

Starling CubeSat Swarm: Flight Results and Lessons Learned

Presented by Nathan Benz



Mission Facts

4 x 6U Blue Canyon Technologies spacecraft in LEO

Launched via Rocket Lab Electron, July 18 2023

575 km, near sun-sync orbit

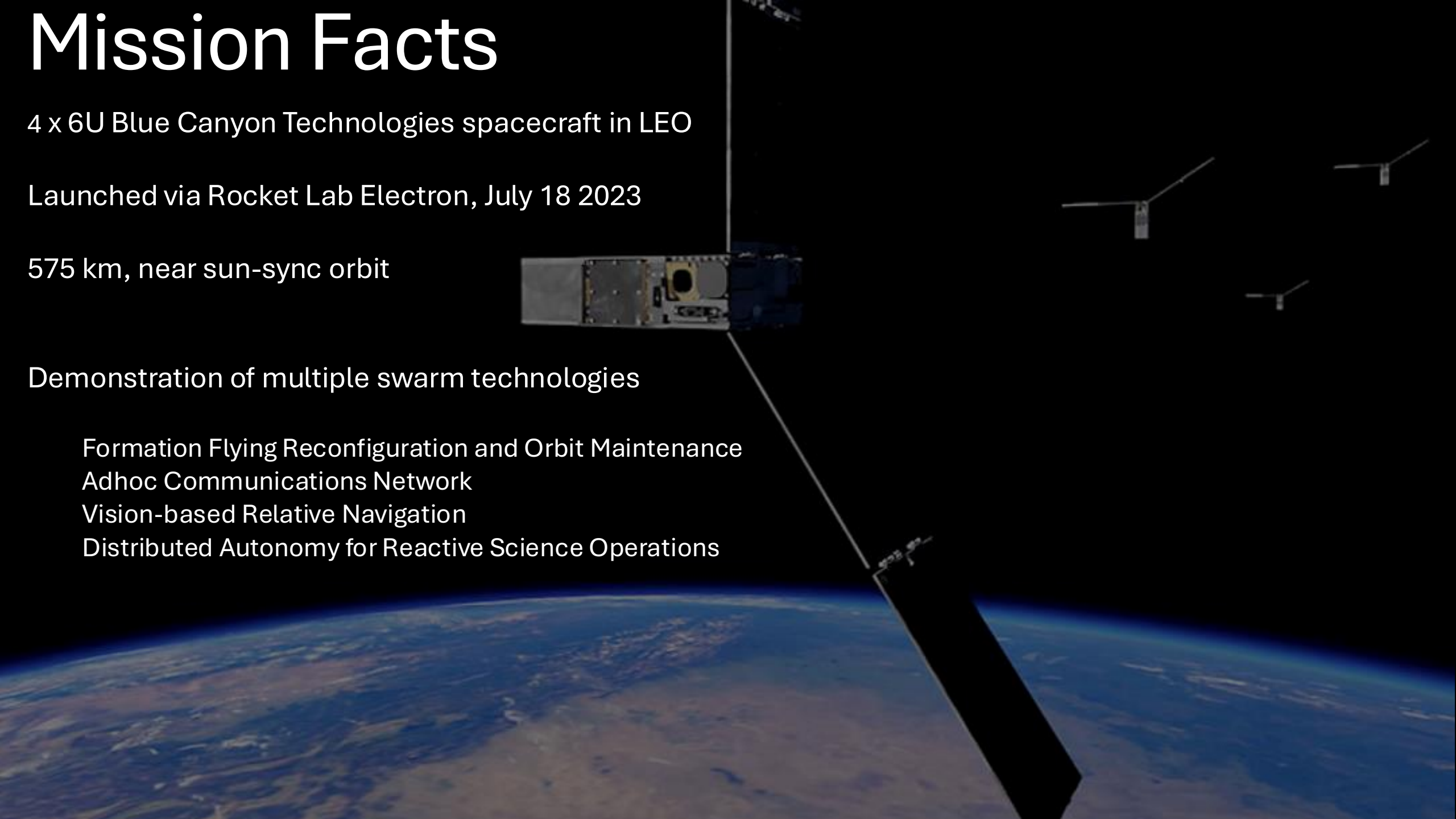
Demonstration of multiple swarm technologies

