The LightSail 2 Solar Sailing Mission Summary

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ABSTRACT

The LightSail 2 mission concluded a 3-year mission in November 2022, having successfully demonstrated controlled solar sailing in low-Earth orbit using a CubeSat platform. Flight data show that LightSail 2 successfully controlled its orientation relative to the Sun, with sustained periods of apogee raising and increasing orbital energy. The LightSail 2 solar sail was 5.6 m on a side and has a total deployed area of 32 m^2. Four independent triangular aluminized Mylar® sail sections 4.6 microns thick were Z-folded and stowed into four sail bays. The sail segments were deployed by four 4 m Triangular Retractable And Collapsible booms made of elgiloy. The booms were wound around a common spindle, with deployment driven by a Faulhaber motor containing Hall sensors. Attitude was controlled using a single-axis Sinclair Interplanetary momentum wheel and magnetic torque rods. During solar sailing operations, two 90 degree slews were performed each orbit to harness momentum from solar photons. The thrust from solar radiation pressure measurably reduced the rate of orbital decay, including an extended period of orbit raising. Two Planetary Society Cameras developed by the Aerospace Corporation were mounted at the tips of opposing solar panels, providing imaging for engineering evaluation and public engagement throughout mission operations. This paper provides a summary of the LightSail 2 mission implementation, including the flight system design and the pre-launch test program. LightSail 2 mission operations are described, including discussion of the ground system. Solar sailing performance is presented, and anomalies encountered during the mission are discussed. The Planetary Society's decade-long LightSail program was entirely donor-funded, with over 50,000 contributors worldwide. With a total cost of about $7M for two flight missions, the LightSail program showed that solar sails can provide a cost-effective option for propulsion of CubeSat-class vehicles.

INTRODUCTION

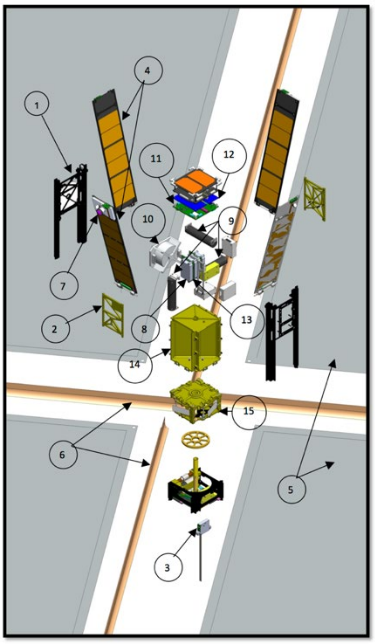
The goal of the LightSail program was to develop and demonstrate the technology of solar sailing, a propulsion method that utilizes sunlight for propulsion in space.[1,2] Solar sailing involves using the pressure of sunlight to propel a spacecraft through space. It relies on the momentum carried by photons, or particles of light, to push against a large reflective sail. By continuously harnessing the momentum of sunlight, solar sails can provide a continuous acceleration without the need for traditional propellants.

Sponsored by The Planetary Society, a nonprofit space advocacy organization, the LightSail program consisted of two CubeSat-based solar sailing demonstration missions.[3,4] LightSail 1 was a proof-of-concept mission with the focused goal of demonstrating solar sailing deployment. Launched in 2015, LightSail 1 successfully deployed its 32 m^2 solar sail from a 3U CubeSat, and downlinked a confirmation image showing the deployed sail prior to reentering the Earth's atmosphere.[5,6]

Building upon the technology demonstrated in LightSail 1, the objective of the LightSail 2 mission was to demonstrate controlled solar sailing in low Earth orbit, and increase orbit apogee via solar radiation pressure.[7-9]

FLIGHT SYSTEM DESCRIPTION

The LightSail spacecraft were designed and fabricated by system contractor Stellar Exploration, Inc. Utilizing the 3U CubeSat standard, the spacecraft avionics were housed in a 1U volume, while the solar sail assembly occupied 2U, including sail storage, boom deployment assembly, and booms. Four deployable solar panels provided power, and a deployable monopole antenna was used for RF communications.



