonomy**: *Provably Correct AI in Flight Code*
8) **Transfer Learning for Autonomous Navigation**: *Train on the Moon, Prospect on an Asteroid*
9) **Robotic Discovery**: *Learn to Identify the Unknown, and then Measure It*
10) **Stem Cell Robots**: *Modular, Reconfigurable Core Flight Executable*
11) **Autonomous navigation without GNSS**: *Dead Reckoning Network in Lava Tubes*

Assistive

12) **Overcome Pressure-Suit Limitations**: *Iron Man Space Suit*
13) **Mobile Planetary Surface Networks**: *Microrover Network for Lunar Operations*
14) **Eliminate Astronaut Risk and Fatigue**: *Astronaut Shadowing*

In-Space Servicing, Assembly, and Manufacturing

15) **Surface Transportation**: *Lunar Superconducting Maglev*
16) **Cislunar Supply Chain Logistics**: *Self-Organizing Propellant Depots*
17) **Large-Aperture Telescope***: Infinite Truss*
18) **ISAM with Non-aerospace Materials:** *Robotic Sintering in Space*
19) **Minimal-Mass Additive Manufacturing**: *Micro-additive Assembly*
20) **Evolutionary Robotics**: *Robots Building Robots*
21) **Spacecraft-Independent Inspection and Repair**: *Eddy-current actuated robotic inspector*
22) **Invisibility**: *Microscale Robotic Inspectors*
23) **Autonomous Lunar Infrastructure**: *Robotically Assembled Lunar Runway*

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The PAN Response

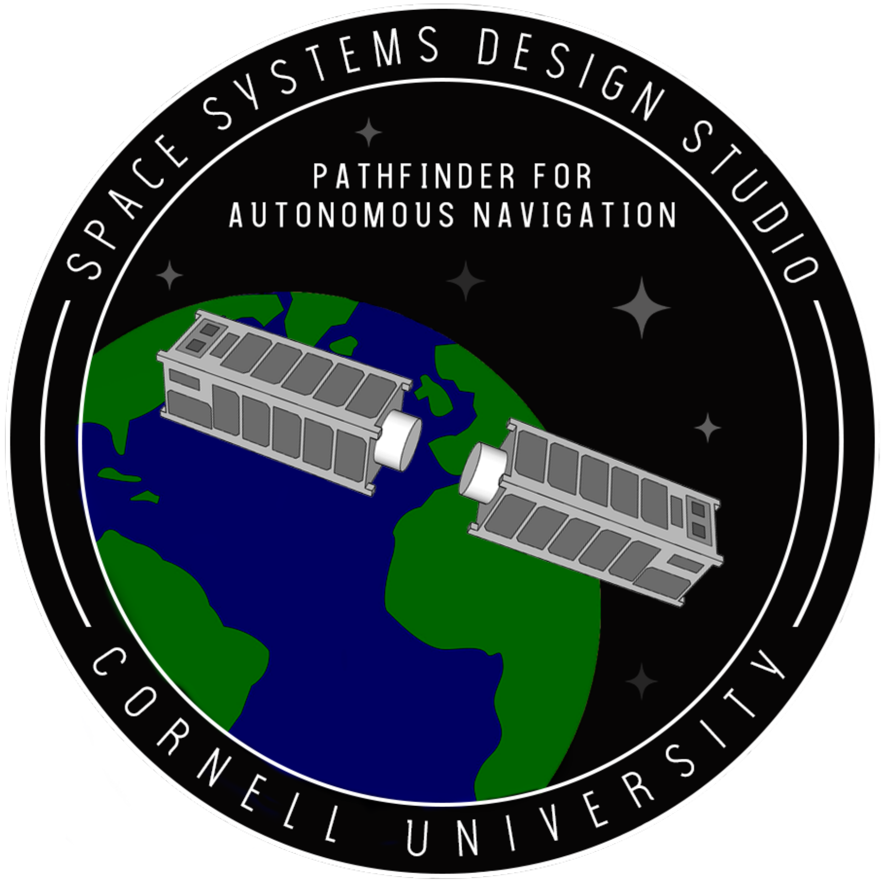
- **Goal:** Autonomous CubeSat rendezvous, docking, and relative navigation for self-assembly of large space structures; a pathfinder for autonomous navigation (PAN)

Highly-Capable, Low-Cost CubeSats

- PAN reduces cost and increases capability:
  - Passive electromagnetic docking technique robust to attitude and position errors,
  - Spacecraft autonomy enables reliance on low-datarate Iridium constellation communications, eliminating the need for costly ground infrastructure,
  - Minimal ΔV for rendezvous at the expense of a long mission
- These cost savings, along with modular and adaptable subsystems, lay out a path toward highly capable, mass-produced smart truss elements

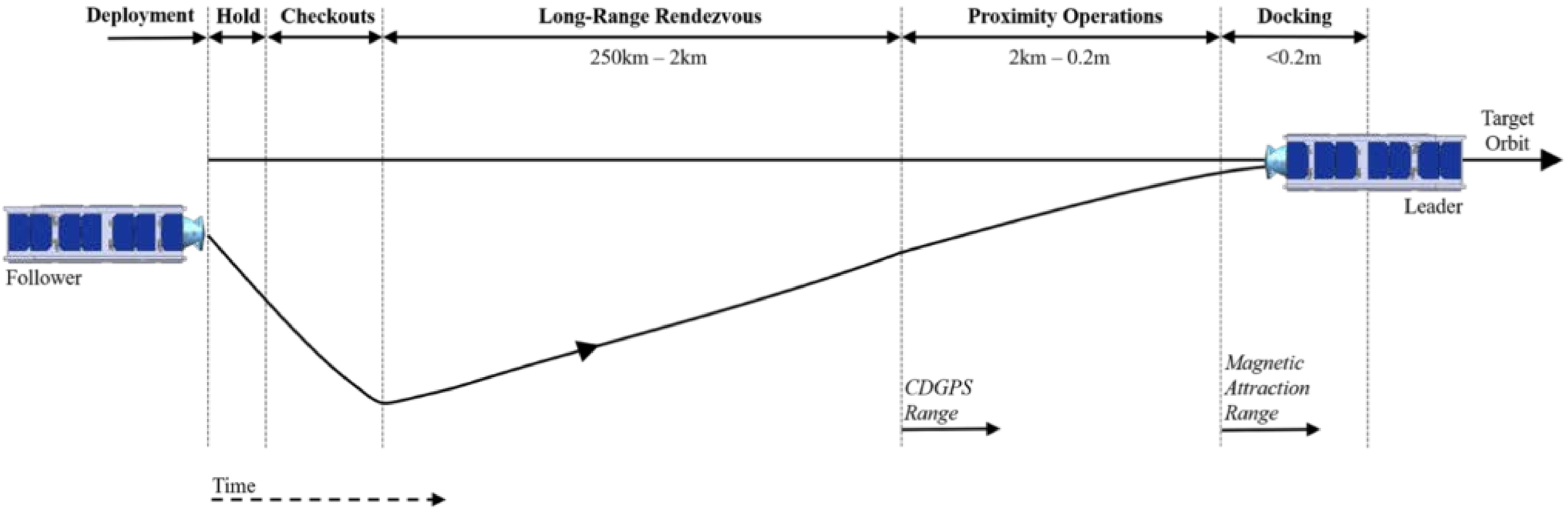
Technology Overview

- Mission Architecture
- Key Subsystems
  - Rendezvous and Docking
  - Guidance, Navigation, and Control
  - Communications
- Flight Experience
- Lessons Learned



