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Spencer, D. et al. (2016): JoSS, Vol. 5, No. 2, pp. 531–550
(Peer-reviewed article available at www.jossonline.com)

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Testing The LightSail Program: Advancing Solar Sailing Technology Using a CubeSat Platform

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Abstract

The LightSail program encompasses the development, launch, and operation of two privately funded 3U CubeSats designed to advance solar sailing technology state of the art. The first LightSail spacecraft—dedicated primarily to demonstrating the solar sail deployment process—successfully completed its mission in low Earth orbit during spring 2015. The principal objective of the second LightSail mission, scheduled for launch in 2017, is to demonstrate sail control in Earth orbit and to increase apogee. Managed by The Planetary Society and funded by members and private donors worldwide, LightSail represents the most ambitious privately funded solar sailing program ever launched. By demonstrating the capability to deploy and control a solar sail from a 3U CubeSat platform, the LightSail program advances solar sailing as a viable technology for in-space propulsion of small satellites. This article provides an overview of the LightSail program, describes the spacecraft design, and discusses results from the initial test flight of LightSail 1.

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1. Introduction

The concept of solar sailing in space—providing low-thrust spacecraft propulsion from the radiation pressure of sunlight—can be traced as far back as a reference in a letter from Kepler to Galileo (Kepler, 1610):

> Provide ships or sails adapted to the heavenly breezes, and there will be some who will brave even that void.

Centuries later, in the 1860s, Maxwell's equations showed that light had momentum, providing a theoretical underpinning to the concept. In 1865, Jules Verne incorporated the concept in *From the Earth to the Moon*—perhaps the first published mention of space travel through the force of light. Further theoretical and lab-based experimental work bolstered the concept from the late 1890s through late 1920s, and for the next several decades, the concept was occasionally addressed by researchers and science fiction authors.

The first detailed solar sail technology and mission-design effort was led by Louis Friedman at JPL, starting in 1976 for a proposed 1985-86 Halley's Comet rendezvous mission. The mission concept was promoted publicly by Friedman's colleague, astronomer/planetary scientist Carl Sagan, but ultimately, the mission was not funded by NASA (Friedman, 1988).

In 1980, Sagan, Friedman, and then-JPL Director Bruce Murray formed a non-profit space advocacy organization "to inspire the people of Earth to explore other worlds, understand our own, and seek life elsewhere." The Planetary Society (TPS) is now the largest such group in the world, with over 40,000 active members, and, among other key objectives, strives "to empower the world's citizens to advance space science and exploration" (The Planetary Society, 2015).

In the early 2000s, led by Executive Director Friedman, TPS developed the Cosmos-1 solar sailing demonstration mission with primary funding from Cosmos Studios, a production company formed by Sagan's widow Ann Druyan after his death in 1996. The spacecraft was designed, built, and tested by the Babakin Science and Research Space Centre in Moscow, and was intended for launch by a submarine-launched Volna rocket. A precursor in-space test of a two-sail deployment system (as a representative subset of the eight sails required for the full-up Cosmos-1 design) ended in failure in 2001, when the Volna's upper stage did not separate from the first stage (Klaes, 2003). Another attempt at a full-up Cosmos-1 mission in 2005 also failed, when another Volna rocket's first stage underperformed, dropping the spacecraft into the Arctic sea.

Following the failed SpaceX Falcon 1 launch of NanoSail-D1 in the summer of 2008, NASA launched NanoSail-D2 on November 20, 2010. Following a delayed deployment from the FASTSAT spacecraft, NanoSail-D2 deployed a 10 m^2 solar sail from a 3U CubeSat, and was deemed a success in January 2011 (Alhorn, 2011).

In 2009, Friedman initiated a program through The Planetary Society to fly a series of three LightSail spacecraft, all using the standard 3U CubeSat form factor for the spacecraft bus. The LightSail 1 mission would be the first to demonstrate solar sailing in Earth orbit, and this spacecraft was projected to be launch-ready by the end of 2010. The LightSail 2 mission would demonstrate an Earth-escape mission profile, while the LightSail 3 craft would "… take us on a mission for which a solar sail spacecraft is uniquely suited: creating a solar weather monitor to provide early warning of solar storms that could affect Earth" (Friedman, 2009). Friedman selected Stellar Exploration Incorporated for the LightSail spacecraft design and construction effort. Stellar was ultimately tasked with building LightSail 1 and LightSail 2.

In May 2010, the Japanese space agency JAXA launched a mission to Venus with a secondary payload called Interplanetary Kite-craft Accelerated by Radiation of the Sun (IKAROS). Three weeks after launch, IKAROS was successfully deployed, and became the first-ever solar sailing demonstrator (Space.com, 2010). Solar sailing missions feature prominently in JAXA's long-range plans for solar system exploration.

In September 2010, long-time TPS member and then-TPS Vice-President Bill Nye became the society's Executive Director, following the retirement of Friedman. In February 2011, a potential flight opportunity for LightSail 1 materialized when the team was competitively awarded a no-charge secondary launch via NASA's Educational Launch of Nanosatellites (ELaNa) program, a key element of the agency's CubeSat Launch Initiative (Cowing, 2011). TPS had requested a minimum orbit altitude of 800 km to enable the solar sailing demonstration, and NASA agreed to seek such an opportunity. Nye is shown in Figure 1 holding a full-scale engineering model of the spacecraft (solar sails not installed).

Figure 1. Bill Nye with a full-scale engineering-model of the LightSail 3U CubeSat.

In September 2011, NASA selected L'Garde, Incorporated to develop the Sunjammer mission, designed to deploy a 1,200 m^2 solar sail as a technology-demonstration mission. The mission was designed to use solar radiation pressure to reach a location near the Sun-Earth L_1 Lagrange point. However, the project was cancelled in October 2014 due to integration issues and schedule risk (Leone, 2014).

By the end of 2011, Stellar had completed the mechanical assembly of LightSail 1 and conducted several successful sail deployment tests (Biddy, 2012). But in May 2012, for a variety of programmatic reasons, including the lack of a viable near-term launch opportunity to 800 km, The Planetary Society put a pause on the LightSail effort and both spacecraft were placed in storage.

TPS investigated contributing the two LightSail spacecraft to another interested company or organization, with the intent that they would eventually be launched. TPS member interest in the program remained high, however, so in August 2012, the Society assembled an advisory panel to assess and review the program and make recommendations about whether the program should be resumed. This panel, led by Northrop Grumman Space Technology President and TPS Board member Alexis Livanos, advised to restart the effort, with recommendations for further testing, risk reduction, and changes to the program management approach.

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 (Okseniuk, 2015). 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 TPS and Georgia Tech to incorporate one of the LightSail spacecraft on the Prox-1 mission. Following launch as a secondary payload, Prox-1 would deploy LightSail 2 and use it as a target for rendezvous and proximity operations; later, with its primary mission completed, Prox-1 would provide imaging of the LightSail's solar sail deployment.

During 2013, a new program management team was established by TPS and the program was restarted. The new LightSail Program Manager, Doug Stetson, and Mission Manager, David Spencer (who was also the Principal Investigator for Prox-1), initiated a deep-dive technical review of the program, established formal objectives for both the LightSail 1 and LightSail 2 missions, and developed a requirements verification matrix for the mission, spacecraft, and ground systems. The integration and testing plan for LightSail 1 was re-baselined, and organizational roles were updated.

