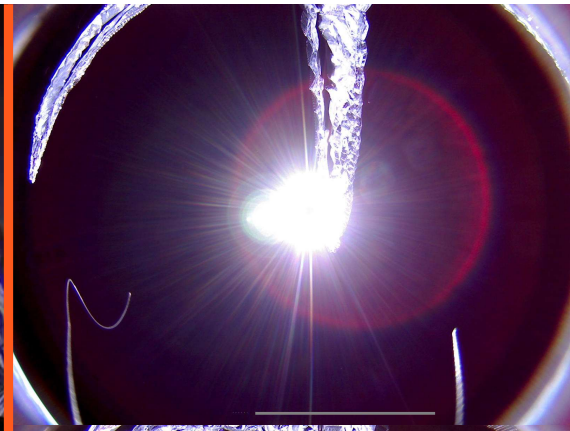
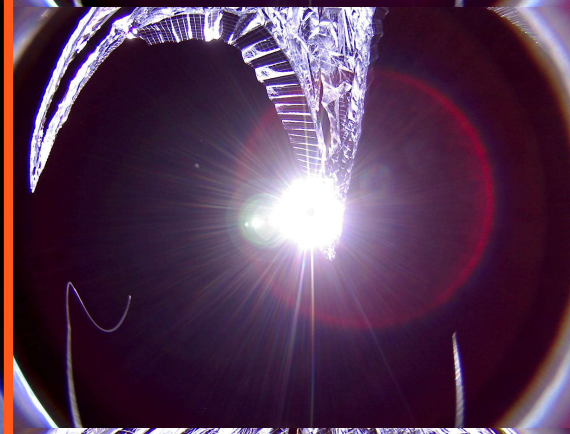
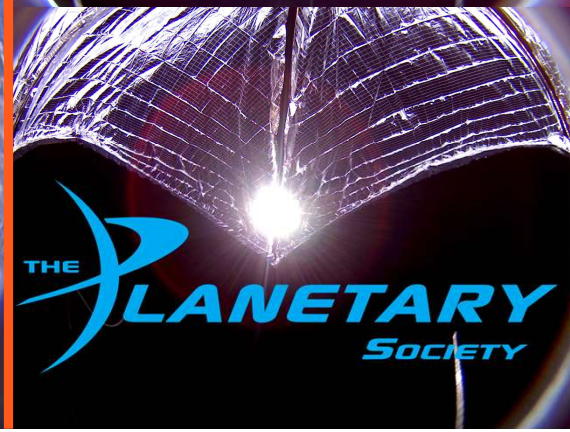
LightSail 2

Orbit Evolution and Attitude Control





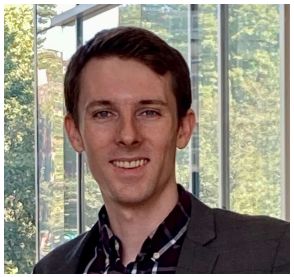


International Space Sailing Symposium

Justin R. Mansell

June 5, 2023

LightSail 2 Extended Mission Flight Team



Dr. Justin R. Mansell
Flight Mechanics
Post Doctoral Researcher
Jet Propulsion Laboratory

50,000+ Members and Donors
The Planetary Society

Dr. John Bellardo
Telecom/Software
Professor
Cal Poly San Luis Obispo

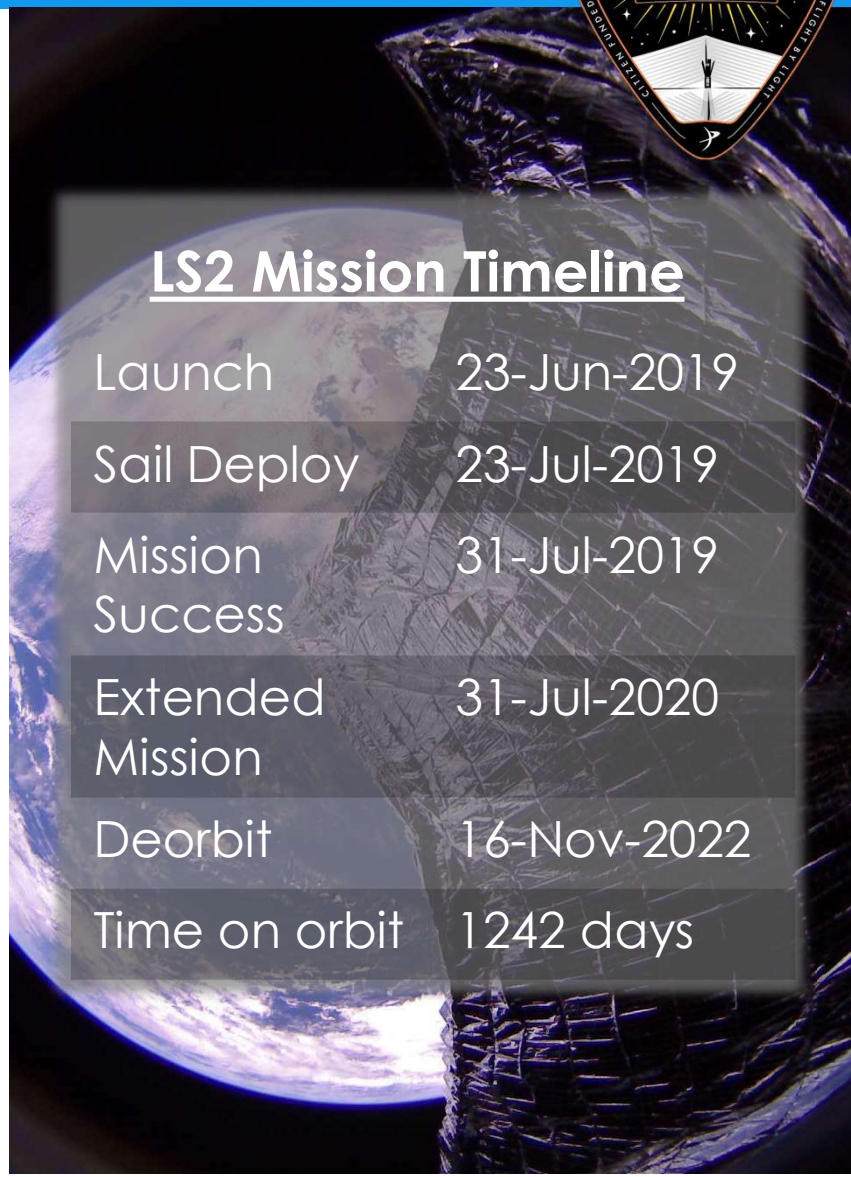
Barbara Plante
Attitude Control Engineer
Rogue Space Systems

Dr. Bruce Betts
Chief Scientist & LightSail
Program Manager
The Planetary Society

Dr. David A. Spencer
LightSail Project Manager
Mission System Manager,
Mars Sample Return
Jet Propulsion Laboratory

The LightSail 2 Mission

- LS2 has been at ISSS before…
- Second CubeSat in a pair of crowd-funded solar sail technology demonstrations
- **Main objective:** Demonstrate controlled solar sailing using a CubeSat
- Previous presentations reviewed performance during the first year, but some of the most exciting results occurred during the extended mission:
  - Period of net orbit raising
  - Behavior during deorbit
- This talk will present the orbit evolution and attitude performance over the full mission and discuss how it changed in response to improvements and anomalies



The LightSail CubeSats

SIZE
5.6 x 5.6 m
(18.4 x 18.4 ft)

BOOM LENGTH
4 m
(13 ft)

TOTAL SAIL AREA
32 m^2
(344 ft^2)

SIZE REFERENCE
Boxing Ring

PROPULSION

Sails have 'rip-stop' seams every few cm to prevent tear spreading from space debris

