LightSail 2 Attitude Determination and Control Lessons Learned

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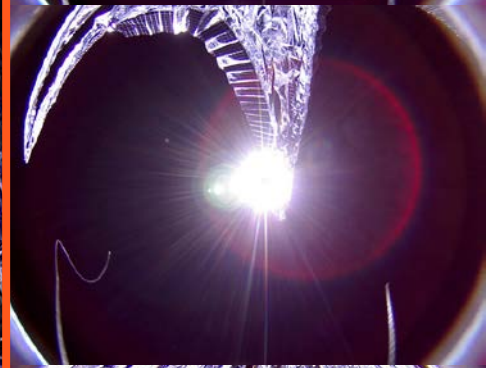

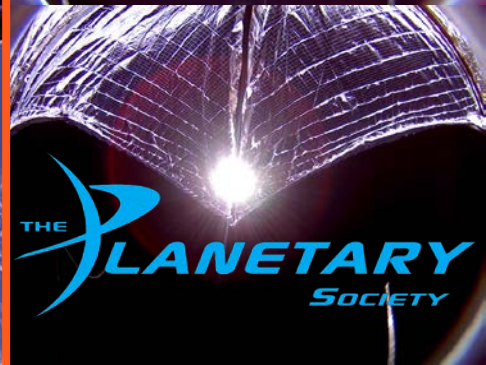

LightSail Program Overview

- The LightSail program was initiated by The Planetary Society in 2010 with the goal of advancing solar sailing technology on a CubeSat platform
  - 10 year program, $7.5M program cost
  - 100% funded through TPS member donations and crowdfunding
- Mechanical assembly of two 3U CubeSats completed by 2012, with 8 successful sail deployment tests
  - Spacecraft contractor Stellar Exploration Inc., San Luis Obispo CA
- Due to cost overruns and lack of launch opportunities to 800 km orbit, program was put on hiatus in 2012. TPS reformulated the program in 2013 with new mission goals:
  - LightSail 1: CubeSat checkout and sail deployment demonstration
    - 2015 ELaNa launch as part of Atlas V ULTRASat payload, to 356 x 705 km orbit.
  - LightSail 2: Controlled solar sailing in Earth orbit
    - 2019 launch as part of Space Test Program-2 payload to 720 km circular orbit
    - Deployed into orbit from Georgia Tech's Prox-1 spacecraft (UNP-7)

The LightSail 2 Team

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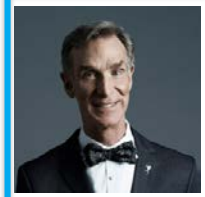

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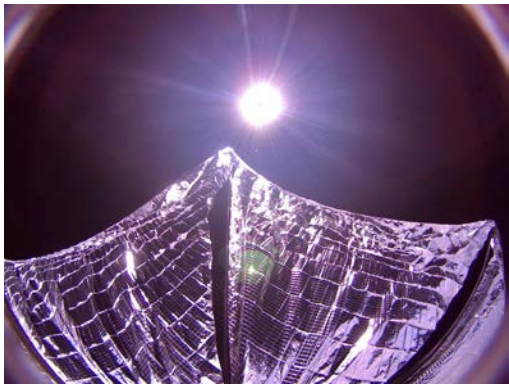
LightSail 1 Feed-Forward to LS2

- LightSail 1 successfully deployed solar sail on June 7, 2015
  - No active attitude control planned for LightSail 1
  - Due to software error (found during pre-launch testing), ADCS sensor readings only immediately following system reboot
- Three major anomalies during LightSail 1 mission
  - Electrical power subsystem anomaly following solar panel deployment
    - Prevented spacecraft operations during eclipse portion of orbit
    - Spacecraft flight software updates for battery fault management for LS2
  - Corrupted images from sail deployment sequence
    - Root cause not determined; possible EMI/EMC from deployment motor
    - Additional images acquired; successfully downlinked one full res image
  - Continuous transmission of RF noise for 3 days prior to reentry
    - Root cause not determined. Not reproduced during ground testing
- Reentry on June 14, seven days after sail deployment



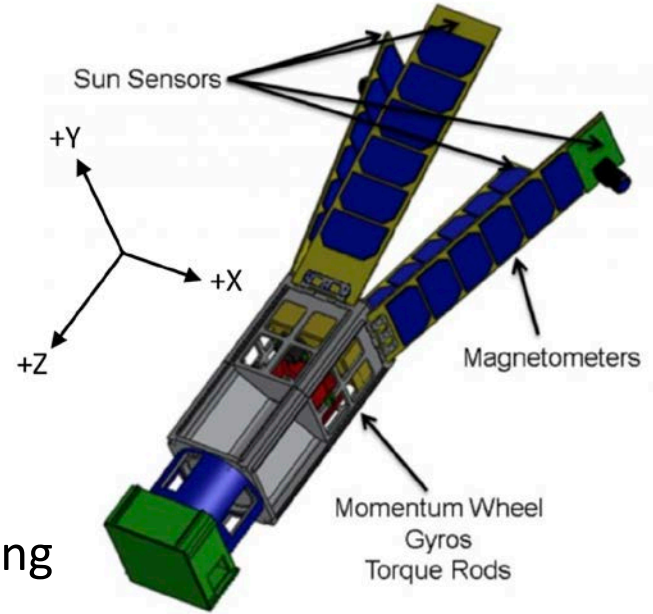
LightSail 2 ADCS Overview

ADCS Sensors & Actuators

- 2 Magnetometers
- 5 Sun sensors
- 3 Mainboard gyros
- 3 Precision gyros
- 3 Torque rods
- Momentum wheel