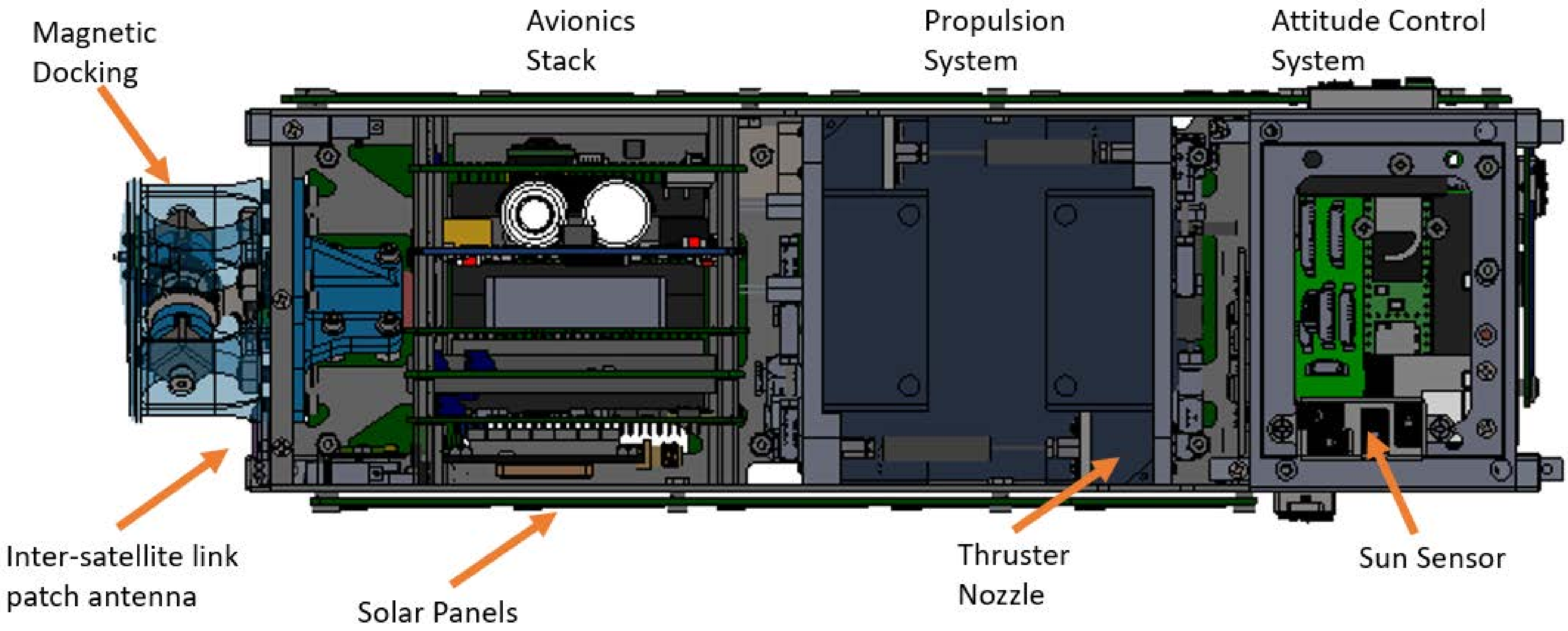
Mission Overview

- Two 3U+ PAN CubeSats deploy simultaneously, drift apart, and rendezvous during the 1-3 month mission
- Short-range communications between the two PAN spacecraft during Proximity Operations facilitates autonomy and precision relative navigation

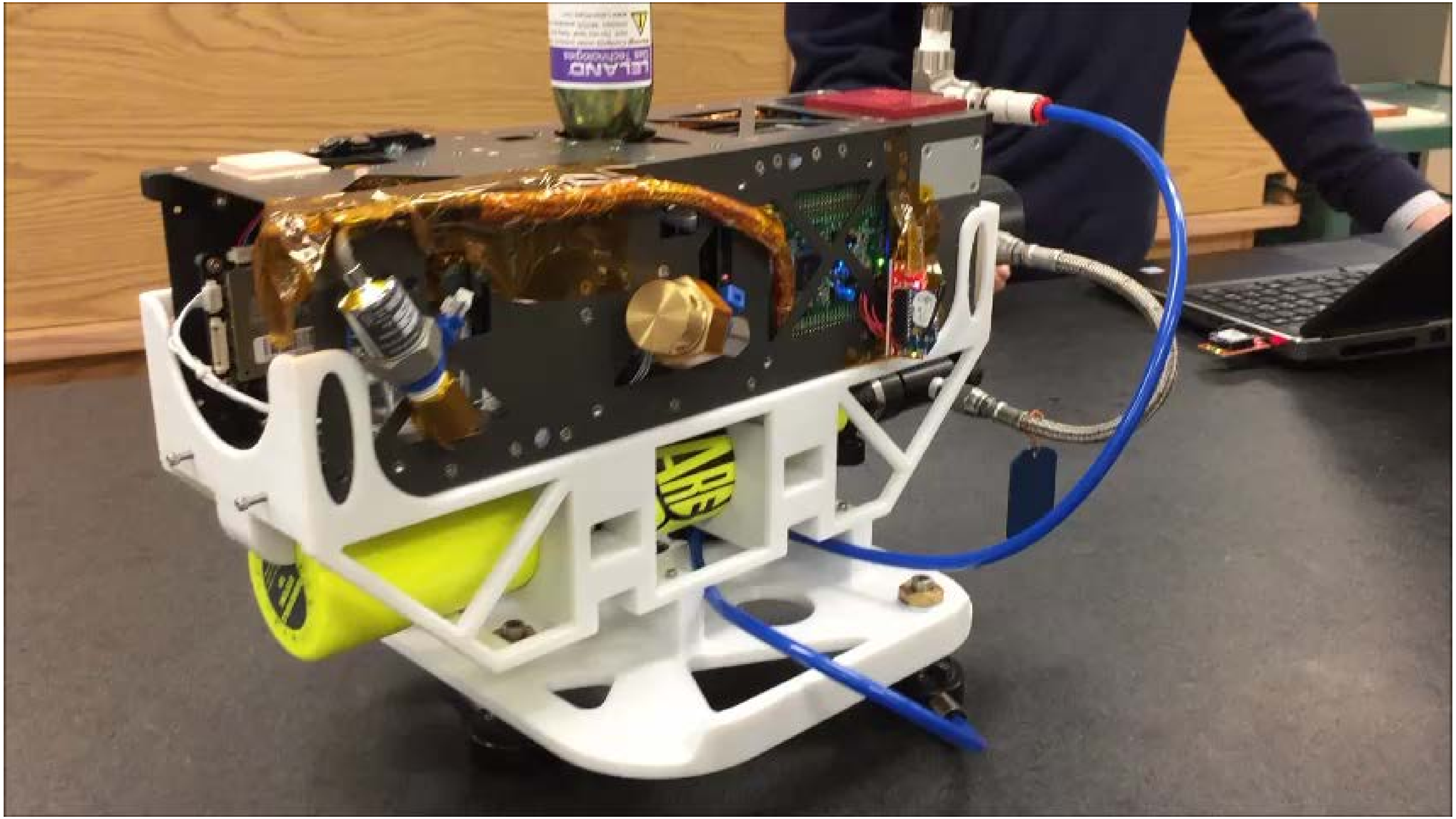


Mission Overview

- PAN's subsystems leverage commercial off the shelf (COTS) parts to reduce cost and maximize modularity and adaptability to other missions.

