Status of the Dual CubeSat LightSail Program

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The LightSail program involves 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 is to demonstrate actual solar sailing in Earth orbit. It is on track for a launch in 2016 or 2017 as a key element of the Prox-1 mission.

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I. Introduction

The LightSail program is privately funded by members and donors of The Planetary Society, the world’s largest non-profit space-advocacy organization. A recent paper [1] includes a brief history of the solar sailing concept and the Society’s long-term interest in this novel space-propulsion technique. This paper provides an overview of the LightSail program, the mission and system designs for both missions, results of the first mission and associated lessons learned, and plans for the second mission.

II. LightSail Program Overview

Lou Friedman, co-founder of The Planetary Society (the Society, or TPS) and its long-time Executive Director, initiated the LightSail Program in 2009, undeterred by prior unsuccessful Society-led missions in 2001 and 2005 attempting to advance solar sailing technology. The increasingly popular 3U CubeSat design standard was baselined for the LightSail spacecraft, inspired by NASA’s successful integration (but unsuccessful launch) of a 3U CubeSat with a deorbit sail, NanoSail D1, in 2008 [2][3]. Stellar Exploration Inc. (then located in San Luis Obispo, California, and later Moffett Field, California) ultimately completed the development and assembly of two LightSail spacecraft (later named LightSail A and LightSail B) and by early 2012 had conducted various subsystem- and system-level tests on them, though more so on LightSail A than LightSail B [4]. Friedman retired in 2010; the same year Bill Nye (The Science Guy®) assumed the overall leadership role at the Society as CEO and is still serving in this position. He was assisted from 2012 through mid-2015 by LightSail Program Manager Doug Stetson (from Space Science and Exploration Consulting Group, Pasadena, California), a role since held by Bruce Betts at the Society.

The program slowed during 2012-2013 due to launch and programmatic uncertainties but had ramped up again by early 2014 (see [1] for details). By mid-2014, Ecliptic Enterprises Corporation (Pasadena, California) had been tapped as lead systems contractor for the program, focused primarily on leading the spacecraft integration and testing effort for both spacecraft. Ecliptic was supported initially by contractors Boreal Space (Hayward, California) and Half Band Technologies (San Luis Obispo, California); as of mid-2015 this support comes from Boreal Space and Aquila Space Systems (Moffett Field, California). California Polytechnic University San Luis Obispo (Cal Poly) provides additional integration and testing services and mission operations support; the Georgia Institute of Technology (Georgia Tech, in Atlanta) provides mission engineering and mission operations support as well as overall mission management.

III. Top-Level LightSail Mission and System Designs

Early mission analyses completed for the LightSail program suggested that a circular Earth orbit of ~800 km altitude would be ideal for demonstrating solar sailing with the 3U CubeSat design devised by Stellar Exploration. In early 2011 a launch opportunity for one of the LightSail spacecraft 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 [5]. NASA agreed to seek a mission opportunity close to the 800 km request, but by mid-2012 only two realistic opportunities had been identified, each going to only about half this altitude. Thus, both were unsuitable for demonstrating solar sailing. Each opportunity involved integrating the spacecraft into a standard 3U CubeSat carrier/deployer system developed years ago by Cal Poly known as the Poly Picosat Orbital Deployer (“P-POD”), and then integrating eight P-PODs into an Atlas 5-specific secondary payload carrier box assembly developed by the Naval Postgraduate School (Monterey, California) called the “NPS CuL”.

By mid-2013 an excellent candidate launch opportunity for the second LightSail spacecraft was identified with the promise of a higher orbit altitude: have it serve as a target for a new technology-demonstration mission called Prox-1, funded by the USAF University Nanosatellite Program and defined and managed by the Center for Space Systems at the Georgia Institute of Technology. Given the Prox-1 opportunity, both low-orbit opportunities for the first LightSail spacecraft now looked promising, because such a mission could still serve as a risk-reduction exercise, demonstrating the critical solar sail deployment system and validating the overall spacecraft design and functionality.

By late 2013, the LightSail program was resumed in earnest with a baseline plan to dedicate the first mission (LightSail A) to the ELaNa opportunity, with the principal objective of demonstrating the solar sail deployment system and overall spacecraft functionality. The second spacecraft (LightSail B) would ride to a higher orbit integrated with Prox-1, and would then be ejected and serve as Prox-1’s target for various proximity operations technology demonstrations before deploying its solar sail and conducting its own demonstration of solar sailing. Cal Poly would serve as the primary mission operations center for LightSail A with Georgia Tech as backup. For LightSail B the roles would reverse.
Orbit and drag analyses conducted for LightSail A suggested that once fully deployed its solar sail would act as a weak but effective aerobrake in the rarified low-orbit atmosphere, bringing the 3U CubeSat into a re-entry situation within a week or so of sail deployment. Furthermore, weak atmospheric torques on the sail system would essentially overpower the control authority of the spacecraft’s magnetic torquer/momentum wheel Attitude Determination and Control Subsystem (ADCS). The magnetic torquers were judged to be adequate for controlling spacecraft attitude before sail deployment, while the momentum wheel—only one, for manipulating LightSail’s long axis—was deemed overkill and unnecessary. So for LightSail A the wheel was dropped from the design.

