LightSail 2 ADCS: From Simulation to Mission Readiness

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After the success of the first LightSail Mission (LS1) in May/June 2015, the LightSail team met in December 2015 at the Planetary Society headquarters to conduct a full mission review and set objectives for the next mission, LightSail 2 (LS 2). The team identified hardware and software changes to the spacecraft baseline, and discussed enhancements to the ADCS subsystem. Unlike LS1, which flew in an elliptical orbit reaching under 400km minimum altitude, LS2 will fly in a circular orbit above 700 km, a more advantageous sailing environment.

One sailing method considered and modeled was the detection of orbital inclination change due to solar radiation pressure (SRP) as presented in the work by Stolbunov, et al. This option was ultimately rejected since the spacecraft would not be in a truly SRP dominated orbit and modeling results showed that the 32 square meter sail would not allow for an observable inclination change over the anticipated mission duration. An apogee raising method using the On/Off switching method proposed by McInnes was explored, which would increase the semi-major axis of the orbit enough to be readily measured during the mission. “On” has the solar sail normal parallel to the sun vector, in the process gaining orbital energy while “Off“ has the sail normal perpendicular to the sun vector. Sail orientation requires a 90-degree slew maneuver twice an orbit. Encouraging modeling results for the apogee raising method drove the decision to use it for the solar sailing demonstration mission.

Specifics of the hardware and software used to control solar sail deployment, on-orbit imaging, and other aspects of the spacecraft have been the subject of other papers by the LightSail team. With respect to ADCS, spacecraft attitude is determined using 4 magnetometers, 5 solar angle sensors, one 3-axis gyro which acts as the primary angular rate sensor, and one 3-axis gyro as the backup. Attitude control is accomplished using 3 variable dipole magnetic torque rods and 1 60mNms reaction wheel. A discussion of the testing and characterization of the ADCS hardware is presented, and the apogee raising concept is characterized. ADCS flight software is described, including operational modes, timing considerations, and fault detection strategies. System and long-duration testing of the integrated software on the flight vehicle, which exercises the entire mission CONOPS, serves to mitigate risks and sets the stage for mission readiness of LightSail 2.

Key Words: LightSail, ADCS, Simulation, Solar Sailing, CubeSat

1. Introduction

LightSail is a flagship program of The Planetary Society (TPS), an organization with over 40,000 active members worldwide which has, among other key objectives, “to empower the world's citizens to advance space science and exploration” (The Planetary Society, 2015).

In 2009, then Planetary Society Executive Director Lou Friedman initiated the LightSail program to demonstrate solar sailing in low earth orbit (LEO) using the standard 3U CubeSat form factor. The program moved ahead and by 2011, the LightSail 1 mechanical assembly was complete and successful deployment tests had been conducted (Biddy, 2012). However, due to the lack of a viable launch opportunity to the desired 800km orbit and other programmatic reasons, TPS paused the program in 2012 until further notice. Spurred on by member interest in LightSail, TPS reviewed its options with the help of an advisory panel, reformulated the program plan and, in 2013, re-activated the program with a new management and technical team.

Ecliptic Enterprises Corporation was selected to complete the integration and testing program for LightSail, with Boreal Space, Hayward, CA, and Half Band Technologies, San Luis Obispo, CA, providing subsystem design and development support. California Polytechnic University at San Luis Obispo (Cal Poly) would lead environmental testing of the spacecraft and the Poly-Picosatellite Orbital Deployer (P-POD) integration effort, as well as coordinate launch approval activities. The Georgia Institute of Technology (Georgia Tech), Atlanta, Georgia, would lead the mission operations and ground data system, with Cal Poly providing spacecraft tracking and mission operations support.

In January 2013, Georgia Tech’s Prox-1 mission, to demonstrate proximity operations relative to a deployed CubeSat, was selected for implementation by the Air Force Office of Scientific Research/Air Force Research Laboratory University Nanosatellite Program (Okseniuk, 2015).

TPS refocused its solar sailing program on building two spacecraft, LightSail 1 (LS1) and LightSail 2 (LS2). In order to capitalize on a NASA ELaNa program launch opportunity, which would provide a less than ideal orbit for solar sailing, LS1 mission objectives were limited to checkout of spacecraft on-orbit operations and demonstration of solar sail deployment. An agreement was reached between TPS and Georgia Tech to incorporate the LS2 spacecraft in the Prox-1 mission. Following launch as a secondary payload, Prox-1 would deploy LS2 and use it as a cooperative target for rendezvous and proximity operations. After completing its primary mission, Prox-1 would image LightSail solar sail deployment for downlink to the Georgia Tech ground station. LS2 would expand LS1 mission objectives to include the demonstration of solar sailing in low Earth orbit.

