70th International Astronautical Congress (IAC), Washington D.C., United States, 21-25 October 2019.

IAC-19,C4,8-B4.5A,2,x51593

LIGHTSAIL 2: CONTROLLED SOLAR SAIL PROPULSION USING A CUBESAT

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Launched June 25, 2019, The Planetary Society's LightSail 2 mission has demonstrated, for the first time, controlled solar sail propulsion using a CubeSat platform. Here we present initial results of this ongoing mission. Through a sail control strategy that requires two 90 degree orientation changes per orbit, LightSail 2 has successfully raised orbit apogee during the first month of solar sailing operations. The LightSail program is entirely privately funded through contributions from Planetary Society members and donors worldwide. More information on the LightSail program can be found at sail.planetary.org.

BACKGROUND

History

Photons carry momentum. Solar sailing uses the momentum of solar photons to propel a spacecraft. The basic concept of solar sailing dates back to the 1600s and Johannes Kepler who observed the effects of sunlight in the creation of cometary tails[1]. Only in recent years has the dream of solar sailing become a reality.

In 2005, the member-supported non-profit The Planetary Society attempted to fly the first solar sail mission, a mission propelled by sunlight. The spacecraft, Cosmos 1, was 100 kg with a 600 m² sail. Cosmos 1 was lost in a rocket launch failure[2].

In 2010, the JAXA spacecraft IKAROS became the first successful solar sail mission[3]. IKAROS was deployed into a heliocentric orbit. Its sail was 196 m² and its mass 306 kg.

Following the loss of Cosmos 1, The Planetary Society re-evaluated their solar sailing program. By that time, small standardized spacecraft known as CubeSats had become popular with universities and other groups for flights in Earth orbit, in part because of their ability to piggyback on launches. But they had only just begun to be considered for interplanetary missions. Their small size limits the amount of ΔV capability using chemical propulsion. However, their low mass makes CubeSats conceptually ideal for solar sailing[4], where acceleration is proportional to the area of the sail divided by the mass of the spacecraft. NASA completed a successful orbital deployment test of a CubeSat sail with its 4 kg NanoSail D-2 spacecraft that had a 10 m² sail[5].

The LightSail® Program and Its Goals

These factors led The Planetary Society to develop the LightSail program. The program has been designed to demonstrate the use of solar sailing as a means to propel small CubeSat spacecraft.

The LightSail program goals include:

- Demonstrate controlled solar sail propulsion using a CubeSat platform
- Raise the public and technical profile of solar sailing
- Excite and engage the public
- Share the program results with future missions, the technical community, and the public

In addition, the program has been funded entirely by private donations. Over the last 10 years, more than 50,000 people from around the world have contributed to the LightSail program.

The LightSail spacecraft are 3U CubeSats with approximate dimensions of 10 cm x 10 cm x 30 cm. Each has a mass of 5 kg and carries a 32 m² sail. More details are given in later sections.

LightSail 1

LightSail 1 was flown as a test mission in 2015. Due to its low orbit where atmospheric drag would dominate over solar radiation pressure, LightSail 1 was intentionally limited to checkout of the CubeSat on-orbit operation, and validation of the solar sail deployment sequence.

LightSail 1 was 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 successfully deployed on June 7, 2015[6,7]. The mission ended upon re-entry on June 14, 2015.

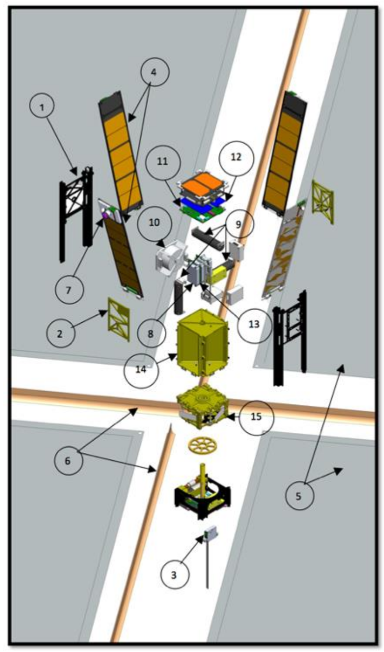
LIGHTSAIL 2 PRE-LAUNCH

Overview

LightSail 2, the focus of this paper, was designed to demonstrate controlled solar sailing in low-Earth orbit by modifying its orbit. 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[8]. 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 addition to incorporating and testing changes based upon lessons learned from LightSail 1, LightSail 2 also included a complete attitude determination and control system (ADCS)[9,10].

Spacecraft Summary

Here we provide a basic summary of the spacecraft design which is addressed more thoroughly in [6, 8, and 11]. The design of the LightSail 2 CubeSat is shown in Figure 1. Avionics are concentrated in the top 1U volume, and the solar sail assembly and deployment motor are located in the lower 2U volume.