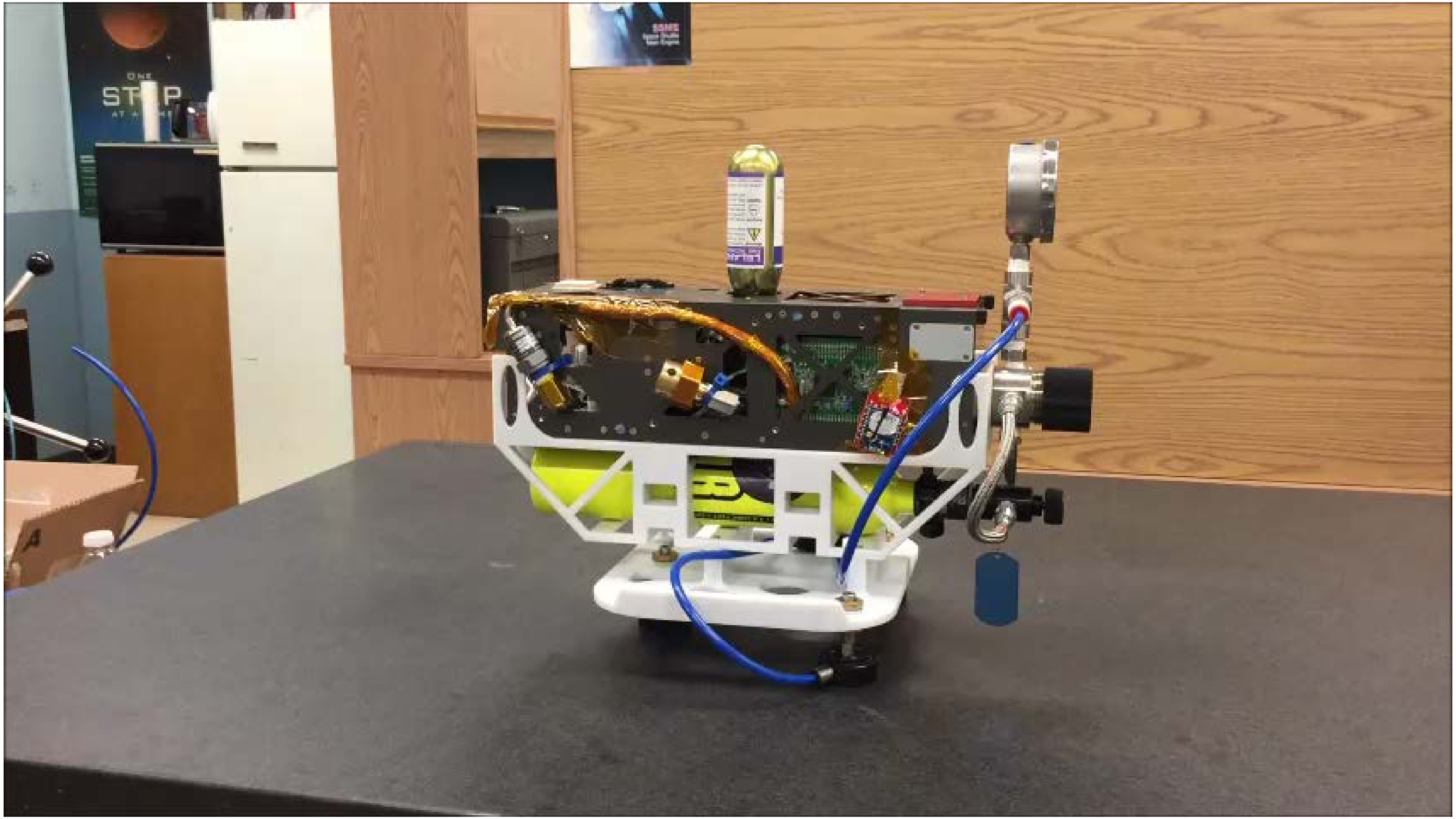


Technology Validation



Prototype Developed for NASA/LaRC for an Early Career Initiative in 2015 with Luke Murchison on the OAAN Project

Technology Validation

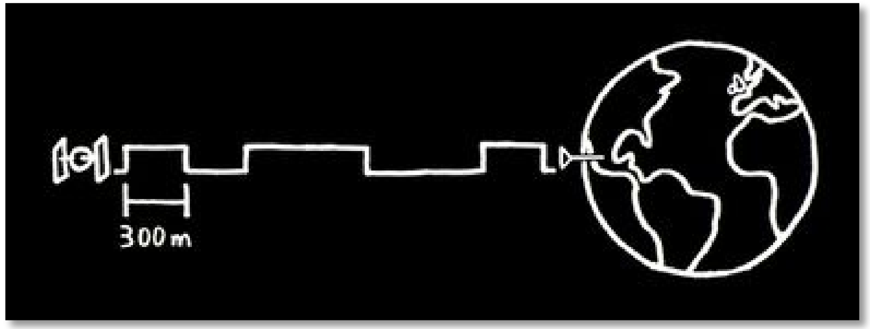


Prototype Developed for NASA/LaRC for an Early Career Initiative in 2015 with Luke Murchison on the OAAN Project

Sensing for Rendezvous and Docking

- Carrier-Phase Differential (CD) GPS estimates relative position on the centimeter scale (2, 3), compared to meter-scale code-phase GPS position estimates (1).
- Existing rendezvous and docking designs use cameras, LIDAR or laser range finders [6], [7], [8], [9].
- PAN uses inexpensive COTS CDGPS receivers for ~3 cm accurate relative navigation
- PAN's magnetic docking system is robust to significant pointing and position errors (<30 deg, <50 cm).

1



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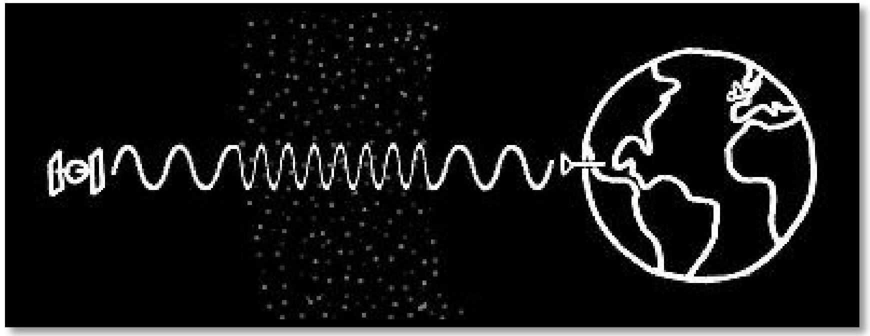