Formation Flying Reconfiguration and Orbit Maintenance

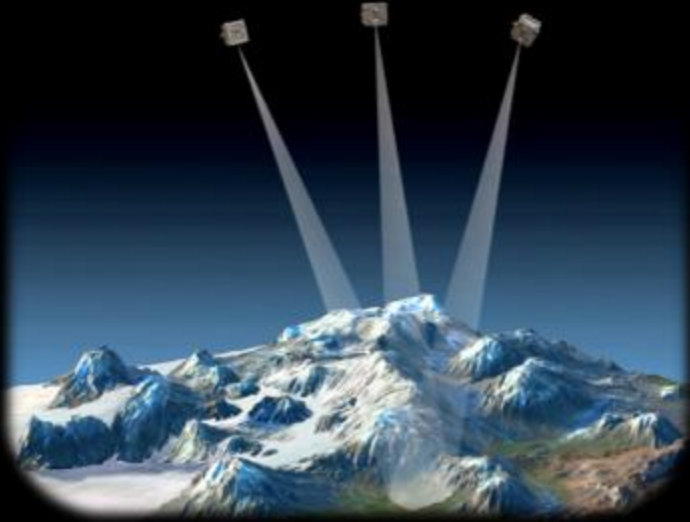
Adhoc Communications Network

Vision-based Relative Navigation

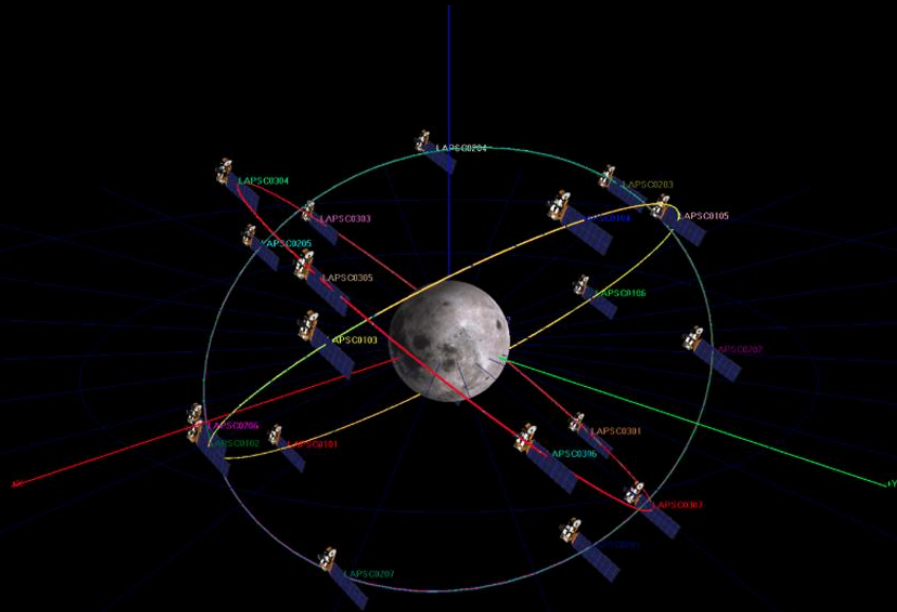
Distributed Autonomy for Reactive Science Operations



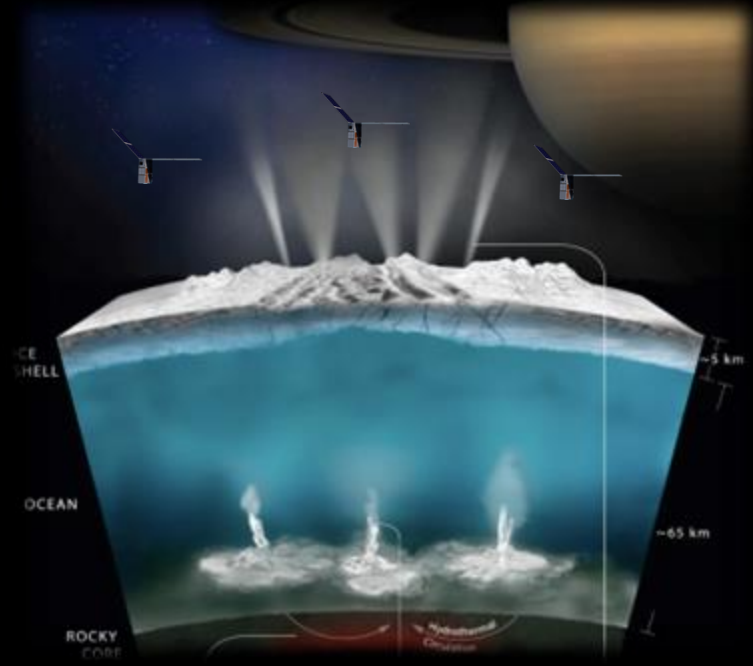
Why Swarms?