Sail thickness: 4.5 microns, less than the width of a human hair

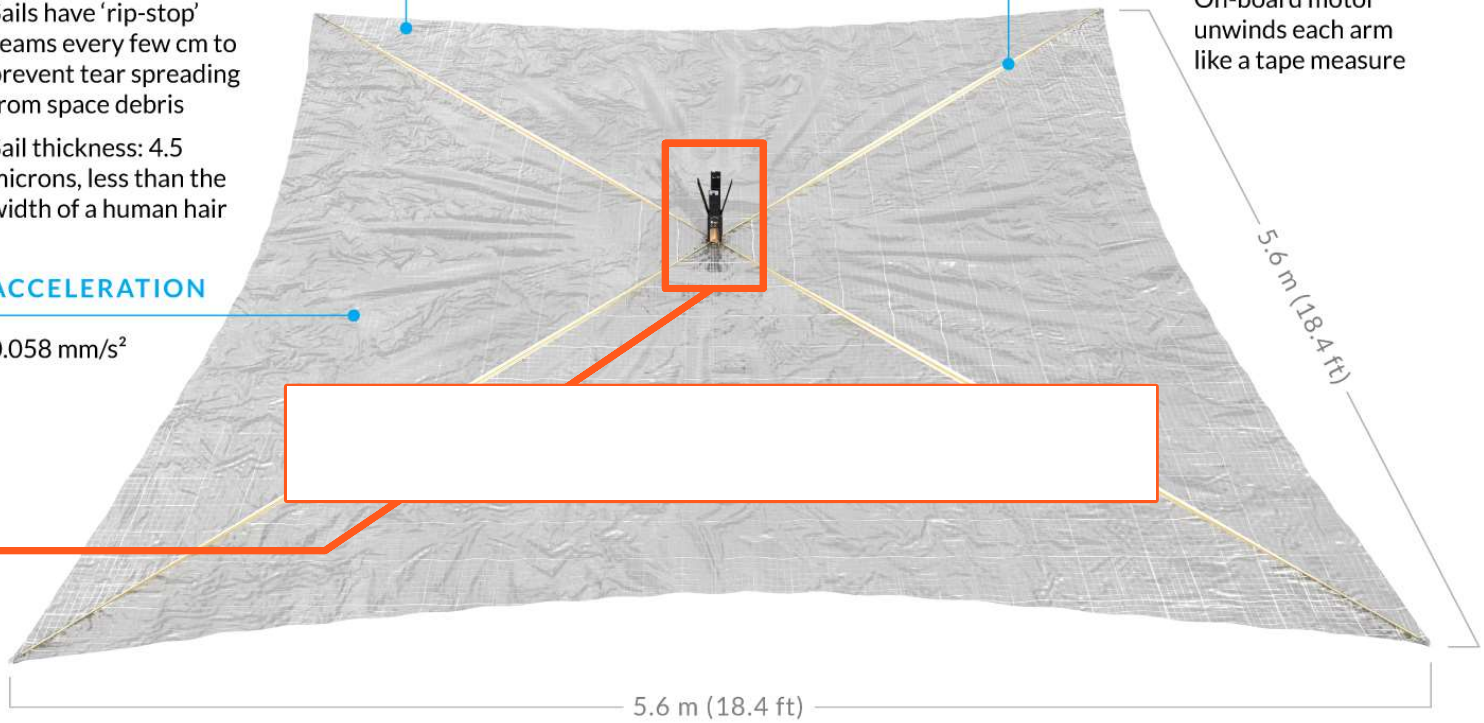
ACCELERATION

0.058 mm/s^2

SAIL DEPLOYMENT

4 cobalt alloy booms

On-board motor unwinds each arm like a tape measure



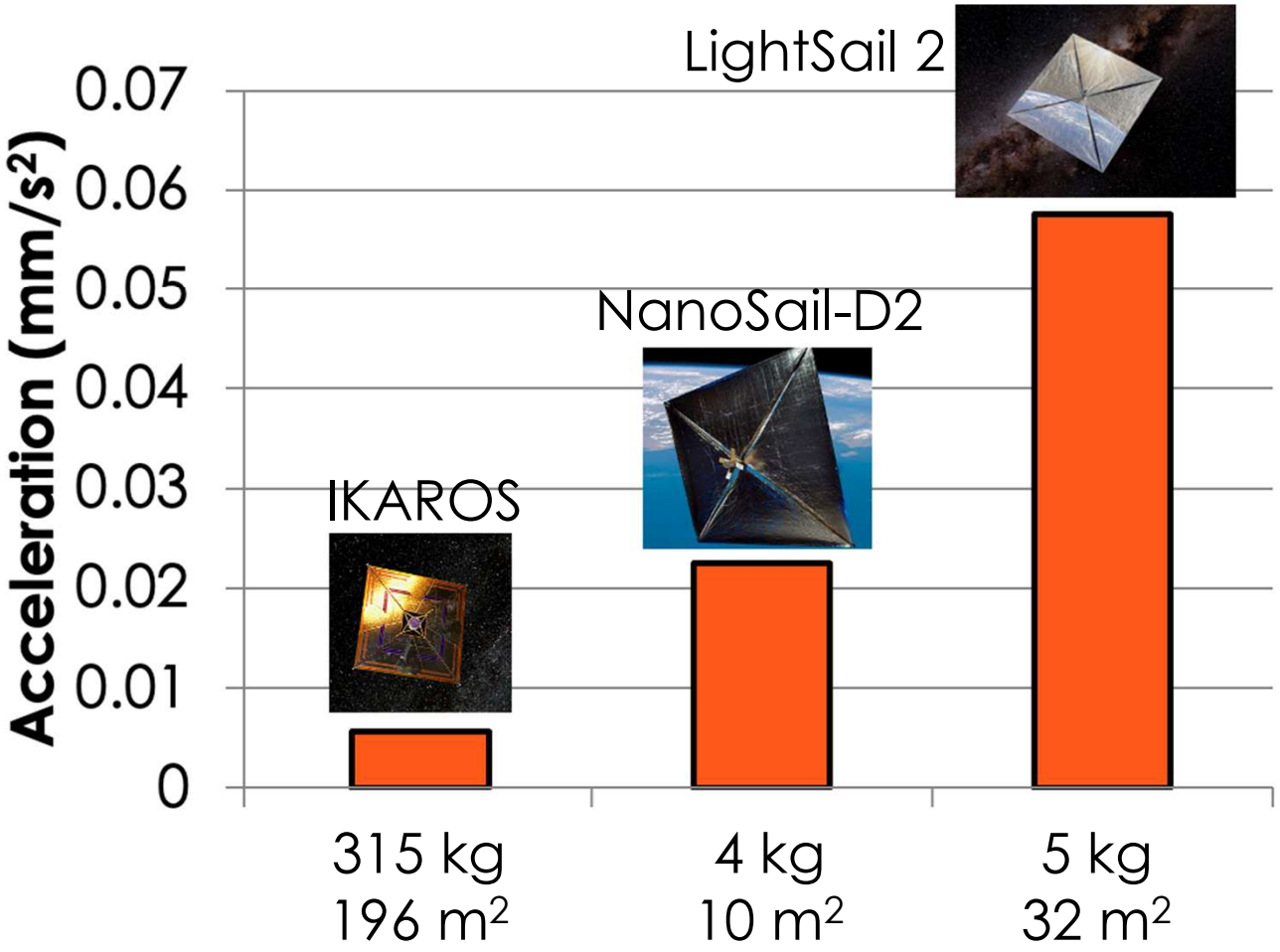
Comparison of Solar Sails

Opportunities:

- Highest characteristic acceleration of any solar sail deployed to-date
- First 3-axis stabilized sail with active attitude control

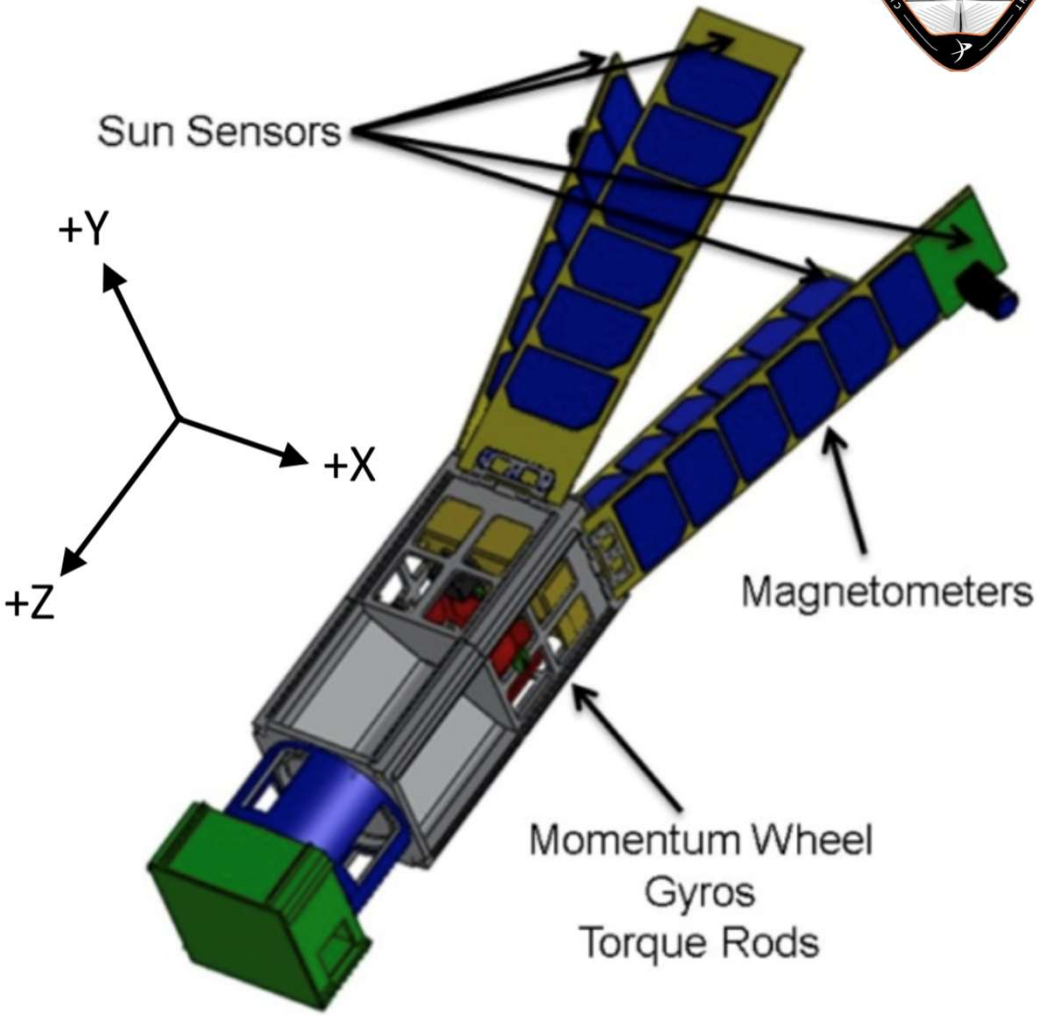
Challenges:

- Sailing in Earth orbit
- Low control authority relative to moments of inertia and environment
- Budget COTS components



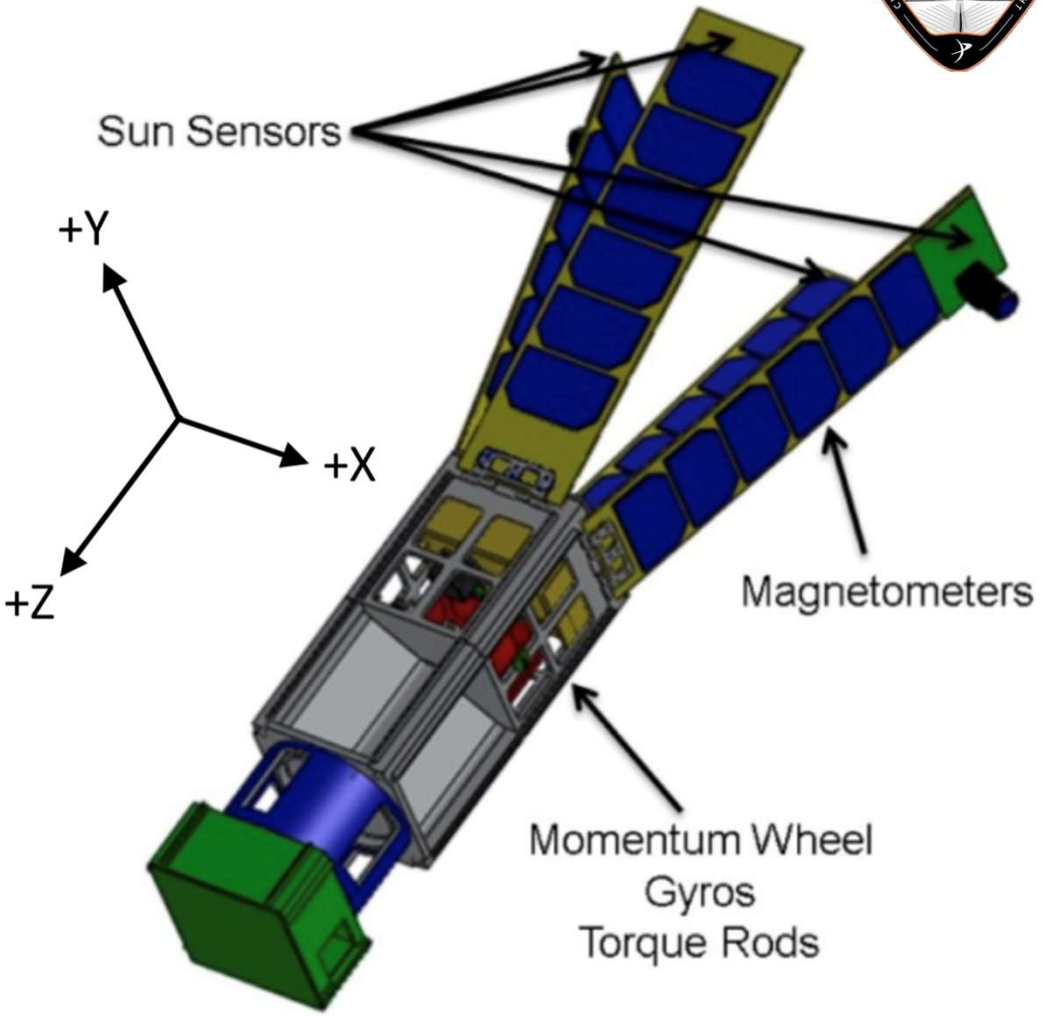
ADCS Overview

- 2 Magnetometers
- 5 Coarse sun sensors
- 3 Mainboard gyros
- 3 Precision (PIB) gyros
- 1 Momentum wheel
- 3 Torque rods
- 2 Cameras
- 5 Control modes