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

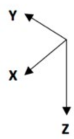


Figure 1. Schematic showing exploded view of LightSail 2 design.

The avionics section housed two processor boards, a radio, batteries, sensors and actuators, and associated harnessing. A small solar panel fixed at the end of the CubeSat and four full-length deployable panels provided power generation. Solar panel deployment is accomplished via a common burn-wire assembly mounted near the RF antenna. Each deployable solar panel carries Sun sensors, magnetometers, power sensors and temperature sensors. Two Planetary Society Cameras (PSCAMs) developed by the Aerospace Corporation were mounted at the tips of opposing solar panels. The 2-megapixel 185 deg fish-eye color cameras acquired 1600 x 1200 pixel JPEG images, along with a 120 x 90 pixel thumbnail. Thermal control maintained camera temperatures between 0 – 70 deg C.

Four independent triangular aluminized Mylar® sail sections 4.6 microns thick were Z-folded and stowed in the four sail bays at the spacecraft midsection. Each sail section was attached to two 4-m Triangular Retractable And Collapsible (TRAC) booms made of elgiloy. The TRAC booms were wound around a common spindle driven by a Faulhaber motor containing Hall sensors. Sail deployment was initiated via flight software, through commanding the Faulhaber deployment motor a specified number of motor counts. When fully deployed, the square solar sail had a total sail area of 32 m^2.

The electrical power subsystem included the solar arrays, batteries, power distribution, and fault protection circuitry. A 5.6 Ah battery pack coupled with a solar panel system produced an average power of 8.5 W. In full Sun, the four deployed solar panels generated a maximum 6 W of power each with the body-mounted -Z panel providing 2 W. Solar power was routed through the main avionics board, charging a set of 8 lithium-polymer batteries. Each battery cell had its own charge monitoring/protection circuitry, providing overvoltage and undervoltage protection as well as overcurrent and short-circuit protection.

Three magnetotorquers, one in each body axis, provided coarse attitude control using the Earth's magnetic field. A Sinclair Interplanetary momentum wheel facilitated slews about the spacecraft Y-axis.

The use of thermal blankets and ambient heat from electronics provided a stable thermal environment for all electronics within the spacecraft.

The primary avionics board for LightSail 2 was a Tyvak Intrepid flight computer (version 8), which was Atmel-based and hosted a Linux operating system. An AX5042 UHF radio transceiver with an operating frequency of 437.025 MHz was mounted on a daughterboard, providing uplink and downlink capability. The main avionics board was tasked with spacecraft commanding, data collection, telemetry downlink, power management and initiating deployments. A payload interface board (PIB) integrated sensor data for attitude control, commanded actuators, and managed deployments as directed by the avionics board.

LightSail 2 flight software and firmware were written in the C programming language, and The ADCS software was designed in MATLAB/Simulink and autogenerated to C code and integrated with the flight software. Attitude control software and interfaces to ADCS sensors and actuators are allocated to the Intrepid board.

ADCS utilized a 1 Hz control loop that first initialized required peripheral devices, then checked for ground commands and performed 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 ceased active attitude control and commanded the Payload Interface Card (PIC) to control the brushless DC deployment motor.

LightSail 2 had the capability to receive and process ADCS and flight software updates in flight. Spacecraft commands were parameterized to maximize flexibility during testing and mission operations. Telemetry was downlinked via 227-byte beacon packets. Mission elapsed time, command counter, power, thermal, ADCS and deployment data were included in the beacon data to provide assessments of on-orbit performance during the mission. Beacon packets were downlinked at a nominal 7-second cadence and were supplemented by spacecraft logs that further characterize spacecraft behavior.

Pre-Launch Testing

Since the major required advancement for LightSail 2 over the prior LightSail 1 mission was active attitude control, the project completed focused attitude determination and control system (ADCS) testing prior to launch. Ecliptic Enterprises Corporation was the implementing organization for the pre-launch testing program. Sensor calibration and phasing tests were performed at the Utah State Space Dynamics Lab and UCLA. Testing of the momentum wheel demonstrated proper functionality across the expected operating ranges.