LightSail 1 was launched in May 2015 and was closely followed by domestic and international media. On June 9th, after several eventful weeks on-orbit, Planetary Society CEO Bill Nye declared the mission a success. Figure 1 shows an image of the deployed solar sail taken on June 8th, 2015 by a camera on-board LS1.

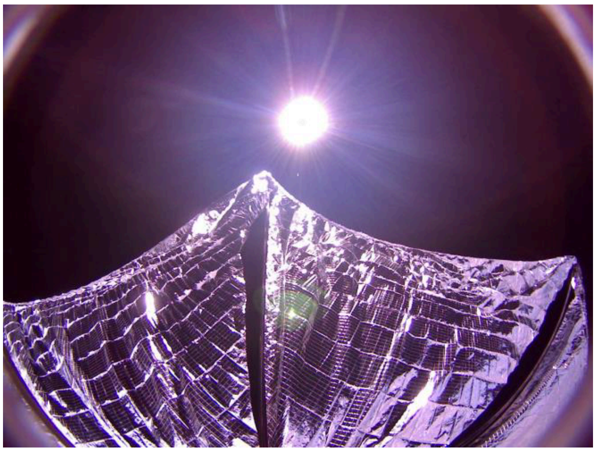

Fig.1. LightSail 1 solar sail deployed in Low Earth Orbit

In July of 2015, the LightSail team conducted a detailed planning workshop to capture lessons learned from LS1 and identify design changes to support new LS2 objectives (Spencer 2016). TPS, with the support of the LightSail team, has communicated on-going LS2 development activities in technical papers, popular media, and Jason Davis' blog (Davis 2014).

This paper describes the LS2 ADCS subsystem from concept to final integration and mission readiness.

2. LS2 CONOPS

After completion of flight qualification, LS2 is encapsulated in the Prox-1 ESPA-class spacecraft in preparation for launch from Cape Canaveral, Florida on a SpaceX Falcon Heavy launch vehicle. After deployment of Prox-1 into a circular orbit at 720km altitude, 24 degree inclination, it performs a 5-day checkout after which it slews to a deployment attitude (cross-track ejection), initiates the P-POD burnwire, and deploys the LightSail 2 3U CubeSat for an approximate 6 week mission. Prox-1 acquires visual and infrared images of LS2 every 0.25 seconds for 3 minutes after deployment and then every 10 seconds for 27 minutes (Figure 2).

LS2 solar panels and sail remain stowed as the flight processor is powered on and batteries begin charging. The telemetry beacon is activated and ground sites begin monitoring for the first beacons from the spacecraft.

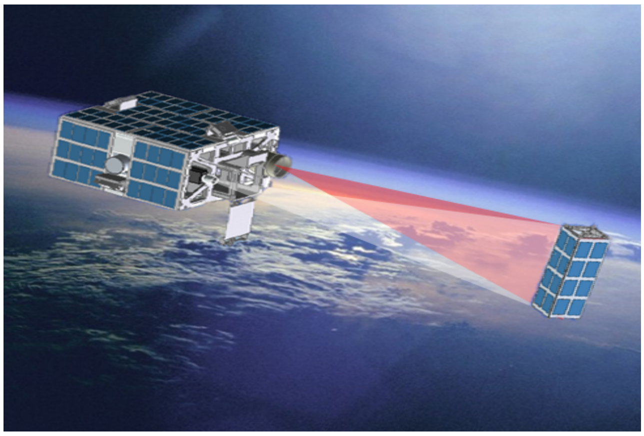

Fig. 2. LS2 deployment and imaging by Prox-1

LS2 is detumbled using magnetometer and solar angle sensor inputs to the ADCS B-dot control algorithm, which commands three torque rods to null spacecraft rates. Detumble is expected to take approximately 2 hours to complete after which ground operations commands LS2 into Z-Alignment, pointing the spacecraft antenna in the direction of the earth's magnetic field, providing an attitude for ground communication.

On-orbit checkout (OOC) of LS2 is planned for 2 days after deployment during which time the operations team will analyze subsystem health and status from beacon telemetry. The spacecraft clock is set by ground command and Two Line Element sets are uploaded to support SGP-4 orbit propagation.

When the spacecraft is in sunlight, the ground commands images to be taken from the inward-facing, panel-mounted cameras. The images are downlinked to allow the ground team to evaluate camera performance. A series of momentum wheel test commands is uploaded to the spacecraft and queued for execution. When commanded, the wheel test starts and runs autonomously to completion. Data from the wheel test is written to an on-board log for downlink and comparison to results obtained during ground testing. On Mission Day 20, LS2 deploys its solar panels and the spacecraft is evaluated for readiness to commence solar sail deployment.