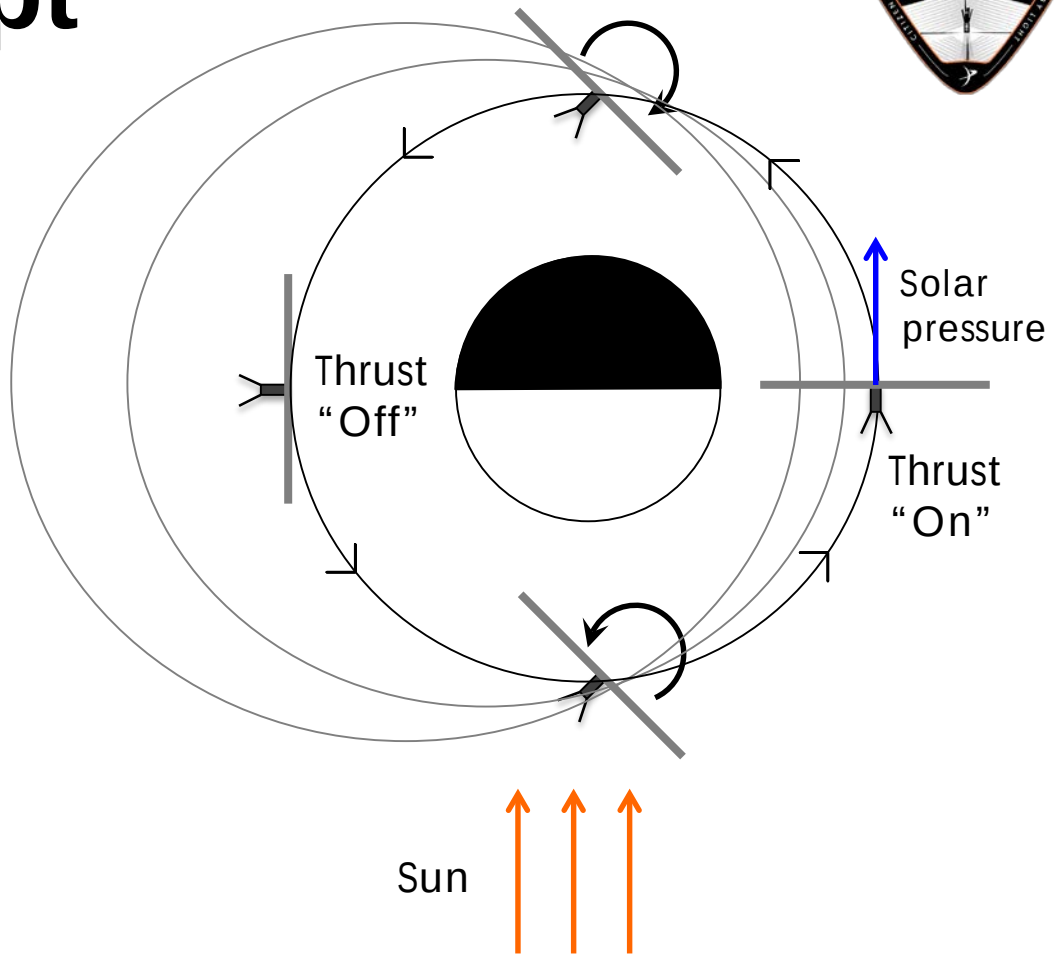
Control modes

- Mode 0: Detumble
- Mode 1: Magnetic alignment
- Mode 2: Solar sailing
- Mode 3: No torques
- Mode 4: Sun pointing
- Mode 5: Velocity pointing



