LightSail 2 Attitude Determination and Control Lessons Learned

David Spencer, Purdue University
February 12, 2020
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

Dr. Bruce Betts  
Program Manager  
The Planetary Society

Dr. David A. Spencer  
Project Manager  
Purdue University

Barbara Plante  
Attitude Control Engineer  
Boreal Space

Michael Fernandez  
Satellite Operator  
Cal Poly San Luis Obispo

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

Justin R. Mansell  
Flight Mechanics  
Purdue University

Cole Gillespie  
Satellite Operator  
Cal Poly San Luis Obispo

Alex Diaz  
Avionics Engineer  
Ecliptic Enterprises

Jennifer Vaughn  
Chief Operating Officer  
The Planetary Society

Bill Nye  
Chief Executive Officer  
The Planetary Society

Jason Davis  
Editorial Director  
The Planetary Society
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 - 22**
- **Spacecraft checkout**
  - Sensors
  - Actuators
  - Software
  - Attitude control
  - Resolve anomalies

**July 23**
- **Sail deployment & solar sailing**
ADCS Checkout: Magnetometers

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

![Graph showing measured magnetic field to spacecraft Z axis]
ADCS Checkout: Sun Sensors

- Measurements subject to voting via comparison to average
- Measurements converge to average when -Z axis pointed towards Sun
- +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.

Attitude knowledge error $\approx 15^\circ$
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

Pre-deployment Mode 2 Test

Flight data
Command
Eclipse

Jul 22, 2019
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

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 $-34.5 \text{ m/day}$ change versus $-19.9 \text{ m/day}$
  - Some intervals show semi-major axis increases of up to $+7.5 \text{ m/day}$