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

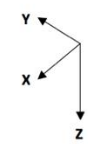


Figure 1. Exploded view of LightSail 2 CubeSat.

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 approximately a 155 degree angle with respect to the spacecraft for the duration of the mission.

The 32 m² solar sail consists of four triangular aluminized Mylar® sail sections 4.6 microns thick. Each sail section is attached to two adjacent 4-m Triangular Retractable And Collapsible (TRAC) booms 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 electrical power subsystem is composed of the solar arrays, batteries, power distribution, and fault protection circuitry. Both cameras are mounted at the ends of their respective solar panels

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 437.025 MHz for both uplink and downlink. Sun sensors are mounted at the tips of each deployable solar panel and magnetometers near each tip. Three-axis gyros are located in the avionics bay. A data beacon detailing the spacecraft's heath is transmitted every seven seconds and is supplemented by telemetry logs stored on the spacecraft and periodically downlinked.

The two LightSail cameras are 2-megapixel fish-eye color cameras built by 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. As images are taken, each 1600 x 1200 JPEG image is stored in camera memory along with a 120 x 90 pixel thumbnail.

Three magnetotorquers, one in each orthogonal axis, provide minor attitude adjustment using the Earth's magnetic field. A momentum wheel facilitates more rapid slews about one axis.

LightSail 2 is commanded from Cal Poly San Luis Obispo using stations there and at Purdue University and Georgia Tech University. An additional receive-only station is at Kauai Community College.

Integration and Launch

LightSail 2 launched hosted within the Georgia Tech spacecraft Prox-1[12] that was selected for flight by the University Nanosat Program of the U.S. Air Force. Prox-1 and LightSail 2 were part of the U.S. Department of Defense STP-2 (Space Test Program-2) payload. LightSail 2 was integrated into a P-POD (Poly Picosatellite Orbital Deployer), which was integrated into Prox-1 at the Air Force Research Laboratory (AFRL) in New Mexico. Prox-1 then shipped to Cape Canaveral and was integrated onto the Falcon Heavy rocket.

The STP-2 payload was launched June 25, 2019 placing Prox-1 and LightSail 2 into an approximately circular 720 km altitude orbit at 24° inclination.

LIGHTSAIL 2 MISSION OPERATIONS

LightSail 2 was deployed from the Prox-1 P-POD at 07:35 UTC on July 2, 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 working through checkout activities per the flight procedure. The recurring autonomous antenna deployment process was disabled, and a file listing was downlinked. The error in the spacecraft clock was determined, and an updated two-line element (TLE) orbit state was uplinked to the spacecraft. The spacecraft clock was then updated, which resulted in an expected spacecraft reboot. Detailed attitude determination and control system (ADCS) information was downlinked for assessment. Test images were acquired from each of the two cameras mounted on the solar panels. The attitude control mode was changed from Mode 0 (detumble) to Mode 1 (Z-axis alignment). Mode 1 aligns the longitudinal axis of the CubeSat with the Earth's magnetic field vector, which is a favorable attitude for communications. A functional checkout of the momentum wheel was successfully performed. The script-driven activity commanded the momentum wheel to wheel 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. The next two weeks were spent testing and updating the ADCS software to validate the pointing control capability that would be needed for solar sailing.

The LightSail 2 flight team successfully commanded solar sail deployment on July 23, 2019. At 18:46:11 UTC a command was sent to initiate the

Figure 2. LightSail 2 sail deployment image shortly before full deployment. Baja California is seen in the background. Image is uncorrected for fisheye lens distortion.

deployment of the four booms that pull out solar sail segments. At 18:49:55 UTC (11:49:55 AM PDT) the deployment motor reached the specified full deployment motor count limit. An image taken during the sail deployment sequence is shown in Figure 2.

SOLAR SAILING PERFORMANCE

The LightSail 2 sail control algorithm is designed to orient the sail edge-on to the Sun direction during the portion of the orbit when the orbit velocity vector is toward the Sun, and face-on when moving away from the Sun, as shown in Figure 3. The desired result of this strategy is to increase orbit apogee over time.

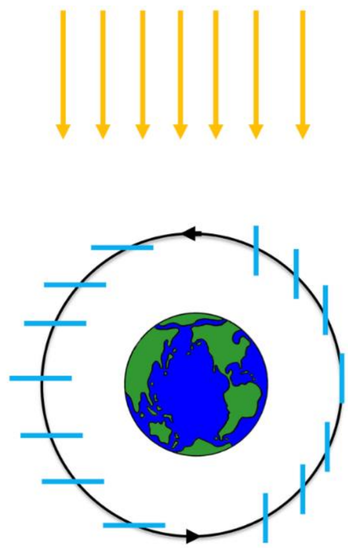


Figure 3. Illustration of LightSail 2 sail control strategy.