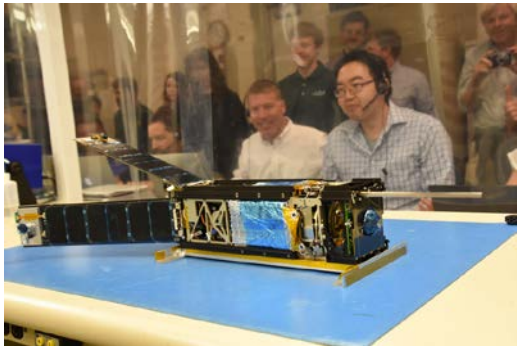
Sailing Concept

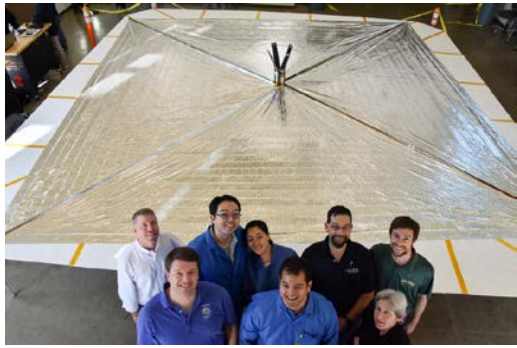
- Slew between “On” and “Off” attitudes
- Control changes in eccentricity and semi-major axis
- Solar pressure contributes a net increase in energy that can oppose losses due to atmospheric drag



Pre-Launch Testing

- Since the major required advancement for LS2 was active attitude control, the project completed focused ADCS testing
  - Utah State Space Dynamics Lab
    - Sensor calibration and phasing tests
  - UCLA
    - Sensor calibration and phasing tests
  - Momentum wheel testing
- System-level Day in the Life Test May 2016
- Three pre-launch Operational Readiness Tests