Responsive Earth Observation



Lunar Position, Navigation, Timing



Deep Space Sensor Arrays

And many more applications

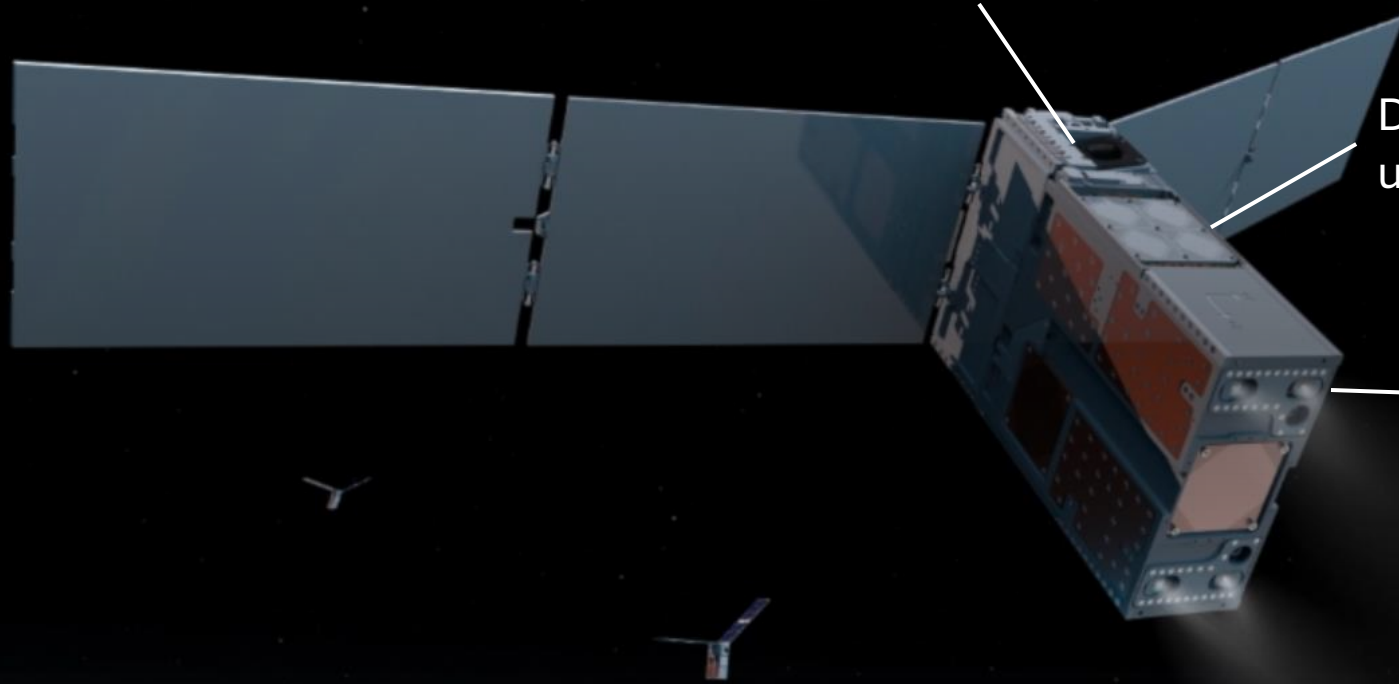
Starling Spacecraft Components

Dual star tracker cameras used by optical navigation experiment.

Dual cross-link radios from CesiumAstro used by adhoc network experiment.

Hamlet additive manufactured propulsion system used for autonomous orbit maintenance experiment.

Dual frequency GNSS used by distributed autonomy experiment.



Access – Lessons Learned

- Large cardinality (30-100) swarms will need small spacecraft.
- Access to Low Earth Orbit spacecraft swarms is achievable now.
- Commercial vendors enable mass production of spacecraft swarms.
- Common interfaces and standardization will be a key enabler for scale.
- Beyond LEO will require new form factors and/or a transfer bus.
- Deployment challenges include maintaining close relative distance and safe separation distance.



