LightSail Program Status: One Down, One to Go

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ABSTRACT
The LightSail program involves two 3U CubeSats designed to advance solar sailing technology state of the art. The entire program is privately funded by members and supporters of The Planetary Society, the world’s largest non-profit space advocacy organization. Spacecraft design started in 2009; by the end of 2011 both spacecraft had largely been built but not fully tested, and neither had a firm launch commitment. Following an 18-month program pause during 2012-2013, the effort was resumed after launch opportunities had been secured for each spacecraft. The first LightSail spacecraft—dedicated primarily to demonstrating the solar sail deployment process—was launched into Earth orbit on 2015 May 20 as a secondary payload aboard an Atlas 5 rocket, and on June 9 mission success was declared. The mission plan for the second LightSail includes demonstration of solar sailing in Earth orbit, among other objectives. It is on track for a launch in 2016 aboard a Falcon Heavy rocket as a key element of the Prox-1 mission. Lessons learned from the 2015 test mission will be applied to the 2016 mission, and lessons from both LightSail missions will inform planned NASA solar sail-based CubeSat missions and hopefully enhance their chances for mission success.

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

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

In the 1860s Maxwell’s equations showed that light had momentum, providing a theoretical underpinning to the concept. In 1865 Jules Verne incorporated the concept in From the Earth to the Moon—perhaps the first published mention of light pushing a spacecraft through space. Further theoretical and lab-based experimental work bolstered the concept from the late 1890s through late 1920s, and for the next several decades the concept was occasionally addressed by researchers and science fiction authors.
The first detailed solar sail technology and mission-design effort was led by Louis Friedman at JPL starting in 1976 for a proposed 1985-86 Halley’s Comet rendezvous mission. The mission concept was promoted publicly by astronomer/planetary scientist and Friedman colleague Carl Sagan, but ultimately the mission was not funded by NASA³.

In 1980 Sagan, Friedman and then-JPL Director Bruce Murray formed a non-profit space advocacy organization “to inspire the people of Earth to explore other worlds, understand our own, and seek life elsewhere.” The Planetary Society (TPS) is now the largest such group in the world with over 40,000 active members, and among other key objectives strives “to empower the world's citizens to advance space science and exploration.⁴”

In the early 2000s, led by Executive Director Friedman, TPS developed the Cosmos-1 solar sailing demonstration mission (Fig. 1) with primary funding from Cosmos Studios, a production company formed by Sagan’s widow Ann Druyan after his passing in 1996. The spacecraft was designed, built and tested by the Babakin Science and Research Space Centre in Moscow, and was intended for launch by a submarine-launched Volna rocket. A precursor in-space test of a 2-sail solar sail deployment system (vs. 8 sails for the full-up Cosmos-1 design) ended in failure in 2001 when the Volna’s upper stage did not separate from its first stage⁵. Another attempt at a full-up Cosmos-1 mission in 2005 also failed when another Volna rocket’s first stage underperformed, dropping the spacecraft into the Arctic sea.

Figure 1. Cosmos-1 spacecraft during final testing (l) and as envisioned in orbit (r)

LIGHTSAIL PROGRAM

Undeterred by the Cosmos-1 mission failures, in 2009 Friedman initiated another TPS member-funded attempt at a solar sailing demo mission—actually three separate proposed missions, LightSail-1, LightSail-2 and LightSail-3—this time employing the increasingly popular 3U CubeSat design standard.

In late 2008 TPS had discussed using NASA’s backup 3U CubeSat NanoSail-D2 as the first LightSail demo mission following the failed SpaceX Falcon 1 launch of NanoSail-D1 in summer 2008, but Friedman opted instead to develop a more capable solar sail system. (NanoSail-D’s sail system was designed for generating atmospheric drag, not solar sailing.) NASA eventually launched NanoSail-D2 in late 2010, and after some hiccups the mission was ultimately deemed a success in late January 2011⁶,⁷.