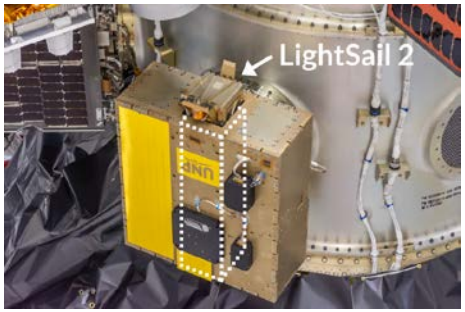




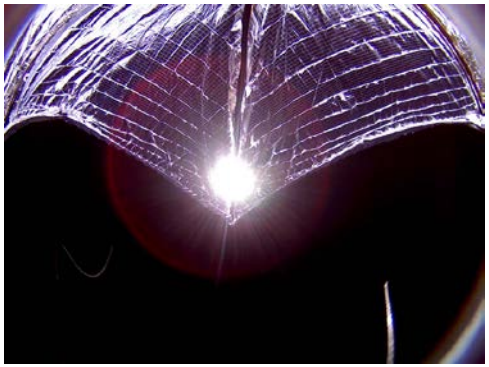
Mission Timeline

STP-2
Launch

June 25
2:30 AM EDT



July 3: Deployment from
Prox 1 & Initial Contact

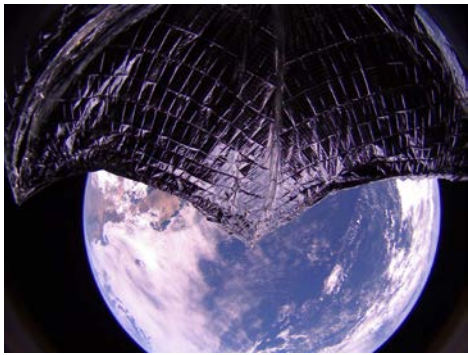


July 23
Sail deployment
& solar sailing

July 3 – 22

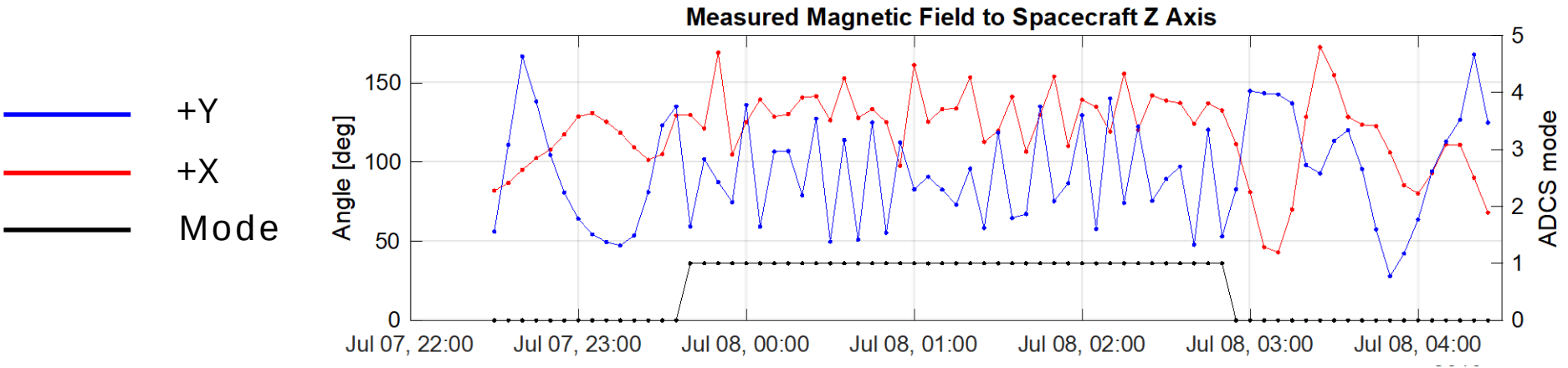
Spacecraft checkout

- Sensors
- Actuators
- Software
- Attitude control
- Resolve anomalies

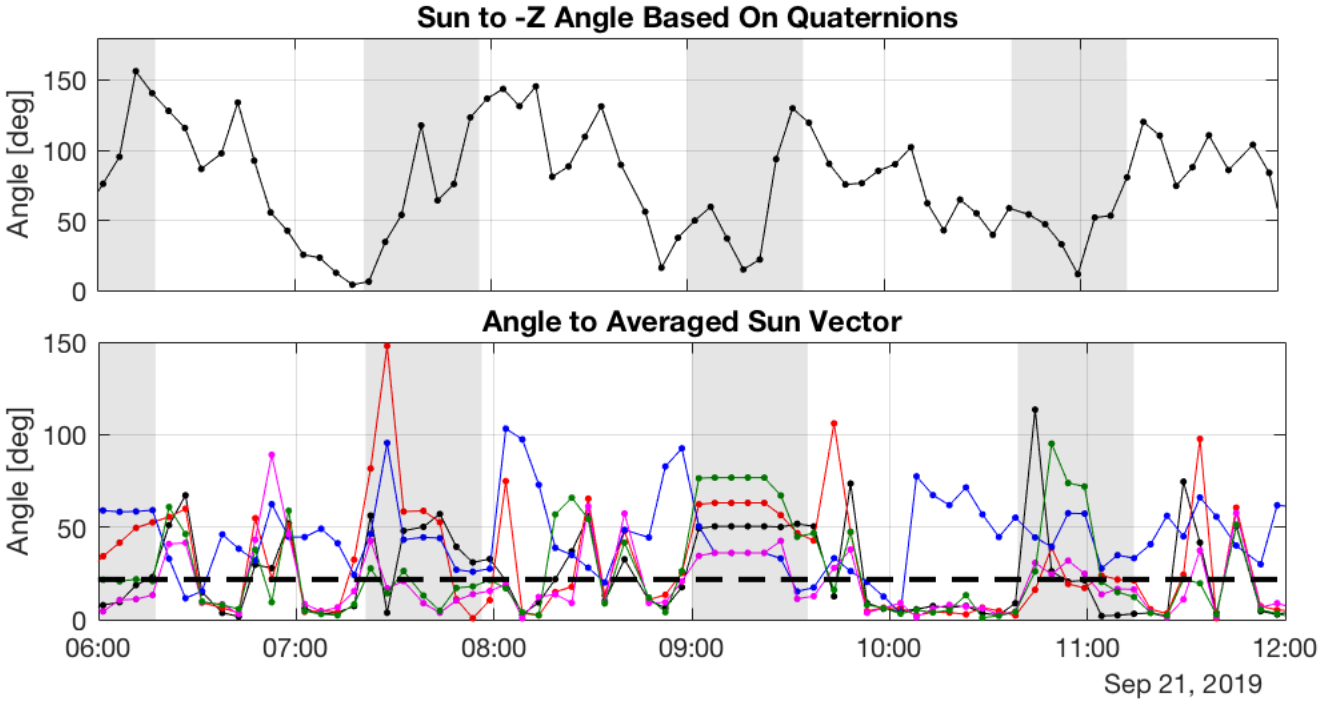


ADCS Checkout: Magnetometers

- Measured magnitudes consistent with IGRF B-field model
- +Y mag sensor gave implausible directions in magnetic alignment mode
  - Taken offline July 8th, leaving only +X mag sensor active