Two day-in-the-life tests were performed during the LightSail 2 integration and testing phase. DITL testing included CubeSat initialization, full sensor checkouts, deployments of the RF antenna, solar panels, and solar sail, and imaging operations. DITL testing was performed using spacecraft power, with commanding and telemetry data return via RF link to the California Polytechnic State University, San Luis Obispo (Cal Poly) tracking station.

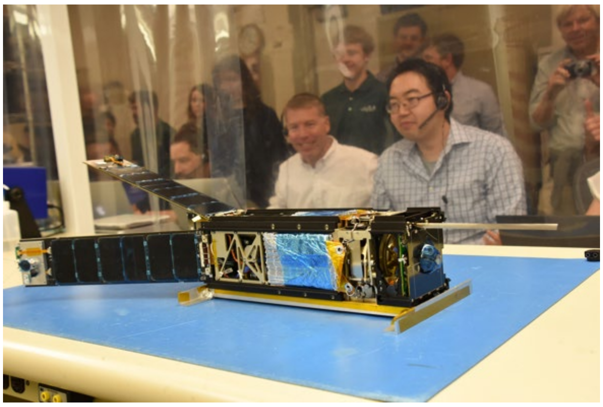


Figure 2. Day-in-the-life testing of the Lightsail 2 CubeSat.

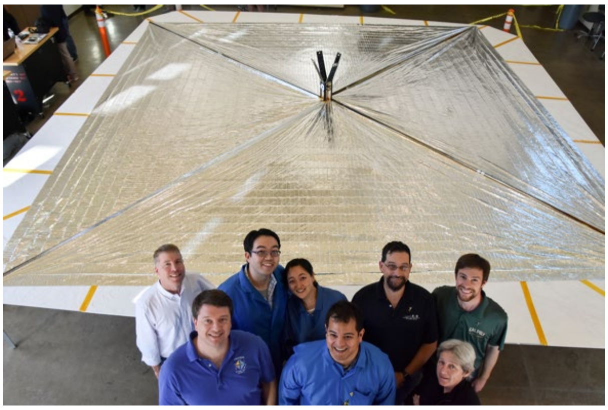


Figure 3. Sail deployment as part of day-in-the-life testing.

A series of three Operational Readiness Tests (ORTs) were performed prior to launch for flight team training and to refine flight procedures. The flight system testbed called BenchSat was used for command and telemetry generation for the ORTs. BenchSat included most of the hardware components of the LightSail 2 spacecraft avionics, including the Intrepid board, payload interface board, cameras, radio, magnetometers, sun sensors, gyros and solar panels. For subsystem components that were not included on BenchSat, simulators were incorporated. For example, BenchSat lacked the actual solar sail deployment motor/spindle, but a clutch mechanism was introduced to simulate the load experienced by the deployment motor. It also did not have actual torque rods, but incorporated torque rod simulators in the form of 30 Ω resistors.

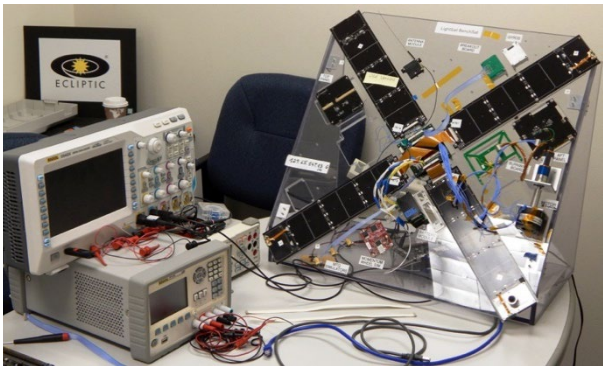


Figure 4: BenchSat provided a test platform for LightSail 2.