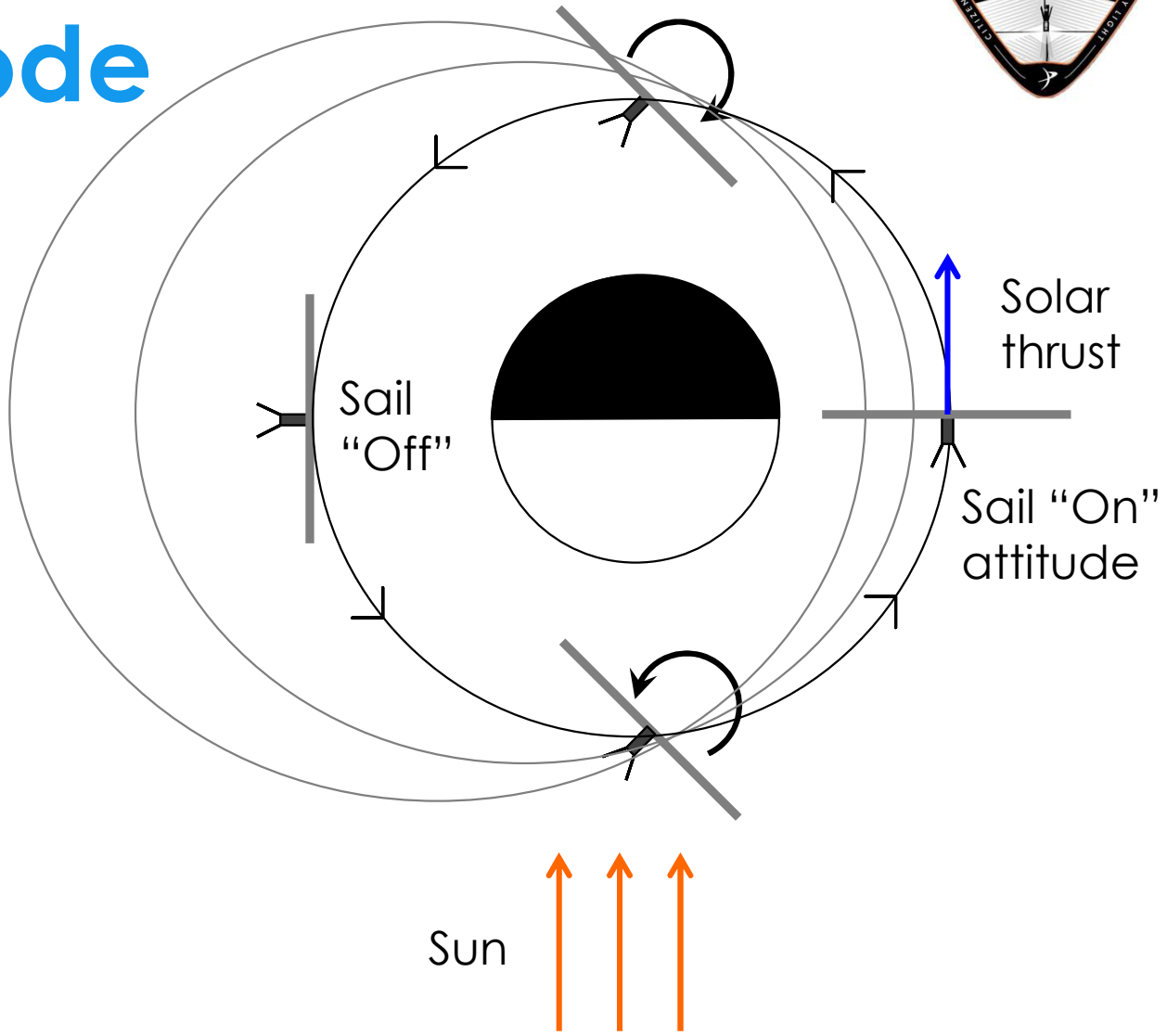
ADCS Overview

- 5 Control modes
  - Mode 0: Detumble
  - Mode 1: Magnetic alignment
  - Mode 2: Solar sailing
  - Mode 3: No torques
  - Mode 4: Sun pointing (introduced on orbit)
  - Mode 5: Velocity pointing (rarely used)



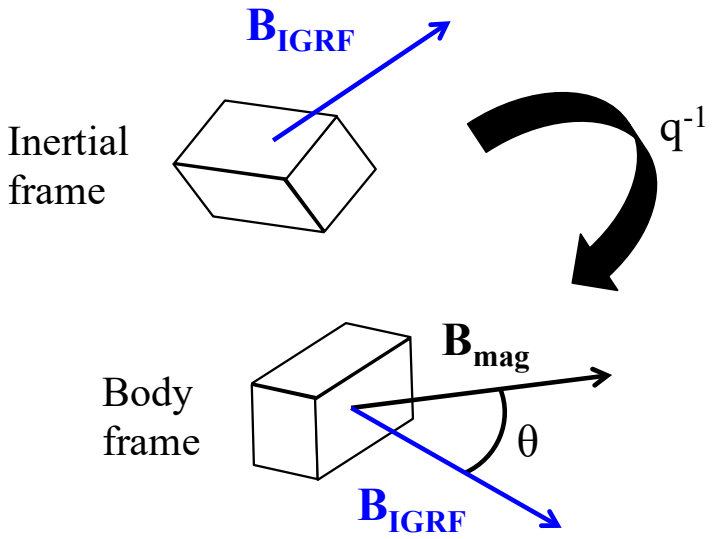
Solar Sailing Mode

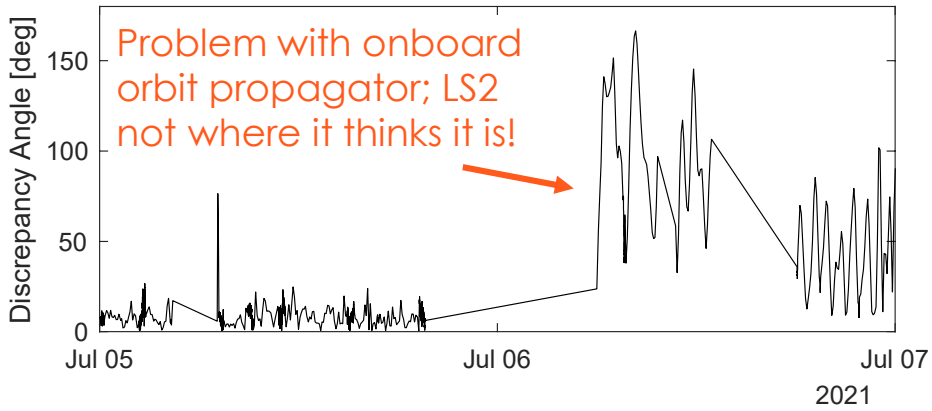
- Slew between “On” and “Off” attitudes
- Solar pressure contributes an increase in energy that can oppose losses due to atmospheric drag



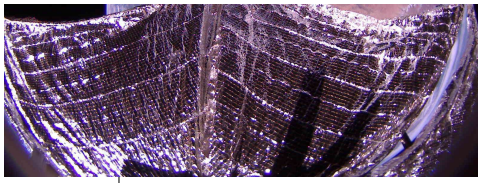
Assessing Attitude Performance

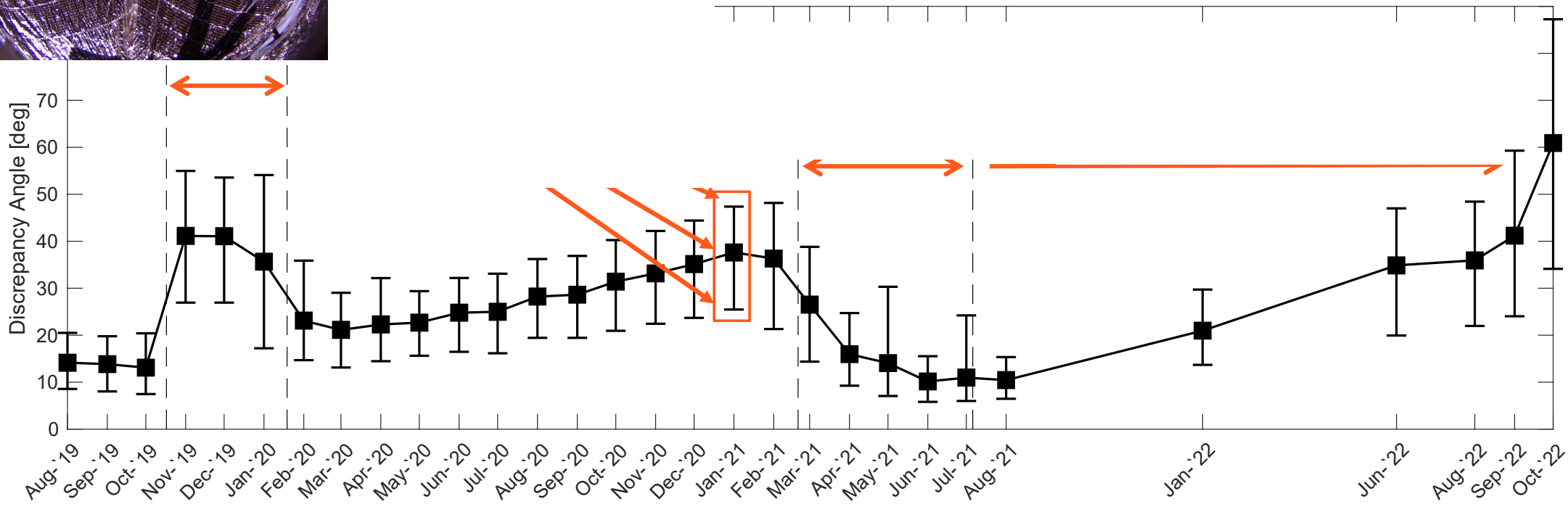
- First, need to assess the accuracy of the onboard attitude estimate
- Estimate performed by an extended Kalman filter, but affected by
  - Time varying noise statistics and biases
  - Errors in spacecraft clock or propagated position
- We developed a "quaternion consistency check" to verify that the filtered attitude estimate did not contradict the raw magnetometer measurements