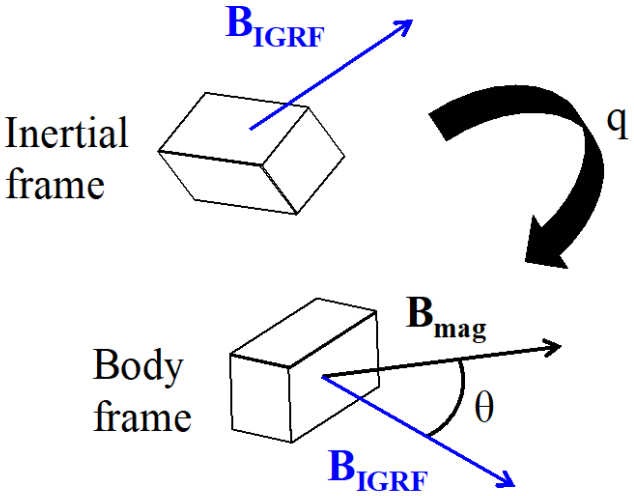
ADCS Checkout: Sun Sensors

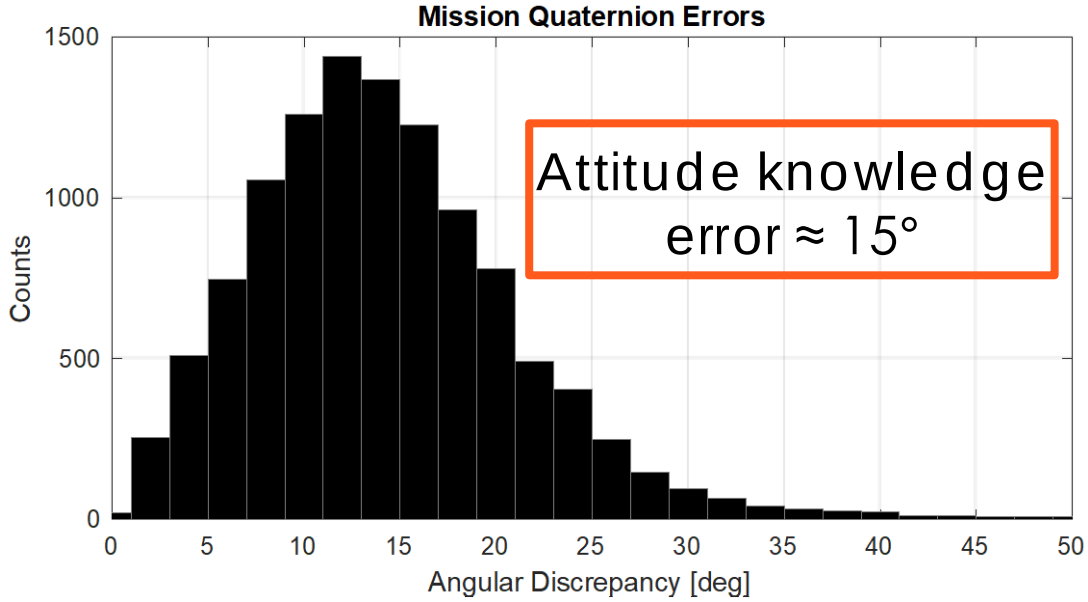


- +Y a clear outlier
- Taken offline Sep. 26

Attitude Determination Accuracy

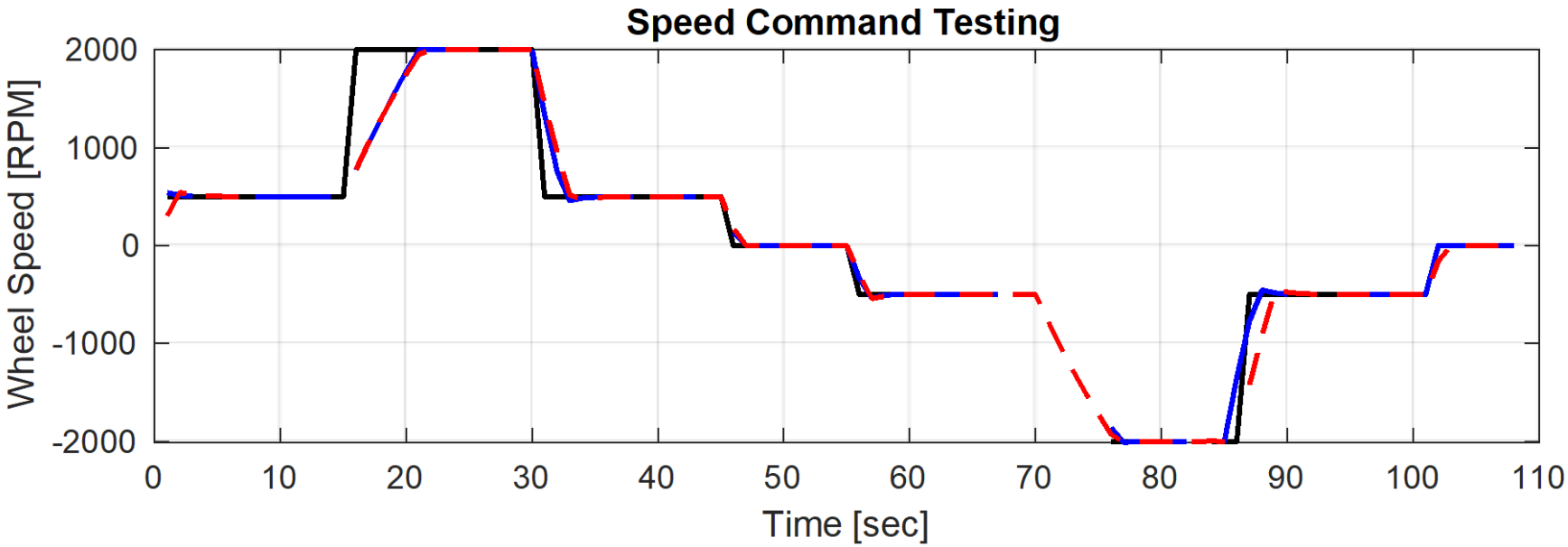
- Magnetic field vector is predicted based on IGRF model and the known position of the spacecraft
- If the attitude quaternion is accurate, rotating the predicted B-field into the body frame should agree with the measured field