After deploying LS2, Prox-1 navigates into a 150m trailing orbit relative to LS2 to demonstrate station keeping and rest-to-rest transfer maneuvers. Ground operations commands Prox-1 to maneuver to within 50 m of LS2. Prox-1 conducts a Natural Motion Circumnavigation (NMC) of LS2 from a passively safe orbit, enabling 360 degree imaging of LS2 in the visual and infrared. Finally, Prox-1 re-establishes its trailing orbit with LS2 in preparation for imaging the solar sail deployment.

On Mission Day 21, LS2 ground operations commands solar sail deployment. Solar panel mounted cameras image the deployment at a basic operating sequence tailored to bracket the ~2.5-minute solar sail deployment sequence: seven minutes of full-resolution imaging (1600 x 1200 pixels) per camera, for up to 32 images per imaging sequence. Prox-1 images the sail deployment from its 150 m trailing orbit. After a successful sail deployment, ADCS transitions to Solar Sailing mode and LS2 accelerates away from Prox-1 through Mission Days 21-49.

ADCS telemetry is collected and analyzed by the ground team to compare on-orbit behavior to simulation results. If desired, modifications to existing algorithm gains can be uploaded to experiment with and potentially optimize spacecraft control. The apogee altitude is expected to increase by roughly 700 m/day during this mission phase. After 28 days of solar sailing, it is expected that atmospheric drag at perigee will preclude further apogee raising.

After primary mission goals have been achieved, additional activities are planned to further demonstrate the value of LS2 as an experimental laboratory for solar sailing. These activities include commanding off nominal orientations of the spacecraft, sail tensioning, additional changes to algorithm gains, manually commanding of the momentum wheel, and removing all actuated control of the spacecraft in the No_Torques ADCS mode.

3. ADCS High-Level Requirements

High-Level requirements for the ADCS subsystem are as follows:

- Provide attitude knowledge to within 5 degrees per axis during all mission phases.
- Sun sensors provide data on the angle of light incidence to the sensors to within +/- 3 degrees accuracy.
- Magnetometers provide attitude knowledge of the body-fixed x-, y-, and z-axes to within +/- 5 degrees relative to the Earth magnetic field.
- Sample spacecraft angular rates using gyro sensors.
- Prior to solar sail deployment, provide attitude control to within 10 degrees per axis.
- Be actively controllable in each of its three-axes.
- Accommodate a tip off rate of up to 25 degree/sec per axis from P-POD deployment.
- Damp attitude rates within 2 hours of P-POD deployment.
- Utilize torque rods to achieve attitude control to within 10 degree per axis prior to solar sail deployment.
- Utilize a momentum wheel to achieve 90-degree slew maneuvers about one axis in < 5 minutes.
- Prior to sail deployment, be capable of providing an angular acceleration of 0.1 degrees/s^2 per axis.
- Following solar sail deployment, be capable of providing an angular acceleration of 0.0005 degrees/sec^2 per axis
- Detumble from a maximum of 10 degrees per second per axis after sail deployment.
- Align +Z axis of the spacecraft with the magnetic field with maximum variation once settled of < 60 degrees.
- Downlink telemetry for sensors, actuators and performance data.

Use Cases provide detailed descriptions of LS2 CONOPS actions and events (Table 1). The Use Cases, in conjunction with high-level requirements, facilitate the derivation of low-level requirements that drive the ADCS design. Requirements and associated Use Cases are captured in an Excel spreadsheet known as the ADCS Requirements Verification Matrix (RVM), which serves as a tracking tool for both requirements and test verification activities.

Table 1. LS2 ADCS Use Cases

Use Case	Description
LS2 ADCS 000	Mission CONOPS Overview
LS2 ADCS 001	Power On and Reboots
LS2 ADCS 002	Ground Contacts, Commanding and Telemetry
LS2 ADCS 003	Modes and States
LS2 ADCS 004	On-Orbit Checkout
LS2 ADCS 005	Solar Panel Deployment
LS2 ADCS 006	Solar Sail Deployment
LS2 ADCS 007	Solar Sailing
LS2 ADCS 008	Extended Mission

4. ADCS Design

LightSail spacecraft hardware, including the deployment mechanism and sail, has been described in previous papers, (Ridenoure, 2015). The ADCS sensor and actuator hardware baseline is summarized in Table 2.

Table 2. LS2 Sensors and Actuators

Component	Number	Vendor
Sun Sensors	5	Elmos
Magnetometers	4	Honeywell
Primary Gyro	1	Analog Devices
Intrepid Gyro	1	Tyvak
Torque Rods	3	Strass Space
Momentum Wheel	1	Sinclair Interplanetary

4.1. Modeling and Simulations

LS1 ADCS incorporated 2Hz and 10Hz Bang-Bang control algorithms for the spacecraft stowed and deployed configurations respectively. After sail deployment, the Bang-Bang control was modified by a principle known as Input Shaping (Banerjee, 2001) to damp out sail vibrations by exercising proportional control of the torque rods. However, given the elliptical orbit of 356 x 705km, the drag effects at perigee overpowered attempts at sail control.

