LightSail 2: Controlled Solar Sailing Using a CubeSat

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The Planetary Society’s LightSail 2 mission will seek to demonstrate, for the first time, controlled solar sailing using a CubeSat platform. Its precursor test mission, LightSail 1, flew a successful mission to demonstrate functionality of the 3U CubeSat and deployment of a 32 square meter solar sail in May-June 2015. Whereas LightSail 1 was a test mission with an altitude too low to demonstrate solar sailing due to atmospheric drag, LightSail 2 will fly at a high enough altitude to enable demonstration of controlled solar sailing. LightSail 2 will launch on the SpaceX Falcon Heavy rocket, as part of the U.S. Department of Defense Space Test Program-2 payload. From a 720 km circular orbit, LightSail 2 will deploy from the Georgia Institute of Technology led Prox-1 spacecraft, which will then rendezvous with LightSail 2 and perform proximity operations including on-orbit inspection of the sail deployment event. Based upon lessons learned from LightSail 1 and the required capabilities for the LightSail 2 mission, we have made numerous modifications, additions, and upgrades to hardware and software to improve the spacecraft function and operability relative to LightSail 1. This paper will present details on the modifications and improvements to LightSail 2 compared to LightSail 1, the concept of operations for LightSail 2, and the testing done to maximize LightSail 2’s probability of success. The LightSail program is privately funded through contributions from Planetary Society members and donors worldwide. More information on the LightSail program can be found at sail.planetary.org.

Key Words: Solar Sailing, CubeSat, In-Space Propulsion

1. Introduction

By the end of 2011, the mechanical assembly of LightSail 1 was complete, and several sail deployment tests had been successfully conducted.1) However, due to programmatic issues including the lack of a viable near-term launch opportunity at an altitude that would enable solar sailing, The Planetary Society suspended the LightSail effort and both spacecraft were placed in storage.2)

In January 2013, the Georgia Institute of Technology Prox-1 mission was selected for implementation through the Air Force Office of Scientific Research/Air Force Research Laboratory University Nanosatellite Program.3) Developed by the Space Systems Design Laboratory at Georgia Tech, the Prox-1 mission was designed to demonstrate automated proximity operations relative to a deployed CubeSat. An agreement was reached between The Planetary Society and Georgia Tech to incorporate one of the LightSail spacecraft on the Prox-1 mission.

The LightSail program was reinitiated and reformulated with new mission objectives. The LightSail 1 mission would be limited to checkout of the CubeSat on-orbit operation, and validation of the solar sail deployment sequence. With this definition, lower orbit altitudes offered through NASA’s Educational Launch of Nanosatellites (ELaNa) program launch opportunities would be acceptable. LightSail 2, launched with Prox-1 to a planned 720 km circular orbit altitude, would be a full demonstration of solar sailing in low-Earth orbit, including control of the solar sail to modify its orbit.

LightSail 1 was ultimately launched as part of the ULTRASat payload on May 20, 2015, inserting into an elliptical orbit with perigee/apogee orbit altitudes of 356 km / 705 km and 55° inclination. Following 18 days of on-orbit checkout and anomaly response actions, the LightSail 1 solar sail was deployed on June 7, 2015. By early afternoon of June 9, an image from an on-board camera was downlinked, showing the deployed sail with the sun in the background (Fig. 1). The image was disseminated globally by The Planetary Society and social media outlets. With the LightSail primary mission objectives accomplished, Planetary Society CEO Bill Nye declared the LightSail 1 mission a success. The mission ended upon re-entry on June 14, 2015.

As an engineering precursor mission, LightSail 1 resulted in a significant number of problem reports and lessons learned that were then addressed during the LightSail 2 integration and testing program. Several hardware design changes were incorporated, and the flight software was modified in order to improve robustness, provide additional insight into subsystem performance, and provide automated fault response to facilitate recovery of the spacecraft in the
event of a system-level anomaly.

In this paper, the design of the LightSail 2 mission is presented in Section 2, including the sail control approach to demonstrate orbit modification via solar sailing. Actions taken to address problem reports and lessons learned from the LightSail 1 mission are discussed in Section 3. Residual risks are described in Section 4.

Fig. 1. LightSail 1 successfully deployed its solar sail on June 7, 2015. LightSail 2 will be capable of controlling the sail orientation to modify the orbit.

2. LightSail 2 Design

2.1. Flight System Design

The design of the LightSail 2 CubeSat is shown in Fig. 2. The subsystem modules stack together into an integrated mechanical package with minimal auxiliary structure. Avionics are concentrated in the top 1U volume, and the solar sail assembly and deployment motor are located in the lower 2U volume.