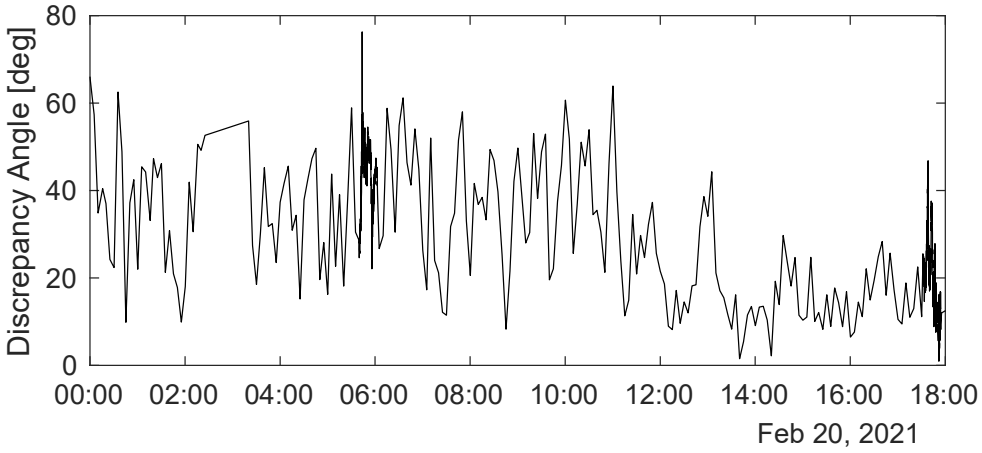
Attitude Knowledge History

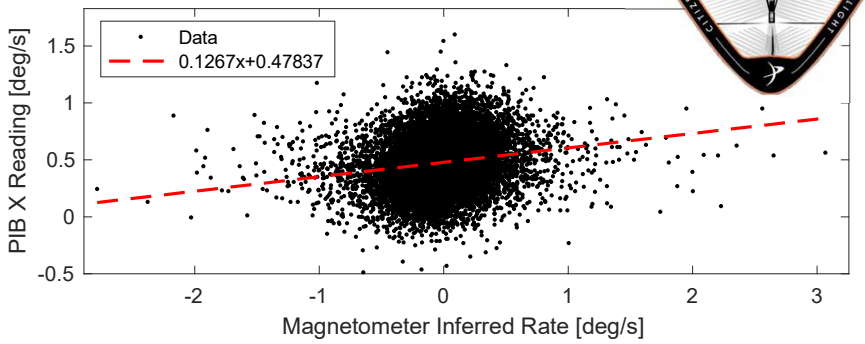


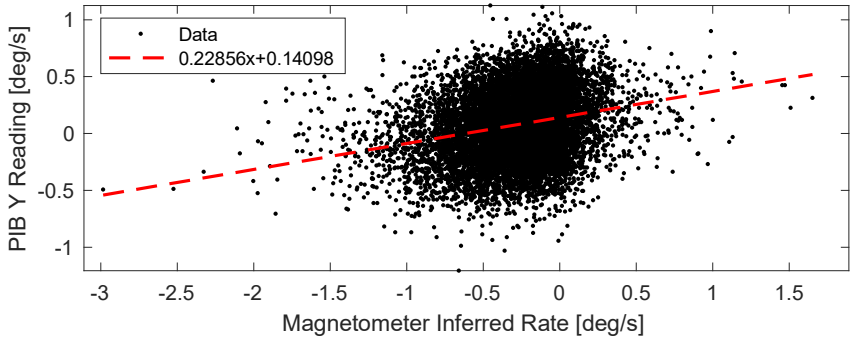


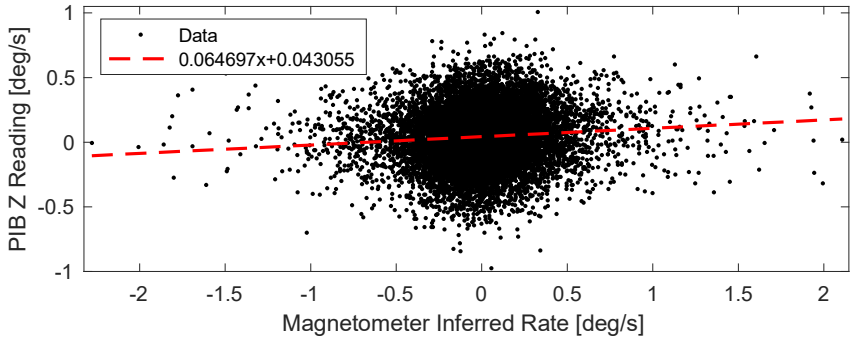
Gyro Re-calibration

- ADCS performance degraded gradually throughout 2020
- January 2021: no recognizable attitude control
- February 2021: derived rates from magnetometers and subtracted offset from primary gyros
- Result: successful control returned almost immediately



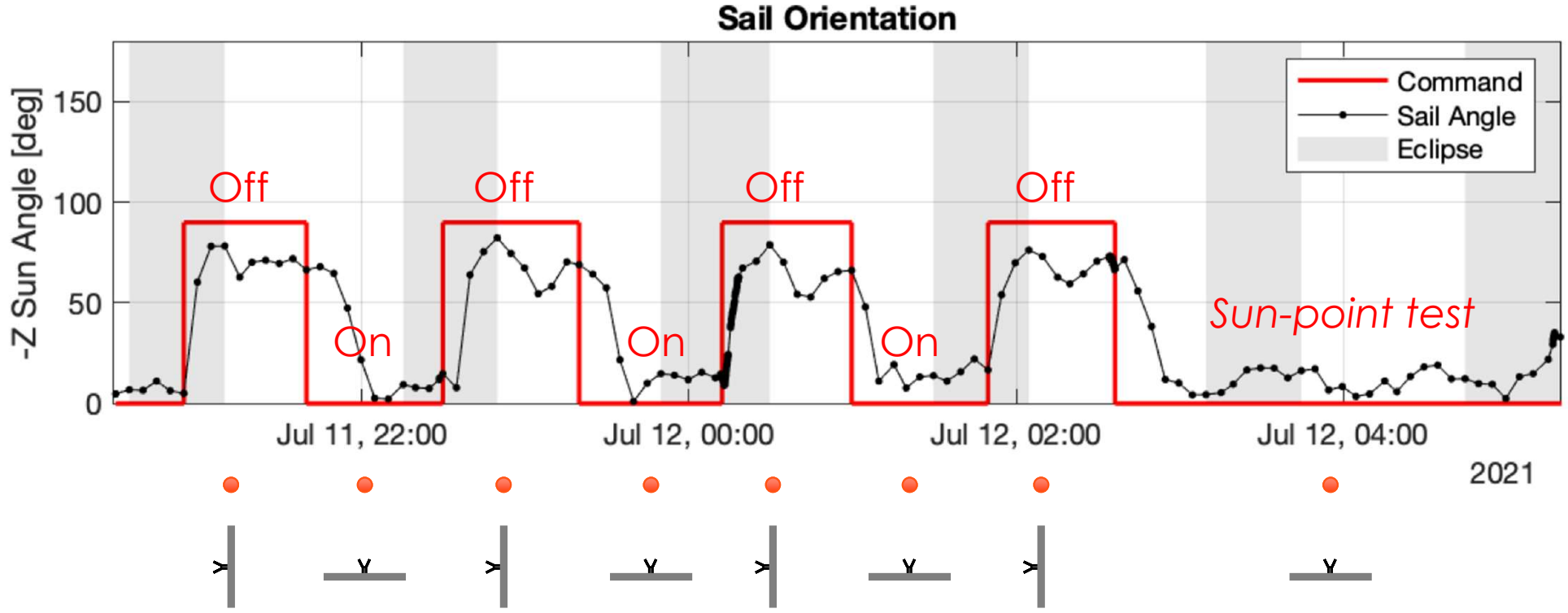




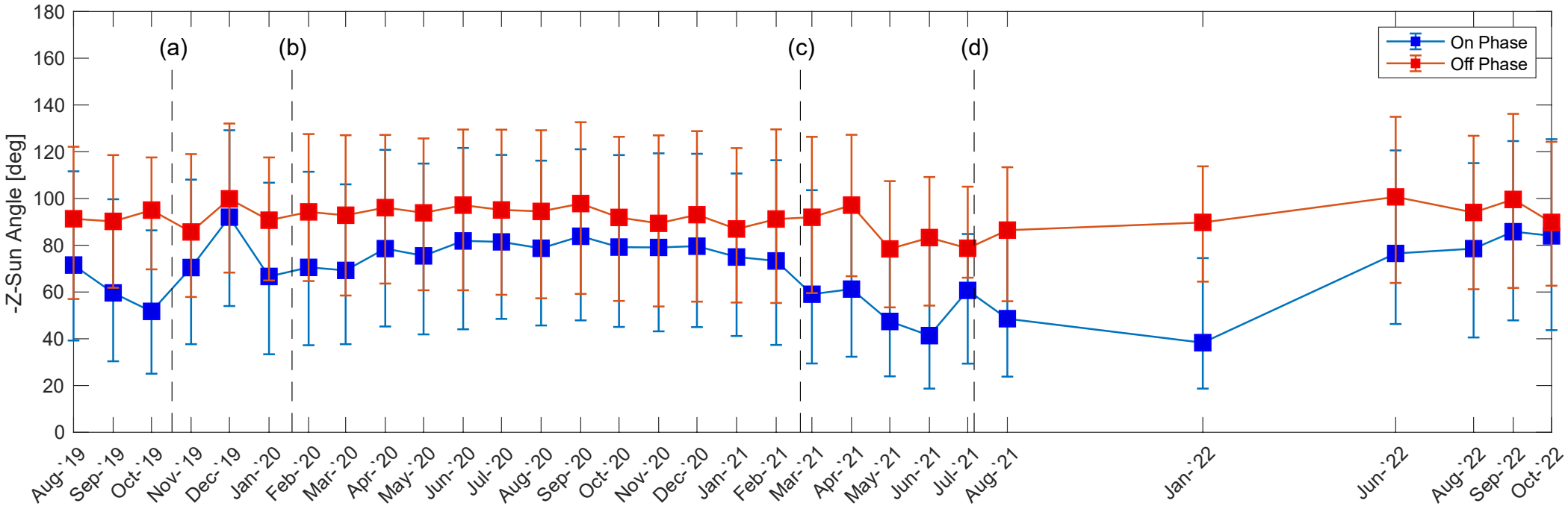


Assessing Attitude Control

- Control performance assessed by comparing downlinked quaternions to pointing commands