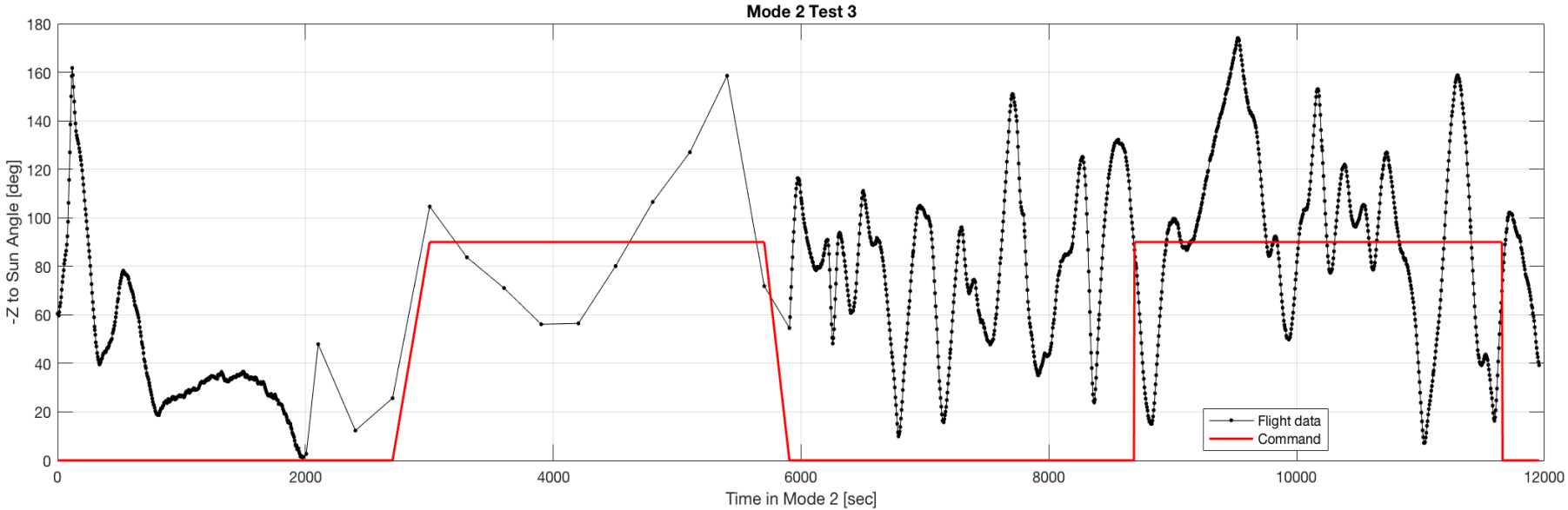
ADCS Checkout: Momentum Wheel

- Autonomous momentum wheel test nominal



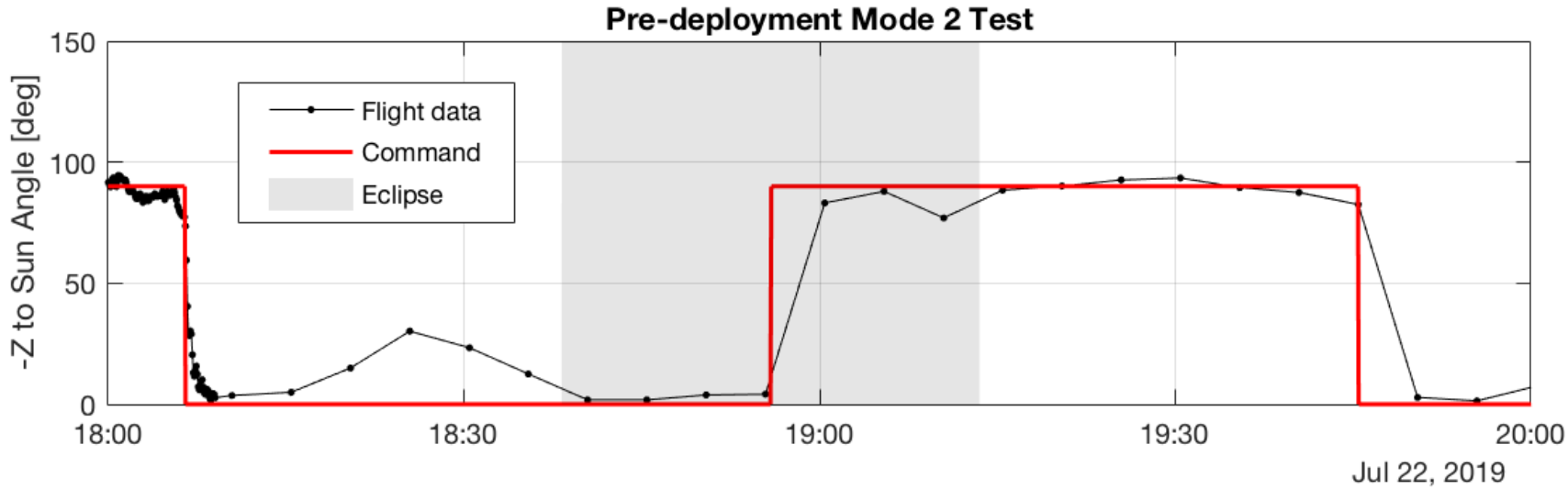
Pre-deployment Attitude Control Tests

- Initial Mode 2 tests did not demonstrate expected “on-off” attitude control signature from recorded quaternions