LightSail-A’s mission, then, became one of demonstrating key mechanical and avionics functions during a relatively short (weeks) mission duration with effectively no attitude control capability after sail deployment, while LightSail-B’s mission depended on full spacecraft and ADCS functionality during a longer (few months) mission timeline. At the time of LightSail program restart in late 2013, these were the principal differences between the two missions and their spacecraft designs. Descriptions of the various spacecraft design features common to both vehicles follow, with other notable differences highlighted.

IV. LightSail Spacecraft Design Features

The overall LightSail architecture [4] (Fig. 1) is very similar to the NASA Marshall / NASA Ames NanoSail-D 3U CubeSat spacecraft architecture. Use of the CubeSat standard helped TPS achieve the program’s goals relatively quickly and cost-effectively. 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 into the increasing number of rideshare opportunities.

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

![Fig. 1 Overall LightSail architecture and size. (Four solar panels shown deployed; note axis convention.)](image)

The two main LightSail configurations are fully stowed and fully deployed, with two transitional configurations of stowed + RF antenna deployed and stowed + RF antenna deployed + solar panels deployed. The fully stowed configuration is the standard 3U CubeSat form factor as required for integration; releasing the RF antenna creates the first transitional configuration. Deploying the four solar panels produces the second transitional configuration, and deploying the solar sails produces the fully deployed state (Fig. 2).
The avionics section houses two processor boards, a radio, batteries, sensors and actuators, and associated harnessing. As discussed in the previous section, LightSail A utilizes only torque rods for attitude control, while LightSail B also includes a momentum wheel for changing sail orientations 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.

A. Mechanical Subsystem and Solar Sail

The various LightSail modules stack together into an integral 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 55 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 there at a 165-deg. angle with respect to the spacecraft for the duration of the mission. This gives the Sun sensors a cumulative hemispherical view as well as allowing roughly equal solar power generation whether the spacecraft points at the Sun or perpendicular to the Sun.

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 m² 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.) Fig. 3 shows LightSail A in a partially deployed state, with two solar panels fully deployed, two partially deployed and two bays with folded sail underneath.

Each sail section is attached to a 4-m Triangular Retractable And Collapsible (TRAC) boom made of eliglloy, 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 (akin to an ENABLE command) and then commands a prescribed number of motor counts to extend the sail sections to their desired positions (the DEPLOY command). Fully deployed, the square sail is about 8 m on the diagonal.
B. Power Subsystem

The power subsystem is composed of the solar arrays, batteries, power distribution, and fault protection circuitry. In full Sun, the four long solar panels generate a maximum 6 watts of power each with the 2 shorter panels providing 2 watts each. Solar power is routed through the main avionics board and charges a set of 8 lithium-polymer batteries providing power during eclipse periods. Each battery cell has its own charge monitoring/protection circuit and ties individually to the spacecraft bus (VBUS). 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 VBUS drops below Vbatt. Fig. 4 summarizes the various battery fault-protection mechanisms, which are more complex. Power analyses were conducted prior to the LightSail-A mission using the following modes: Detumble, Magnetic Pointing, Deploy Sail and Image, and Downlink. Depth of discharge values were analyzed for all modes, with a maximum (worst-case) of 15% in the Deploy Sail and Image mode.

C. 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. The cameras require an operating range from 0°C to 70°C. A heater is installed in series with a thermostat set to trip ON
if the camera temperature falls below 0°C. Flight Software turns OFF the camera if the operating temperature climbs above 70°C. Avionics board temperatures are relayed in beacon telemetry.

D. Avionics and RF Subsystem

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

Besides the temperature sensors mentioned above, the spacecraft also have Sun sensors at the tips of each deployable solar panel and magnetometers near each tip, and gyros measuring X-, Y- and Z-axis rates in the avionics bay.

The PIB design was changed from the original Stellar design once the LightSail-B concept for mission operations (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. For example, the torque control circuit was changed to PWM control to enable proportional control vs. simple ON/OFF (Bang-Bang) control, and other modifications were made to allow a PIC processor on the PIB to read the gyro data and close the loop with the torquers.

E. Flight Software

LightSail FSW (software and firmware) is written in the C programming language and is 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 LightSail application-level control processes that are supported by user space drivers built and integrated into the Intrepid architecture.