After LS1 was flight qualified and encapsulated for launch, the team turned its attention to other possible approaches to solar sailing control for LS2. One option was to keep the solar sail in a minimum drag configuration and demonstrate inclination change of the spacecraft (Stolbunov, 2013). The LS2 circular orbit at 720km is a high enough altitude to study the combined effects of solar radiation pressure and atmospheric drag acting on the spacecraft.

4.1.1. Inclination Change

In February of 2015, Boreal Space began modeling studies of inclination change using Matlab/Simulink. Work was performed in three phases; 1) model a pointing controller that included LightSail sensors and actuators 2) model the z-axis alignment controller and 3) model orbital inclination change.

Magnetometers were assigned 5 degrees of uncertainty in direction and solar angle sensors 3 degrees uncertainty in direction. Gyros were not modeled in the first phase. Magnetorquers with a maximum 1Am^2 torque authority provided roll and pitch axis control with a reaction wheel controlling yaw axis motion (max 0.06 Nm).

Disturbances modeled included drag, solar radiation pressure, gravity gradient, magnetometer misalignment, magnetorquer misalignment and residual dipole. The simulation used an 11 degree tilted magnetic field dipole model rotating with the earth, with field strength of 22.7 micro tesla at a mean altitude of 625km. A PID controller with cross coupling cancellation was constructed, with a bandwidth of 0.004 Hz (limited by the sensor noise and the Dipole strength) and 1 second sampling time, with 0.2 second oversampling sensors limited by the sensor noise and the Dipole strength with 3rd order 0.03Hz Low Pass Filter (LPF).

Results show that for a typical Earth magnetic field B, the 1σ sun pointing error is about 1.8 degrees (Figure 3). The time varying Earth magnetic field is the main contributor to the error. The yaw error is well controlled by RWA and is very small compared to Roll and Pitch errors. The system is only marginally stable if the Earth magnetic field is half of the typical value (Figure 4.).

Next, a Z-axis alignment controller was modeled using magnetometers and gyros while actuating the torque rods and momentum wheel. Gyro uncertainty is ~1 degree per axis.

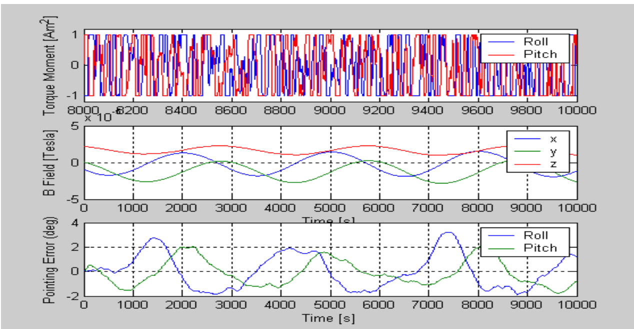

Fig. 3. B=22.7 microTesla; 1σ pointing error = 1.8 degrees

The algorithm aligns the spacecraft to the Earth magnetic field by controlling the Roll and Pitch of the B vector. Figure 5 shows linear detumbling from 0 to 500 seconds with dB/dt settling after 300 seconds. The bandwidth is 0.02 Hz, limited by the magnetometer sensor noise.

The momentum wheel is turned on at t=500 seconds and is commanded between 500 and 1000 seconds. The resulting RPM depends on wheel inertia and the B field. Torque Rods generate opposite torques. The gyros are turned on and the switch to angular velocity controller occurs at 1000 seconds. Pitch and roll controls are weak around 90 degrees alignment because the B field is very small around the Z-Axis.

Figure 6 shows a rapid alignment of the spacecraft z-axis to the magnetic field when the algorithm switches to the z-alignment controller at t=2000 seconds. After settling, the primary gyro can be turned off if there are power considerations, however the z-axis angular velocity slowly drifts depending on the disturbances.