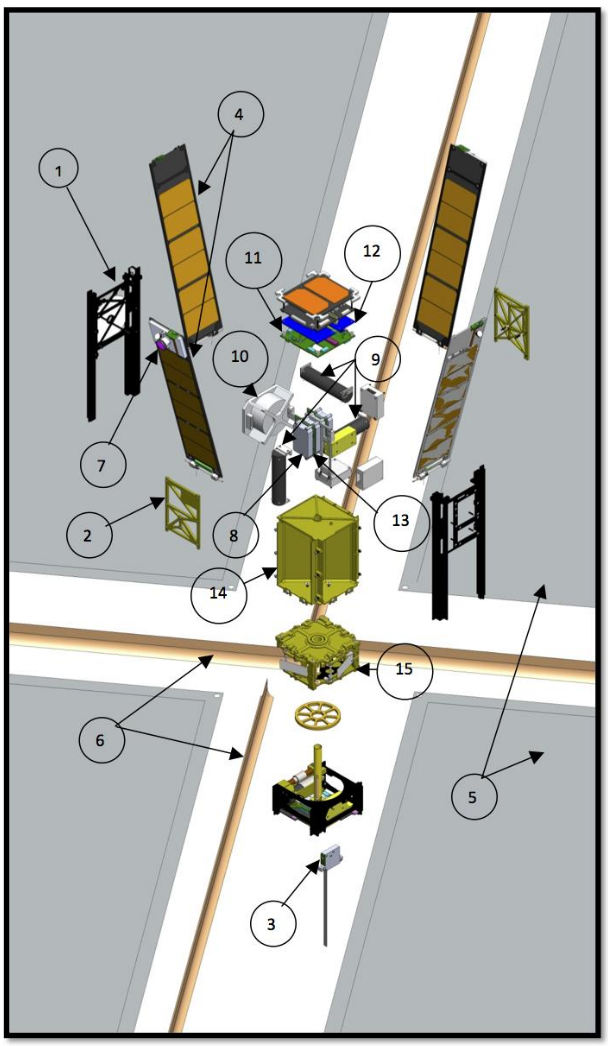
By the time a Midterm Program Review was held in December 2013, the reformulated program plan had come into focus. The LightSail 1 mission objectives would be limited to checkout of the spacecraft on-orbit operations and demonstration of the solar sail deployment event. With this definition, lower orbit altitudes offered through the ELaNa program launch opportunities would be acceptable. LightSail 2, launched with Prox-1, would be a full demonstration of solar sailing in low-Earth orbit, including control of the solar sail to modify its orbit. There were no resources to support a LightSail 3 mission for solar weather monitoring, and this mission was not included in the reformulated program.

Ecliptic Enterprises Corporation was selected to complete the integration and testing program for both LightSail spacecraft, with Boreal Space and Half Band Technologies providing subsystem 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, and coordinate launch approval activities. Cal Poly would also lead the mission operations and ground data system, while Georgia Tech would provide spacecraft tracking and mission operations support.

The remainder of this paper will summarize key features of the LightSail spacecraft and mission design, detail of the integration and testing experience for LightSail 1, results and lessons learned from the LightSail 1 mission, and plans for LightSail 2.

2. LightSail Spacecraft Design

The LightSail spacecraft design (Figure 2) adopted the 3U CubeSat standard, to take advantage of available cost-effective CubeSat subsystem compo-



No.	Subsystem
1	CubeSat Structure: Main Side
2	CubeSat Structure: Plate
3	Antenna
4	Solar Panels
5	Solar Sail
6	Solar Sail TRAC Boom
7	Camera
8	Batteries
9	Torque Rod
10	Momentum Wheel
11	Payload Board
12	Radio Board
13	Battery Board
14	Sail Housing
15	Boom Housing

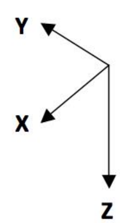


Figure 2. Exploded view of LightSail CubeSat configuration.

nents. This choice leveraged a growing vendor supply chain of off-the-shelf spacecraft components, proven deployment mechanisms, well-defined environmental test protocols, and higher-level assemblies that facilitated integration.

In the LightSail 3U CubeSat design, a 1U volume is reserved for the avionics section, which has hinges near its top end for four full-length deployable solar panels. The solar sail assembly occupies 2U, partitioned into the sail storage section (1U, in four separate bays) and the sail motor/boom drive assembly (1U, with four booms), which also accommodates at its base the monopole radio-frequency (RF) antenna assembly (a steel carpenter's ruler-like stub) and the burn-wire assembly for the deployable solar panels.

In the stowed configuration, LightSail has the standard 3U CubeSat form factor as required for deployment from the P-POD. Following launch, the RF monopole antenna is deployed. The four side-mounted solar panels are deployable, and deploying the solar sail produces the fully deployed state (Figure 3).

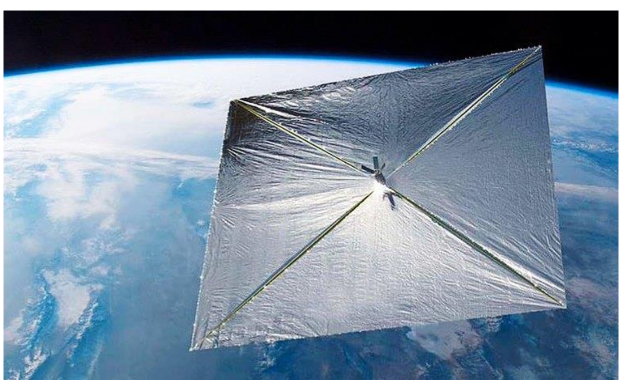


Figure 3. Fully deployed LightSail configuration (sail is 5.6 m on a side, 8 m on diagonal).

The avionics section houses two processor boards, a radio, batteries, sensors and actuators, and associated harnessing. LightSail 1 uses only torque rods for attitude control, while LightSail 2 also includes a momentum wheel for changing the sail orientation on-orbit.

Two small solar panels (one fixed at each end) and four full-length deployable panels provide power and define the spacecraft exterior. The larger solar panels are in their stowed configuration until either autonomously commanded by onboard software or manually commanded from the ground. With solar cells populating both sides of each large panel, they generate power whether in the stowed or deployed configuration. However, the panels must also be deployed before solar sail deployment. Each solar panel carries Sun sensors, magnetometers, power sensors, and temperature sensors. Two opposing large solar panels are equipped with cameras for imaging opportunities, including sail deployment.

The spacecraft is controlled by flight software (FSW) that allocates unique functionality to two different processor boards. The main avionics board is tasked with spacecraft commanding, data collection, telemetry downlink, power management, and initiating deployments. The payload interface board (PIB) integrates sensor data for attitude control, commands actuators, and manages deployments as directed by the avionics board.

The following subsections describe the various LightSail subsystems in more detail.

2.1. Mechanical Subsystem and Solar Sail

The various LightSail modules stack together into an integrated mechanical package with relatively minimal auxiliary structure—primarily truss-like close-out elements concentrated in the avionics module. Each deployable solar panel also has a slim structural frame.

The RF antenna deployment via burn-wire is the first LightSail deployment event to occur after P-POD ejection. It is autonomously commanded by the FSW to occur 45 minutes into the mission, enabling radio communications. 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-degree angle with respect to the spacecraft for the duration of the mission. This gives the Sun sensors a cumulative hemispherical view, and allows adequate solar power generation for a broad range of spacecraft attitudes.

The LightSail solar sail system has several design features quite similar to NanoSail-D's, but at 5.6 m on a side and 32 m^2 in deployed area, it is about twice the size and four times the area. 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.) Figure 4 shows LightSail 1 in a partially deployed state, with two solar panels fully deployed, two partly deployed and two bays with folded sail underneath.

Figure 4. LightSail 1 solar panels and sail bays.

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. Fully deployed, the square sail measures about 8 m on the diagonal.

2.2. Power Subsystem

The 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 eight 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 prior to the LightSail 1 mission for each planned mode in the Concept of Operations (CONOPS). Depth of discharge values were analyzed for all modes, with a worst-case depth-of-discharge of 15% during the sail deployment sequence.