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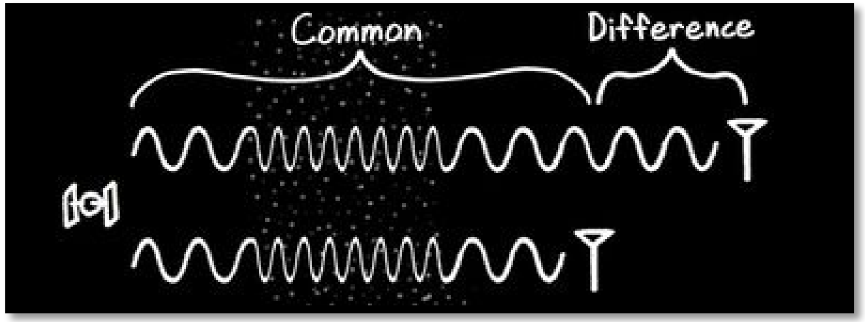
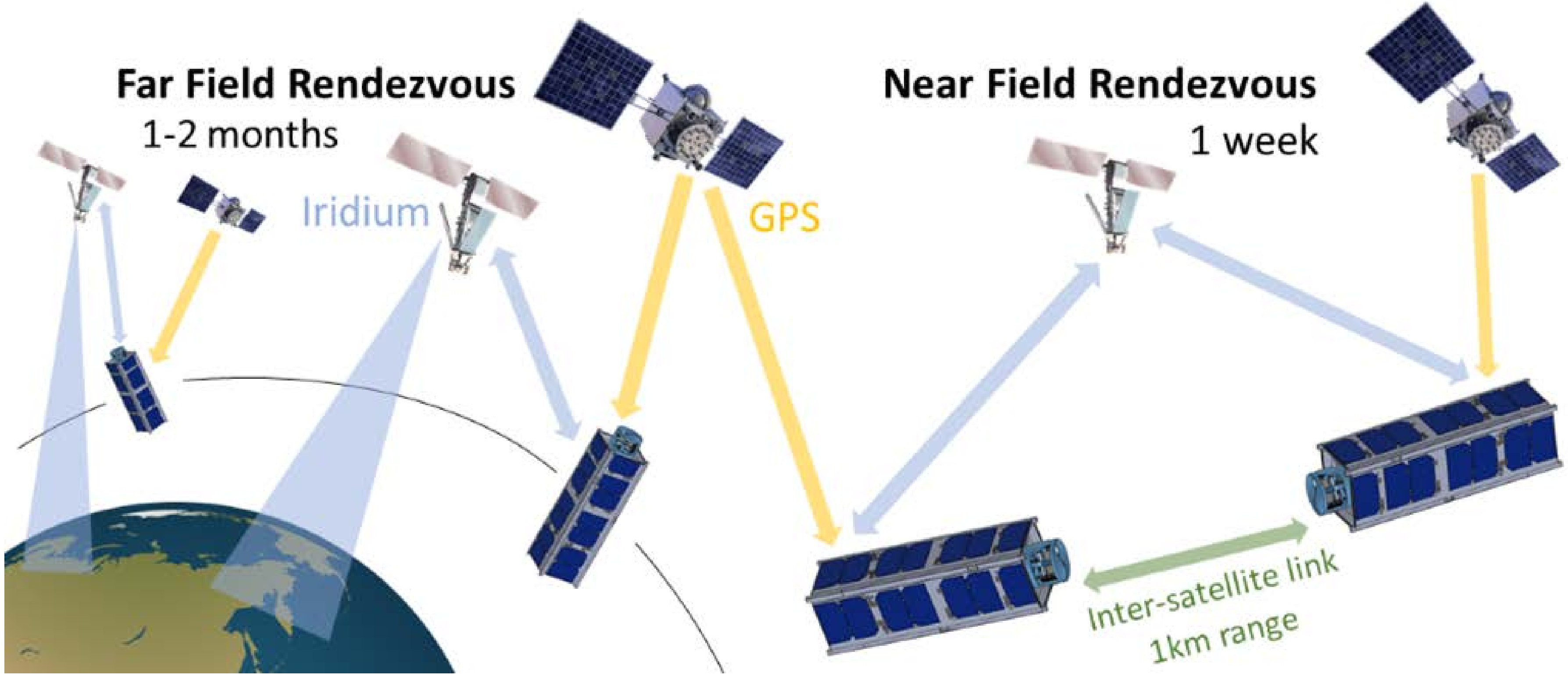


Code-Phase vs. Carrier-Phase GPS, Courtesy of Swift Navigation

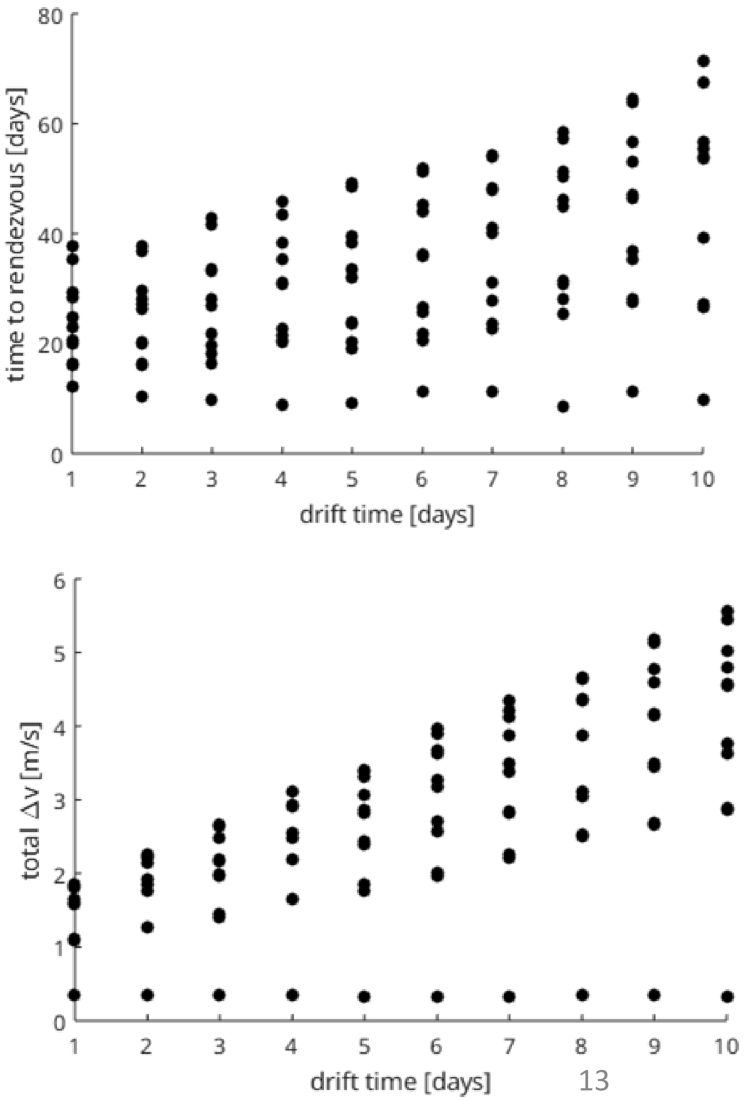
Communications for Rendezvous & Docking

- Far Field Rendezvous
  - Ground acts as a relay between the two PAN spacecraft when they are outside of inter-satellite link range
- Near Field Rendezvous
  - CDGPS position shared by inter-satellite link for precision relative navigation