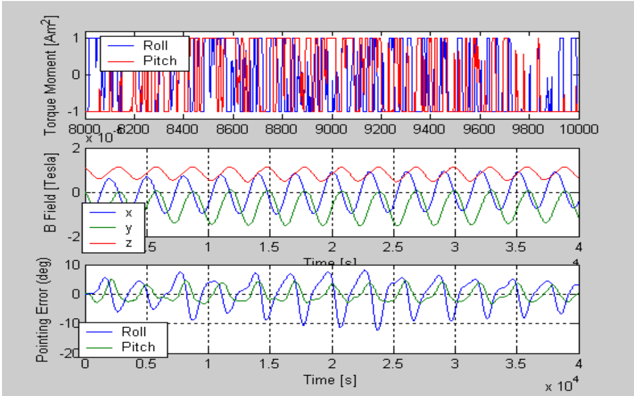

Fig. 4. B=11.4 microTesla; 1σ pointing error = 5.3 degrees

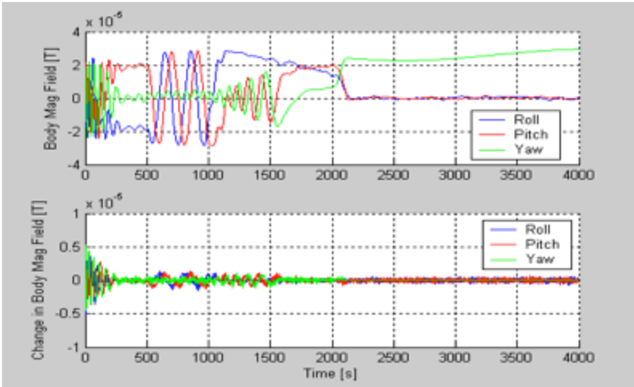

Fig. 5. Linear detumbling of spacecraft

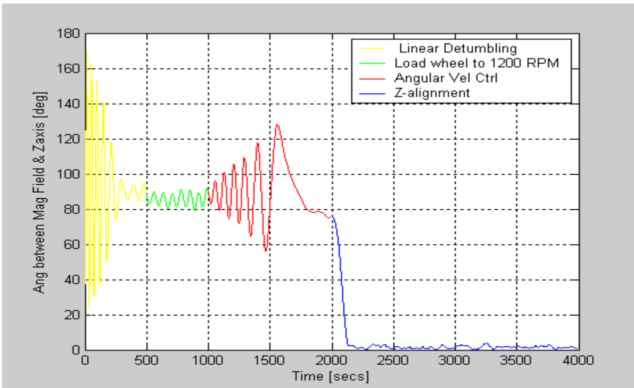

Fig. 6. Spacecraft z-axis alignment to magnetic field

Inclination pointing, adopted from Stolbunov, was simulated using a distributed control law that continuously varies the sail angles throughout the spacecraft orbit. The simulation model uses the simplified 11 degrees tilted Dipole magnetic field.

Assuming that $\hat{r}_{S\odot}$ = the sun vector, $\hat{N}$= a vector normal to a solar sail modeled as a reflective flat plate and $\hat{t}$= a vector aligned with the spacecraft velocity, all being unit vectors in ECI coordinates, then the optimal inclination for an SRP dominated case is expressed mathematically as follows:

$$\alpha_N = \alpha_\odot \qquad \text{Eq. (1)}$$

$$\tan \beta_N = (3 \tan \beta_{\odot} \pm \sqrt{9 \tan^2 \beta_{\odot} + 8}) / 4 \qquad \text{Eq. (2)}$$

where α_N = yaw of the $\hat{N}$ vector, $\alpha_{\odot}$ = yaw of the $\hat{r}_{S\odot}$ vector, β_N = pitch of the $\hat{N}$ vector, and $\beta_{\odot}$ = pitch of the $\hat{r}_{S\odot}$ vector. For the simulations, pitch and yaw are modeled in degrees.

Simulations were run with a circular orbit period of 5951 seconds, and a sun direction vector = [1 0 0]. For initial conditions, r = [7098 0 0] km and velocity v = [0 6.9 3] km/sec. Figure 7 shows optimal pointing angles resulting in a positive inclination.

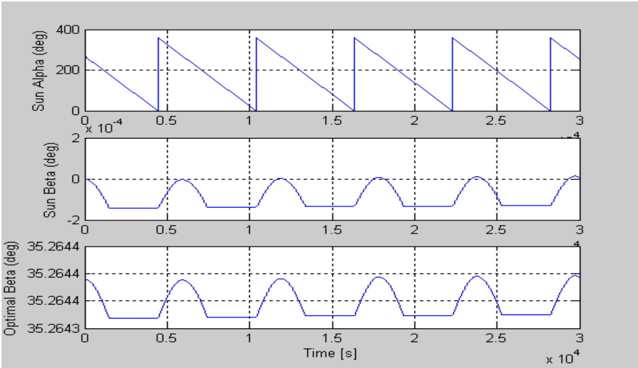

Fig. 7. Optimal Pointing Angles – Positive Inclination

Figure 8 shows pointing errors of for a B field of 23 microTesla. The 1σ pointing error is 4.1 degrees. For a magnetic field strength of 40 microTesla, the 1σ error

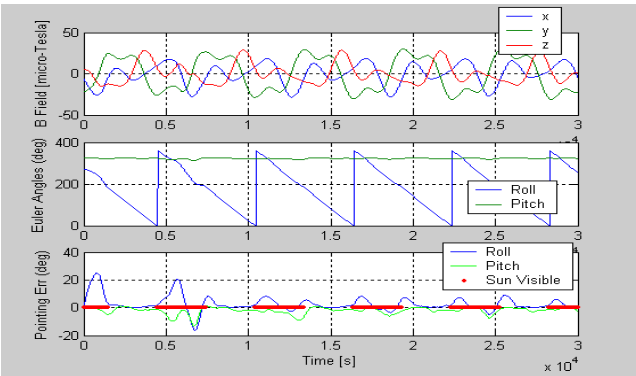

Fig. 8. B=23 MicroTesla; Pointing Errors

improves from 4.1 to 2.6 degrees. Pointing errors increase significantly when the z component of the magnetic field is small.