Communicate

Mobile Adhoc Network Experiment (MANET)

Successes

Completed all experiment objectives

First demonstration of dynamic routing in space

First demonstration of ad-hoc networking in space

Inter-satellite network reliability >90%

“Side-Load” software updates

Limitations

Large-file transfers unreliable

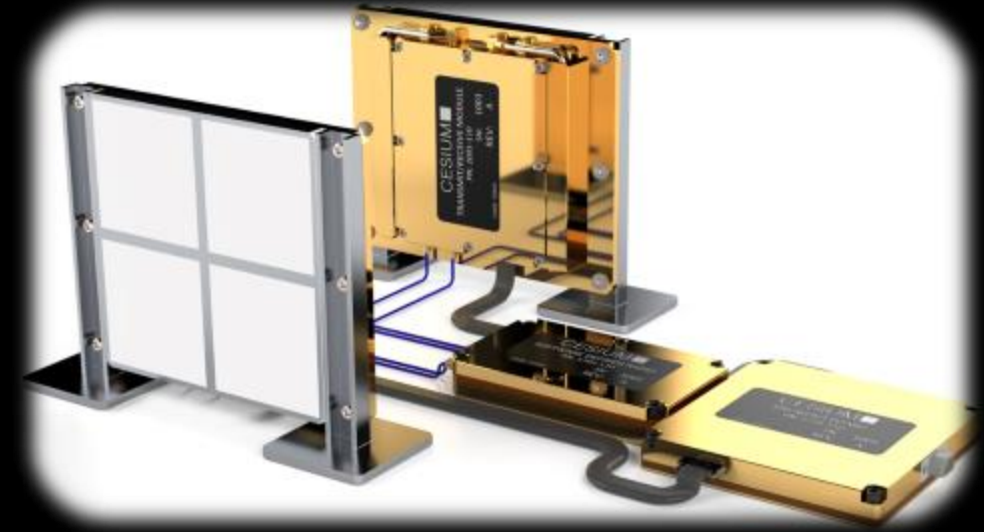
Animation by Cesium Astro

STMD Shortfall

1438: Autonomy, Edge Computation, and Interoperable Networking for Small Spacecraft

Communicate - Lessons Learned

- Mesh network simplifies swarm communication
- Maximum range exceeded expectations.
- For reliable data transfers, follow CCSDS protocols.
- Emulating RF network in the lab was a challenge.
- For swarms, communication links can also be used for relative ranging.



Credit: Cesium Astro

Navigate

Starling Formation Flying Optical Experiment (StarFOX)

Successes

Completed all experiment objectives.

First demonstrations of autonomous angles-only navigation for a satellite swarm.

First demonstration of multi-target and multi-observer relative navigation in space.

First autonomous vision-based initialization of navigation for unknown targets in space.

First simultaneous absolute and relative orbit determination using optical measurements.

Limitations

High computational resource utilization.

Sparse measurements reduces performance.