Attitude Control History



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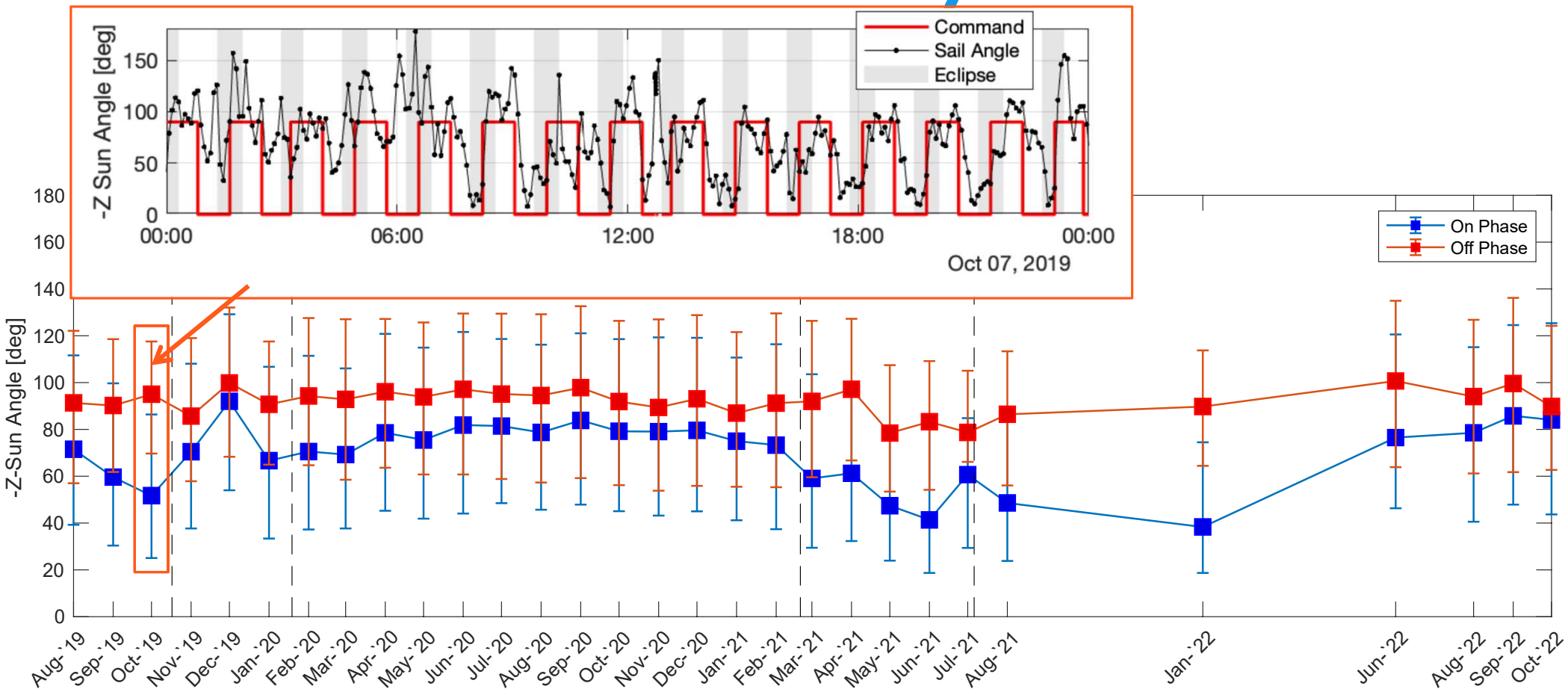
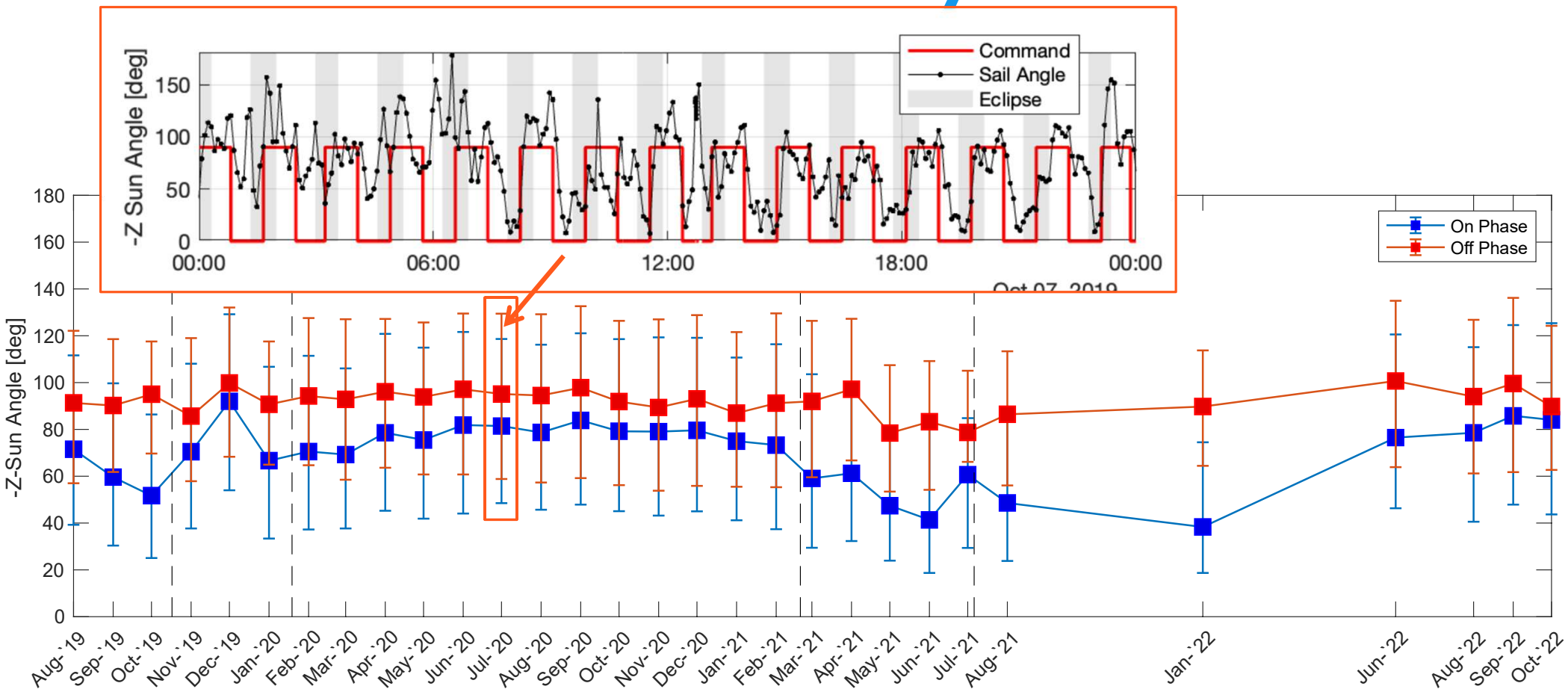
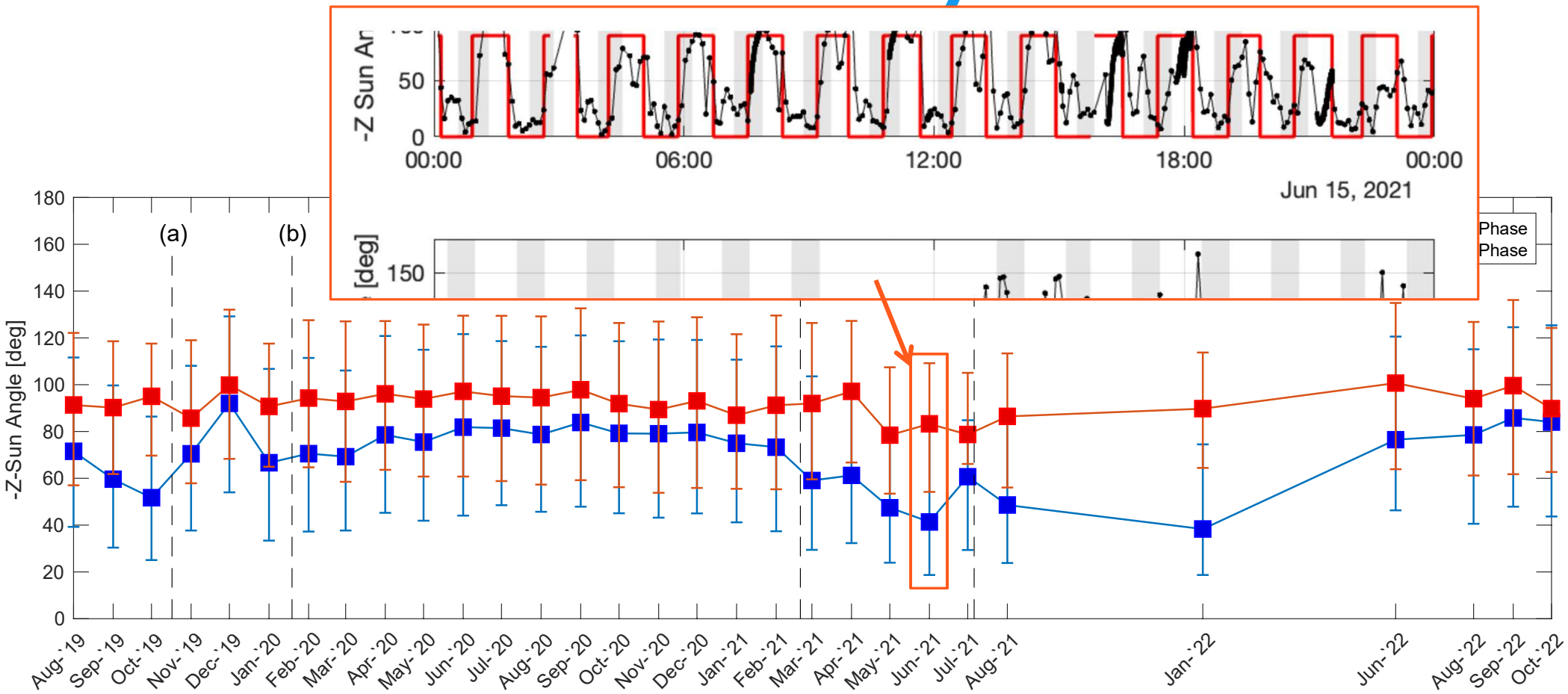