2.3. Thermal Subsystem

Temperature sensors are installed on each of the four deployable solar panels, in both cameras, and in the primary avionics board. Solar panel temperature sensors inform the ambient environment of the stowed and deployed solar panels through telemetry. Both LightSail 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 performed by The Aerospace Corporation (Figure 5). 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 climbs 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 LightSail thermal model using the Thermal Desktop software for the

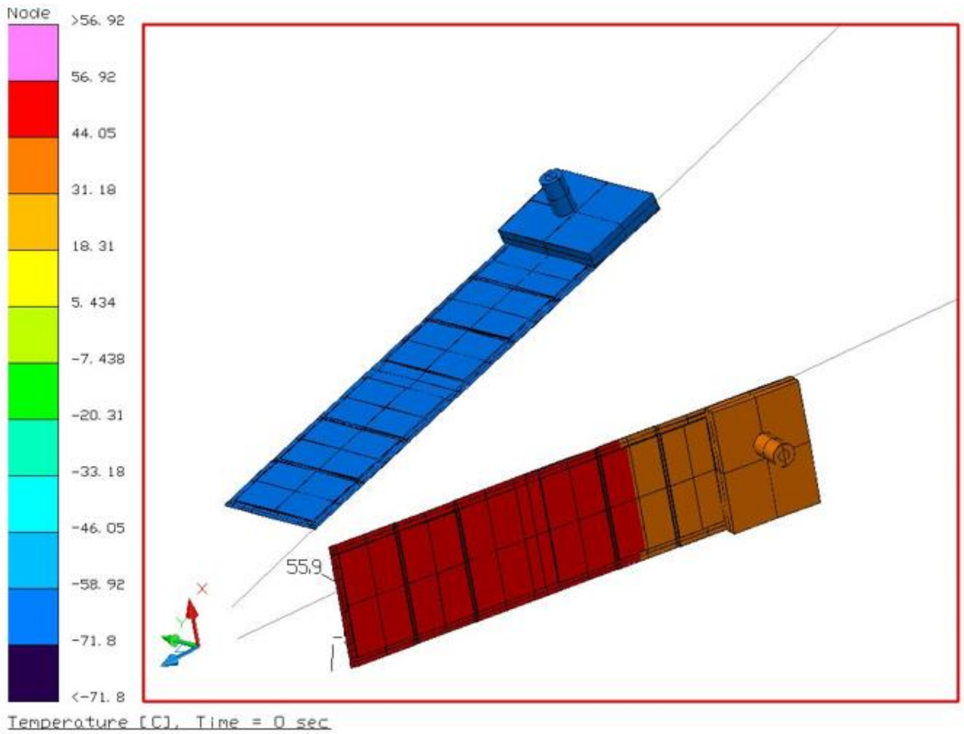


Figure 5. Thermal analysis results for satellite deployed panels.

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.

2.4. Avionics and RF Subsystem

The primary avionics board for LightSail 1 is a Tyvak Intrepid computer board (version 6), which is Atmel-based and hosts a Linux operating system. LightSail 2 was upgraded to a version 8 Intrepid board. Integrated onto this main board onto a separate daughterboard is an AX5042 UHF radio transceiver with an operating frequency of 437.435 MHz. 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.

The PIB design was changed from the original Stellar design once LightSail 2 CONOPS were considered, as well as to rectify some layout and pin-out issues that were uncovered during functional testing. Most of the core changes to the board addressed Attitude Determination and Control Subsystem (ADCS) interfaces. The torque rod control circuit was changed to pulse-width modulation control to enable proportional control vs. simple on-off (Bang-Bang) control, and other modifications were made to allow a processor on the PIB to read the gyro data and close the loop with the torque rods, and also with the momentum wheel for LightSail 2.

2.5. Flight Software

LightSail FSW (software and firmware) are written in the C programming language, and are functionally partitioned between the Intrepid board and the 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 1. Intrepid Board FSW Control Processes

Process	Functionality
acs_process	Collect data from PIB over I2C and stage for inclusion in beacon packet.
deployment_process	Manage deployment sequence on PIB.
beacon_process	Packages collected telemetry for downlink to ground station.
camera_process	Camera monitoring, commanding and telemetry, take images during deployment and move to processor board memory.
sc_state_process	Implements spacecraft autonomy via a state machine; initiates deployments, performs key time dependent sequences, restores state if reboot.

Attitude control software and interfaces to ADCS sensors and actuators are allocated to the PIB, driven by a Microchip PIC microcontroller (Table 2). The PIC33 16-bit CPU runs a 5 Hz control loop that first initializes required peripheral devices. It then checks for commands relayed from the Intrepid board FSW, i.e., modifies the ADCS control loop rate, collects sensor data, and executes the ADCS control law including the actuation of torque rods and the momentum wheel. During sail deployment, the PIB ceases active attitude control and commands the sail deployment motor to perform the required movements to guide the spindle and boom mechanisms. The PIB 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. The LightSail telemetry is downlinked via a 220-Byte beacon packet. 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 Figure 6, 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 a deployment mechanism akin to the actual LightSail 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 being 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.

2.6. Imaging Subsystem

The two LightSail cameras (dubbed Planetary Society Cameras, or PSCAMs) are 2-megapixel fisheye color cameras licensed from the Aerospace Corporation, successfully used in their CubeSat mission series. Mounted on opposing solar panels (the +X

Table 2. PIB FSW Control Processes

Routine(s)	Functionality
main	HW and SW initialization, implements 5Hz loop, mode and state changes
acs	Implements acs algorithms
gyro, magnetometer, Sun sensor	Sensor data collection
motorControl, torquers, solarPanelDeployment	Component actuation; deployments
pibManager	Commands from and telemetry to Intrepid
spiWrapper, I2CWrapper	Wrappers for Microchip drivers

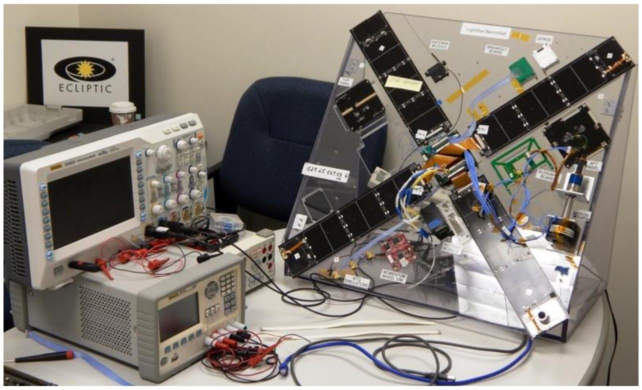


Figure 6. BenchSat as used for FSW development.

and -X panels), they are inward-looking when the panels are in their stowed positions and outward-looking when deployed, providing views as shown in Figure 7. Raw images of the deployed sails (upper right in Figure 7) can be stitched together with software for a 'birds-eye' view (lower right).

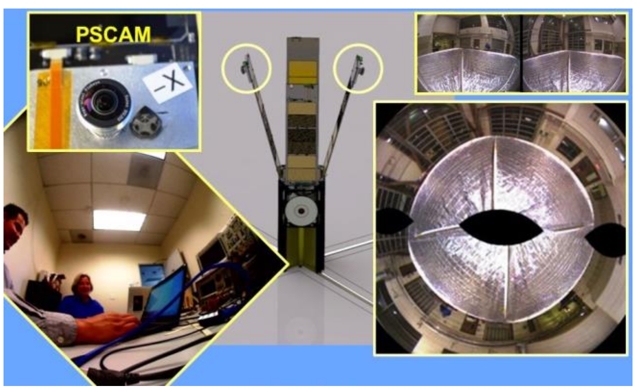


Figure 7. PSCAM details.

Though the cameras have several operating modes and settings to choose from, for LightSail 1, one basic operating sequence was programmed, 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. As images were taken, each JPEG image was stored in camera memory, along with a 160 x 120 pixel thumbnail of each image. Later, each image was then selectively moved by command to the memory in the Intrepid board, for subsequent downlink to the ground, also by command.

2.7. Attitude Determination and Control Subsystem

The ADCS monitors and controls attitude and body rates. It detumbles the stowed spacecraft after P-POD deployment from a maximum 25 °/s tipoff rate in any axis to 2–10 °/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 communication. After sail deployment, ADCS detumbles the spacecraft from up to 10 °/s in any axis to ~2–5 °/s. Table 3 summarizes the sensors and actuators supporting ADCS. The ADCS

Table 3. ADCS Sensors and Actuators

Component	Number	Vendor
Sun Sensors	4	Elmos
Gyros	3	Analog Devices
Magnetometers	4	Honeywell
Torque Rods	3	Strass Space
Momentum Wheel	1*	Sinclair Interplanetary

*LightSail 2 only

hardware was sized for significantly varying moments of inertia (for the stowed and deployed configurations).