STMD Shortfalls

1559: Deep Space Autonomous Navigation

1531: Autonomous Guidance and Navigation for Deep Space Missions

Navigate



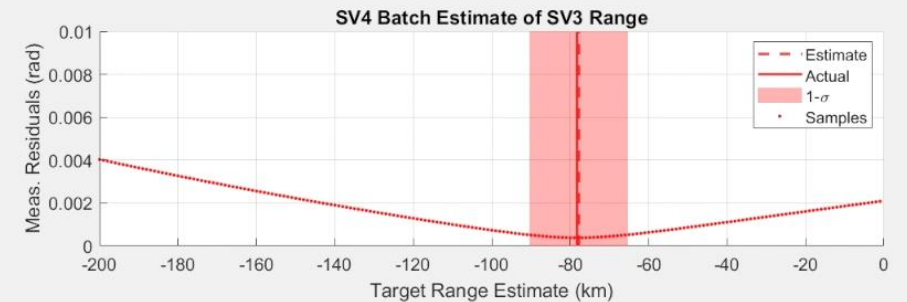
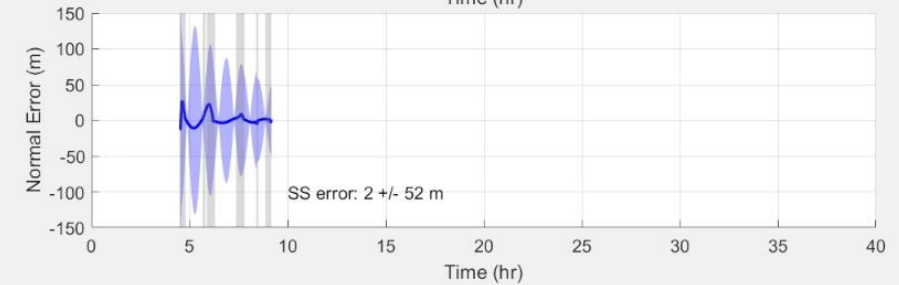
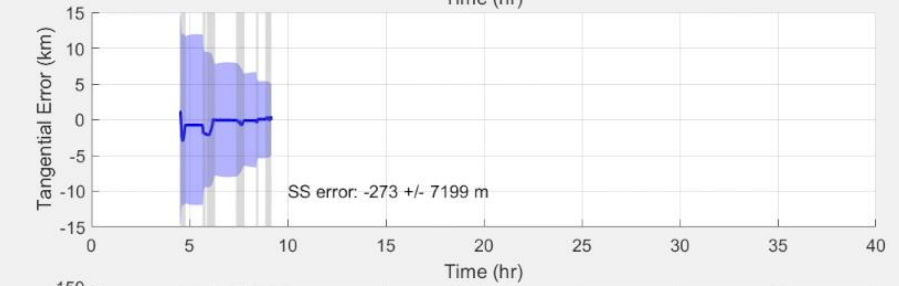
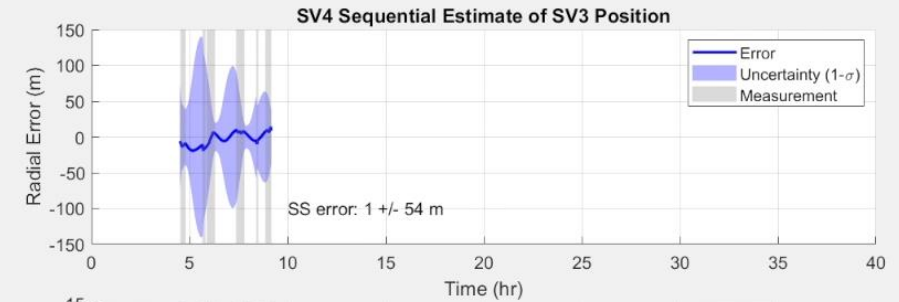
SV4 Tracker 2 View

Time: 2024/02/11 10:39
Status: targets visible

Objects: 21
Swarm: 1
Stars: 6

Distance to SV2: 142 km
Distance to SV3: 77.4 km

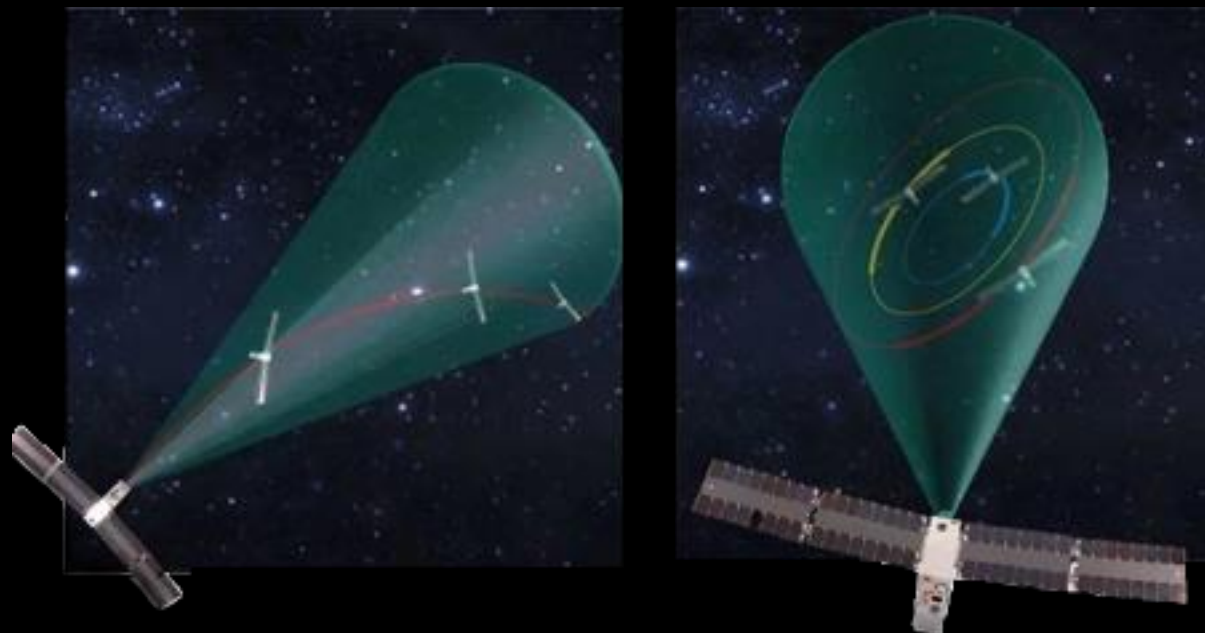
- True Swarm Position
- Potential Target
- Tracked Target
- Known Star
- Unknown