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.

Since LightSail has no method to upload code once on orbit, spacecraft command definitions were developed to maximize flexibility for a test mission within reason and schedule. For example, the FSW responds to commands to modify the primary ADCS execution rate, magnetometer data read timeout values, beacon rate and the reset of mission elapsed time, to name a few.

The FSW team reviewed the LightSail test mission objectives and CONOPS, and defined a set of telemetry that would yield key information and would fit in a small (~220-Byte) beacon packet data allocation. 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.

<table>
<thead>
<tr>
<th>Process</th>
<th>Functionality</th>
</tr>
</thead>
<tbody>
<tr>
<td>acs_process</td>
<td>Collect data from PIB over I2C and stage for inclusion in beacon packet.</td>
</tr>
<tr>
<td>deployment_process</td>
<td>Manage deployment sequence on PIB</td>
</tr>
<tr>
<td>beacon_process</td>
<td>Packages collected telemetry for downlink to ground station</td>
</tr>
<tr>
<td>camera_process</td>
<td>Camera monitoring, commanding and telemetry, take images during deployment and move to processor board memory</td>
</tr>
<tr>
<td>sc_state_process</td>
<td>Implements spacecraft autonomy via a state machine; initiates deployments, performs key time dependent sequences, restores state if reboot</td>
</tr>
</tbody>
</table>
### Table 2 PIB FSW control processes.

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

FSW development activities are facilitated by a test article known as BenchSat (Fig. 5), which comprises most of the hardware components of the LightSail flight system with a few exceptions. For example, BenchSat lacks a deployment mechanism akin to the actual LightSail motor/spindle, etc. Instead, 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). Other differences are captured in FSW test procedures so as to not cause confusion during qualification testing.

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 for verification of on-orbit procedures during mission operations.

![Fig. 5 BenchSat and how it fits in with the overall testing and operations activities.](image)

### F. Imaging Subsystem

The two LightSail cameras—dubbed Planetary Society Cameras, or PSCAMs—are 2-megapixel fish-eye color cameras licensed from the Aerospace Corporation, successfully used in their CubeSat mission series. Mounted on opposing solar panels (the +X 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 Fig. 6.

Though the cameras have several operating modes and settings to choose from, for LightSail A 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 they are taken, each JPEG image is stored in camera memory along with a 160 x 120 pixel thumbnail of each image. Later, each image is then selectively moved by command to the memory in the Intrepid board for subsequent downlink to the ground, also by command.
G. Attitude Determination and Control Subsystem

The ADCS monitors and controls LightSail 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 deemed 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 LightSail ADCS. The ADCS hardware was sized for significantly varying moments of inertia (for the stowed and deployed configurations). Based on ADCS simulations conducted during 2014, a decision was made to modify the torquer control method to allow for proportional control vs. simple ON/OFF (Bang-Bang) control, deemed to be too abrupt in the stowed configuration. Proportional control was judged to be essential for fine attitude control during the planned LightSail-B solar sailing demonstration phase.

<table>
<thead>
<tr>
<th>Component</th>
<th>Number</th>
<th>Vendor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun Sensors</td>
<td>4</td>
<td>Elmos</td>
</tr>
<tr>
<td>Gyros</td>
<td>3</td>
<td>Analog Devices</td>
</tr>
<tr>
<td>Magnetometers</td>
<td>4</td>
<td>Honeywell</td>
</tr>
<tr>
<td>Torque Rods</td>
<td>3</td>
<td>Strass Space</td>
</tr>
<tr>
<td>Momentum Wheel</td>
<td>1*</td>
<td>Sinclair Interplanetary</td>
</tr>
</tbody>
</table>

* LightSail-B only

ADCS modeling and simulation results for LightSail-A highlight the expected performance (see Fig. 7). 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 Fig. 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 becomes fairly stable and detumbles in about ¼ orbit (stowed). When 60 orbits were simulated the final settled rates are all less than 1.2%. Z-axis alignment eventually converges to about 20°.
Two ACS modes were implemented for LightSail-A. 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. But the 2 Hz mode would tend to induce resonances with the sail deployed, so 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>
<thead>
<tr>
<th>Loop Number</th>
<th>Time (sec)</th>
<th>Control and Actuation Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-1</td>
<td>Bang-Bang B-Dot</td>
</tr>
<tr>
<td>2</td>
<td>1-2</td>
<td>OFF</td>
</tr>
<tr>
<td>3</td>
<td>2-3</td>
<td>Bang-Bang B-Dot</td>
</tr>
<tr>
<td>4</td>
<td>3-4</td>
<td>+Z axis ON only</td>
</tr>
</tbody>
</table>

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 Fig. 8). The input shaping strategy is intended to result in zero vibration for a single-DOF damped system after N impulses [6], [7].