Attitude Control History

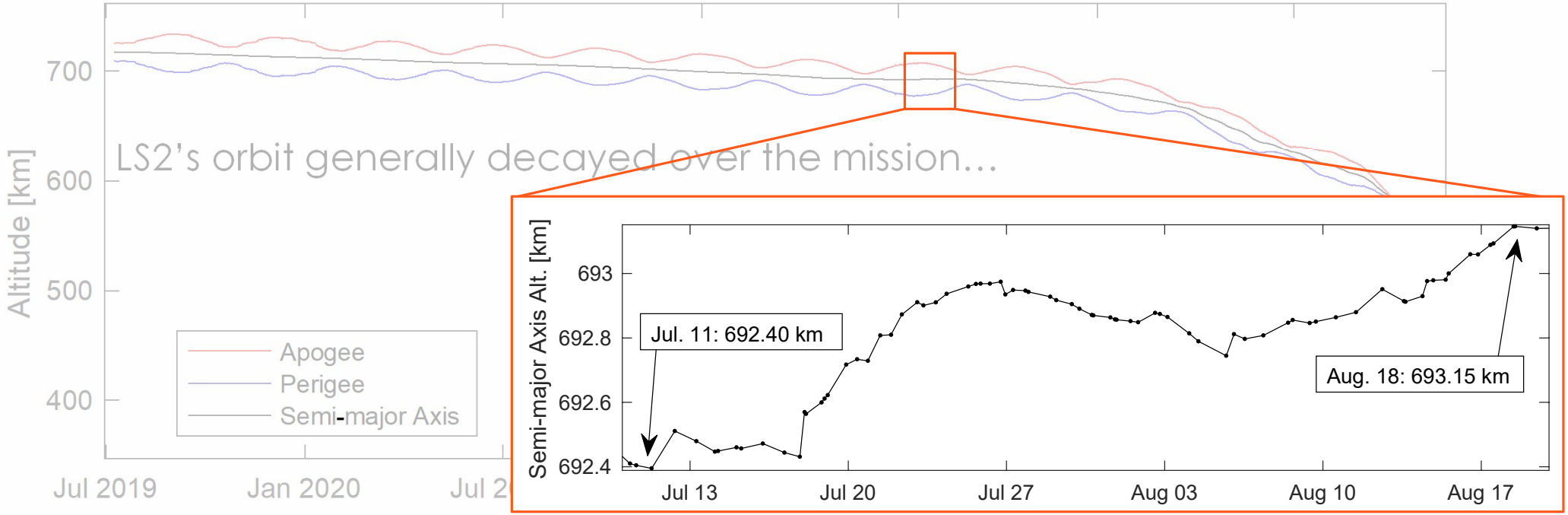


Attitude Control History



Orbit History

- Source of orbit knowledge: Two-line elements

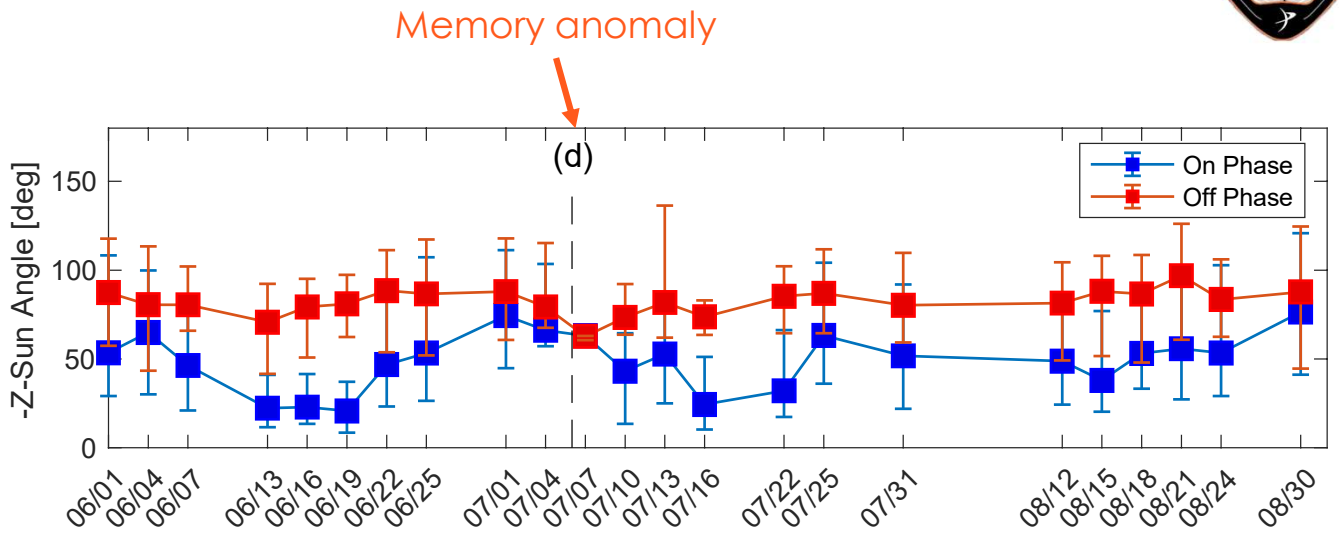


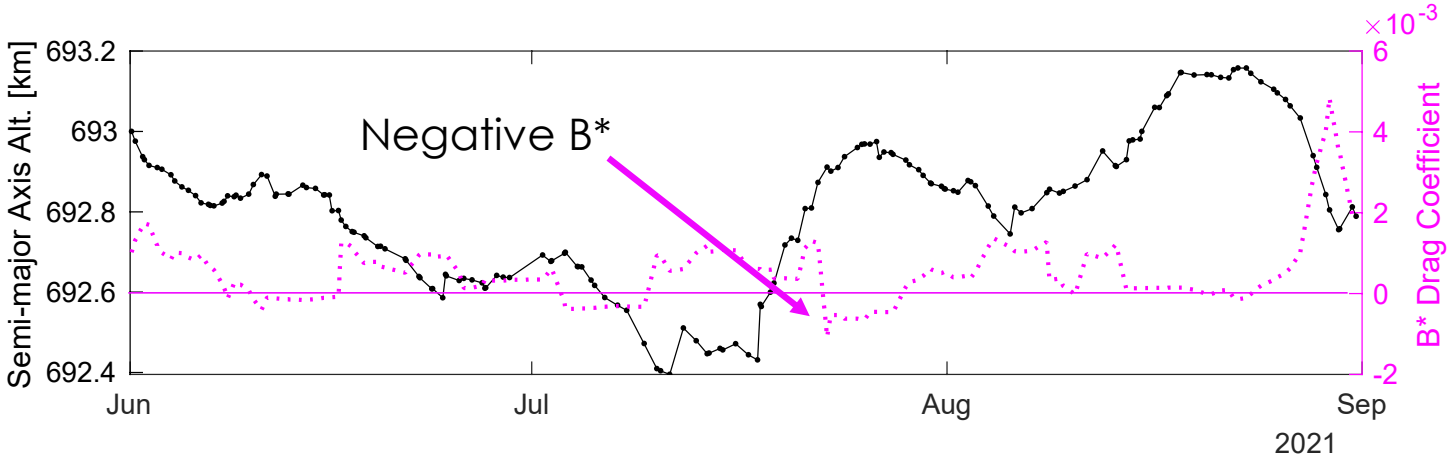
During 2021, a net gain of 758 meters was achieved July-August, coincident with a period of good sail control

Orbit Raising

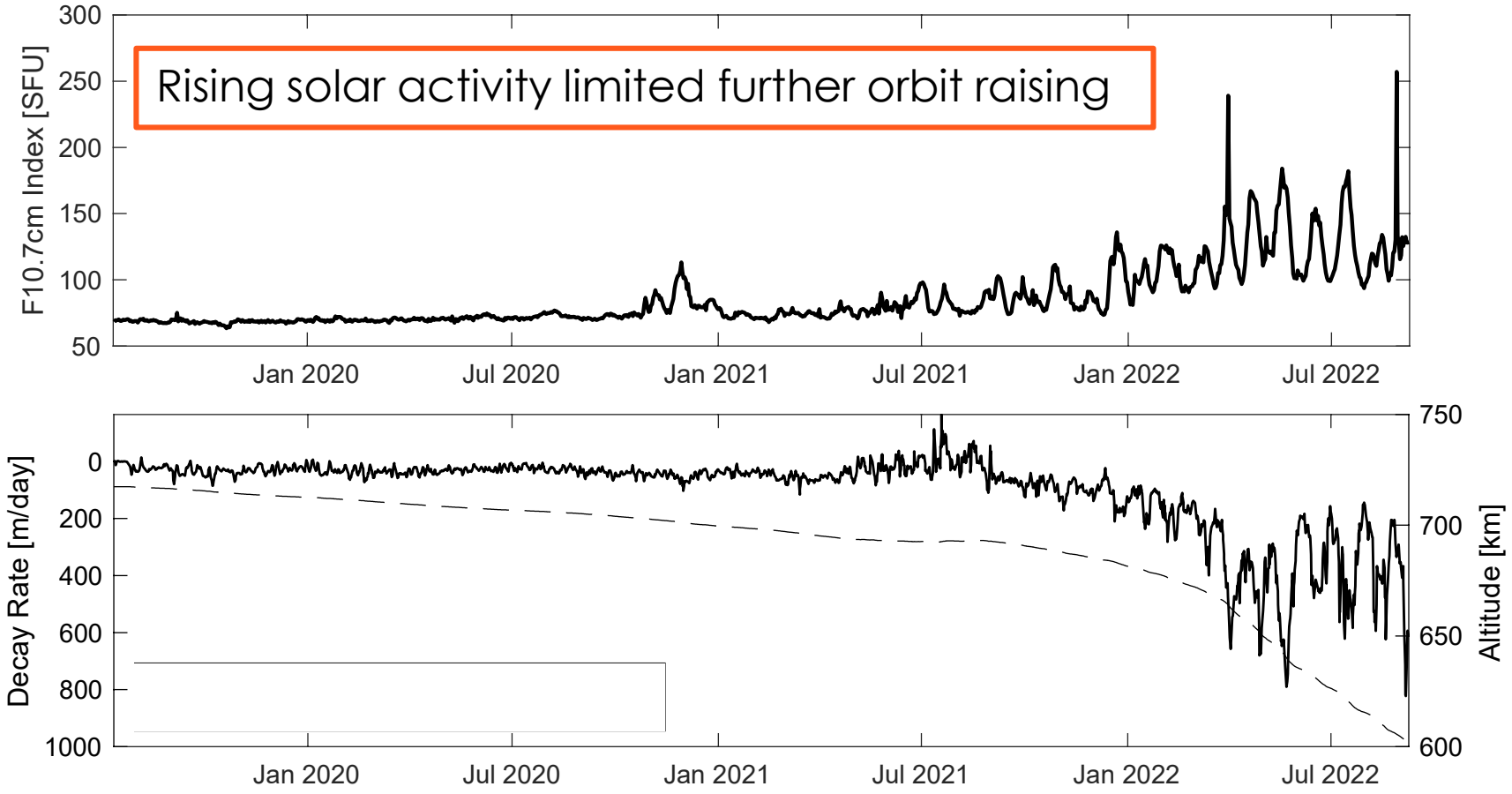
- Directly correlating sail control with orbit changes is difficult due to the limitations of the SGP4 model on which TLEs are based

- However, B* < 0 shows that the best fit for the orbit is one which is rising with time





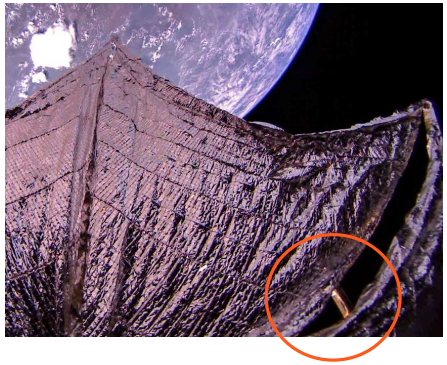
Impact of Solar Activity

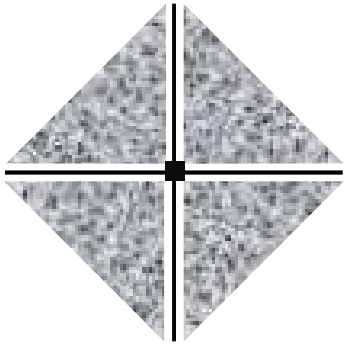


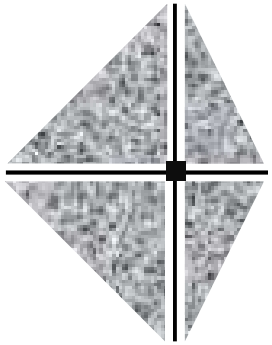
Time On Orbit

- Solar sailing over the mission extended LS2's orbit lifetime
- We used two NASA propagators to model the decay without solar sailing and found deorbits >10 months earlier than actual
  - Constant C_d assumed, but reference areas scaled by 2/π to represent the long-term average of a tumbling sail