Navigate – Lessons Learned

Starling Formation Flying Optical Experiment (StarFOX)

- GPS-free relative navigation enable deep-space swarm missions.
- Relative and Absolute navigation can be done using existing SmallSat components.
- Objects not as bright as expected, impacts maximum swarm distance.
- Growing need for advanced computing avionics for SmallSat.



Credit: Stanford Space Rendezvous Lab

Control

Reconfiguration and Orbit Maintenance Experiments Onboard (ROMEEO)

Successes

Partial demonstration of objectives.

Demonstration of autonomous station keeping maneuver creation.

Demonstration of onboard orbit determination convergence.

Limitations

Timing inconsistencies have prevented execution of autonomous maneuvers.

Swarm level maneuver plan generation has not yet been demonstrated.

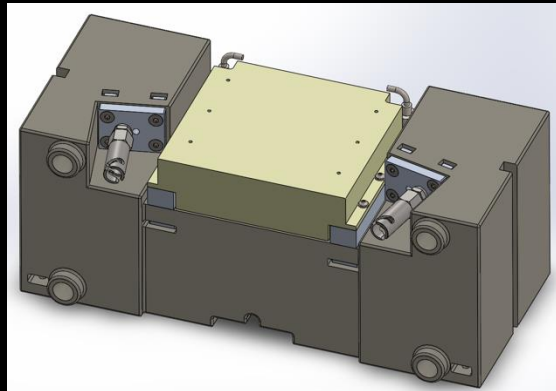


STMD Shortfall

1625: Intelligent Multi-Agent Constellations for Cooperative Operations

Control – Lessons Learned

- Full-success for ground-based formation control using Relative Orbital Elements (ROEs)
- General-purpose on-board formation control software remains the biggest need.
- Hamlet propulsion system has proved very capable, however there remain opportunities for improvement.



Operate

Distributed Spacecraft Autonomy (DSA) Successes

Demonstrated minimum success for experiment objectives.