Deployment of all four deployable solar panels is accomplished with a common burn-wire assembly mounted near the RF antenna assembly. Once spring-deployed, they remain at a 165-deg. angle with respect to the spacecraft for the duration of the mission. This gives the Sun sensors a hemispherical view, and allows adequate solar power generation for a broad range of spacecraft attitudes.

The solar sail system is 5.6 m on a side and has a total deployed area of 32 m². Four independent triangular aluminized Mylar® sail sections 4.6 microns thick are Z-folded and stowed (one each) into the four sail bays at the spacecraft midsection. When stowed, the deployable solar panels help hold each sail section in place. Each sail section is attached to a 4-m Triangular Retractable And Collapsible (TRAC) boom made of elgiloy, a non-magnetic non-corrosive alloy; these booms are wound around a common spindle driven by a Faulhaber motor containing Hall sensors. The sail system is deployed when FSW initializes the motor and then commands a prescribed number of motor counts to extend the sail sections to their desired positions.

The electrical power subsystem is composed of the solar arrays, batteries, power distribution, and fault protection circuitry. A 5.6 Ah battery pack coupled with a solar panel system that produces an average of 8.5 W allows power positive operation throughout the mission. In full Sun, the four long solar panels generate a maximum 6 watts of power each with the two shorter panels providing 2 watts each. Solar power is routed through the main avionics board and charges a set of 8 lithium-polymer batteries providing power during eclipse periods. Each battery cell has its own charge monitoring/protection circuit and ties individually to the spacecraft bus. Each cell monitor independently provides overvoltage and undervoltage protection as well as overcurrent and short-circuit protection to that cell.

The main avionics board contains a low state-of-charge recovery system that initiates when the bus voltage drops below the specified limit. Power analyses were conducted for each planned mission mode. Depth of discharge values were analyzed for all modes, with a worst-case depth-of-discharge of 15% during the sail deployment sequence.

Temperature sensors are installed on each of the four deployable solar panels, in both cameras, and in the primary avionics board. Both cameras are mounted at the ends of their respective solar panels and, after panel deployment, are subject to temperatures as low as −55°C during orbital eclipse periods, based upon a thermal assessment for the deployed solar panels. The cameras require an operating range from 0°C to 70°C and are the most sensitive sensor to thermal effects on board the spacecraft. A heater is installed in series with a thermostat set to turn on if the camera temperature falls below 0°C. FSW turns off the camera if the operating temperature rises above 70°C.

The use of thermal blankets and ambient heat from electronics provides a stable thermal environment for all electronics within the spacecraft. Hot and cold cases were evaluated in a thermal model using the Thermal Desktop software for the planned orbit, evaluated over a range of orbit ascending node locations. Scenarios corresponding to the stowed configuration (prior to solar panel deployment) and the deployed configuration (solar panels and solar sail deployed) were evaluated. Avionics board temperatures are contained in the telemetry beacon, and are routinely downlinked.

The primary avionics board for LightSail 2 is a Tyvak Intrepid computer board (version 8), which is Atmel-based and hosts a Linux operating system. Integrated onto a daughterboard is an AX5042 UHF radio transceiver with an operating frequency of 437.325 MHz for both uplink and downlink. Sun sensors are mounted at the tips of each deployable solar panel and magnetometers near each tip, and gyros measuring X-, Y- and Z-axis rates are located in the avionics bay.
LightSail flight software and firmware are written in the C programming language, and are functionally partitioned between the Intrepid board and the payload interface board (PIB). A Linux-based operating system hosted on the Intrepid board features libraries, (e.g., event handling, command handling) and kernel space drivers (e.g. SPI, I2C, RTC) that facilitate FSW development. Table 1 lists application-level control processes that are supported by user space drivers built and integrated into the Intrepid architecture. Table 2 lists functions performed by the PIB. Attitude control software and interfaces to ADCS sensors and actuators are allocated to the Intrepid board. ADCS runs a 1 Hz control loop that first initializes required peripheral devices. It then checks for ground commands and performs functions including modification of the ADCS control loop rate, sensor data collection, and execution of the ADCS control law including torque rod and momentum wheel actuation. During sail deployment, Lightsail-2 ceases active attitude control and commands the Microchip Payload Interface Card (PIC) to deploy the sail. The PIC actively commutates and controls the brushless DC deployment motor.

LightSail has a capability to receive and process flight software updates once on-orbit, limited to ADCS and payload software. Spacecraft commands are parameterized to maximize flexibility for testing and mission operations. Telemetry is downlinked via 227-byte beacon packets. Mission elapsed time, command counter, power, thermal, ADCS and deployment data were optimized to provide an assessment of on-orbit performance during the mission. Beacon data, downlinked at a nominal 15-second cadence, is supplemented by spacecraft logs that further characterize spacecraft behavior.