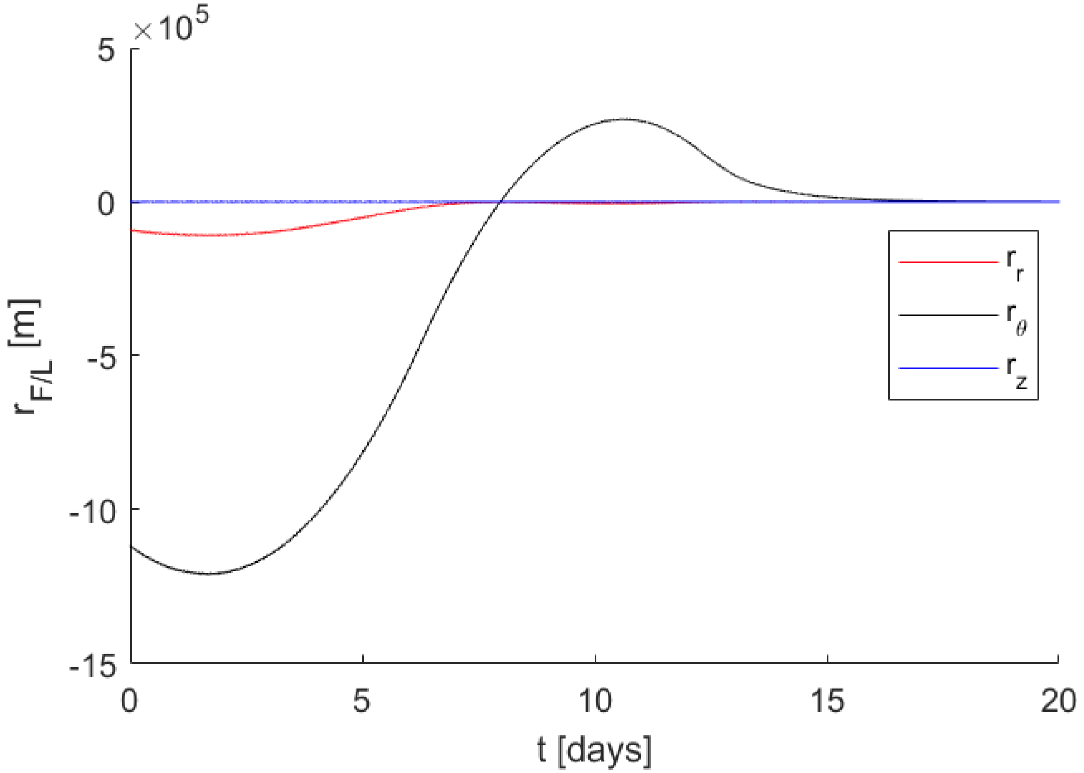
Guidance, Navigation, and Control

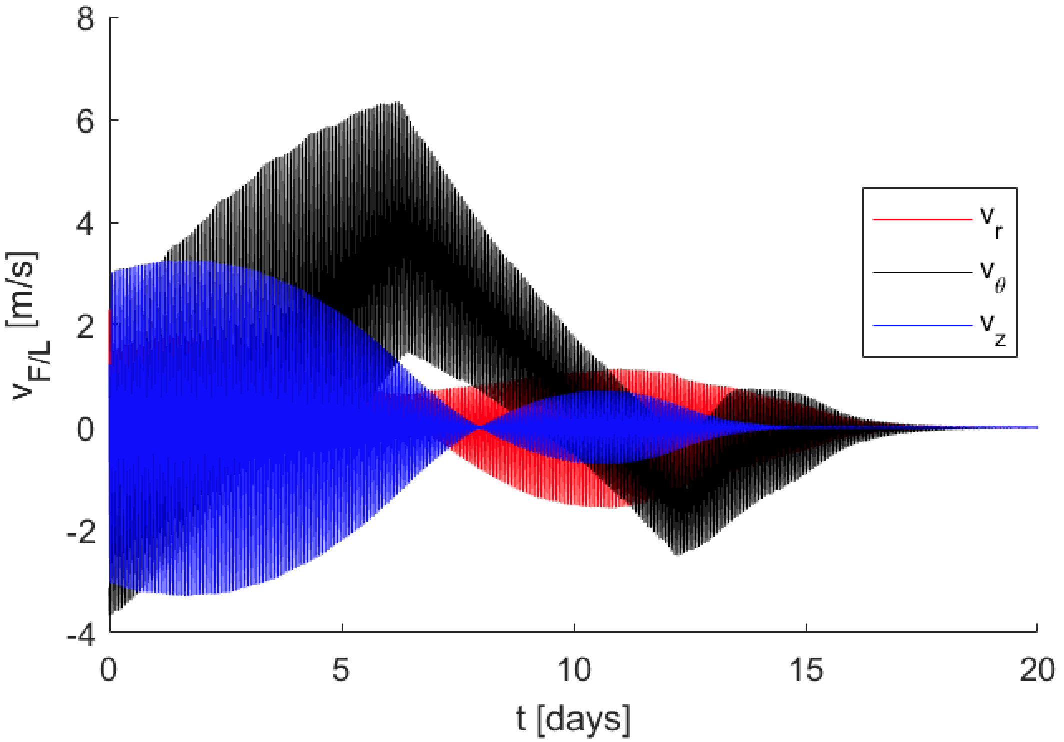
- A novel orbit matching algorithm was developed with an emphasis on minimizing Δv at the cost of increased mission duration [15]
  - Allows the use of a simple, inexpensive, cold-gas propulsion system with low Δv and thrust capability
- Thruster firings are scheduled autonomously at three points along the orbit delivering between 0.125 mNs and 25.0 mNs impulse per firing
  - Compatible with low-thrust cold gas or electric propulsion systems
- A group of 110 flight-like scenarios shows:
  - The required Δv is significantly less than the 14 m/s capability of PAN’s propulsion system [10]
  - The rendezvous is completed within the required mission length of three months



Guidance, Navigation, and Control

Simulated Position and Velocity





Simulated rendezvous starting from initial conditions with the largest difference in position and velocity between the two spacecraft in the $\hat{\mathbf{e}}\boldsymbol{\theta}$ direction. The Follower spacecraft took approximately 18 days to rendezvous with the Leader, firing three times per orbit and using approximately 4.25 m/s of ΔV.

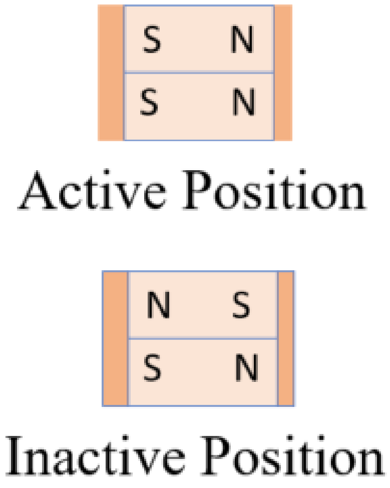
Communications

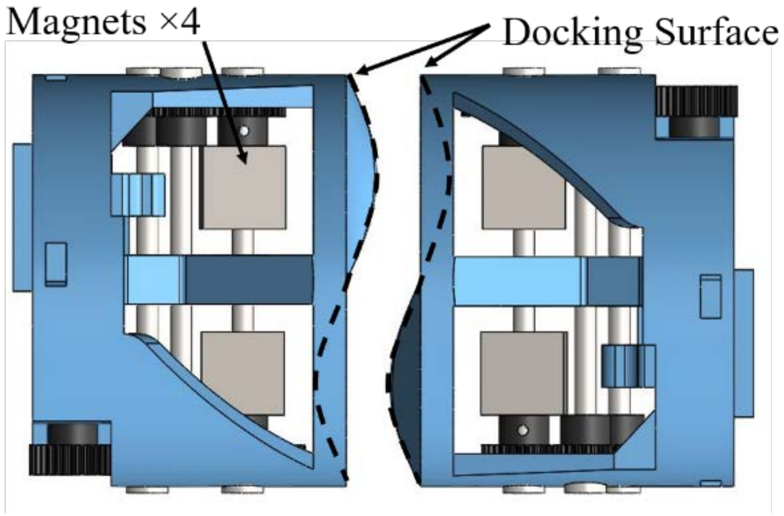
- Increased CubeSat autonomy enables low-bandwidth communication with relatively infrequent downlinks
  - An inexpensive Iridium transceiver on board PAN sends and receives 70-byte packets through the Iridium constellation
- Leveraging Iridium's existing network eliminates the need for dedicated ground resources
  - PAN's ground segment consists of a single server and laptop computer, reducing the overall cost of the mission
- TechEdSat demonstrated Iridium communications on orbit [16]. From this data we expected about 100 downlinks per day.
- PAN is the first CubeSat to rely solely on an existing satellite constellation for telemetry and command, as far as the literature indicates

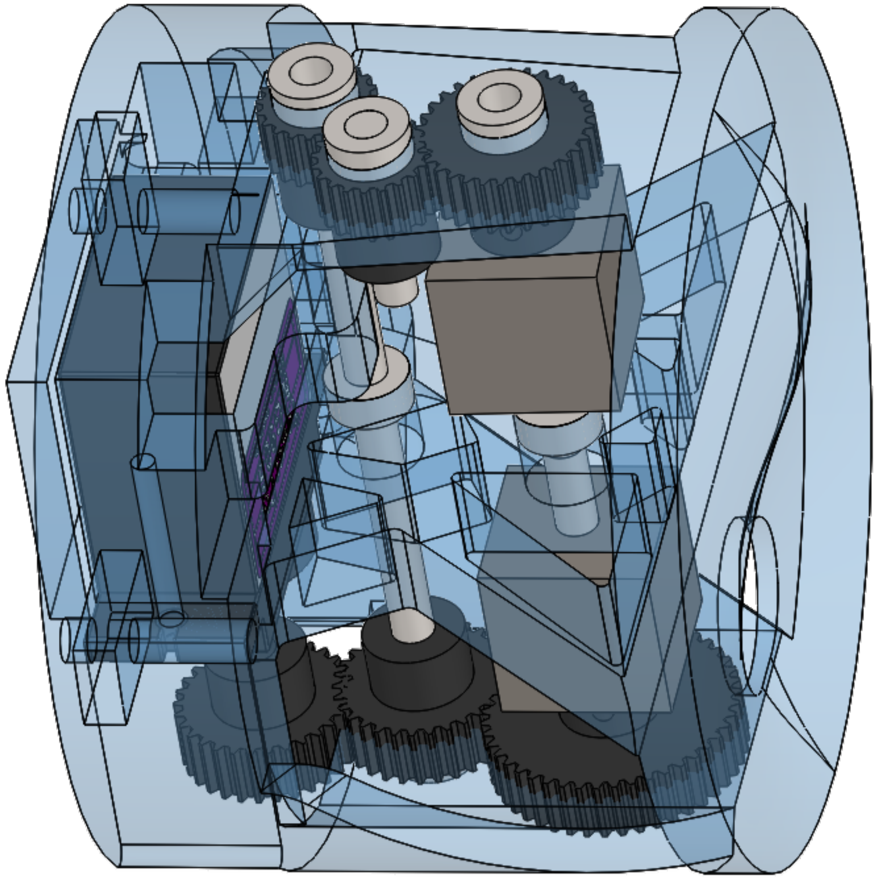
Quake Qlocate Iridium Radio & GPS receiver