Friedman’s original LightSail program plan (mid-2009) baselined the LightSail-1 mission as the first ever to demonstrate solar sailing in Earth orbit, and this spacecraft was projected to be launch-ready by the end of 2010. The LightSail-2 mission would demonstrate an Earth-escape mission profile, while the LightSail-3 craft would “… take us on a mission for which a solar sail spacecraft is uniquely suited: creating a solar weather monitor to provide early warning of solar storms that could affect Earth.” (NASA’s Sunjammer mission concept, canceled in 2014 after a years-long development effort before a targeted 2015 launch, addressed the LightSail-3 primary mission objective with a 37x larger solar sail area.)

In 2009 TPS tapped Stellar Exploration Inc. (then located in San Luis Obispo, California, and later Moffett Field, California) for the LightSail spacecraft design and construction effort. For several reasons, the scope of the effort was scaled back first from three spacecraft to one, and eventually back up to two. By the end of 2011 Stellar had largely completed the development and assembly of both LightSail 3U CubeSat spacecraft (later named LightSail A and LightSail B) and had conducted various subsystem- and system-level tests on them, though more so on LightSail A than LightSail B⁸.

Meanwhile, in May 2010 the Japanese space agency JAXA launched a mission to Venus with a secondary payload called IKAROS (Interplanetary Kite-craft Accelerated by Radiation Of the Sun), a dedicated solar sail demonstration spacecraft. Three weeks after launch IKAROS was successfully separated from its piggyback ride and became the first-ever solar sailing demonstrator. The project’s very successful primary mission continued through most of 2010, and even today its mission controllers establish intermittent communications⁹. Solar sailing missions feature prominently in JAXA’s long-range plans for solar system exploration.

In September 2010, long-time TPS member and then-TPS Vice-President Bill Nye (The Science Guy®, Fig. 2) became the society’s Executive Director following
the retirement of Friedman. In February 2011 a launch opportunity for one of the LightSails 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\textsuperscript{10}. TPS had requested a minimum orbit altitude of 800 km to enable the solar sailing demonstration, and NASA agreed to seek such an opportunity.

Figure 2. Bill Nye with a full-scale engineering-model mockup of the LightSail 3U CubeSat developed by Stellar Exploration, Inc. (Solar sails are not installed.)

Stellar continued to make progress testing the spacecraft (mostly LightSail A) and managed to get it through several sail deployment tests and an approximation of a mission-sequence test. But in May 2012 for a variety of programmatic reasons, including the lack of firm near-term launch opportunity to 800 km (NASA had only identified two other opportunities going to half this altitude, and thus unsuitable for solar sailing), Nye put a pause on the LightSail effort and both spacecraft were placed in storage.

TPS actually investigated selling the two LightSail craft to another interested company or organization, giving them to a NASA center to support R&D and training efforts, and even donating them to a museum.

TPS member interest in the program remained high, however, so in August 2012 the society assembled a panel of experienced space technologists and space-mission managers to assess and review the program and make recommendations about whether the program should be resumed. This panel, led by Northrop Grumman Space Technology President and TPS Board member Alexis Livanos, advised to restart the effort, given certain assumptions and constraints\textsuperscript{11}.

During the following twelve months, several promising factors buoyed confidence in the restart recommendation\textsuperscript{11}:

- 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 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 launch opportunities identified by NASA to the lower orbits now looked promising, because such a mission could still serve as a risk-reduction exercise, demonstrating the critical solar sail deployment system (much like the first attempted Cosmos-1 demo mission) and validating the overall spacecraft design and functionality
- A new CubeSat-focused space-technology firm had been formed in collaboration with California Polytechnic University, San Luis Obispo (Cal Poly), Tyvak Nanosatellite Systems, which had licensed and improved several key Cal Poly subsystems incorporated into the LightSail spacecraft design
- Interest in employing CubeSats for deep-space and planetary missions was rising, especially at NASA
- Support for LightSail by members and donors of TPS continued to be strong, in spite of the program pause

During this period, a new program management team was identified. The overall LightSail Program Manager for TPS would be independent consultant Doug Stetson, an experienced ex-JPL mission designer, advanced technology planner and planetary program analyst. The overall LightSail Mission Director would be Georgia Tech Professor of the Practice Dave Spencer, an ex-JPL Mars mission manager and mission engineer, Director of Georgia Tech’s Center for Space Systems and Principal Investigator and Mission Manager for Prox-1.