ADCS modeling and simulation results for LightSail 1 detumble are shown in Figure 8. The orbit was propagated using two-body dynamics with a simple magnetic dipole model for the Earth's magnetic field. Tuning parameters include control frequency (limited by the non-rigid configuration with the sails deployed), duty cycle, and torque rod dipole. Initial conditions were varied to analyze settling time and stability. Perturbations included magnetometer and torque rod axis misalignments, aerodynamic torque, solar radiation pressure torque, and gravity gradient torque. The plots in Figure 7 were generated using assumed worst-case initial spacecraft rates of a 22 °/s roll, -14 °/s pitch and 6 °/s yaw. It is seen that the spacecraft detumbles in about one quarter of an orbit in the stowed configuration. When 60 orbits were simulated, the final settled rates are all less than 1.2°/s. Z-axis alignment eventually converges to about 20°.

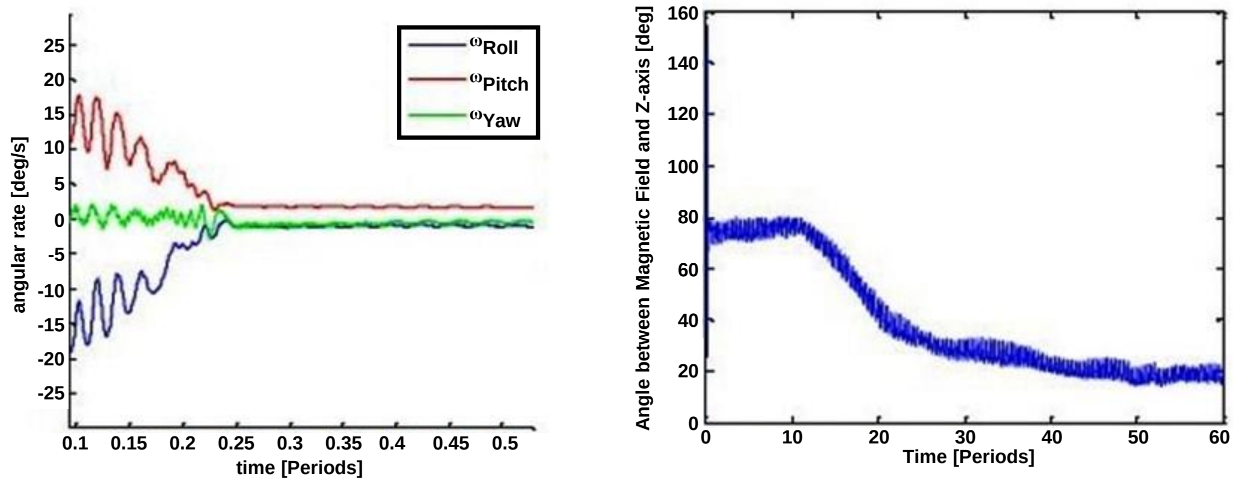


Figure 8. ADCS detumble simulation results (l) and magnetic field alignment simulation results (r).

Two ACS modes were implemented for LightSail 1. The first mode is the Stowed Mode, which operates on a 2 Hz control loop. This rate is fast enough to detumble from high-end tip-off rates. Because the 2 Hz mode would tend to induce resonances with the sail deployed, the Deployed Mode operates within a 10 Hz control loop. Table 4 summarizes the stowed detumble/stabilization profile. ADCS ensures the magnetic torquers are OFF when reading magnetometer data due to the concern for interference from the torquers.

Table 4. ADCS Detumble/stabilization Torque Command Profile

Loop Number	Time (sec)	Control and Actuation Mode
1	0–1	Bang-Bang B-Dot
2	1–2	OFF
3	2–3	Bang-Bang B-Dot
4	3–4	+Z axis ON only

After sail deployment, the Bang-Bang control law is modified by a principle known as Input Shaping. This overlay to the Bang-Bang control allows for a damping of the vibration of the sail after deployment. Input shaping requires proportional control of the torque rods, and is possible because of the modifications to the PIB for PWM previously described.

Certain simplifying assumptions were made regarding the natural frequencies of the spacecraft and sail system. The principle is to identify one or two modes, based on Fourier analysis of Bang-Bang torque and nearest one or two system frequencies, the latter taken from a Finite Element Model. The torque command is “input shaped” to damp out the vibrations in the system (see Figure 9). The input shaping strategy is intended to result in zero vibration for a single-DOF damped system after N impulses (Singhose, 1997; Banerjee, 2001).

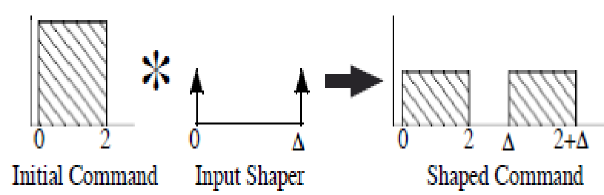


Figure 9. Effect of input shaper on torque rod command.

The LightSail 2 mission includes a momentum wheel that aids in solar sail maneuvers to demonstrate the capability to increase orbit apogee. The on-off switching technique, as illustrated in Figure 10, is implemented in the ADCS flight software to orient the solar sail edge-on to the Sun direction (yellow arrows coming down from top) for half the orbit, and reorient the sail to face the Sun for the other half orbit

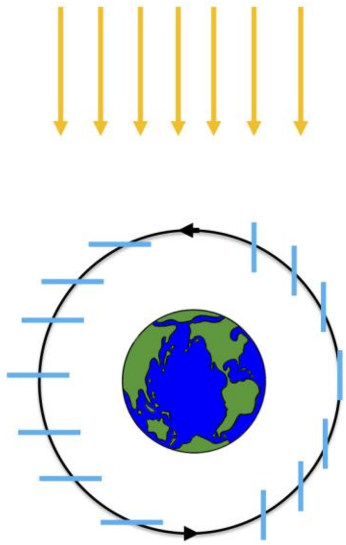


Figure 10. Sail orientation approach for apogee raising, planned for LightSail 2. (Sun at top.)

(McInnes, 1999). Rotation maneuvers of 90° are required twice an orbit. Through this approach, the apogee altitude and the orbital energy are increased.

3. Mission Objectives for LightSail 1 and LightSail 2

Capitalizing upon two complete flight systems, the program objectives for LightSail 1 and LightSail 2 were tailored to the available launch opportunities to incrementally demonstrate key solar sailing functionality. LightSail 1's baseline orbit was not ideal for demonstrating solar sailing. From mid-2013 through early 2014, NASA's ELaNa program identified two Atlas 5 launch opportunities for LightSail 1, both targeted for placing classified primary payloads into elliptical low-Earth orbits with relatively low perigees and mid-latitude inclinations. Each Atlas 5 would carry a fully integrated, box-like secondary payload carrier system designed by the Naval Postgraduate School for use on Atlas 5 Centaur upper stages, the NPS Cul system. Each NPS Cul would contain eight P-PODs loaded with various CubeSats, and each box was assigned a unique name for manifesting purposes. The missions on the ELaNa list were named GRACE and ULTRASat, respectively. LightSail 1 was ultimately included in the ULTRASat launch. With a perigee altitude of 356 km and apogee at 705 km, the LightSail 1 orbit was too low to allow solar sailing, and aerodynamic torques near perigee would make attitude control problematic. The LightSail 1 mission objectives were therefore focused on the checkout of the spacecraft bus on-orbit, and the validation of the solar sail deployment sequence.

The momentum wheel originally designed into both spacecraft for facilitating solar sail tacking was removed from LightSail 1 and replaced with a mass model. All other subsystem elements were the same between the two spacecraft. (Based upon lessons learned from the LightSail 1 mission, several subsystem design changes will be incorporated for LightSail 2, as discussed later in this summary.)