Flight system bakeout and thermal cycle testing were performed at Cal Poly prior to shipment to the Air Force Research Laboratory (AFRL) in Albuquerque, New Mexico. LightSail 2 was integrated into the flight Poly Picosat Orbital Deployer (P-POD), hosted by the Georgia Institute of Technology Prox-1 satellite.[10-12] The Prox-1/LightSail 2 integrated system was then environmentally tested at AFRL. Upon completion of environmental testing, LightSail 2 was removed from the P-POD, and a functional test was performed. The battery was fully charged, and the spacecraft was reintegrated into the P-POD for launch.

MISSION SUMMARY

LightSail 2 was launched into space aboard SpaceX's Falcon Heavy rocket on July 2, 2019. LightSail 2 was deployed from Prox-1, and 45 minutes later the LightSail 2 radio signal was received by the flight team via the Cal Poly tracking station. The radio signal was confirmed to be LightSail 2 based upon a Morse code signal containing the assigned mission call sign, WM9XPA.

The initial health and status assessment showed that the spacecraft was in good condition, with the batteries fully charged. Temperatures were within the expected ranges. The attitude control subsystem was in detumble mode, and angular rates were low (< 2 deg/s). The flight team established two-way communications with the spacecraft and began checkout activities. Test images were acquired from each of the two PSCAM cameras mounted on the solar panels. The attitude control mode was changed from Mode 0 (detumble) to Mode 1 (Z-axis alignment), aligning the longitudinal axis of the CubeSat with the Earth's magnetic field vector, a favorable attitude for communications. A functional checkout of the momentum wheel was performed, commanding the momentum wheel to speeds of 500 and 2000 rpm in each direction, followed by commanded torques of +/- 0.001 Nm. The flight team then proceeded with solar panel deployment, and acquired additional test images from the panel-mounted cameras.

Attitude control of LightSail 2 was accomplished using three magnetic torque rods and a momentum wheel. The momentum wheel rotated about the +Y axis of the spacecraft, allowing slews about this axis. Attitude knowledge was provided by two 3-axis magnetometers on the +X and +Y solar panels, supplemented by a suite of four sun sensors located on ends the deployable solar panels plus one additional sun sensor on the -Z face. The ADCS software included six attitude control modes, as described in Table 1.

Table 1: LightSail 2 ADCS modes.

ADCS Mode	Mode Description
Mode 0	Detumble. Magnetometer readings are converted into the spacecraft body frame and B-dot control is used to generate torque rod commands to oppose the spacecraft's rotation as measured by secondary gyros located on the Intrepid board. The primary gyros and momentum wheel are not used.
Mode 1	Magnetic alignment. The Z-axis torque rod is set to constant maximum power while the others act as in the detumble mode. This approximately aligns the +Z axis with the local magnetic field vector. The primary gyros and momentum wheel are not used.
Mode 2	Solar sailing. The primary gyros and momentum wheel are powered on and LightSail 2 slews between thrusting and edge-on attitudes relative to the Sun
Mode 3	No torques. All actuators and the primary gyros are powered off.
Mode 4	Sun-pointing mode. Aligns -Z axis (solar sail normal) toward the Sun. Tested in March 2020.
Mode 5	Velocity pointing. Aligns +Z axis in the inertial velocity direction. Currently unused.

For two weeks following deployment from the P-POD, the LightSail2 flight team worked to resolve errors in the attitude determination and control system. Despite the ADCS focused pre-launch testing, the flight team addressed errors in ADCS flight software direction cosine matrices, sun sensor logic, and momentum wheel control software. To improve ADCS performance, a moving average filter was introduced for wheel torque commands, and a momentum wheel control gain setting was increased to improve wheel responsiveness.

Proper performance of LightSail 2 ADCS in Mode 2 was demonstrated on July 22, 2019. The desired angle between the spacecraft -Z axis and the Sun direction is indicated by the red line. The vehicle successfully performed three 90 deg slews relative to the sun direction during slightly more than one orbit period.