![Fig. 8 Effect of input shaper on torque rod command.](image)

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The LightSail-B mission includes a momentum wheel to facilitate the required ~90-deg. solar-sail slewing twice per orbit for changing orbit parameters (e.g., energy, eccentricity, apogee, etc.), per an ADCS concept articulated in 1999 [8]. A preliminary simulation model for these operations has been developed and is shown in Fig. 9.

![Simulink model for LightSail-B orbital parameter change.](image)

**Fig. 9** Simulink model for LightSail-B orbital parameter change.

### V. Mission Objectives for LightSail A and LightSail B

The LightSail mission designs were tailored to deal with the orbits handed to them as dictated by the primary payloads’ orbit requirements. The mission team strived to make the best of a possibly non-ideal situation.

#### A. LightSail-A Mission

LightSail-A’s baseline orbit was definitely not ideal for demonstrating solar sailing. From mid-2013 through early 2014, NASA’s ELaNa program carried two Atlas 5 launch opportunities for LightSail A, both targeted for placing classified primary payloads into elliptical low-Earth orbits with relatively low perigees and mid-latitude inclinations. The fully integrated NPS CuL systems (each with eight P-PODs inside) planned for these missions were named GRACE and ULTRASat, respectively. Being classified launches, the exact orbit parameters, launch dates and launch times were not divulged to the LightSail team, though estimates usable for mission planning were.

It was known over a year before launch that the orbit perigees would be so low that LightSail-A attitude control would be problematic after solar sail deployment (due to atmospheric effects), and that solar sailing simply would not be possible (atmospheric effects >> solar sailing thrust). This consideration was the principal reason that the LightSail-A mission was baselined as a tech-demo mission, regardless of which launch opportunity solidified. Because of a slightly higher perigee, the GRACE opportunity was favored over ULTRASat.

With this reality in mind, the momentum wheel originally designed into both spacecraft for facilitating solar sail tacking was removed from LightSail A and replaced with a mass model. And, a set of prototype MEMS accelerometers baselined for both spacecraft were also removed from both because they were deemed non-critical for meeting the primary mission objectives. All other subsystem elements, to first order, were the same between the two spacecraft (not considering yet lessons learned from the LightSail-A mission, which eventually led to some design changes, as discussed later in this paper).

Key features of the baseline LightSail-A mission sequence included:
- Ride unpowered to orbit inside a NPS CuL 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 ADCS subsystem and onboard cameras
- Deploy solar panels
- Deploy solar sails while imaging entire sequence
- Downlink images; assess deployed sail characteristics
- Assess overall spacecraft status
- Conduct extended mission objectives (if possible)
- Re-entry

The baseline mission plan called for all mission events leading up to sail deployment except the ADCS and camera checkouts to be on a 28-day timer following the initial power-ON event. With sails deployed, predictions were that the spacecraft would re-enter and burn up within 3 to 10 days. Thus, the LightSail-A mission was projected to last for approximately 31 to 38 days after ejection from the P-POD.

B. LightSail-B Mission

The orbit for LightSail B will allow for a full-up 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 ESPA ring port; the ESPA ring, in turn, is part of a cluster of payloads scheduled for a 2016 USAF-sponsored Falcon Heavy launch from Florida—the first planned operational Falcon Heavy launch following one test launch planned for a few months before.

A depiction of the Prox-1 spacecraft and its LightSail-B companion and the Prox-1/LightSail-B mission design is summarized in Fig. 10. Key mission events include:

- Ride unpowered to orbit inside the Prox-1 P-POD
- Remain inert inside P-POD ~1 week during Prox-1 initial mission ops
- Eject from P-POD; Prox-1 follows for ~2 weeks
- 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
- Wait for Prox-1 approach and rendezvous (~1 week)
- Serve as target for Prox-1 proximity operations for ~1 week, after which Prox-1 conducts stand-off observations of LightSail-A deployments
- Test ADCS subsystem and onboard cameras
- Deploy solar panels
- Deploy solar sails while imaging entire sequence
- Downlink images; assess deployed sail characteristics; Prox-1 attempts to follow
- Assess overall spacecraft status
- Go separate way from Prox-1; begin solar sailing demo (~3-5 months?)
- Conduct extended mission objectives (if possible)
- Re-entry

The joint Prox-1/LightSail-B mission sequence is expected to last ~6 weeks from P-POD ejection. The LightSail B-only portion of the mission, during which the solar sailing demonstration will occur, is expected to last 3-6 months—or more if spacecraft health supports extended mission operations.