Docking Technology

- Variable magnetic field without electromagnets.
- Mechanically rotates permanent magnet to produce north- or south-directed field for attraction or repulsion.
- Enables docking with very low power.

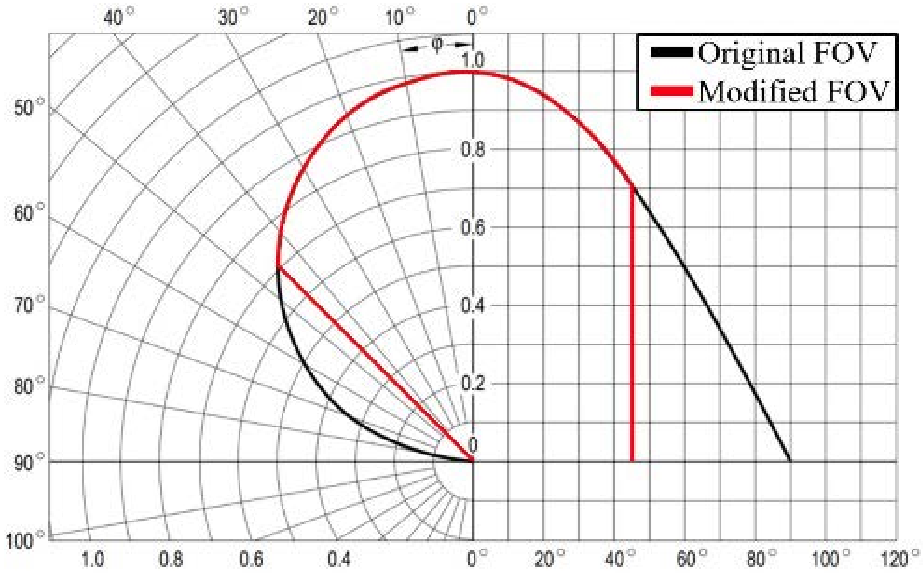




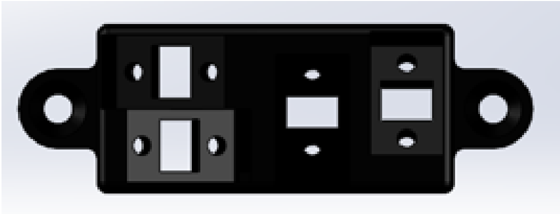


Other Technologies: Sun Sensors

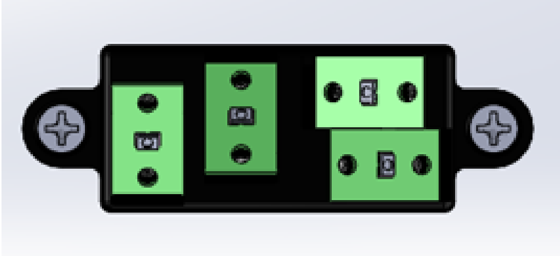
- 3D Printed Mounting brackets for 4 COTS photodiodes with shallow baffles.
- Each photodiode returns an analog voltage, and the combination of 4 could provide a least-squares estimate of the sun unit vector
- 5 such units are distributed across the spacecraft, one on each face except the docking side.
- Flight-system implantation used a look-up table of all 20 photodiodes' responses to test data to provide an optimal 4π steradian sun-angle estimate.
- After a Kalman Filter, the result is accurate to σ=0.2°



Photodiode voltage response to sun angle



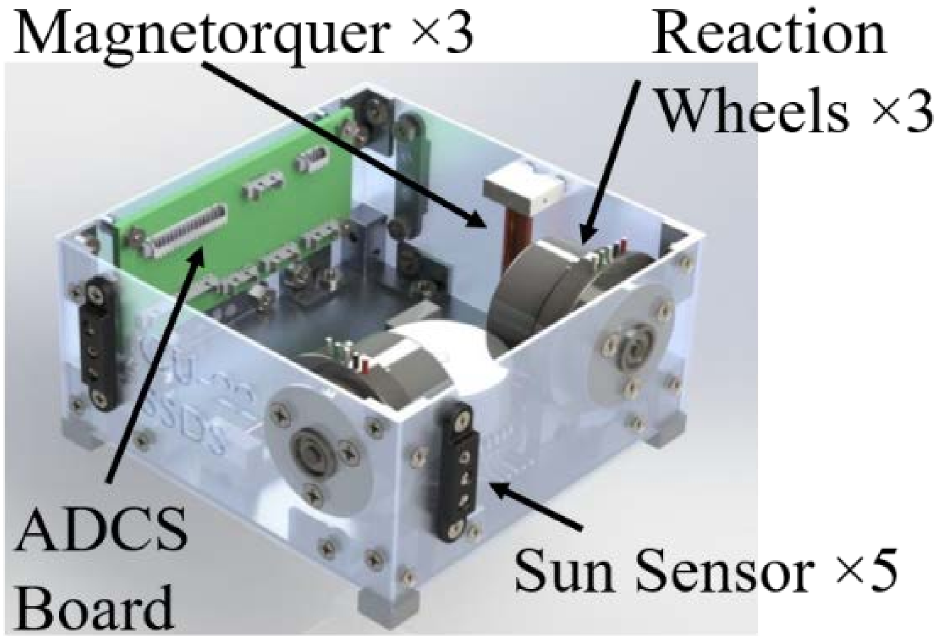
3D printed base



Photodiodes and PCBs

Other Technologies: Magnetorquers

- Hand-wound ferrite-core electromagnets with scale magnetometers.
- ACS torque command is achieved with a closed-loop control of the current based on the magnetometer’s measurement, virtually eliminating hysteresis and any unwanted residual magnetic moment.
- Steady-state torque is possible through residual magnetic moment (i.e. without power) as the control input goes to zero.
- Very low-cost performance comparable to high-quality, high-cost components.