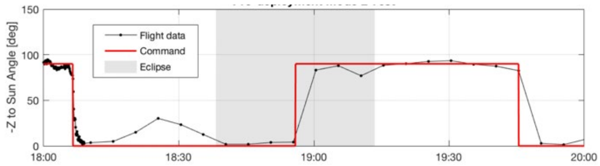


Figure 4. Successful demonstration of on-off slews prior to sail deployment.

Solar sail deployment was commanded on July 23, 2019. As the deployment motor drove the four booms through the deployment sequence, the PSCAMs each captured a sequence of 32 images as the sail segments were extended into shape. An image taken during the sail deployment sequence is shown in Figure 5.

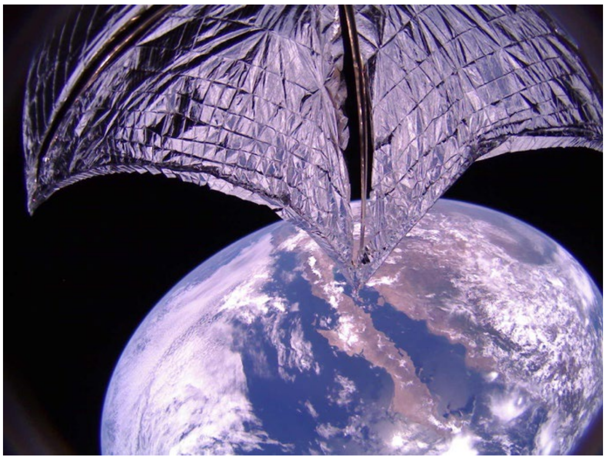


Figure 5: LightSail 2 sail deployment image, acquired shortly prior to reaching full deployment. Credit: The Planetary Society.

The PSCAMs were useful throughout the mission to perform engineering assessment of the flight system. An image acquired in January 2020 (see Figure 6) showed that one of the four solar panels had only partially deployed. This discovery allowed the flight team to update the flight software to account for the correct orientation of magnetometers and sun sensors on the partially deployed panel. As the mission progressed, images showed some sagging of the sail material and a portion of a TRAC boom in an unexpected location, as seen in Figure 7. Despite this apparent boom anomaly, the solar sail maintained its structural integrity throughout the 3.5 year deorbit phase.

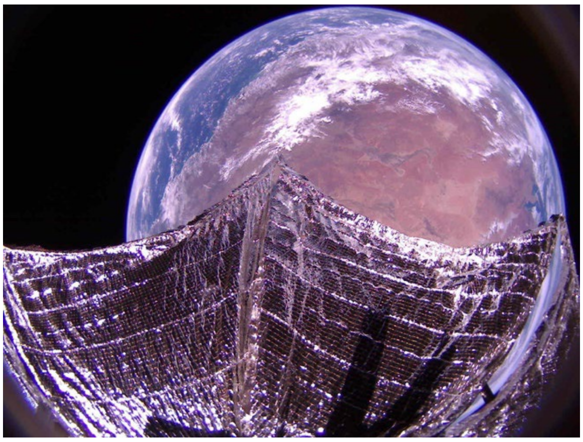


Figure 6: Shadows of the deployed solar panels projected onto the sail allowed detection of partial solar panel deployment. Credit: The Planetary Society.

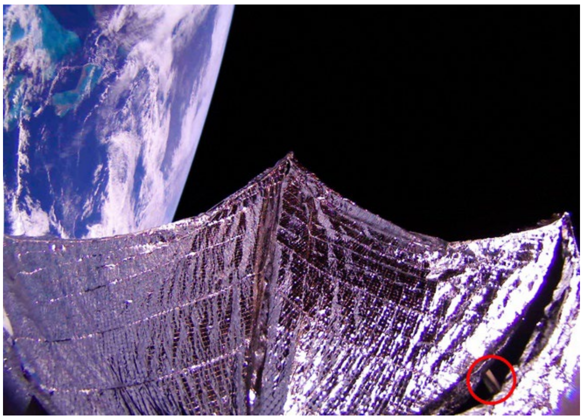


Figure 7: Image showing TRAC boom in unexpected location. Credit: The Planetary Society.