![Fig. 10 LightSail-B shortly after ejection from Prox-1 (l) and Baseline LightSail-B mission plan in conjunction with the Prox-1 mission (r).](image-url)
VI. Highlights of LightSail-A Integration and Testing

Starting with both spacecraft in storage cases since mid-2012, the LightSail-A integration and testing effort got started in earnest fall of 2013. Many details about the steps taken by the team—and technical issues addressed—to ready the spacecraft for launch during the subsequent year and a half are included in [1].

During the last few months of 2013 the engineering team at Stellar completed spacecraft de-integration, modification and re-integration and selected testing of LightSail A (and to a lesser extent LightSail B), 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 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, and during this period most of the day-to-day activities were shifted from the Stellar team to the Ecliptic team. The launch opportunity was also pinned down during this timeframe: LightSail A would ride with ULTRASat on an Atlas 5 in early 2015.

With a launch date a year away, the team focused their efforts during the rest of 2014 solely on LightSail A. Many tweaks to hardware and FSW were completed, numerous component-, subsystem- and system-level tests (see Fig. 11) were conducted and re-conducted, and final launch integration paperwork and mission-related licenses were secured (see [1]). Final launch approval was granted in early December, 2014. By this time, the scheduled launch date had slipped to early May, 2015. LightSail-A launch integration (Fig. 12) was completed in January, 2015. The final mass of LightSail A came in at 4.93 kg—within the maximum allowed 5.0 kg. The ULTRASat payload arrived at the launch site in Florida in early March.

![Fig. 11  LightSail A after a successful deployment test (with sail edges manually stretched to straight).](image1)

![Fig. 12  LightSail A integration into the P-POD (l) and ULTRASat fully loaded with P-PODs (r).](image2)
VII. LightSail-A Mission

With mission plans and expected orbit details becoming clearer, a series of mission ORTs were conducted during March and April, 2015. Both ORTs were in general quite successful. The principal surprise was that an error in the FSW was revealed which essentially locked up the ADCS control routines after 4 sec of their starting—after a reboot, say. (The error was attributed later to a coding error in a single line of code, and was not correctable because the FSW configuration had been locked down months before, and FSW patches during actual 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.

A. Launch and Initial Mission Operations

The Atlas 5 launch with ULTRASat aboard occurred on May 20, inserting the primary payload—the X-37B spaceplane—into the desired elliptical orbit (as it turns out, 356 km x 705 km and 55° inclination) [9]. LightSat A—in the last of the eight ULTRASat P-PODs to be actuated—was ejected into its own orbit two hours after launch.

Telemetry data from LightSat A, in the form of several small data packets—“beacon packets,” each with ~220 Bytes of useful engineering data chirped out of the radio 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. This quick success confirmed that the RF antenna deployment event occurred as sequenced.

The telemetry data indicated that the ADCS routines had hung as expected; but the useful snapshot of ADCS parameters was also captured as expected. 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 DEPLOYED, and, more unexpectedly, that the gyros were left ON by the event sequencer.

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-A vibration tests.) The gyro issue was a simple coding error that was not caught during testing or the ORTs, and will be corrected on LightSail B.

Nine successful tracking passes were completed during the first 24 hours of the mission, including one about 12 hours into the mission that successfully established commanding to the spacecraft from Cal Poly (to turn the gyros OFF to reduce battery drain during eclipse periods), confirming additional spacecraft functionality.

During the first 48 hours of the mission over 140 useful beacon packets were received, and the operations team was gearing up for some planned initial checkout activities to be scheduled at the Mission Director’s discretion before the onboard 28-day timer would time out and deploy the solar panels and solar sail. But on the morning of May 22 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.

Chris Biddy, the principal designer of LightSail’s solar sail system while at Stellar, and now CEO of startup Aquila Space Systems (Moffett Field, California), had notified the team a month before that during some testing at Aquila of a newer version of Tyvak’s Intrepid software development kit he had discovered that there was a likely quirk in LightSail’s version that could cause the board to crash when more than ~32 MB of data had been written to the beacon.csv file. Alex Diaz on the LightSail team contacted Biddy, got a test program from him, ran it on BenchSat and in a few hours confirmed Biddy’s suspicion. LightSail’s Linux system was likely to crash—and soon.

The board did indeed crash, 55 hours after launch—just before the next planned pass, when the operations team was going to try uplinking a command sequence to delete the then-active beacon.csv file with the expectation that this might head off the crash. (Later testing revealed that write volume and not file size caused the system errors; deleting the file would not have had an effect.) LightSat A fell completely silent for days, in spite of the operations team commanding dozens of 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 LightSat A.)

After consulting with other CubeSat operators familiar with the class of avionics on LightSail, it was generally agreed that the only hope for LightSat was for the Intrepid board to spontaneously reboot following a random cosmic ray-induced charged particle impact. Most of these operators had seen this happen to their own CubeSats every 3 to 6 weeks.