The change in orbital inclination that would result from this control strategy over a 60-day period is quite small, less than 0.01 deg. This is due to the fact that the 720 km nominal orbital altitude is in a regime where solar radiation pressure is only marginally greater than atmospheric drag (roughly a factor of two greater, depending upon solar activity conditions), the LightSail 2 solar sail area to mass ratio is fairly low (6.4 m^2/kg), and the attitude knowledge and control errors result in pointing errors of the solar sail normal of up to 30 deg. Because the small change in orbital inclination may not be easily observed over the course of the mission, the alternate strategy of apogee raising was evaluated.

4.1.2. Apogee Raising

Using a 6 Degree of Freedom (6 DOF) Matlab/Simulink simulation at the Georgia Institute of Technology, an On/Off approach for raising the orbit and increasing semi-major axis and orbital energy was evaluated. The On/Off strategy, adopted from McInnes (McInnes, 1999), is illustrated in Figure 9. The control implementation aligns the sail normal with the sun vector when the spacecraft is moving away from the sun in the geocentric orbit, and aligns the sail normal orthogonal to the sun direction when the spacecraft is moving toward the sun. Starting from a circular orbit, the effect of this control strategy is to increase orbit velocity when outbound from the sun, thus raising orbit apogee on the opposite side of the orbit.

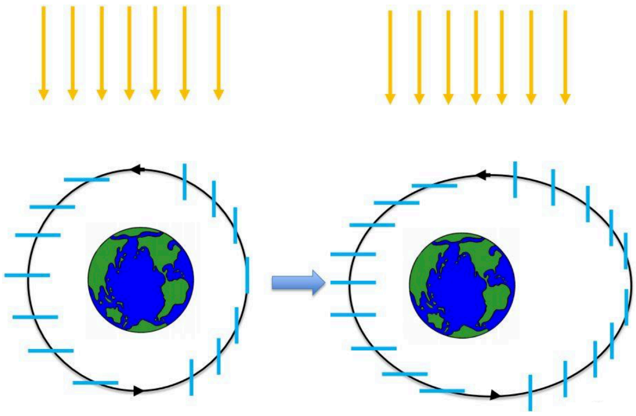

Fig. 9. On/Off control strategy for apogee raising

Mathematically, the apogee raising control strategy can be expressed as:

$$\hat{z} = -\hat{s}, \bar{v} \bullet \hat{s} > 0 \qquad \text{Eq. (3)}$$
$$\hat{x} = -\hat{s}, \bar{v} \bullet \hat{s} < 0 \qquad \text{Eq. (4)}$$

where $\hat{z}$ is the solar sail normal unit vector, $\hat{s}$ is the unit vector direction from the spacecraft to the Sun, and $\bar{v}$ is the spacecraft velocity vector, with all vectors expressed in the Earth-centered inertial coordinate system. Implementation of this approach requires 90-degree slew maneuvers twice per orbit.

When modeled in the 6 DOF simulation environment, with perfect attitude knowledge and control, the result is a secular increase in orbit semi-major axis, as shown in Figure 10. With attitude knowledge and control errors incorporated, the expected ADCS performance compared with the desired attitude profile is shown in Figure 11. The resulting semi-major axis versus time is shown in Figure 12. The expected rate of increase of apogee is 700 m/day over the first 14 days of solar sailing. By day 28 of solar sailing, the perigee altitude will decay to the point that atmospheric drag offsets solar radiation pressure, and it will no longer be possible to increase apogee.

The Simulink model for the On/Off control strategy was autocoded into the C programming language for flight software implementation.

4.2. ADCS Algorithms

Boreal Space and Georgia Tech co-created an Algorithm Design Document (ADD) to serve as an Interface Control Document (ICD) for both groups and to guide software development for LS2. The ADD details ADCS process sequencing and algorithm interactions, including fault detection and responses.