Actual deployed sail area unknown due to partially collapsed boom







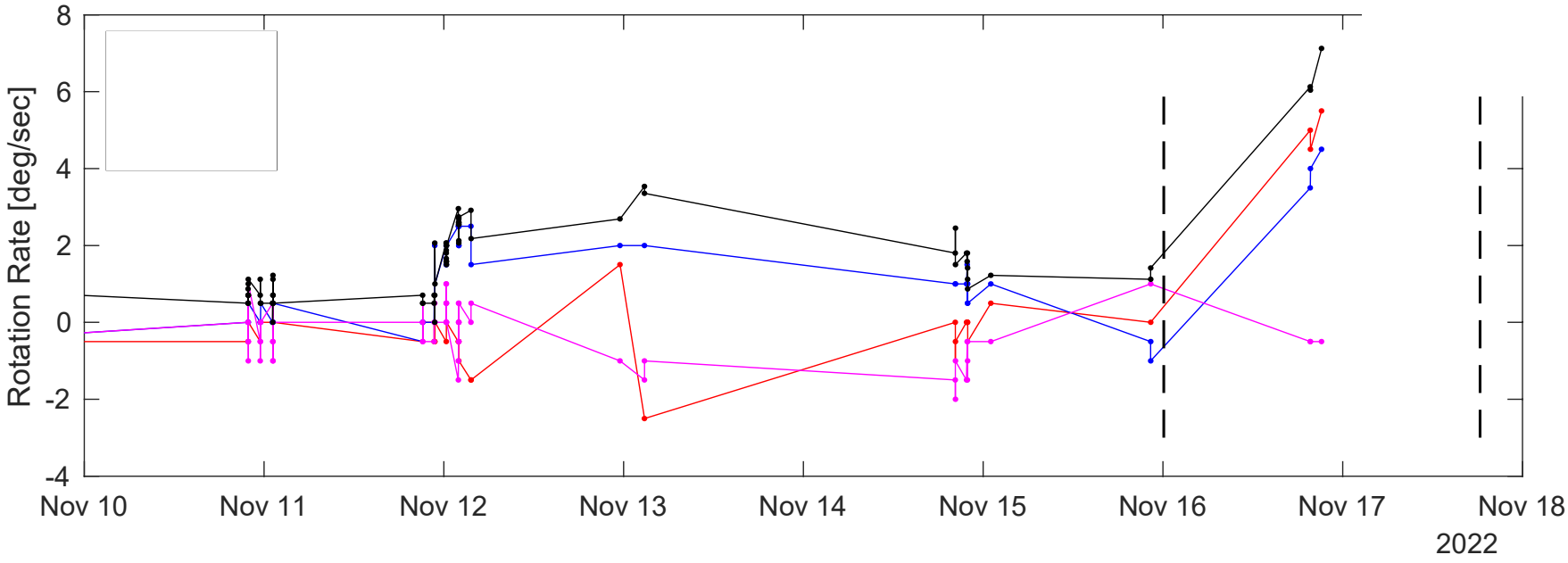
Assuming a half-length boom on one side bounds uncertainty

Propagator	Full Sail Area	0.75 Sail Area
DAS	10-Jul-2021 (718 days)	02-Jan-2022 (894 days)
GMAT	06-Nov-2020 (471 days)	21-Feb-2021 (579 days)

Actual deorbit date: late 16 or 17-Nov-2022 (1211 days after sail deploy)

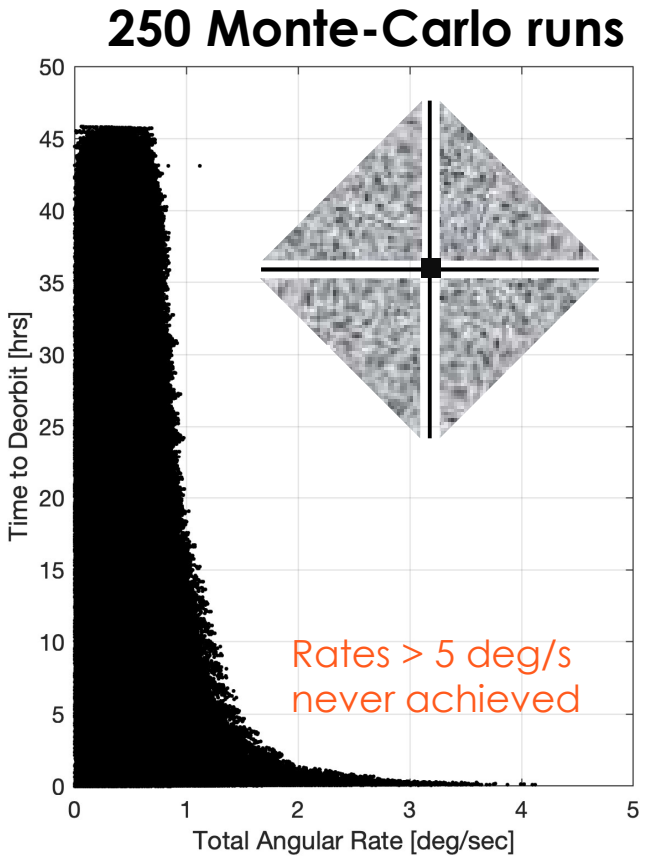
Deorbit

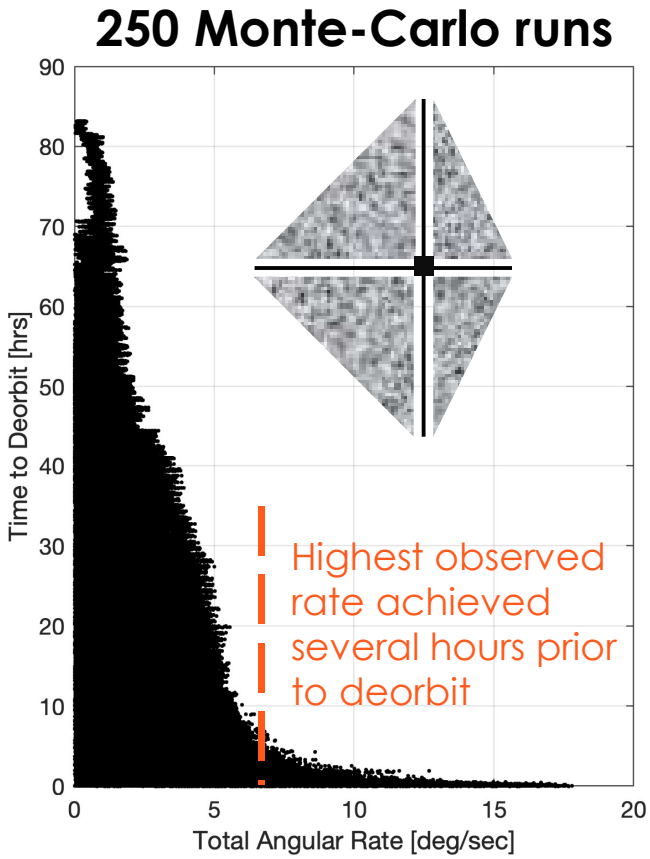
- Final week: LS2 placed in no-torques mode to observe uncontrolled attitude rates
- Rates much higher than any other time during mission
- No evidence for aerodynamic stabilization



Deorbit Reconstruction

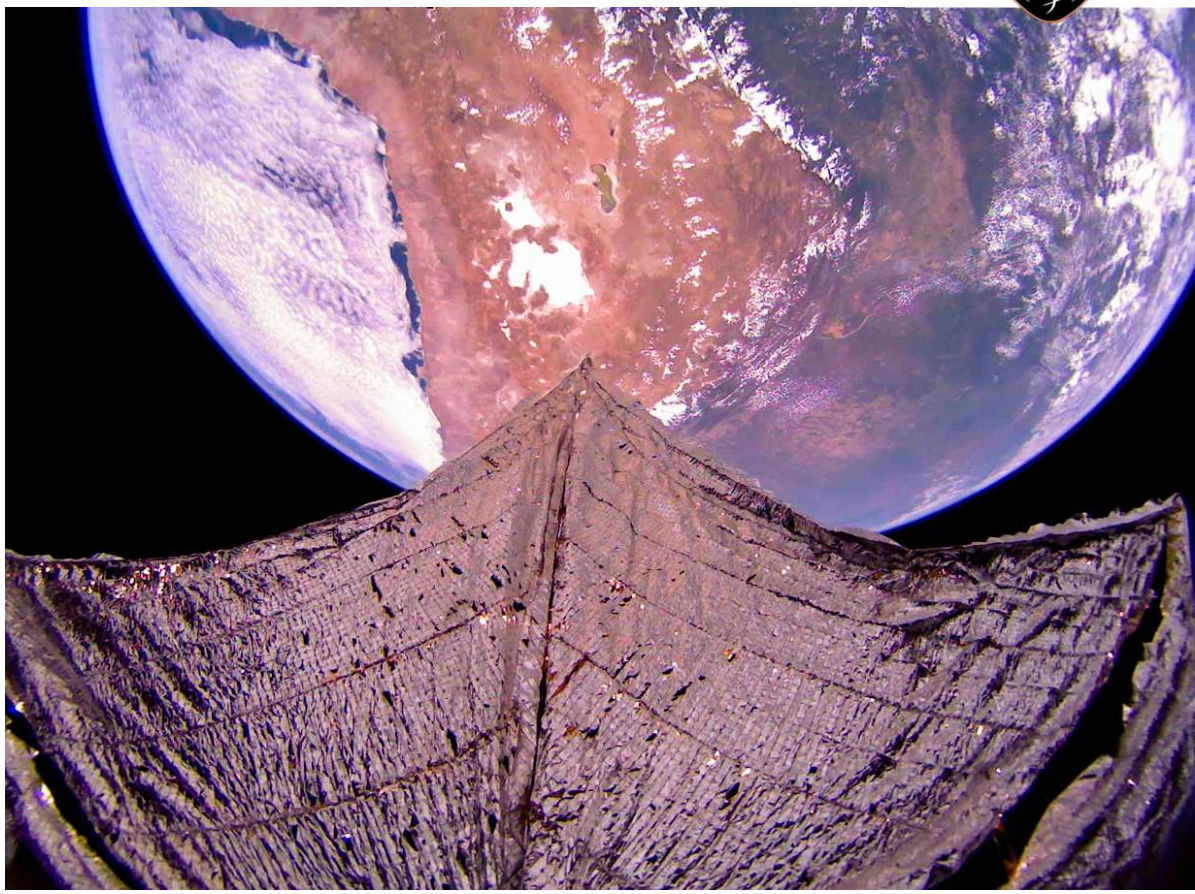
- We used a commercial 6DOF drag sail simulator to reconstruct final TLE to deorbit
- Observed rates exceed what can be modeled by a fully deployed sail, but not one with a half-length boom
- Conclusion: no evidence that sail had collapsed by the last telemetry





Conclusions

- LightSail 2 demonstrated control of a 3-axis stabilized CubeSat solar sail
- On-orbit gyro recalibration enhanced sail control
- Improved control enabled a period of sustained orbit raising
- LS2's duration on orbit was increased by solar sailing
- No evidence of passive stabilization or sail collapse prior to deorbit