Extensive meetings during the summer of 2013 involving Stetson, Spencer and TPS as well as Stellar, Cal Poly, NASA and others resulted in considerable refinement of the program plan\textsuperscript{11}:

- Overall program objectives were defined, with distinct mission objectives for LightSail A and B. (LightSail A would take whichever ELaNa launch opportunity was ultimately selected, while LightSail B would ride with Prox-1.)
- A requirements-verification matrix was established for the overall mission, spacecraft system and ground system
The overall concept for mission operations (CONOPS) and mission timelines were defined, with potential de-scopes and simplifications. Spacecraft technical resources budgets (mass, power, component temperature limits) were updated. Attitude disturbance torques and orbit decay estimates were refined for LightSail A. The launch environment for LightSail A was characterized and implications to the spacecraft design were characterized. A baseline integration and testing plan for LightSail A was developed. A trade study for possible upgrades to the flight processor and radio was conducted.

All of this progress led to a decision at a Program Assessment Review in August 2013 to formally restart the LightSail program. By the time a Midterm Program Review was held in December 2013 the reformulated program plan had come into focus:

- LightSail A, would be couched as a risk-reducing tech demo mission; LightSail B, would be a full-up solar sailing demo mission.
- Stellar would continue in its role as lead spacecraft system contractor, augmented by space avionics and sensor systems firm Ecliptic Enterprises Corporation, who in turn would also have Boreal Space and Half Band Technologies as support contractors, with Tyvak on call as needed.
- Cal Poly would develop the baseline ground operations system and lead mission operations for LightSail A, while Georgia Tech would serve as the backup from their Center for Space Systems facility; for LightSail B, these roles would reverse.
- Cal Poly would provide selected staff and students its environmental test facilities to the program, and would also lead the CubeSat integration effort with the “P-POD” CubeSat carrier/deployer system and coordinate other selected launch approval activities.
- TPS would provide program funding and coordinate all outreach and media interactions.

When the decision was made to resume the program in fall 2013, the baseline date for having LightSail-A spacecraft integration and testing complete and ready for shipment to the launch site was May 2014—a very aggressive schedule. By December NASA had moved this date to the right by ~6 months to December 2014. The best estimate for the Prox-1/LightSail-B launch date was August 2015.

The LightSail-A integration and testing effort got started in earnest fall of 2013 at Stellar; by spring 2014 Ecliptic was assigned lead responsibility for the effort, supported by Boreal Space and Half Band. Stellar and Tyvak continued to assist the effort on contract through the fall of 2014, and then were consulted occasionally until the end of the LightSail-A mission in mid-2015.

The remainder of this paper will summarize key features of the LightSail spacecraft and mission design (including differences between LightSail A and B), highlights of the integration and testing experience for LightSail A, highlights from the LightSail-A mission and plans for LightSail B. (In the interest of meeting the page limit for this paper, few details will be provided here for either ground segment; these will be left for another paper to address.) The focus here is on what transpired since the program’s restart in late 2013 and not the 2009-2011 timeframe.

**LIGHTSAIL SPACECRAFT DESIGN**

The overall LightSail architecture (Fig. 4) 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.

![Figure 3. LightSail program patch.](image)

![Figure 4: Overall LightSail architecture. (Four deployable solar panels not shown.)](image)
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.

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 (like Fig. 4, but with the four solar panels attached) is the standard 3U CubeSat form factor as required for P-POD integration; releasing the RF antenna creates the first transitional configuration. Deploying the four solar panels produces the second transitional configuration (like Fig. 2, but with the RF antenna deployed), and deploying the solar sails produces the fully deployed state (Fig. 5).