Key features of the baseline LightSail 1 mission sequence included:

- Ride unpowered to orbit inside a NPS Cul Lite P-POD
- Eject from P-POD
- Power ON and boot up computer
- Activate ADCS; initiate rate damping (detumbling)
- Deploy RF antenna; start transmitting data packets
- Conduct spacecraft health and status assessment
- Test onboard cameras
- Deploy solar panels
- Deploy solar sails while imaging entire sequence
- Downlink images; assess deployed sail characteristics
- Evaluate attitude behavior in deployed configuration
- Re-entry

The baseline mission plan called for all mission events (except camera checkouts) through sail deployment to be on a 28-day timer following the initial power-on event. With the sail deployed, predictions were that the spacecraft would re-enter and burn up within three to ten days. Thus, the LightSail 1 mission was projected to last for approximately 31 to 38 days after ejection from the P-POD.

In contrast to LightSail 1, the planned orbit for LightSail 2 will allow for a complete solar sailing demonstration. The spacecraft will ride to a 720-km circular Earth orbit inside a P-POD, which in turn will be fully integrated inside the Prox-1 spacecraft. The entire Prox-1 payload rides to orbit attached to an EELV Secondary Payload Adapter (ESPA) ring port. Prox-1 is one of a cluster of payloads to be deployed as part of the U.S. Department of Defense Space Test Program-2 (STP-2) launch. STP-2 will launch from Cape Canaveral, Florida in late 2016 on SpaceX Falcon Heavy launch vehicle—the first planned operational Falcon Heavy launch following an earlier test launch.

The LightSail 2 mission sequence is expected to last approximately six weeks following solar sail deployment. The concept of operations for the Prox-1 and LightSail 2 missions are shown in Figure 11. During the first 28 days after the solar sail is deployed, the sail will be controlled as shown in Figure 10 to enable apogee-raising. 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.

The LightSail avionics are not radiation hardened, and multiple processor resets due to radiation-induced events are expected during the course of the mission. These were experienced by the LightSail 1 spacecraft during flight operations, as described in Section 5. The mission operations architecture is robust to radiation-induced resets, with ground-in-the-loop commanding of all critical events, on-board storage of key telemetry and images in non-volatile memory, and transition to a safe spacecraft state following processor reboots. Due to the short mission duration, radiation environment effects on the solar sail are negligible. There is minimal autonomy used in the LightSail mission. Watchdog timers are employed to monitor the health and status of the key processes that are active on the flight processor, and initiate a reboot in response to off-nominal conditions.

4. LightSail 1 and 2 Ground Segment

LightSail 1 was controlled from ground stations located at California Polytechnic University, San Luis Obispo (Cal Poly), and Georgia Institute of Technology (Georgia Tech). The stations were networked to a telemetry database server at Cal Poly, and commanded by operators at terminals at Cal Poly and Georgia Tech.

For LightSail 1, the Cal Poly station used a dual-phased yagi antenna connected to an amateur satellite radio, shown in Figure 12, which was then connected to a computer to encode and decode telemetry. The computer also gimbals the antenna to point at satellites as they pass overhead. Georgia Tech used a single yagi antenna connected to nearly identical radio and encoding/decoding equipment.

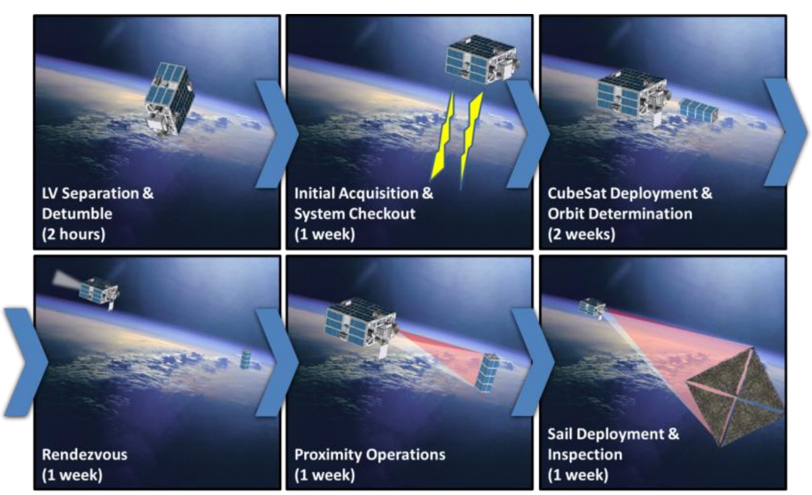


Figure 11. Prox-1 and LightSail 2 Concept of Operations.

Figure 12. Cal Poly Ground Station Antennas tracking LightSail 1.

For LightSail 2, Georgia Tech will use an upgraded dual-phased yagi setup nearly identical to Cal Poly's. Cal Poly will be using the existing antennas, plus the added gain of a new quad-phased yagi for additional link margin, shown in Figure 13. In addition to the stations used for LightSail 1, there are plans to use a ground station at the Sacred Hearts Academy (SHA) private all-girls' school in Honolulu, Hawaii, which has been used for CubeSat missions with the University of Hawaii. The SHA ground station will greatly improve coverage of the low inclination orbit for LightSail 2 and provide hands-on operations experience for students at the school.

Figure 13. Cal Poly quad-phased yagi.

5. LightSail 1 Integration and Testing

Following an extended period in storage, the LightSail 1 spacecraft entered the integration and testing phase in the fall of 2013. During the last three months of 2013, the engineering team completed spacecraft de-integration, modification and re-integration, and selected testing of LightSail 1 (and to a lesser extent LightSail 2), plus such tasks as inventorying and labeling parts, updating CAD models, assessing battery health, cleaning and upgrading the BenchSat unit, performing boot-ups of the avionics and performing functional and communications checks, making the momentum wheel and accelerometer changes and selected structural changes, swapping the original sail deployment motors with new motors, and conducting motor tests and selective upgrades to the avionics. By late 2013, the re-integration of both spacecraft was well along, but neither one was fully ready for end-to-end functional testing. Limited testing and FSW modifications ramped up in early 2014.

With a launch date a year away, the team focused their efforts during the rest of 2014 solely on LightSail 1. Many tweaks to hardware and FSW were completed, numerous component-, subsystem- and system-level tests (see Figure 14) were conducted, and final launch integration paperwork and mission-related licenses were secured (Ridenoure, 2015). Final launch approval was granted in early December

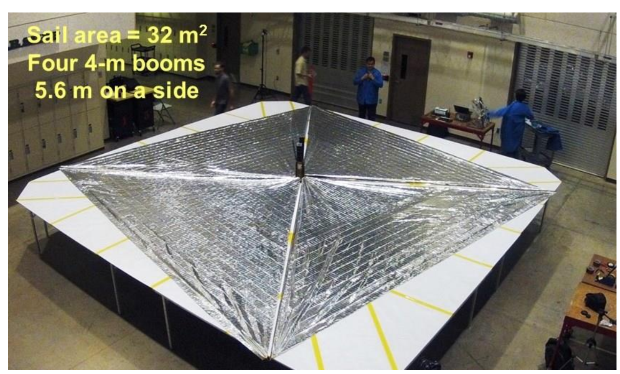


Figure 14. LightSail 1 after a successful deployment test (with sail edges manually stretched to straight).

2014. By this time, the scheduled launch date had slipped to early May 2015. LightSail 1 launch integration (Figure 15) was completed in January 2015. The final mass of LightSail 1 was 4.93 kg. The ULTRASat payload arrived at the launch site in Florida in early March.