The sail control algorithm incorporated a cycle of "On-Off" slews about the spacecraft Y-axis that changed the sail orientation between edge-on and face-on to the sun direction twice per orbit as illustrated in Figure 8. When the spacecraft was moving away from the Sun, the sail normal was directed parallel to the Sun direction to maximize the solar radiation pressure on the sail and provide thrust in the orbital velocity direction. When the spacecraft was moving toward the Sun in its orbit, the edge-on attitude was used to minimize thrust from solar radiation pressure.

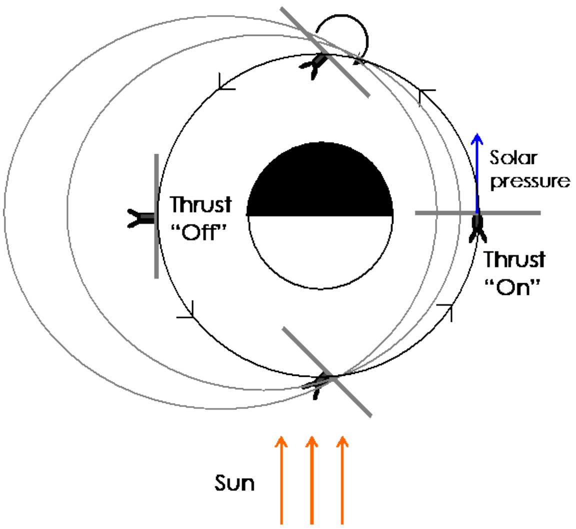


Figure 8: Illustration of LightSail 2 on-off sail control method.

Sail control performance was reconstructed from the onboard attitude quaternions, derived from magnetometer and Sun sensor measurements.[13] An example of the reconstructed sail control performance from August 4, 2019 is shown in Figure 9. The sail control algorithm was effective in reorienting the sail twice per orbit through momentum wheel control. Daily angular momentum desaturation activities were required to maintain the momentum wheel within its maximum spin rate capacity.

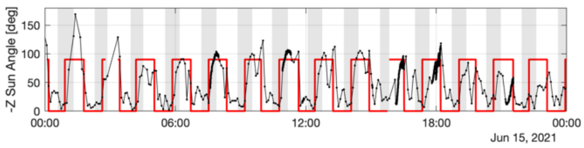


Figure 9: Example of on-off slewing with sail deployed.

In 2021, the flight team introduced a flight software change to correct gyro biases. The updated gyro bias settings dramatically improved solar sailing performance. Orbital energy increased steadily in July – August 2021, with a 758 m gain in orbit semi-major axis over a 38 day period, including a 600 m semi-major axis increase in 10 days. This was the best solar sailing performance during the mission.

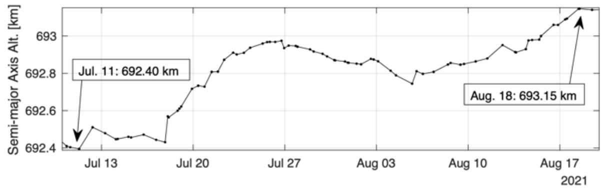


Figure 10: Sustained orbit raising was demonstrated for 38 days in July-August 2021.

LightSail 2 completed its deorbit in November 2022, nearly 3.5 years after launch. Throughout its solar sailing mission, LightSail 2 downlinked 225 full resolution PSCAM images that inspired the public and drew attention to solar sailing technology.

CONCLUSION

The Planetary Society's decade-long LightSail program was entirely donor-funded, with over 50,000 contributors worldwide. With a total cost of about $7M for two flight missions, the LightSail program showed that solar sails can provide a cost-effective option for propulsion of CubeSat-class vehicles. The LightSail 2 mission demonstrated the potential of solar sailing as a means of propulsion for small spacecraft and paves the way for future applications in space exploration, including missions to explore asteroids, monitor space weather, and reach distant destinations within our solar system and beyond.

Acknowledgments

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