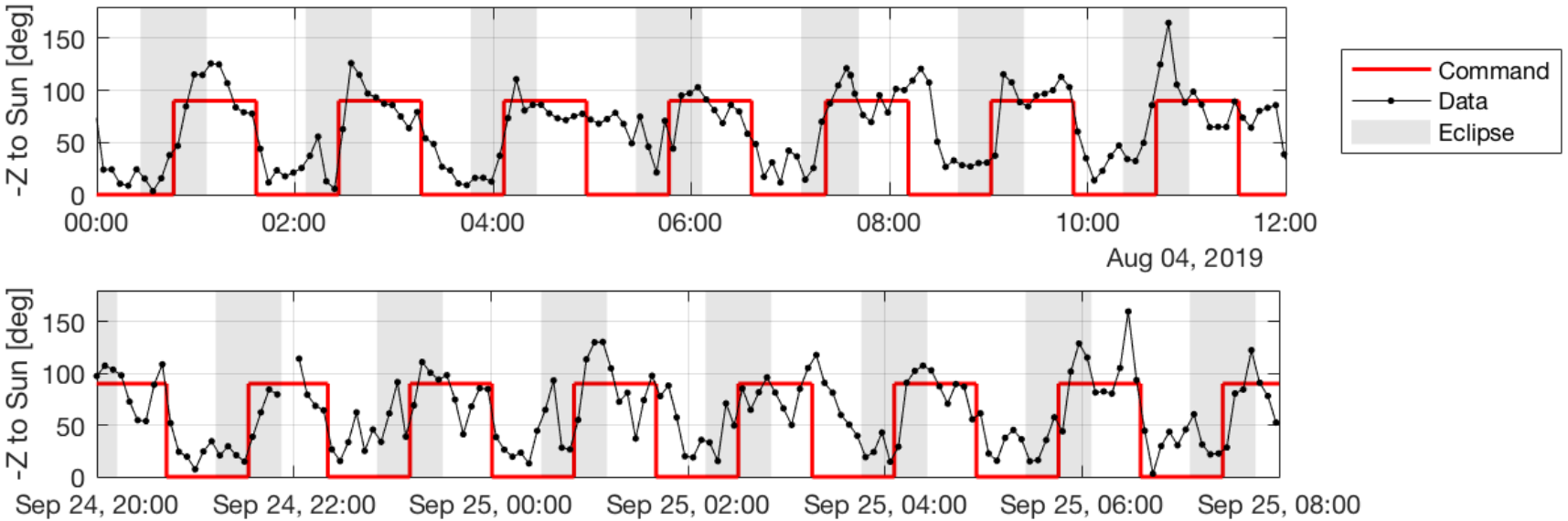
Successful Mode 2 Test

- Two weeks of ADCS troubleshooting resulted in successful Mode 2 test
  - Corrected errors in direction cosine matrices
  - Corrected sun sensor software logic error
  - Moving average filter for wheel torque commands
  - Increase control gain setting to avoid wheel settling at 0 rpm
  - Corrected a software error that prevented wheel speed sign change



Active Sail Control

- Following sail deployment, ADCS successfully controlled to targeted attitude
- Apogee raised by 9 km over first 30 days of solar sailing
  - Long term secular decrease in semi-major axis due to atmospheric drag at <720 km
- Daily momentum wheel desaturations needed for momentum management



Conclusions

- LightSail 2 prioritized ADCS testing during the I&T program to ensure proper phasing and operability
- Despite a robust I&T program, numerous ADCS problems were not uncovered until the on-orbit checkout phase
  - Both software and hardware issues found
- Having the flight team co-located during early mission operations allowed the rapid identification of ADCS error sources, mitigation, and validation of fixes
  - BenchSat was a valuable resource for lab-based ADCS testing
- After six months of successful operations, the flight team continues to address momentum management and tune solar sailing performance.