The team didn’t have to wait that long: LightSat A rebooted and started sending telemetry again eight days later, on May 30.
With a refined view of what had happened, during and after the 8-day outage the operations team implemented a new protocol to head off any more Intrepid board crashes and stay on top—if not ahead of—the mission plan:

- Automated scripts were prepared to reboot the Intrepid board at least once a day, which warded off the beacon.csv file I/O issue
- With the beacon.csv bug traced to an I/O issue and not a file-size issue, a patch was prepared and tested on BenchSat to modify the Intrepid FSW to write the beacon.csv file to another memory location, and BenchSat was used to probe other aspects of FSW behavior
- After the re-contact, fresh gyro data indicated that the worst-case rate (about X) had increased ~50%, and the rates about the other two axes were increasing too, so planning began for manually deploying 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 A, which was still not completely understood, nor was it clear which of the various CubeSats ejected from ULTRASat was LightSail A

On May 31, solar sail deployment was targeted for June 1, to be preceded by uplinking of the FSW patch for the Intrepid board (which required a successful two-way SSH connection between the Cal Poly ground-station computer and LightSail A, expected to be problematic with the spacecraft in orbit vs. the lab); taking a test image with the onboard cameras, downlinking the image and verifying camera functionality; and deploying the solar panels to free up the sail bays.

Attempts to establish the SSH connection during passes on May 31 were unsuccessful, so this plan was dropped in favor of diligent FSW rebooting, which was working well. Commands tasking each camera to snap a test image were also successfully sent on May 31, so panel and sail deployments were tentatively scheduled for June 2.

It took well into June 2 until only one of two test images had been fully downlinked, requiring most of the prime time during several good tracking passes (Fig. 13). This excellent image confirmed that at least the camera that took it was working fine, and so was the rest of the spacecraft, so there was strong support for going ahead with the deployments—and soon.

![Fig. 13 Results of test image in orbit (r) as compared to one take from a lab-based system-level test (l). The PCAM view is from inside the spacecraft as indicated by the yellow oval in the side view above. The hint of sunlight penetration in the on-orbit image confirmed suspicions that the solar panels had jiggled loose slightly during the launch and/or P-POD deployment phase.](image)
B. Solar Panel Deployment

By June 2 it was clear that stepping through the mission sequence was taking longer than expected, and it was also obvious that the spacecraft was not operating with full capabilities due to the FSW bug and lack of ADCS control. Plus, by this time Georgia Tech had still not been able to successfully command LightSail A, so Cal Poly was the sole commanding site.

After considerable discussion among the LightSail team and with Biddy at Aquila, it was decided to separate the solar panel deployment event from the sail deployment sequence with a 2-day gap, to allow for some post-panel-separation assessments and very thorough sail deploy preparations. (These two events were separated by mere minutes in the timed sequence to preclude untoward sail ‘blooming’ after the panels uncovered the sail bays.) Panel deployment was slipped a day to June 3, and sail deployment was rescheduled into June 5.

With the regular FSW reboots, gyro rate updates were coming in at a good pace (Fig. 14), and had leveled out at ~2x the original tip-off rates—still within the worst-case assumptions. Panel deployment commands were sent early in the morning Cal Poly time on June 3, and subsequent beacon packets indicated successful deployment from gyro rate data (the RSS spiked briefly and then dropped by 50%), solar panel temperatures (colder) and Sun sensor data (varied vs. similar readings). So the operations team was buoyed by the prospect of sail deployment on June 5.

But just a few hours after panel deployment another big issue intervened and derailed this plan. Telemetry indicated that all eight batteries were close to their nominal charge levels but off-line, i.e., 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 considered to be doubtful that 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 until the situation was under control.

During the first good pass on June 4 (after a 10-hour gap of no usable passes) and for ten more passes that day, LightSail A was silent. There was no telemetry, and the reboot commands were not working. The operations team pored over a chart created by Diaz (Fig. 4) which captured the rather complex battery fault-protection mechanisms, suspecting that LightSail-A’s power subsystem had fallen into that chart somewhere. The team discussed commanding the spacecraft in the blind to turn components ON or OFF to force the loads on the bus one way or the other, but did not have enough insight to make a crisp decision. So nothing was done—except working up a plan for what to do if the spacecraft came alive again.

After a 3-day hiatus, LightSail A started transmitting beacon packets again over Cal Poly the morning of June 6, a Saturday. Over the course of two good passes, 23 packets were received.

A rapid sail deployment was briefly considered—pre-tested procedures were ready—but with battery levels still unsteady, or at least not quite understood, and with just one good pass remaining on June 6 before an 8-hour outage, the team scrapped the idea. During that last pass of the day, telemetry showed that the batteries were charging—the first time since solar panel deployment three days before.