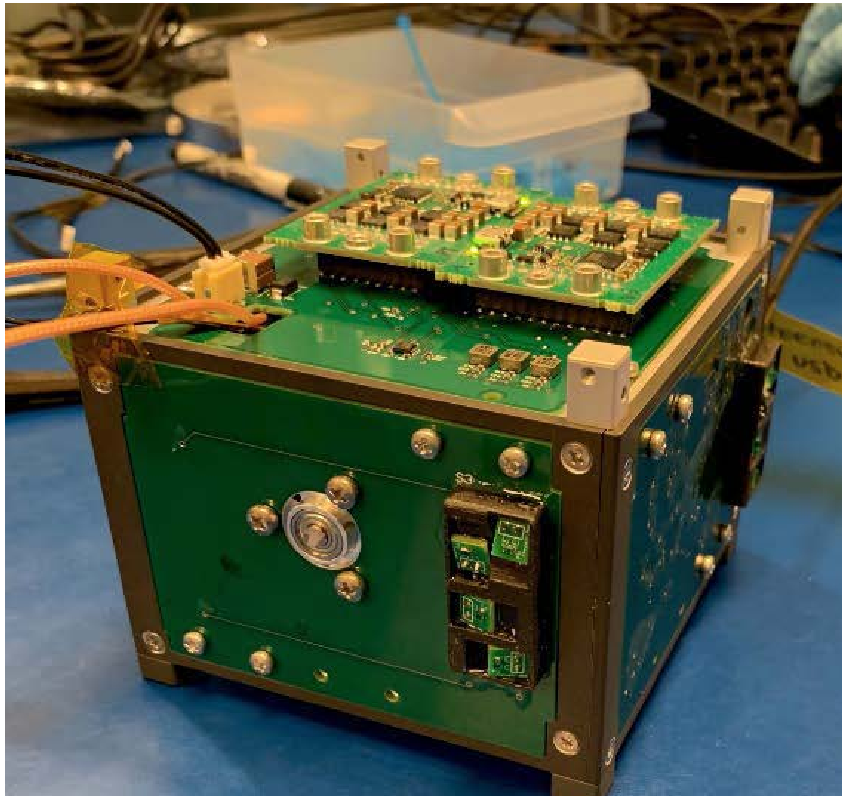


Other Technologies: ACS Subsystem

- Attitude-Control Subsystem (ACS) includes
  - 3 reaction wheels (COTS pancake motors with shafts cut off)
  - 3 mag torquers (see above)
  - Multi-axis sun sensors (see above)

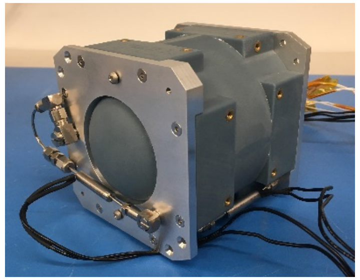
- Integrated as a 1U subsystem that mates to 2U rails.
- Replaces 3rd party subsystem from a vendor that delivered 8 months late, did not provide required software emulator, and did not support I&T

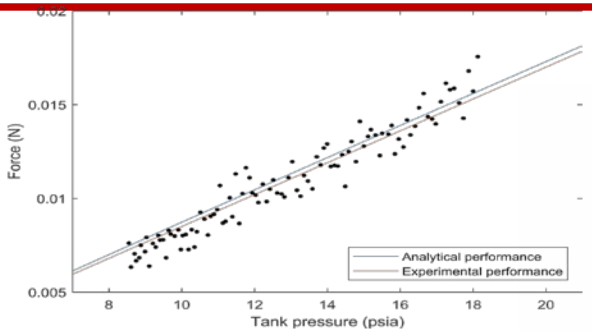
Single-axis momentum storage capacity [mNms]	Single-axis torque capability [mNm]	Pointing accuracy [deg]	Mass [kg]	Avg, power consumption [W]
3.67	3.67	0.7 (3-sigma)	0.791	1.997

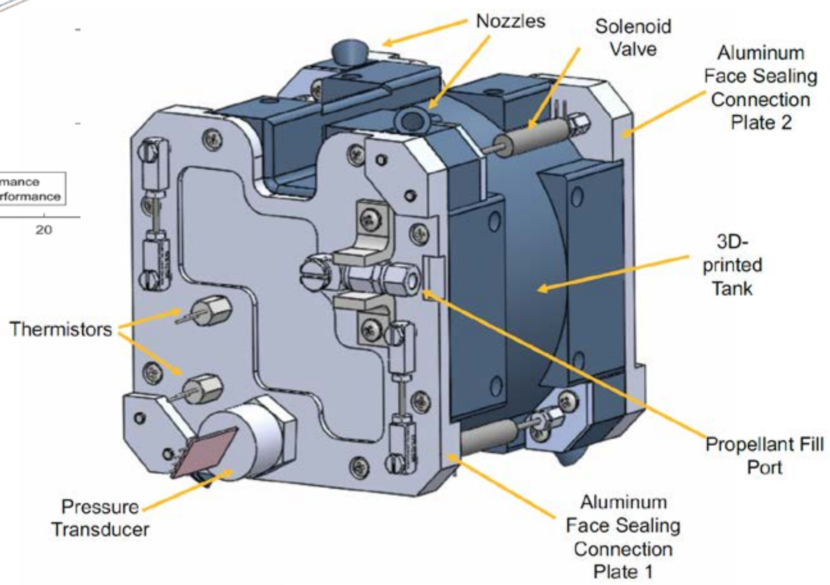


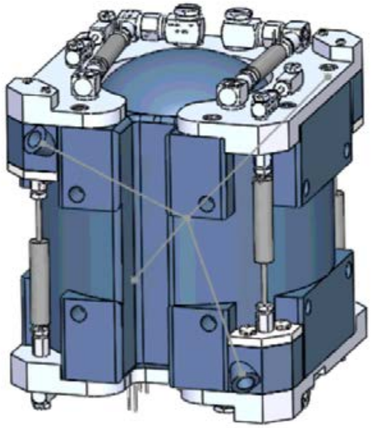
Other Technologies: Propulsion Subsystem

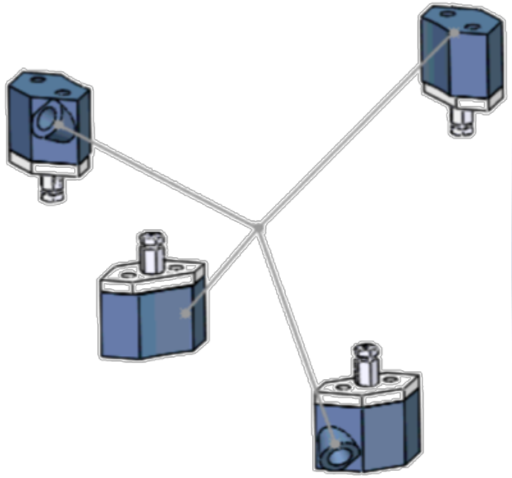
- Cold Gas ()
- COTS solenoid valves
- 3D printed nested tanks
  - Inner tank maintains pressure for liquid storage
  - Outer tank stores propellant in gaseous form
- 3D printed nozzles can be reconfigured (reprinted) to align optimally with measured, as-built spacecraft CM during I&T