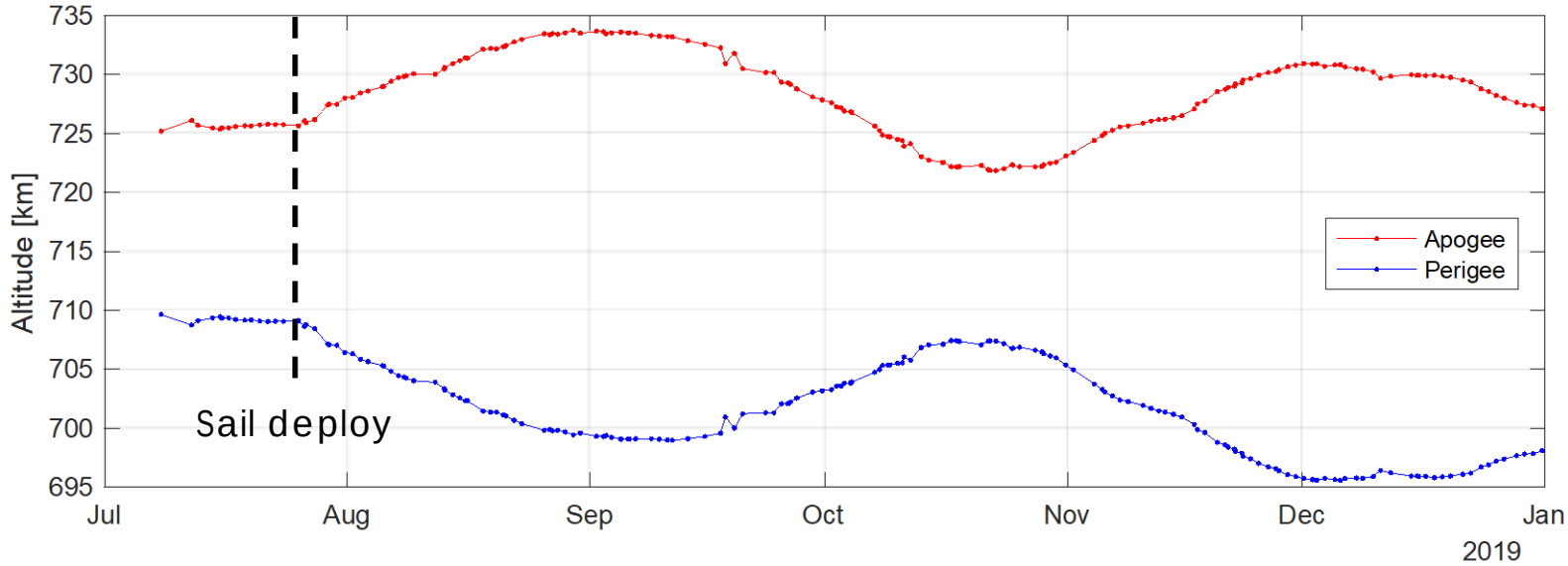
References

- Mansell, J., Spencer, D.A., Plante, B.A., Diaz, A., Bellardo, J.M., Betts, B., “Orbit and Attitude Performance of the LightSail 2 Solar Sailing Spacecraft,” AIAA Science and Technology Forum and Exposition, Orlando, FL, January 2020.
- Betts, B., Spencer, D., Bellardo, J., Nye, B., Diaz, A., Plante, B., Mansell, J., Fernandez, M., Gillespie, C., Garber, D., “LightSail 2: Controlled Solar Sailing Propulsion Using a CubeSat,” 70th International Astronautical Congress, Washington, D.C., October 2019.
- Betts, B., Nye, B., Greeson, E., Vaughn, J., Chute, R., Spencer, D.A., Ridenoure, R.W., Munakata, R., Wong, S.D., Diaz, A., Stetson, D.A., Foley, J.D., Bellardo, J.M., and Plante, B.A., “LightSail 1 Mission Results and Public Outreach Strategies,” 4th International Solar Sailing Symposium, Kyoto, Japan, January 2017.
- Betts, B., Spencer, D., Nye, B., Munakata, R., Bellardo, J.M., Wong, S.D., Diaz, A., Ridenoure, R.W., Plante, B.L., Foley, J.D., Vaughn, J., “LightSail 2: Controlled Solar Sailing Using a CubeSat,” 4th International Solar Sailing Symposium, Kyoto, Japan, January 2017.
- Plante, B.A., Spencer, D.A., Betts, B., Chait, S., Bellardo, J.M., Diax, A., Pham, I., “LightSail 2 ADCS: From Simulation to Mission Readiness,” 4th International Solar Sailing Symposium, Kyoto, Japan, January 2017.
- Ridenoure, R., Munakata, R., Diaz, A., Wong, S., Plante, B., Stetson, D., Spencer, D., and Foley, J., “Testing The LightSail Program: Demonstrating Solar Sailing Technology Using a CubeSat Platform,” *Journal of Small Satellites*, Vol. 5, No. 3, October 2016.

BACKUP SLIDES

Orbit Evolution

- Orbit changes visible almost immediately
- Apogee increased while perigee showed a mirrored decrease
- Eventually the trend reversed and oscillated



Orbit Decay Rate

- The rate of orbit decay is demonstrably reduced by solar sailing
  - Average –34.5 m/day change versus –19.9 m/day
  - Some intervals show semi-major axis increases of up to +7.5 m/day