By late June 6, after much discussion and analysis of the relatively meager available data, the team had converged to the likely reason the batteries had tripped into a safe mode-like condition following solar panel deployment. It appeared very likely that the spacecraft was stuck in a loop where power levels were too low during eclipse periods, but too high during sunlit periods. This power ping-ponging was likely preventing the batteries from re-attaching their circuits to the spacecraft and allowing normal operations to resume.

Late on June 6 it was decided that if beacon data from Sunday’s early 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 (one excellent, one not very good at all) serving as backups.

There was another reason for pressing all-out with sail deployment: gyro rates were at over 20 °/s and rapidly increasing by almost 6 °/s per day (Fig. 14). By Sunday morning they would be triple what they were just days before. And the dominate spin was now about the long Z axis. LightSail A was becoming a spinning dart.

### C. Solar Sail Deployment

Telemetry from the first good Sunday morning (June 7) pass looked good across the board, so the team elected to go for sail deployment during the first good late morning pass over Cal Poly. As expected, the spin rate had climbed overnight to over 30 °/s, so there was no time to lose.

The final versions of the command sequences required to initiate the sail deployment (including imaging) had been double-checked on BenchSat and were ready to go, as were several short command bursts required to configure the spacecraft into the most ideal state for deployment. Essentially, the sail deploy sequence involved getting separate ENABLE and DEPLOY commands into the spacecraft in series, with a built-in pause between the two to allow for human confirmation that the ENABLE command got in before sending the DEPLOY command.

On the primary deploy pass Sunday morning over Cal Poly spacecraft health looked great so the precursor commands were uplinked quickly and promptly confirmed. The ENABLE command was then sent, but confirmation could not be made, so the DEPLOY command was not sent. It was suspected that the spin rate was causing spurious communications, though this was just a hunch and could not be confirmed.

For the next Cal Poly pass 90 min. later, an excellent pass, it was decided to try the sequence again by sending both commands back-to-back whether the ENABLE was confirmed or not, since there was no harm if only one or the other command got in. This time, one of the two got in, but the operations team could not tell which one. It didn’t matter, because the sails remained stowed.

The last Cal Poly pass of the day was a very poor one—only 12° above the horizon to the west, and only about 10-minutes long. Start to finish, the actual sail deployment sequence took about 2.5 minutes. Controllers at Cal Poly sized up spacecraft health (good) and sent and confirmed all other configuration commands in about 5 minutes. The ENABLE command was sent and confirmed. After a very brief team discussion lasting a minute or so and an off-net discussion for another minute between LightSail Program Manager Stetson and Mission Director Spencer, it was decided to send the DEPLOY command with about two minutes left in the pass, knowing that if the sail started deploying the team would only see part of the sequence via telemetry.

The DEPLOY command was sent and got in, and the sail motor started driving (Fig. 15). A bit over two minutes of motor count telemetry showed that the sails were coming out—or at least that the motor was operating. And then the pass ended. TPS CEO Bill Nye later dubbed this pass the “Sail Mary Pass.”
Fig. 15 A key two minutes of sail deployment motor count telemetry.

D. Sail Imaging

Telemetry from the Monday morning (June 8) passes gave all indications that the sails were fully deployed, or nearly so. The gyro rates dropped to nearly zero (Fig. 14), and all other subsystems looked nominal.

The team spent all other passes on June 8 stepping through the command sequences to downlink the stored PSCAM deployment images off the camera memories and into the Intrepid board’s memory, and then downlink one full image to the ground to hopefully see the fully deployed sail—half, actually, since each PSCAM covered half of the total sail area.

By the end of the day, indications were that all of the images were either corrupted or otherwise undecodable into recognizable images: they were all essentially gray (see upper frame, Fig. 16). After much discussion among the team and with PSCAM designers at the Aerospace Corporation (El Segundo, California), the tough decision was made to delete all of the original deployment image files, reshoot an entire image sequence from each PSCAM and run through the process again. This worked, and by the end of the day recognizable portions started coming down (lower pair of frames in Fig. 16).

Everyone wanted to see a full, unambiguous image of the deployed sail, but this had to wait until the morning passes of Tuesday, June 9. Bits and pieces started coming in during the morning passes, and by early afternoon the entire image was reconstructed (Fig. 17). It was disseminated globally by TPS and social media outlets shortly after.

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

Based on this single image—the only complete image downlinked from LightSail A, as it turns out—it was surmised by the project, Biddy at Aquila and solar sail experts at NASA that the sails were most likely 90-95% fully deployed.

On June 10 the team worked to downlink an image similar to the first from the other PSCAM, and managed to get a partial reconstruction with a hint of the Earth in the background. The team also considered sending a command sequence to nudge the sail booms out slightly in an attempt to tighten up the sails, but in the end this was deemed unnecessary.