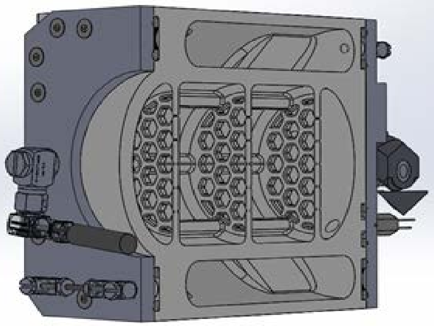


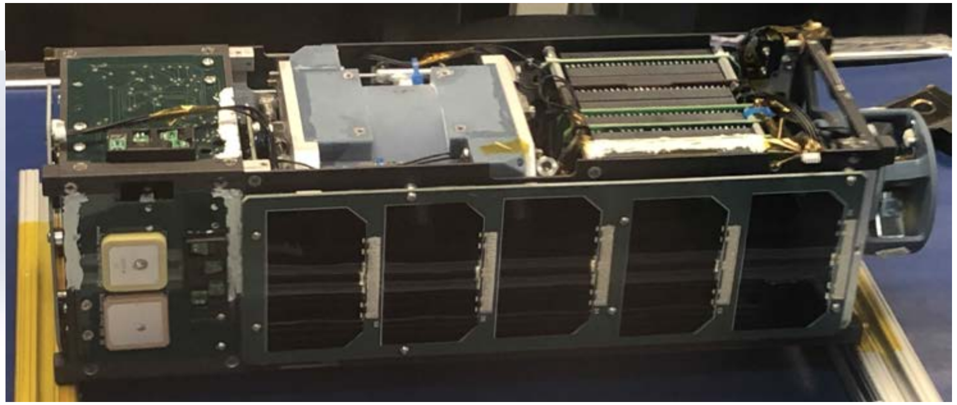






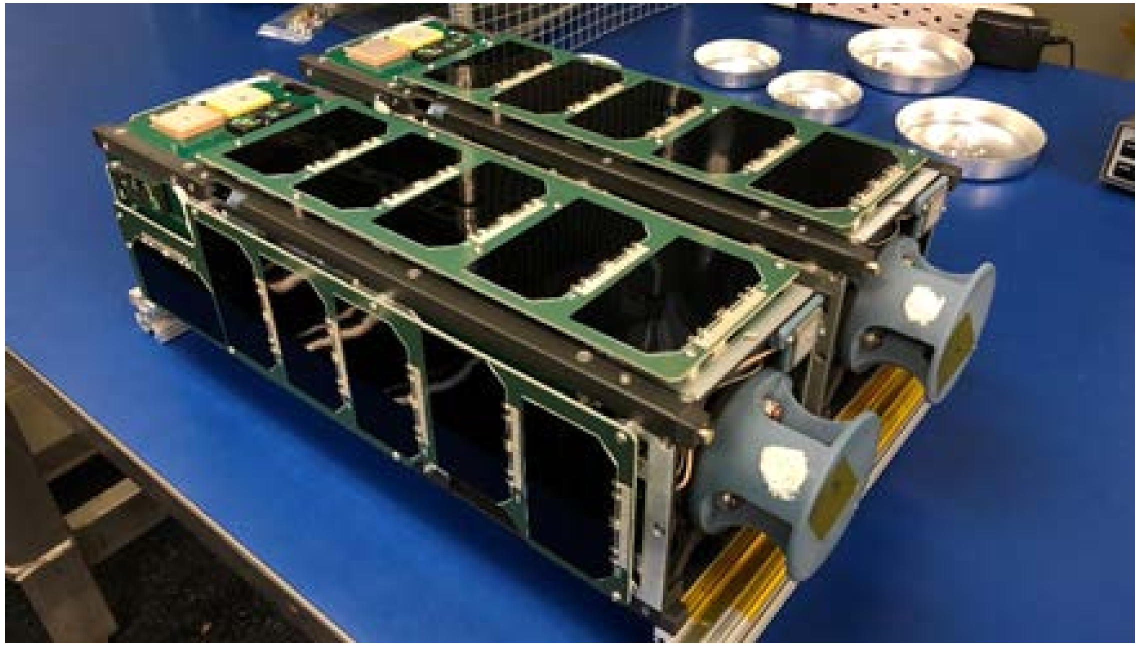






Mission Operations and Flight Experience

- Selected for NASA’s CubeSat Launch Initiative in March 2018
- Manifested on STP-27VPB (Virgin Orbit launch)
- Launched January 13, 2022



Mission Operations and Flight Experience

ELaNa Mission Number: 29

Launch Date: January 13, 2022

Deployment Date: January 13, 2022

CubeSat Mission End Date: 5/1/2022 ☐ Still operating on orbit

Participation:

Total # Students involved in the CubeSat mission:	183	Undergraduate:	142
Grades K-8:	0	Graduate:	41
Grades 9-12:	0	# Faculty involved in the CubeSat mission:	1

Mission Operations and Flight Experience

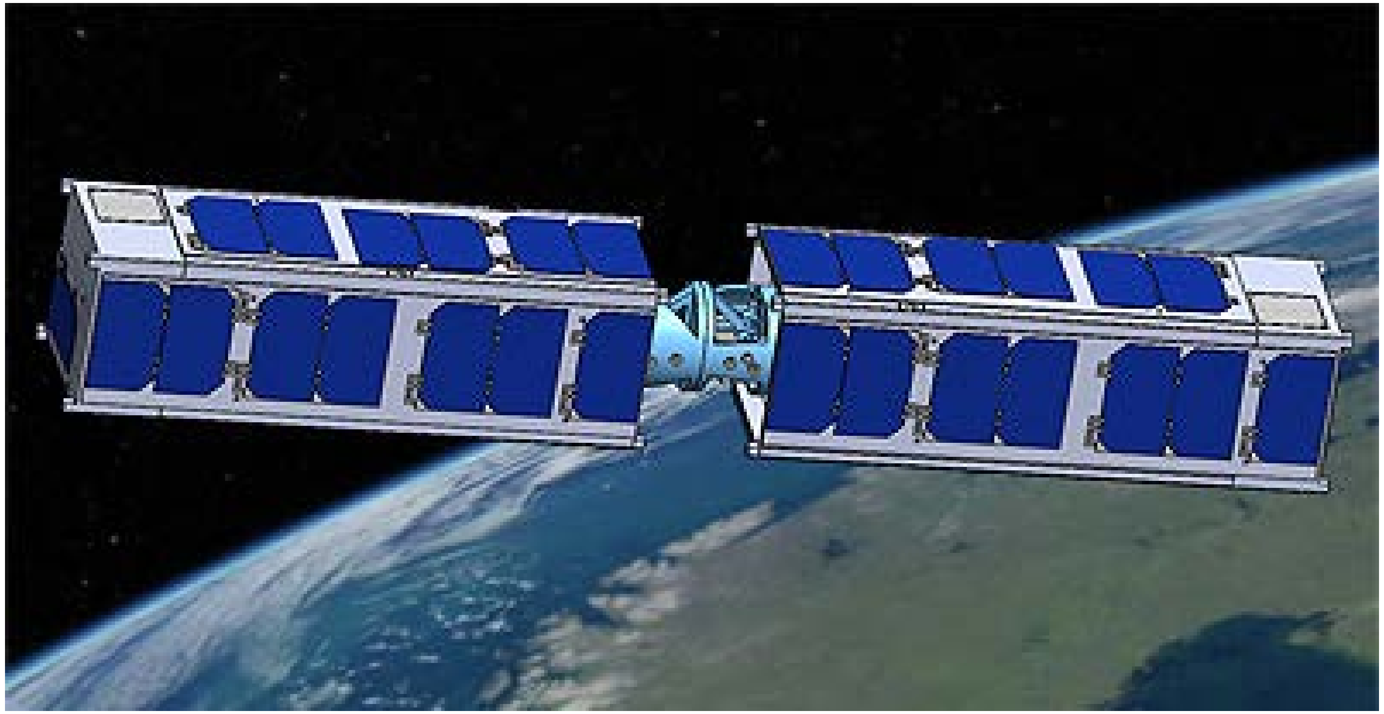
- Outcome: minimal success
  - No “infant mortality”
  - Near-continuous communications (by implication, power positive) through atmospheric entry in May 2022
- After separation from the LV, telemetry confirmed fundamental health, status, and performance of key subsystems.
- Anomaly
  - A late, uninformed, and unapproved software change made the low-power safe-hold mode a very high-power state.
  - Consequently, when the spacecraft began charging its batteries after separation in safe-hold mode, the power drain caused repeated reboots of the flight computer (a two-fault response scenario).
  - Ultimately, the spacecraft never was able to enter normal mode to demonstrate rendezvous.

Lessons Learned

- Program length was not atypical
  - 2 Years on related NASA project ultimately identified key issues to address in the flight PAN build—analogous to “pre Phase A”
  - 4 Years of development (ATP through TRR) and 1.5 years of I&T
  - Continuity of key personnel was surprisingly high, with consistent leadership through the beginning of I&T
- This successful program then experienced loss of expertise, failure to keep up previously rigorous standards of mission assurance, and unwillingness to admit problems, led to poor decisionmaking
  - E.g. rails were out of spec, and issue was ignored, leading to rework after delivery in LA
  - E.g. flight software change by inexperienced engineers without review

Lessons Learned

- If there is another opportunity to fly a build-to-print PAN, we would pursue it because the design as tested—not the design after this unapproved change—may well have met objectives.



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