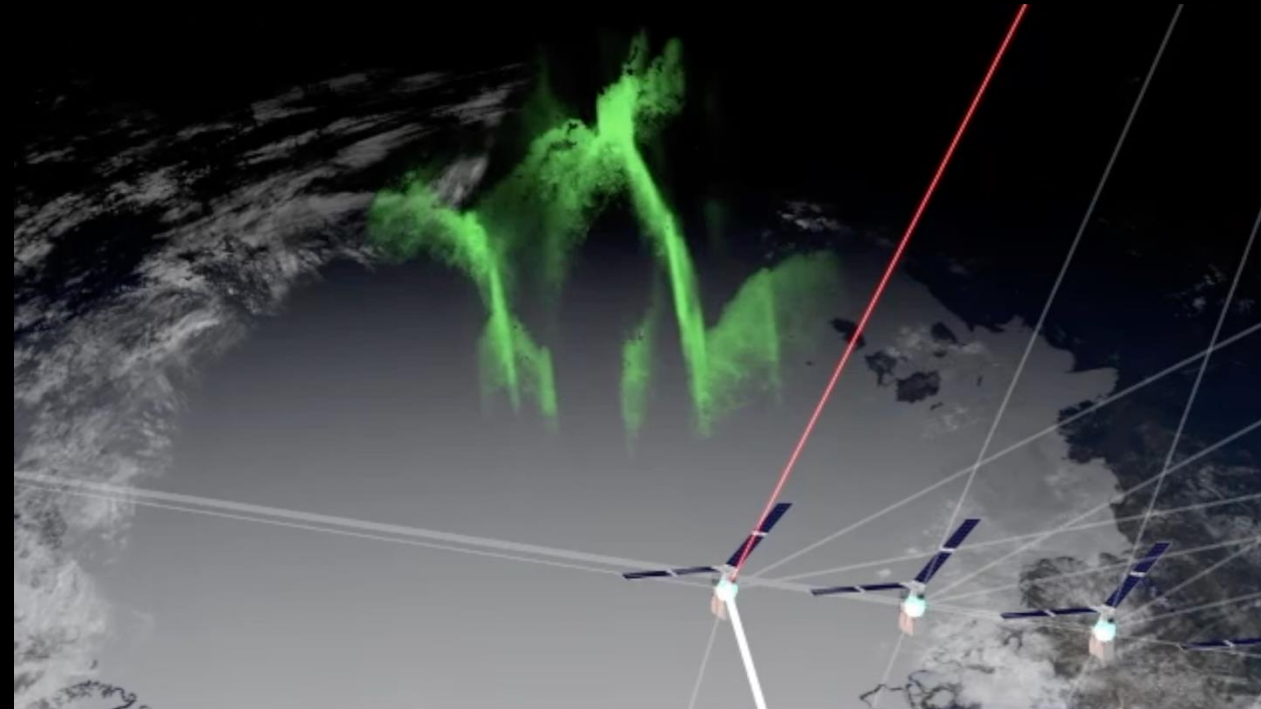
First fully distributed autonomous operation of multiple spacecraft.

First use of space-to-space communications to autonomously share state information between multiple spacecraft.

First demonstration of fully distributed reactive operations onboard multiple spacecraft.

Limitations

Software overhead limitations prevented meeting key performance parameter objective for command reduction.

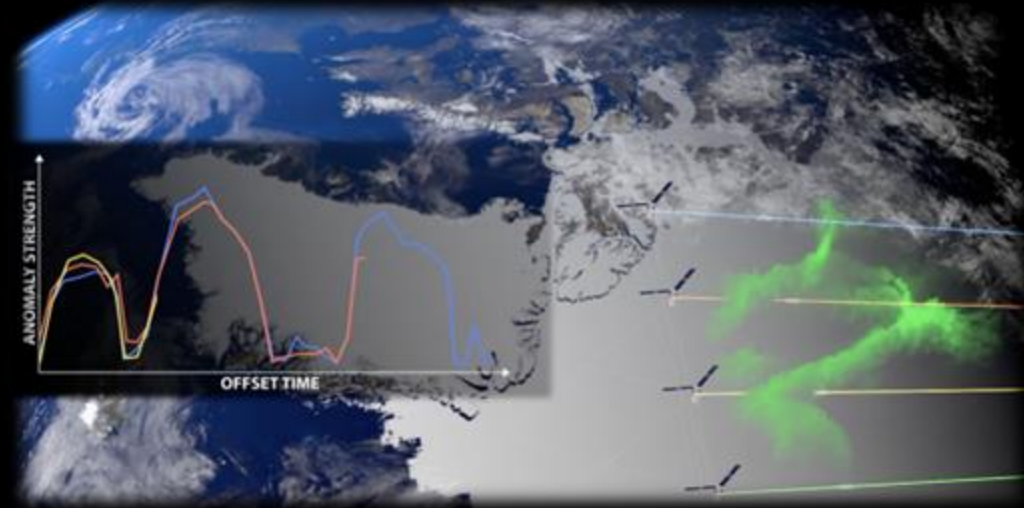
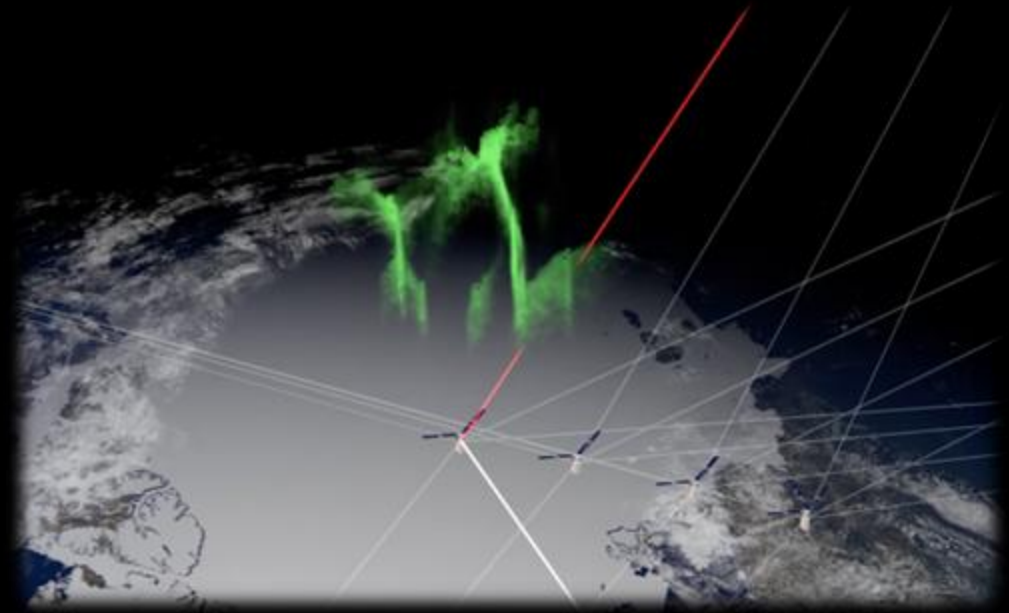