6. LightSail 1 Mission Operations

With the LightSail 1 mission plan in place, two operations readiness tests (ORTs) were conducted during March and April 2015, in preparation for the mission. ORT-1 covered initial acquisition and spacecraft checkout, while ORT-2 simulated mission operations of solar panel and solar sail deployment events, including image acquisition and downlink. The ORTs involved all mission personnel, spanning TPS, Ecliptic, Cal Poly, and Georgia Tech. ORT-1 was fully successful, although a FSW coding error was discovered which, within four seconds of a computer restart or reboot, resulted in the suspension of subsystem telemetry related to the PIB and suspension of ADCS control functionality. The coding error was not correctable, because the FSW configuration had been locked down months before, LightSail 1 was already installed in the P-POD ready for launch, and FSW patches during mission operations were not a feature of the spacecraft design. After such a restart, a snapshot of key ADCS parameters (e.g., gyro rates) would be captured in telemetry, but the ADCS algorithms themselves (e.g., routines to generate commands to the torquers) would not be operable. This FSW error highlighted the need for more comprehensive testing during the verification and validation efforts for the follow-on LightSail 2 mission, including ORTs earlier in the integration and testing phase involving the full flight team.

The Atlas 5 launch with ULTRASat and LightSail 1 aboard occurred on May 20, 2015, inserting the primary payload—the X-37B spaceplane—into the desired elliptical orbit (356 km x 705 km and 55° inclination) (Ray, 2015). LightSail 1—in the last of the eight ULTRASat P-PODs to be actuated—was ejected into orbit two hours after launch. Telemetry data from LightSail 1, in the form of several 220-Byte beacon packets of useful engineering data transmitted every 15 seconds, were received during the first two planned back-to-back tracking passes over Cal Poly and Georgia Tech, starting 75 minutes after P-POD ejection. Receipt of this initial data set confirmed that the RF antenna deployment event occurred as sequenced.

The telemetry data indicated that the ADCS routines had been suspended as expected; but the useful snapshot of ADCS parameters was also captured. Tip-off rates about the X, Y and Z axes from gyro data indicated -7.0, -0.1 and -0.3 °/s, respectively—3x less than pre-launch worst-case estimates. All other telemetry was nominal, except that a solar panel deployment indicator switch indicated that all panels were in the deployed configuration, and that the gyros were left on by the event sequencer.

Figure 15. LightSail 1 integration into the P-POD (l) and ULTRASat fully loaded with P-PODs (r).

Based on the other telemetry readings, the deployment switch was presumed to have triggered due to the launch vibration environment and not because of an actual deployment event. (A similar occurrence happened during one of the LightSail 1 vibration tests.) The gyro on state was unexpected, but upon investigation was found to be as programmed in the initialization sequence.

Nine successful tracking passes were completed during the first 24 hours of the mission, including one 12 hours into the mission that successfully established commanding to the spacecraft from Cal Poly (to turn the gyros off to reduce battery load during eclipse periods), confirming additional spacecraft functionality. During the first 48 hours of the mission, over 140 useful beacon packets were received.

Two days into the mission, it was noticed that a file in the Linux file system on the Intrepid board that keeps track of beacon packets (beacon.csv) was rapidly growing in size. There was concern that the Linux system could crash due to a file size overload. The board did indeed crash, 55 hours after launch—just before the next planned pass, when the operations team was going to uplink a command sequence to delete the then-active beacon.csv file with the expectation that this might prevent the crash. LightSail 1 fell completely silent for days, in spite of the operations team sending FSW reboot commands and trying to capture fresh telemetry during dozens of passes over Cal Poly, Georgia Tech, and several amateur sites. (Hardware- and software-based watchdog timers in the Intrepid board were not functional for LightSail 1.) After consulting with other CubeSat operators familiar with the class of avionics on LightSail, it was generally agreed that the best hope for LightSail was for the Intrepid board to reboot following a random radiation-induced charged particle impact. This scenario did indeed occur, and LightSail 1 rebooted and started sending telemetry again eight days later, on May 30.

Upon the recovery of LightSail 1 operations, the flight team implemented a new protocol to prevent Intrepid board crashes and continue with the mission plan. Via ground commanding, the mission team would reboot the Intrepid board at least once a day, to truncate the beacon.csv file write overload issue. For the remainder of the mission, the file write volume vulnerability was managed via commanded reboots.

After the reboot, fresh gyro data indicated that rotation rates had increased by roughly 50% since the initial readings from the gyros following injection. Planning began for the commanded deployment of the solar panels and sails as soon as possible. Close coordination continued with the U.S. Joint Space Operations Center (JSPoC) at Vandenberg AFB, California, to refine the orbit for LightSail 1. It was not clear at this point which of the various CubeSats ejected from ULTRASat was LightSail 1.

Commands tasking each camera to acquire test images were successfully sent on May 31, and downlinked over the next two days (Figure 16). The PCAM view is from inside the spacecraft as indicated by the yellow oval in the side view (top of Figure 16). The hint of sunlight penetration in the on-orbit image confirmed suspicions that the solar panel restraining lines had loosened slightly during the launch and/or P-POD deployment phase, resulting in the spurious deployment switch readings indicating that the panels were deployed. The image confirmed that the camera was functioning properly, and it also provided positive confirmation that the solar panels were in the stowed configuration.

After considerable discussion among the LightSail team and with Chris Biddy (Aquila Space), the principal engineer responsible for the LightSail mechanical design, including the sail deployment assembly, it was decided to separate the solar panel deployment event from the sail deployment sequence with a two-day gap, to allow post-panel-separation assessment. It was also desired to issue the sail deployment command early in a tracking pass to allow visibility into the sail deployment sequence. Panel deployment was scheduled to occur on June 3, and sail deployment was rescheduled into June 5.

With the regular FSW reboots, the flight team had good visibility into the CubeSat angular rates (Figure 17), which had increased to ~2x the original tip-off rates. Panel deployment commands were sent early in the morning Cal Poly time on June 3, and subsequent beacon packets indicated successful deployment based upon the gyro rate data, solar panel temperatures (colder) and sun sensor data.

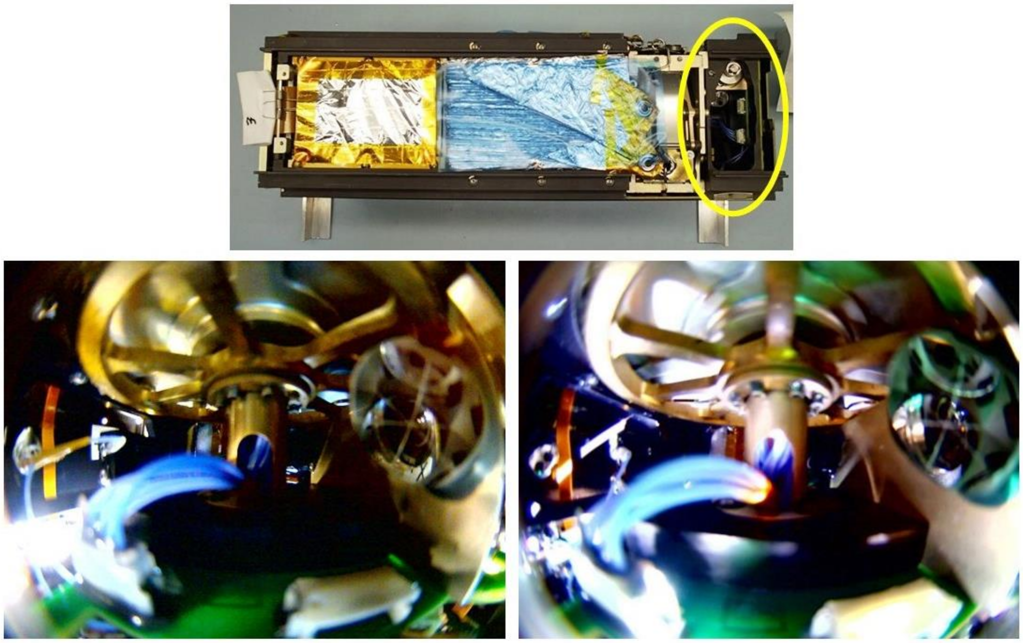


Figure 16. Results of test image in orbit (r) compared to one from lab-based system-level test (l).