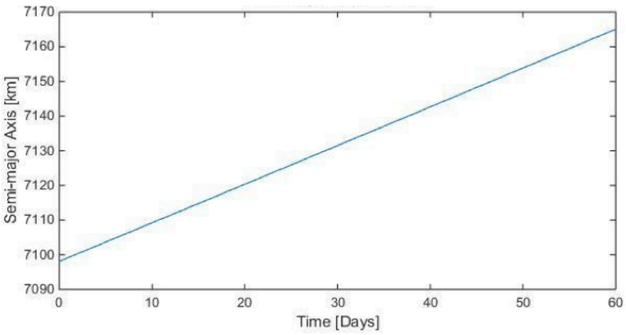

Fig. 10. Secular increase in semi-major axis with On/Off control strategy and perfect pointing.

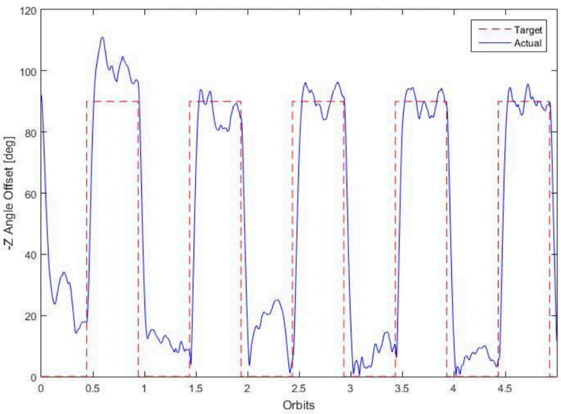

Fig. 11. Angle between solar sail normal and the Sun, with attitude knowledge and control errors included.

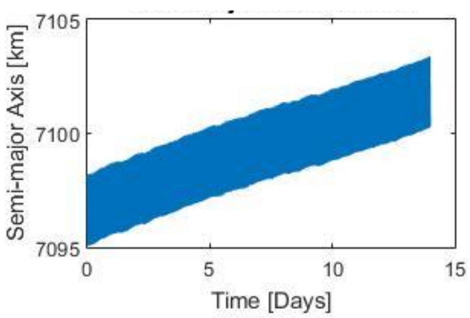

Fig. 12. Semi-major axis grows ~700 m/day during the first 14 days of solar sailing, with expected ADCS performance.

An appendix to the ADD is an Excel spreadsheet that defines inputs required by the attitude control algorithm such as sensor readings, gains, etc. The spreadsheet defines the outputs from the algorithm that command the actuators for spacecraft attitude control. Upon completion of simulation testing and autocoding, Georgia Tech delivered the algorithm code to Boreal Space for integration into the ADCS flight software. ADCS also includes a Simplified General Perturbations (SGP-4) algorithm, with flight heritage on prior Cal Poly CubeSat missions, to perform LS2 orbit propagation.

4.3. ADCS Flight Software

LS2 flight software and firmware are written in the C programming language, and execute on a Tyvak Intrepid processor board. A Linux-based operating system hosted on Intrepid features libraries, (e.g., event handling, command handling) and kernel space drivers (e.g., SPI, I2C, RTC) that support FSW development.

The FSW driver library provides low-level application programming interfaces (API's) to sensors and actuators. ADCS Process Management running at 1 Hz controls program flow through interactions with the driver library and the ADCS algorithms. The attitude control algorithm is accessed via function calls and is driven by data exchanges defined in the Algorithm Design Document. ADCS FSW implements the operational modes shown in Table 3.

Table 3. ADCS Modes

Mode	Description
Detumble	Null angular rates
Z-Align	Ground pointing attitude
Sailing	Apogee raising
No_Torques	Torque rods and wheel not actuated
Recharge	Low power mode
Extended Mission	Performance tests

Spacecraft commands are parameterized to maximize flexibility for testing and mission operations. All mode transitions can be commanded from the Ground. The only autonomous mode transition occurs during the on-orbit wheel test, where a transition from Z-Align to Detumble after test completion nulls angular rates imposed by the wheel. ADCS states (stowed, panels deployed and sail deployed) reflect physical configurations of the spacecraft that require different sets of gains and are changed autonomously after deployment events.

Processor reboots were experienced frequently during the LS1 mission. An enhanced configuration table in persistent memory tracks spacecraft modes, states, errors and sensor and actuator status to establish an ADCS baseline for both initial power-on, and after a processor reboot.

Timing considerations in the FSW include function callbacks (polls) to manage the momentum wheel, gyros, torque rod phasing in relation to magnetometer sensor readouts (to prevent interference), and system manger process status requests. Queue-driven command processing for the momentum wheel allows flexibility to conduct experiments on-orbit.

LightSail telemetry is downlinked via a 220-Byte beacon packet at a nominal 15-second cadence. Spacecraft logs can be downloaded which help to further characterize spacecraft behavior.

ADCS fault management detects and reports on invalid or anomalous events. Commanding errors include invalid parameter lengths, invalid data such as Two Line Element sets that do not pass a checksum test, and invalid deployment states. A wheel speed check prevents the momentum wheel from being commanded past a threshold rate by the ADCS algorithm. A dynamic configuration table directs restart of the ADCS process after an unexpected processor reboot. On-board error reporting can be cleared by ground command.