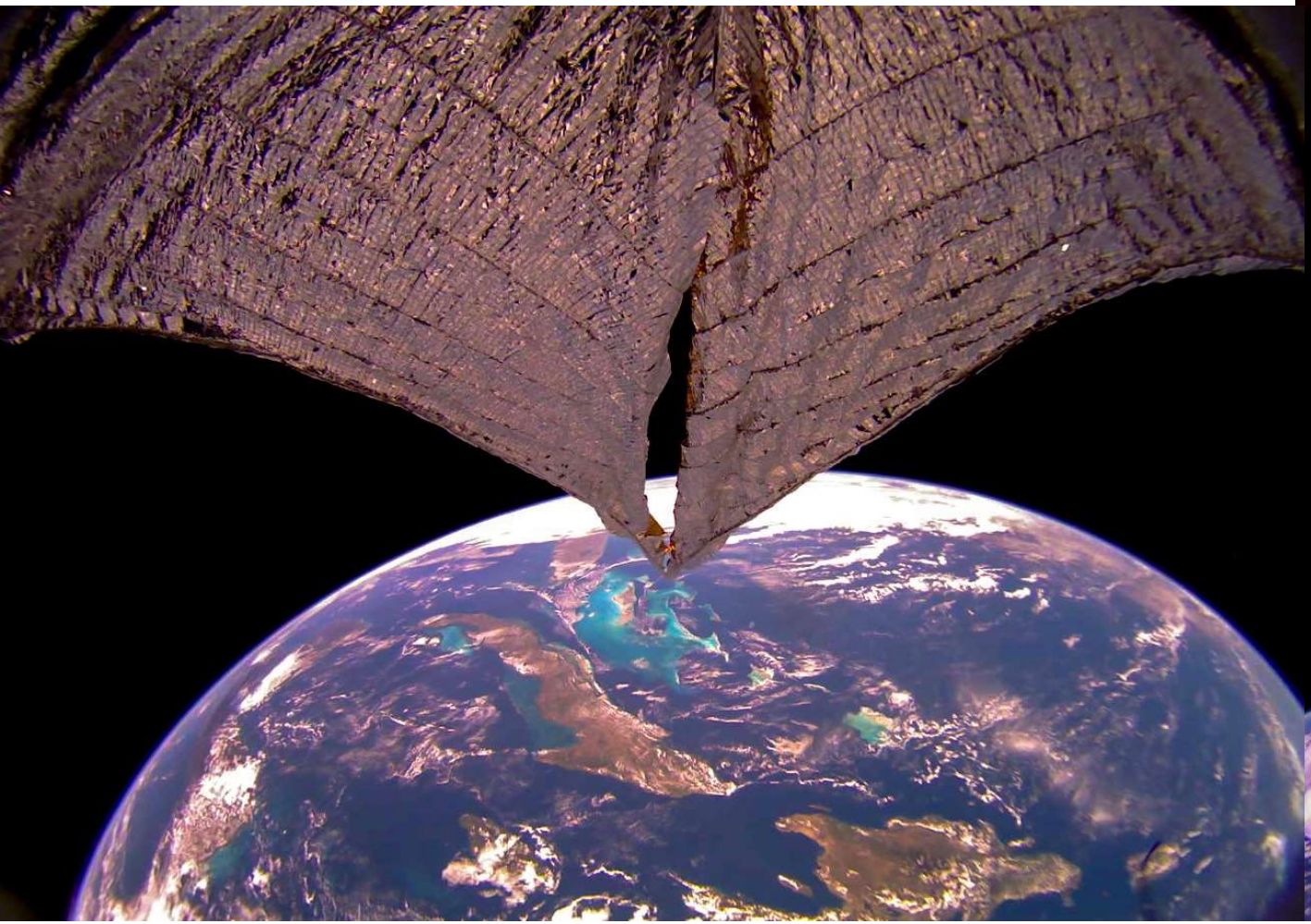


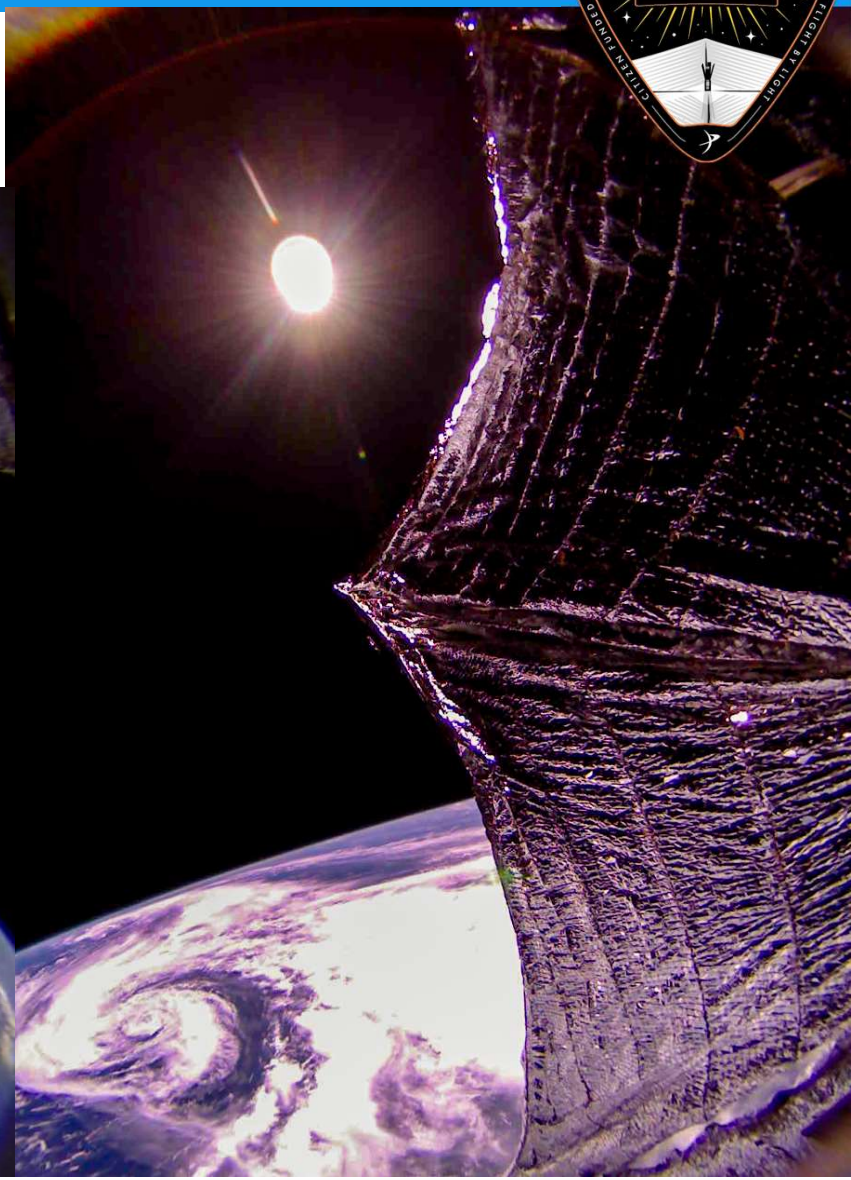
Final Image

Acknowledgements

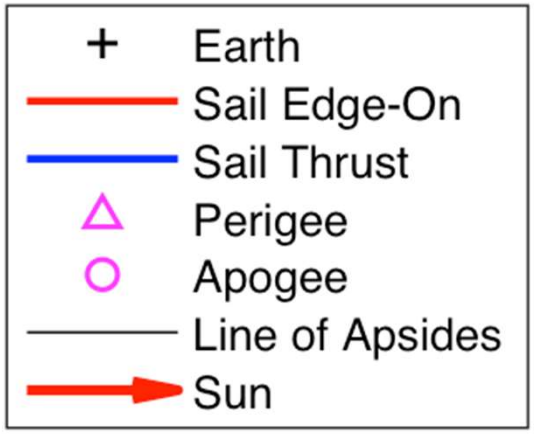
- Donors and members of The Planetary Society
- University NanoSat Program
- Air Force Research Laboratory
- Prox-1 team
- U.S. Department of Defense Space Test Program
- NASA Near Earth Asteroid Scout team
- Purdue Space Flight Projects Laboratory

Questions

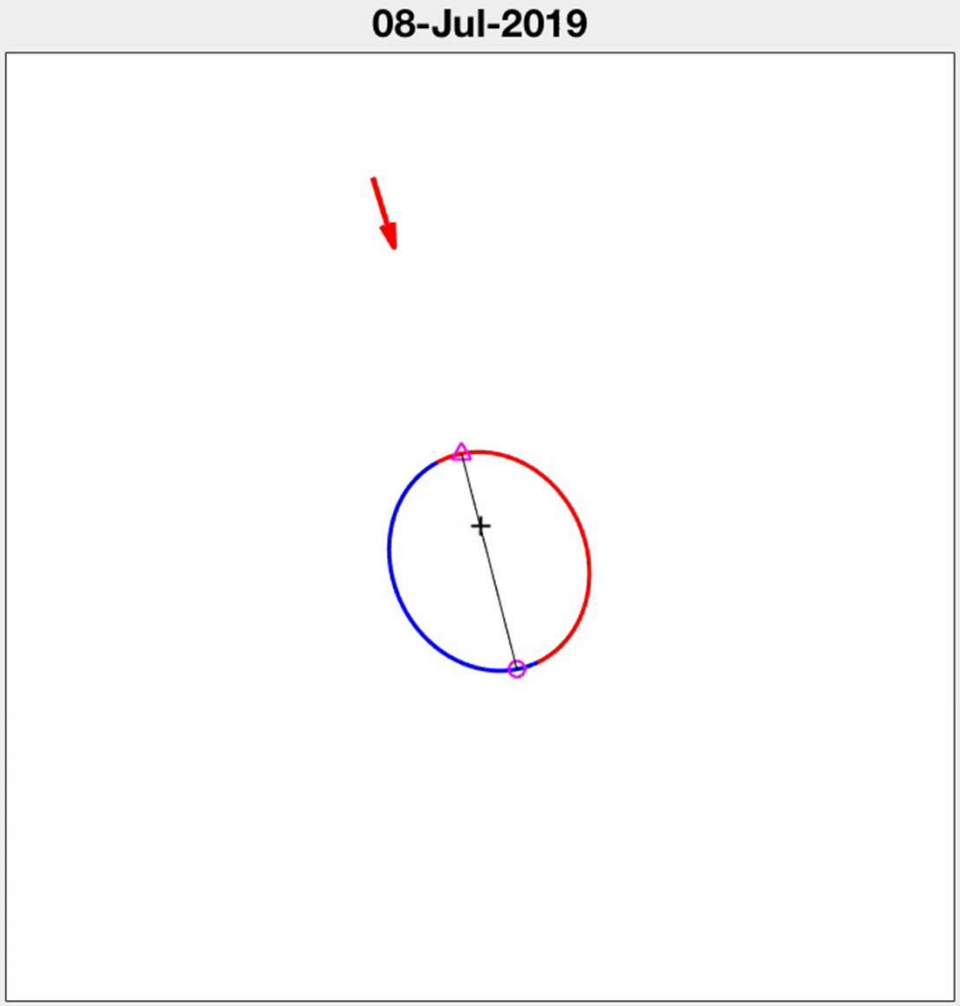




Backup Slides



*Eccentricity exaggerated for visualization



Pre-deployment Sail Control