Sail control performance is reconstructed from the onboard attitude quaternions that are derived from magnetometer and Sun sensor measurements. An example of the reconstructed sail control performance from August 4, 2019 is shown in Figure 4. The desired angle between the spacecraft -Z axis and the Sun direction is indicated by the red line. It is seen that the sail control algorithm is effective in reorienting the sail twice per orbit through momentum wheel control. Daily angular momentum desaturation activities are required to maintain the momentum wheel within its maximum spin rate capacity.

The effects of the sail control strategy were apparent in the evolution of the LightSail 2 orbital state based upon two-line elements (TLEs) from the 18TH Space Control Squadron. Orbit apogee increased steadily following sail deployment and the initiation of sail control, and perigee altitude decreased as the orbit became more eccentric. The apogee and perigee histories for the first month after sail deployment are shown in Figure 5. Based upon the TLE data, The Planetary Society declared mission success for LightSail 2 on July 31, 2019.

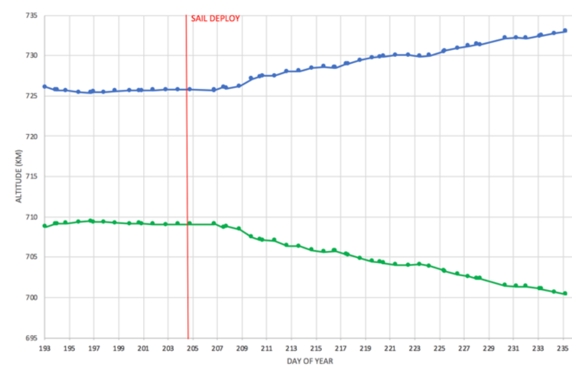


Figure 5. Apogee and perigee altitude history.

During the sailing-based orbit-change phase of the mission, the flight team is continuing to fine-tune solar sailing operations in an effort to improve the attitude control performance. Gain parameters have been updated on the proportional-derivative control algorithm used for sail control. The momentum management strategy has been updated, with a scheduled daily momentum wheel desaturation lasting two orbit periods. Long-term trending of sun sensor performance resulted in the passivation of one sun sensor.

As the orbit perigee decays, it will no longer be possible to raise orbit apogee through solar sailing. Possible extended mission objectives include the characterization of orbit decay rates with the sail controlled to be oriented edge-on and face-on to the aerodynamic flow direction. Imaging operations will

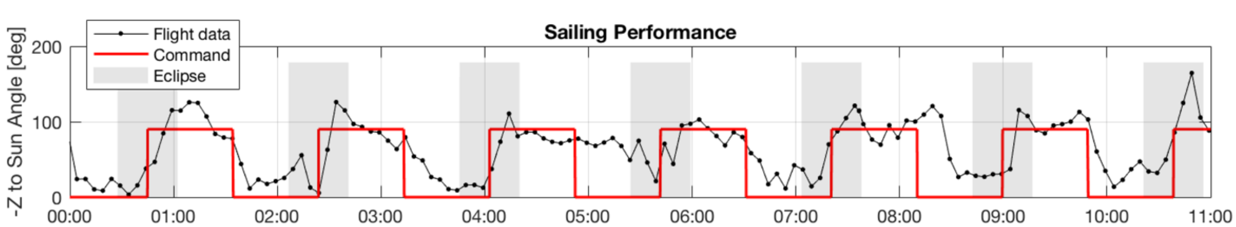


Figure 4. Example sail control performance from August 4, 2019 (UTC).

continue during the deorbit phase. It is anticipated that LightSail 2 will re-enter the Earth's atmosphere in mid-2020.

CONCLUSIONS AND FUTURE

LightSail 2 has achieved the goals established for the LightSail program. Through demonstrating controlled solar sailing, LightSail 2 has made a key contribution to the advancement of solar sailing technology[13].

The LightSail program raised the profile of solar sailing with the public as well as technical communities. In the process it has excited the public about space exploration.

Funded entirely by private donations, the LightSail CubeSats were truly the peoples' spacecraft. The program acted as a pathfinder for public funding of exciting, high risk technology/science missions. Through papers, presentations, and direct collaborations, the LightSail 2 team aims to share what we learn with future solar sailing missions, as well as with the broader community and the public.

ACKNOWLEDGMENTS

The authors would like to thank the donors and members of The Planetary Society, and the Kickstarter campaign contributors, who supported the LightSail program. Also, we are grateful for the crucial assistance of the University Nanosat Program, AFRL, the Prox-1 team, the U.S. Department of Defense Space Test Program, and the USAF 18TH Space Control Squadron. We also thank NASA's Near Earth Asteroid Scout team for informative discussions and long-term collaboration.

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