5. Integration and System Testing

Preliminary ADCS software development and testing was performed on a standalone Intrepid Board, to which a Payload Interface Board (PIB) was later added as the direct interface to ADCS hardware. FSW development activities are facilitated by a BenchSat, shown in Figure 13, which consists of most of the hardware components on the LightSail spacecraft. For missing subsystem components, simulators have been incorporated as proxies, e.g., a momentum wheel simulation.

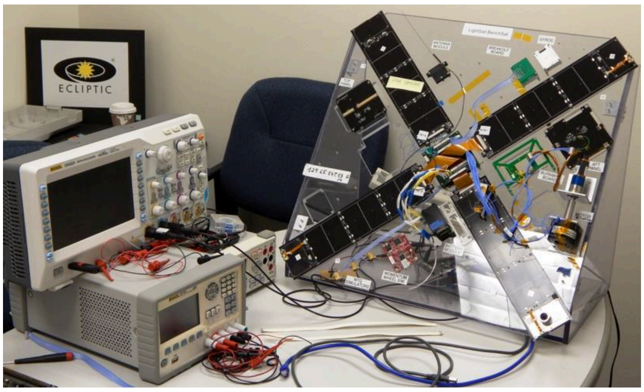

Fig. 13. BenchSat Test System

Based on reports that the LightSail magnetometers were "noisy", they were the first sensors to be tested on BenchSat. Sensor readings were out of the expected range of magnetic field measurements according to NOAA predictions for the BenchSat location (NOAA, 2016)

Out-of-range values were also recorded from magnetometers on the flight unit. Ecliptic Engineers brought the Flight Unit to the University of California, Los Angeles (UCLA) for calibration testing in a Helmholtz cage. During testing, the –Y panel magnetometer was found to be non-functional, and was subsequently invalidated in the ADCS FSW. Sensor characterization showed that the magnetometer readings were out of range, and that calibrations needed to be applied. The LS2 motor was found to have a varying effect on magnetometer readings in the stowed state based on motor positions. It was decided that a single calibration would be applied in the deployed state. Fortunately, in the stowed state, delta magnetometer readings vs. absolute readings are sufficient to support the ADCS algorithm for spacecraft detumbling.

Sensor and actuator hardware characterization continued in May 2016 at the Space Dynamics Lab in Logan, Utah. In addition to isolating the magnetometers in a Helmholtz cage, a 2-degree of freedom platform allowed for characterizing the behavior of the torque rods and momentum wheel while under ADCS control. The max dipole for each torque rod was validated, and a polarity error for the momentum wheel was found and fixed in flight software. The solar angle and gyro sensors were tested and found to be performing nominally.

Once the FSW was nearly complete, long duration tests were conducted first on BenchSat and later on LS2 to verify software behavior over extended periods of time. Operational Readiness Tests (ORT's), which involved all mission personnel, were run to validate the LS2 CONOPS in a "flight-like" manner. Commands were verified, and telemetry collected for trending and evaluation by the mission operations team. While actual solar panel and sail deployments can't be tested on BenchSat, these activities have been validated in separate tests of the flight unit at Cal Poly.

As of this writing, all planned testing of the LS2 spacecraft is complete with test procedures in place and test data archived for comparison to on-orbit spacecraft performance.

6. Conclusion

The LS1 mission served as an important engineering pathfinder for the goal of demonstrating solar sailing in Low Earth Orbit. The brief mission gathered valuable information on spacecraft and sail behavior, as well as providing flight experience for the operations team. The data analysis and lessons learned from LS1 provided a knowledge base from which to define expanded mission goals for LS2.

The simulation and evaluation of solar sailing concepts has been a key area of investigation for LS2. Given the relatively short mission duration, an apogee raising approach was selected, modeled and integrated into the ADCS FSW. In order to facilitate on-orbit investigations of spacecraft behavior in relation to simulations, ground commands can modify algorithm control parameters. Manual control of spacecraft actuators provides the ability to experiment with response to controlled torques. Sail tensioning and non-nominal spacecraft orientations are planned for the extended mission phase. Imagery taken by the nearby Prox-1 spacecraft will provide an unprecedented perspective of LS2 both prior to and post solar sail deployment.

LightSail missions are paving the way for solar sailing within our solar system, to interstellar space, and to our closest neighboring star, Alpha Centauri. The Breakthrough Starshot initiative (Davis, 2016) recognizes solar sailing as a way to 'leave the fuel behind' for space travel, using lasers to accelerate small spacecraft to 20 percent speed of light. The LightSail team is proud to be making a contribution towards defining a pathway to the stars.

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