STMD Shortfall

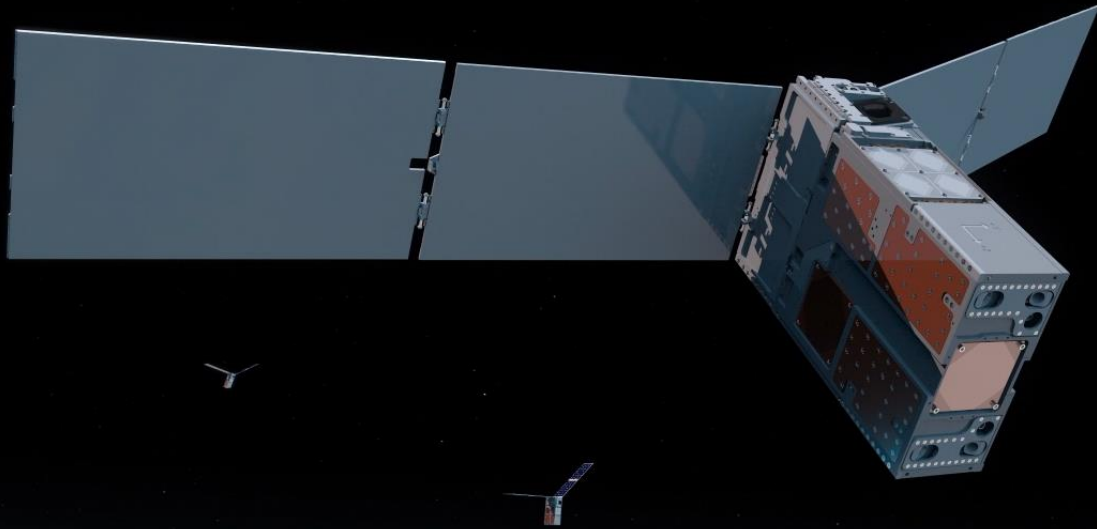
1532: Autonomous Planning, Scheduling, and Decision-Support to Enable Sustained Earth-Independent Missions

Operate – Lessons Learned

- Traditional operating approaches will not scale large swarm missions.
- Autonomy and goal-based commanding is a solution to solve the complexity.
- Autonomous swarms will enable new reactive (tip and cue) science missions.
- Multiple spacecraft can be useful to debug anomalies.
- Multiple spacecraft allow continued operations even if one spacecraft becomes inoperable.



Mission Anomalies



Radio anomaly on Spacecraft-1

Propulsion anomaly on Spacecraft-1

Software Bug handling GPS data

Next Steps

New Experiments with Starling-1

- Space Traffic Coordination
- Improved Edge Computing for Autonomy
- Detection and tracking of Resident Space Objects
- More robust networking
- Radiometric Ranging

Remaining Gaps for Swarms

- Coordinated Swarm Maneuver Planning and Execution
- Integration of swarm technologies
- Improved Avionics
- Human-Swarm Interaction
- Demonstration beyond LEO