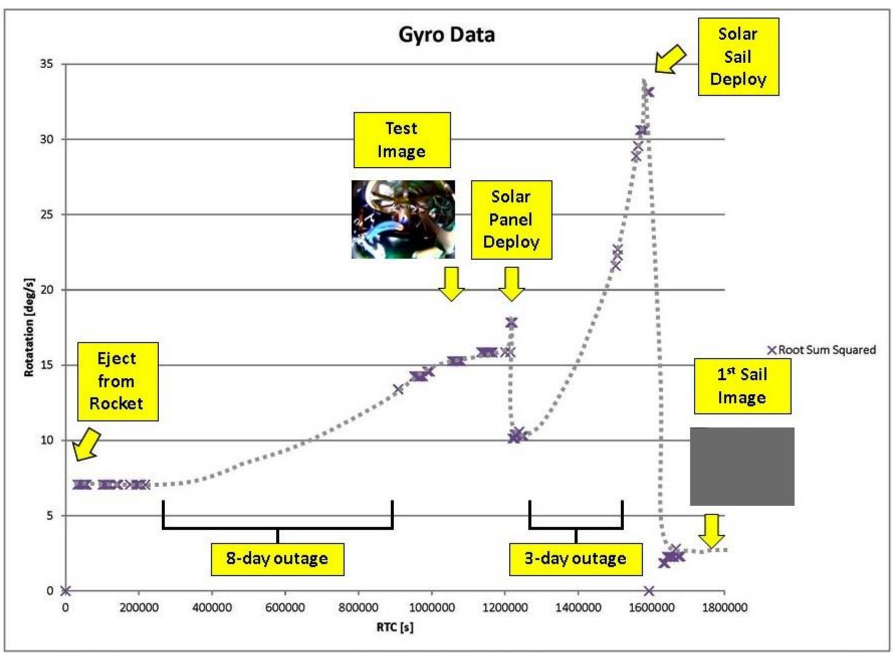


Figure 17. RSS of gyro rates during course of mission.

Several hours after solar panel deployment, telemetry indicated that all eight batteries were close to their nominal charge levels, but the batteries were not connected to the main power bus. Current was neither flowing into nor out of the batteries. This indicated that all batteries were likely in a fault condition stemming from the solar panel deployment event.

Contact was regained on the next pass, but the battery situation remained unchanged, and the spacecraft appeared to have rebooted unexpectedly. The operations team discussed the option of commanding an emergency solar sail deployment, but all ground testing of the solar sail deployment sequence had been performed under battery power, with all battery cells online and fully charged. It was uncertain whether the sail deployment could be successfully completed without battery power, relying only upon direct input from the solar panels. The team decided to address the power subsystem issues first and approach solar sail deployment in a known state consistent with ground testing, so sail deployment was deferred pending investigation of the power anomaly.

During the first good pass on June 4 (after a ten-hour gap of no useable passes) and for ten more passes that day, LightSail 1 was silent. There was no telemetry, and the reboot commands were unsuccessful in reestablishing communications. After a three-day hiatus, LightSail 1 started transmitting beacon packets again over Cal Poly the morning of June 6. Over the course of two good passes, 23 packets were received. During that last tracking pass of the day, telemetry showed that the batteries were charging—the first time since solar panel deployment three days before. Based upon analysis of the available data, it appeared that the spacecraft was stuck in a loop where power levels were too low during eclipse periods, but too high during sunlit periods. Battery fault protection in this condition was likely preventing the batteries from re-attaching their circuits to the spacecraft.

Late on June 6 it was decided that if beacon data from the June 7 morning passes suggested that battery levels were continuing to trend toward a more stable state, sail deployment would be commanded during the late morning Cal Poly pass, with two more remaining passes that day serving as backups. It was noted that gyro rates were at over 20 °/s and rapidly increasing by almost 6 °/s per day (Figure 14)—and now the dominate rate was about the Z-axis (the longitudinal axis of the CubeSat).

Telemetry from the first June 7 tracking pass was nominal, with good power levels and the batteries discharging as expected, so the team elected to command sail deployment. The final versions of the command sequences required to initiate the sail deployment (including imaging) had been validated on BenchSat and were ready to transmit, as were several short command bursts required to configure the spacecraft into the most ideal state for deployment. Essentially, the sail deploy sequence involved sending separate ENABLE and DEPLOY commands in series, with a built-in pause between the two to allow for human confirmation that the ENABLE command was received before sending the DEPLOY command.

Due to spurious communications with the rapidly rotating spacecraft, confirmation that the ENABLE command was activated were not received in the initial attempt. However, on a subsequent pass it was confirmed that the ENABLE command had been activated and the spacecraft was fully initiated for sail deployment. During the final tracking pass on June 7, controllers at Cal Poly sent the command to deploy the solar sail. The DEPLOY command was successfully executed, and the sail motor began deploying the booms (Figure 18). Over two minutes of motor count telemetry were received, indicating that the motors were driving the sail booms out at a rate consistent with ground testing.

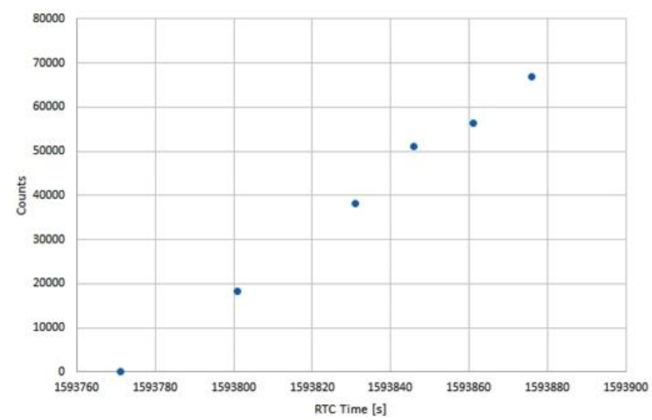


Figure 18. A key two minutes of sail deployment motor count telemetry.

Telemetry from the June 8 tracking passes showed that gyro rates had dropped to nearly zero (see Figure 14), an indication of a successful sail deployment. All other subsystems were nominal. The team spent June 8 stepping through the command sequences to transfer the stored deployment images from the camera memories into the Intrepid board's memory, and then downlink one full image to the ground. By the end of the day, indications were that all of the images 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. By early afternoon of June 9, an entire image was downlinked and reconstructed from Camera A, showing the deployed sail with the sun in the background (Figure 19). The image was disseminated globally by TPS and social media outlets. With the primary mission

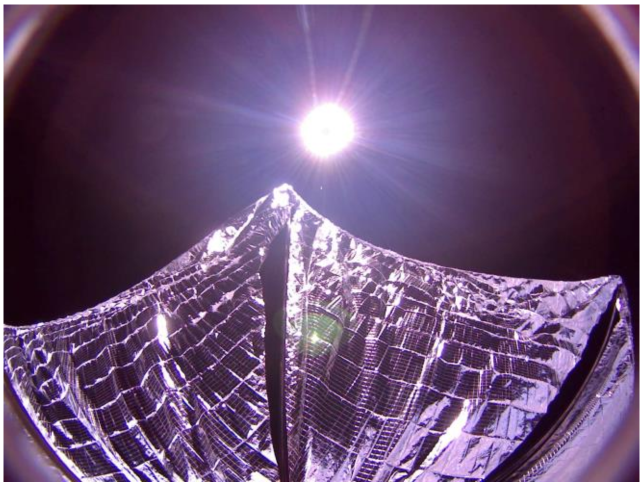


Figure 19. LightSail 1 image of deployed sail.

objectives accomplished, Nye at TPS declared the LightSail 1 mission a success the afternoon of June 9—more than one week ahead of the pre-launch mission plan.

On June 10, the team worked to downlink an image from Camera B, and managed to get a partial reconstruction of an image. On June 11, LightSail 1 entered an anomalous mode of continuously transmitting RF noise. Ground controllers were unable to recover from this anomalous condition. LightSail 1 reentered the atmosphere and burned up off the east coast of Argentina over the Falkland Islands on the morning of June 14, seven days after sail deployment.