FSW development activities are facilitated by a BenchSat, shown in Fig. 3, which consists of most of the hardware components of the LightSail spacecraft system. For subsystem components that are lacking, simulators have been incorporated. For example, BenchSat lacks the actual solar sail deployment motor/spindle, but a clutch mechanism was introduced to simulate the load experienced by the deployment motor. It also does not have actual torque rods, but instead has torque rod simulators in the form of 30 Ω resistors (27 Ω is the nominal torque rod impedance at steady state). In addition to its role in FSW development, BenchSat is used to perform component testing prior to integration into flight units, serves as a ground station during communications testing, is a stand-in for flight units during Operations Readiness Testing (ORTs), and is used for verification of on-orbit procedures during mission operations.
The ADCS monitors and controls attitude and body rates. It detumbles the stowed spacecraft after P-POD deployment from a maximum 25 deg/s tipoff rate in any axis to < 10 deg/s. It performs a coarse alignment of the RF antenna on the +Z axis of the spacecraft with the Earth’s magnetic field with maximum variation, once settled, of <60°, which is sufficient for ground communications. After sail deployment, ADCS detumbles the spacecraft, and sail orientation is controlled using the torque rods and momentum wheel. Table 3 summarizes the ADCS sensors and actuators. A full description of the LightSail 2 attitude determination and control subsystem design is presented in a separate paper.

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<th>Component</th>
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### 2.2. Mission Design

LightSail 2 will be launched in the stowed configuration within a Poly-Picosatellite Orbital Deployer (P-POD), which is integrated within the Prox-1 microsatellite. Launch is planned on the Falcon Heavy launch vehicle, as a secondary payload through the Department of Defense Space Test Program-2. Prox-1 will be deployed into a 720 km circular orbit, with an inclination of 24 deg.

The concept of operations for LightSail 2 is shown in Fig. 4. During the first four days after launch, Prox-1 will perform an on-orbit checkout, and LightSail 2 will remain in the P-POD. Deployment of LightSail 2 is nominally planned on day 5 of the mission. The P-POD will impart a relative velocity of ~1.2 m/s to LightSail-2. Prox-1 will acquire a sequence of images as LightSail-2 recedes following P-POD deployment.

Over the next two weeks, Prox-1 will perform a series of propulsive maneuvers to rendezvous with LightSail 2. During this time period, LightSail 2 will conduct on-orbit checkout activities, including setting the spacecraft clock, uplinking the orbit ephemeris, changing the ADCS mode to Z-axis alignment, acquisition and downlink of test images from each camera, and operation of the momentum wheel. At the completion of the rendezvous phase, Prox-1 will enter a trailing orbit, 150 – 200 m behind LightSail 2. Prox-1 will then perform automated station keeping and a circumnavigation of LightSail 2 over several orbits.

Deployment of the LightSail 2 solar panels is planned on day 20 of the mission. Spacecraft status will be monitored over the next 24 hours, and if the spacecraft state is nominal, sail deployment will be commanded. Onboard cameras will be used to acquire images during the 2.5 minute sail deployment event, and Prox-1 will acquire visible and infrared images during sail deployment from a range of 50-100 m. Following sail deployment, thumbnail images will be downlinked, and selected full resolution images will be downlinked over the next several days.

The two LightSail cameras are 2-megapixel fish-eye color cameras licensed from the Aerospace Corporation. Mounted on opposing deployable solar panels, they are inward-looking when the panels are in their stowed positions and outward-looking when deployed. For LightSail 2 sail deployment imaging, seven minutes of full-resolution (1600 x 1200 pixels) images are acquired, for up to 32 images per camera. As images are taken, each JPEG image is stored in camera memory along with a 160 x 120 pixel thumbnail. Later, each image is then selectively moved by command to the Intrepid board memory for subsequent downlink to the ground.
Once the sail is deployed, LightSail 2 will transition to solar sailing mode, using the on-off switching technique, as illustrated in Fig. 5. Sail control is implemented in the ADCS flight software to orient the solar sail edge-on to the Sun direction (yellow arrows from top) for half the orbit, and reorient the sail to face the Sun for the other half orbit. Rotation maneuvers of 90° are required twice an orbit. Through this approach, the apogee altitude and the orbital energy are increased. Additional discussion on the sail control algorithm is described in Ref. 4.

Solar sailing will occur for about 28 days after sail deployment. During this time, it is expected that apogee will be raised 500 – 700 m per day. However, perigee altitude will slowly decay due to atmospheric drag, and the larger drag at perigee will overcome the ability to raise apogee via solar pressure. The full LightSail 2 mission duration is expected to be approximately two months.