And in case there was any doubt about this boom-nudging decision, LightSail A made the final call anyway: on June 11 all communications ceased—telemetry and commanding—when the radio entered a perplexing mode of continuously radiating noise, from which it never exited no matter what its controllers tried. As of this writing root-cause analysis on this anomaly continues, with something amiss in the Intrepid board and/or FSW as the leading suspect. Diagnostic testing continues.
Fig. 16  Progression of first images of the deployed sail.

Fig. 17  Full image of deployed sail.
E. Atmospheric Entry

As predicted by analyses completed years before, it didn’t take LightSail A long to re-enter, given its low orbit perigee and large area-to-mass ratio. It burned up off the east coast of Argentina over the Falkland Islands the morning of June 14.

VIII. Planning for the LightSail-B Mission

The 25-day LightSail-A mission occurred between May 20 and June 14, 2015, with total mission success declared on June 9. Much has been learned from this mission that will be fed into planning for the LightSail-B mission. TPS is committed to disseminating the detailed mission results and analyses once available.

The LightSail team learned in March 2014 that the Prox-1 launch date, tied to not only SpaceX’s Falcon Heavy development schedule but also scheduled for after the first Falcon Heavy test launch, would likely slip from mid-2015 to sometime in 2016. In March 2015 this did occur, and then on June 28 the first Falcon 9 launch failure occurred, impacting the backlog of Falcon 9 launches and SpaceX’s Falcon Heavy plans. As of this writing the expected launch date is still mid-2016, suggesting a LightSail-B ship date of early December 2015. This is the date the team is working toward (as of early August, 2015).

Serious planning for the LightSail B mission started with a thorough review and discussion of mission objectives held at The Planetary Society’s Pasadena offices in December, 2014, two days after LightSail A was cleared for launch on ULTRASat. A similar LightSail-B planning meeting was held in July, 2015, four weeks after the LightSail-A mission ended.

The LightSail-A development effort and mission operations were anything but smooth, and many useful design insights and operational lessons were learned along the way—much more so that if everything had gone smoothly. All of this experience informs the LightSail team’s planning for LightSail B, which is focused on improving the LightSail-B spacecraft design and related operations procedures and techniques to ensure that the significantly more demanding mission objectives can be attempted with confidence and robustness—and with plenty of pre-launch testing underpinning the effort. Several relatively easy design fixes and related tests for LightSail B are already in work, and others are still in planning stages:

- The most current Tyvak Intrepid board (version 8) will be used, eliminating some known timing and memory-use bugs
- An extra BenchSat will be built to allow for additional FSW development and related testing
- FSW coding errors found after the code had been frozen are being corrected
- Some 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 fixed
- Various software-driven watchdog timers will be enabled
- Many commands used only during testing for LightSail A will be enabled for use during mission operations for LightSail B
- 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 may be slightly modified to preclude false indications
- Because the ADCS functionality was not operational during the LightSail-A mission and is essential for the LightSail-B mission—including more functionality—a considerable analysis, FSW re-design and simulation activity will be conducted for this subsystem
- The PIB design will be slightly modified to improve its interfaces with other elements of the spacecraft
- PSCAM 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
- Consider modifying the design and/or placement of laser reflectors to enhance the likelihood of laser ranging
- The entire subsystem- and system-level test plan will be reassessed, and more and longer testing in selected areas will be baselined
- Telemetry and status displays and related data archiving will be improved to better support testing and mission operations
- The Georgia Tech mission control center will be upgraded for its prime status during the LightSail-B mission
IX. Conclusion

The LightSail program seeks to advance the state of the art in solar sailing technology by demonstrating that a sail of useful size can be deployed and operated from the popular 3U CubeSat platform. The LightSail-A mission successfully demonstrated the sail-deployment sequence and, in spite of a series of challenging hardware, software and operational issues, gave the LightSail team confidence that the 3U platform is up to the task of supporting a full-up solar sailing demonstration in Earth orbit in the near future. This pair of missions should lay useful groundwork for other CubeSat-based solar sail missions (3U and 6U) which are well into their development phase, and should also inspire many other missions not yet conceived.

Acknowledgments

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—not easy. NASA and the USAF essentially enabled the restart of the program by securing firm launch opportunities for LightSail A and LightSail B, respectively.

Staff and students at Cal Poly, Tyvak and SRI provided essential support during the LightSail-A integration and testing effort, during several mission ORTs and on console during mission operations. Helping everyone to understand what was happening with LightSail A 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), who tried diligently to bounce lasers off LightSail A to help improve the orbit knowledge, but were ultimately unsuccessful.

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-A mission.

Finally, a big thanks to the ~40,000 members of The Planetary Society and—setting a new record for the most popular space-themed campaign ever—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. These missions are their missions.

References