7. Planning for the LightSail 2 Mission

Much has been learned from the LightSail 1 mission that is being incorporated into the planning for the LightSail 2 mission. A detailed planning workshop for the LightSail 2 was held in July 2015, four weeks after the LightSail 1 mission ended. Based on LightSail 1 lessons learned, a number of design changes and FSW fixes are being implemented, as follows:

- The most current Tyvak Intrepid board (version 8) will be used, eliminating some known timing and memory-use errors.
- An extra BenchSat will be built to allow for additional FSW development and related testing.
- FSW coding errors found during LightSail 1 testing and operations are being corrected.
- Voltage and current threshold settings in the Intrepid board and for the battery fault-detection circuits will be adjusted to allow for more margin before fault tripping.
- A spacecraft grounding issue which precluded use of the Intrepid board's watchdog timer has been corrected.
- Software-driven watchdog timers will be enabled.
- The majority of attitude control operations, including sail slewing, will be automated.
- Command and test sequences will be shortened to simplify operations during short passes.
- A second solar panel burnwire will be added to eliminate a high-risk single-point failure.
- Commands used during ground testing will be enabled for use during mission operations for LightSail 2.
- More precise RF antenna tuning will be completed, and more thorough pattern measurements will be taken.
- Modifications to the beacon telemetry approach will be made to improve understanding of spacecraft health and status.
- The design of the solar panel deployment switch assembly is modified to preclude false indications.
- Camera behavior will be better characterized and related FSW and operational procedures will be modified to allow for

additional operational modes and improve ease of use.

- Various other FSW modifications will be made to improve onboard timing, file management and robustness.
- Laser retro-reflectors will be added to the +Z face to enable laser ranging in the stowed configuration.
- Long-duration testing of the FSW is planned.
- The Georgia Tech tracking station will be upgraded to a dual-Yagi system.

8. Conclusions

The LightSail program seeks to advance the state of the art in solar sailing technology by demonstrating that a sail may be deployed and controlled from the standard 3U CubeSat platform. The LightSail 1 test flight successfully demonstrated the solar sail deployment sequence. A number of technical issues were identified during pre-launch testing and mission operations that will be corrected for the follow-on LightSail 2 mission. LightSail 2 will complete the program technology demonstration objectives by controlling the solar sail and increasing the orbit apogee via solar radiation pressure, the first time that this will be accomplished from a CubeSat platform.

The LightSail program demonstrates technology that will enable future solar sailing missions, with applications spanning the inner and outer solar system, and potentially interstellar travel. NASA's planned NEA Scout mission will use a solar sail to propel a spacecraft to a near-Earth asteroid in 2018. It is hoped that the LightSail program will provide lasting benefits to the global space flight community, establishing solar sailing as a proven technique for spacecraft propulsion in achieving science and technology mission objectives.

Acknowledgments

The LightSail program has spanned six years, and is expected to continue for at least another two years. Many people and organizations have been directly involved with the technical execution of the program, still more have served in various supporting roles, and many thousands of others have provided support and contributions. It would be a significant challenge, if not impossible, to list them all. But certainly Lou Friedman deserves credit for keeping the vision of a solar sailing demonstration mission alive since 1976.

The experience with the NASA Marshall/NASA Ames NanoSail-D CubeSat program served as a worthy architectural precursor to LightSail. For LightSail, engineers at Stellar Exploration, Inc. managed to double the solar sail area and add active attitude control, cameras and other diagnostics while maintaining the 3U CubeSat form factor set by the NanoSail-D effort. NASA, Georgia Tech, and the Space Test Program enabled the restart of the program by securing firm launch opportunities for LightSail 1 and LightSail 2, respectively.

Staff and students at Cal Poly, Georgia Tech, Tyvak and SRI provided essential support during the LightSail 1 integration and testing effort, during several mission ORTs, and on console during mission operations. Helping everyone to understand what was happening with LightSail 1 during the mission, many amateur and serious astronomers and spacecraft observers around the world contributed analyses, predictions, received beacon packets, images, and video clips for consideration. And thanks to Scott Wetzel, Dave Arnold, and team from the International Laser Ranging Service (http://ilrs.gsfc.nasa.gov/index.html) for their efforts in laser ranging of LightSail 1.

Management and staff at The Planetary Society encouraged the technical team to act quickly when the schedule was tight, and secured all funding for this work. They also did an admirable job of spreading the word about the program to conventional and social media before, during and after the LightSail 1 mission (Davis, 2014).

Finally, the authors would like to thank the ~40,000 members of The Planetary Society, key donors, and the 23,331 contributors to its LightSail Kickstarter campaign conducted during spring 2015. These interested and generous people actually funded these missions, and their support was essential.

References

Alhorn, D., Casas, J. et al. (2011): NanoSail-D: The Small Satellite That Could!, presented at the 2011 Conf. on Small Satellites, Logan, UT, Paper SSC11-VI-1.

Banerjee, A. (2001): “Reducing Minimum Time for Flexible Body Small-Angle Slewing With Vibration Suppression,” *J. of Guidance, Control, and Dynamics*, March-April, pp. 1040–443.

Biddy, C. and Svitek, T. (2012): “LightSail-1 Solar Sail Design and Qualification,” 41st Aerospace Mechanisms Symposium, May, pp. 451–463.

Cowing, K. (2011): “NASA Announces Candidates For CubeSat Space Missions,” SpaceRef, Available at: http://spaceref.com/nasa-hack-space/nasa-announces-candidates-for-cubesat-space-missions.html (last accessed June 12, 2016).

Davis, J. (2014): LightSail Is Happening, and I’ll Be Your New Guide. Available at: http://www.planetary.org/blogs/jason-davis/2014/20140602-lightsail-is-happening.html (last accessed June 12, 2016).

Friedman, L. D. (1988). *Starsailing: Solar Sails and Interstellar Travel*, (1st ed.). Wiley, New York, New York.

Friedman, L. D. (2009): LightSail: A New Way and a New Chance to Fly on Light, The Planetary Report, The Planetary Society, Nov.–Dec.

Kepler, J. (1610). Solar Sail. Available at: https://en.wikipedia.org/wiki/Solar_sail, referenced June 11, 2016.

Klaes, L. (2003): Cosmos-1 Solar Sailing Mission, *The Ithaca Times*, Vol. 26, No. 4, Sept. 24.

Leone, D., (2014): NASA Nixes Sunjammer Mission, Cites Integration, Schedule Risk, *Space News*, October 17.

McInnes, C. R., (1999): Solar Sailing, Technology, Dynamics and Mission Applications, *Springer-Praxis Series in Space Science and Technology*, Praxis Publishing, Chichester, UK.

Okseniuk, K. J., Chait, S. B., Schulte, P. Z. et al. (2015): Prox-1: Automated Proximity Operations on an ESPA-Class Platform, presented at 29th Ann. AIAA/USU Conf. on Small Satellites, Logan, UT, August, Paper SSC-15-IX-4.

Ray, J. (2015): X-37B Spaceplane Embarks On Fourth Voyage In Orbit. Available at: SpaceflightNow.com, http://spaceflightnow.com/2015/05/20/recap-story-x-37b-embarks-on-fourth-voyage-in-space/ (last accessed June 12, 2016).

Ridenoure, R. et al. (2015): LightSail Program Status: One Down, One to Go,” presented at Ann. AIAA/USU Conf. on Small Satellites, Logan, UT, August, Paper SSC-15-V-3.

Singhose, W., Banerjee, A., and Seering, W. (1997): Slewing Flexible Spacecraft with Deflection Limiting Input Shaping. *J. of Guidance, Control, and Dynamics*, Vol. 20, No. 2, March-April, pp. 291–298.

Space.com (June 11, 2010): Japanese Spacecraft Deploys Solar Sail. Available at: http://www.space.com/8584-japanese-spacecraft-deploys-solar-sail.html (last accessed June 12, 2016).

The Planetary Society (2015): About Us, Our Founders. Available at: http://www.planetary.org/about/our-founders/ (last accessed June 12, 2016).