3. Actions Taken to Address LightSail 1 Anomalies and Lessons Learned

During the late stages of system-level testing of LightSail 1, a flight software error was exposed that resulted in the inability to control torque rod actuation, and also pre-empted beacon telemetry from sensors that interfaced with the PIB, including sun sensors, rate gyros, and temperature sensors. However, a full set of telemetry would be captured in the telemetry beacon following a system reboot; the sensor readings would remain static in the beacon until the next reboot occurred. Because this error was discovered on BenchSat after the flight unit was integrated with the P-POD and ready for launch, the decision was made to fly the mission without correcting the flight software. The error has been corrected for LightSail 2.

LightSail 1 experienced four major anomalies during mission operations. The first was a memory leak triggered by the rapid growth of a file that contained beacon data. This resulted in a Linux crash, and repeated attempts to command a reboot were unsuccessful. Ultimately, a spontaneous reboot occurred (presumably due to a solar particle event) and the flight team regained control of the spacecraft. From that point forward, the memory leak was managed with daily commanded reboots. The memory leak was determined to originate in the uClibc library used by the flight software. LightSail 2 uses an updated version of uClibc that fixes this bug.

Following solar panel deployment, the electrical power subsystem behaved erratically for the remainder of the mission. Battery circuitry protection did not appear to be maintaining the batteries in the desired state, and the spacecraft periodically entered an anomalous condition where it was only operating in sunlight, and was not receiving current from the batteries during eclipse operations. Root cause of this anomaly was not determined, however the leading theory is a poor interaction between the independent hardware charge protection circuitry in each cell of the battery pack. To mitigate this problem for Lightsail 2, software charge protection has been implemented that operates on pack-level telemetry and engages prior to the hardware protection present in the individual cells. Lightsail 2 also provides additional battery telemetry and recovery commands to help streamline operations should this issue reoccur.

Images of the sail deployment event from both cameras were corrupted, and could not be decoded. The decision was made to delete all of the original deployment image files, and capture an entire image sequence from each camera. This led to the successful acquisition and downlink of the image shown in Fig. 1. The root cause for this anomaly was not determined, and the problem could not be replicated during ground testing of the LightSail 2 flight cameras. As a mitigation, updated firmware was installed on the cameras by the Aerospace Corporation. No image corruptions have been seen after acquisition and transfer of thousands of test images in the laboratory.
Near the end of the mission, the LightSail 1 telecommunications subsystem entered an anomalous telecommunications state, in which RF noise was continuously transmitted. Repeated attempts to kill the transmit process and reboot the flight system were unsuccessful, and LightSail 1 remained in this anomalous mode for several days until reentry. No root cause has been found for this anomaly. However, watchdog timers have been implemented that will result in a telecommunications subsystem reset if the transmit process hangs or becomes inactive for 3 minutes, and a long-duration watchdog timer that results in a flight processor reboot if a command is not received within a three-day time period. Responses to these watchdog timers will directly address the anomalous transmit mode, should it occur.

A general lesson learned is that LightSail operations is command-intensive, and additional tracking stations would be beneficial for LightSail 2 operations. To address this need, the Arizona State University School of Earth and Space Exploration will provide UHF tracking support. The Sacred Hearts Academy in Honolulu, Hawai‘i has also been added to the tracking station network in support of LightSail 2. Additionally, the existing tracking stations at Cal Poly (quad-phased yagi) and Georgia Tech (dual yagi) have been upgraded for LightSail 2 operations.

Finally, the extent of boom deployment could not be conclusively determined. While the motor counts for boom deployment were as expected, it was not conclusive from Fig. 1 that the booms were fully extended, with a fully-deployed sail. Boom fiducials have been added for LightSail 2, to provide a robust means for validating the extent of boom deployment.

4. Residual Risks

Residual risks for the LightSail 2 mission are shown using the standard NASA 5x5 risk matrix in Fig. 6. The most significant risk is the failure of Prox-1 to initiate P-POD deployment of LightSail 2. Testing of the Prox-1 functionality has been done during system-level testing, including after the completion of the environmental testing program.

The highest likelihood risk is an inability to complete apogee raising via sail control. This could be caused by degraded attitude knowledge or control capability, deformation of the booms and solar sail, or higher than expected atmospheric drag. The remaining three risks, encountered in LightSail 1, are being carried because root cause has not been determined. However, mitigations are in place for each risk item.

5. Conclusion

The LightSail 2 mission will conclude a technology development program that was established in 2010. If successful, it will be the first demonstration of controlled solar sailing using a CubeSat platform. Funded through donors and members of The Planetary Society, the mission represents an important advancement in privately-funded space exploration. It is hoped that the LightSail program will lead to the use of solar sails for scientific investigations and radiation environment monitoring in cis-lunar space and throughout the solar system.

Acknowledgments

The authors would like to acknowledge the donors and members of The Planetary Society, and the Kickstarter campaign contributors, who supported the LightSail program development.

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