The avionics section houses two processor boards, a radio, batteries, sensors and actuators, and associated harnessing (see Fig. 6.) LightSail A utilizes only torque rods for actuation, 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 the 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.

![Figure 5: Fully deployed configuration.](image)

![Figure 6: Overall LightSail architecture—exploded view. (Note axis convention.)](image)

<table>
<thead>
<tr>
<th>No.</th>
<th>Subsystem</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<tr>
<td>2</td>
<td>CubeSat Structure: Plate</td>
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<td>8</td>
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<td>14</td>
<td>Sail Housing</td>
</tr>
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<td>15</td>
<td>Boom Housing</td>
</tr>
</tbody>
</table>

Ridenoure 5 29th Annual AIAA/USU Conference on Small Satellites
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.

**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 for a variety of spacecraft attitudes with respect 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. 7 shows LightSail A in a partially deployed state, with two solar panels fully deployed, two party 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 elgiloy, a non-magnetic non-corrosive alloy; these booms are wound around a common spindle driven by a Faulhaber motor containing Hall sensors. The sail system is deployed when FSW initializes the motor (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.

**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 two shorter panels providing 2 watts each. Solar power is routed through the main avionics board and charges a set of 8 lithium-polymer batteries providing power during eclipse periods. Each battery cell has its own charge monitoring/protection circuit and ties individually to the spacecraft bus (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 a specified threshold. Fig. 8 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.

**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 $-55^\circ C$ during orbital eclipse periods. The cameras require an operating range from $0^\circ C$ to $70^\circ C$. A heater is installed in series with a thermostat set to trip ON if the camera temperature falls below $0^\circ C$. FSW turns OFF the camera if the operating temperature climbs above $70^\circ C$. Avionics board temperatures are relayed in beacon telemetry.

**Avionics and RF Subsystem**
The primary avionics board is a Tyvak Intrepid computer board (version 6), which is Atmel-based and hosts a Linux operating system. Integrated onto this main board onto a separate daughterboard is an AXS042 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 LightSail-B 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 torquer control circuit was changed to pulse-width modulation (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, and also with the momentum wheel for LightSail B.

**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,
Tables 1 and 2 detail the Intrepid board FSW control processes and the PIB FSW control processes, respectively. The thermal, ADCS, and deployment data were optimized to provide a comprehensive assessment of on-orbit performance during the mission. Beacon data, downlinked at a nominal 15-second cadence, is supplemented by spacecraft logs that further enhance our understanding of spacecraft behavior.

FSW development activities are facilitated by a test article known as BenchSat (Fig. 9), 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.

The Imaging Subsystem

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.

Figure 9: BenchSat and how it fits in with the overall testing and operations activities.

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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. 10.
Figure 10. PSCAM details. Raw images of the deployed sails (upper right) can be stitched together with software for a ‘birds-eye’ view (lower right).

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.

**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 sufficient for ground communication. After sail deployment, ADCS detumbles the spacecraft from up to 10 °/s in any axis to ~2-5 °/s.

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.

ADCS modeling and simulation results for LightSail-A highlight the expected performance (see Fig. 11). 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.

Figs. 11 and 12 were generated using 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°/s. Z-axis alignment eventually converges to about 20°.

Figure 11: ADCS detumble simulation results.

Figure 12: ADCS magnetic field alignment simulation results.
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.

The following table summarizes the stowed detumble/stabilization profile.

<table>
<thead>
<tr>
<th>Loop Number</th>
<th>Time (s)</th>
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<tr>
<td>1</td>
<td>0-1</td>
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<tr>
<td>2</td>
<td>1-2</td>
<td>OFF</td>
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<td>3</td>
<td>2-3</td>
<td>Bang-Bang B-Dot</td>
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<td>4</td>
<td>3-4</td>
<td>+2 axis ON only</td>
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ADCS ensures the magnetic torquers are OFF when reading magnetometer data due to the concern for interference from the torquers.

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. 13).

The input shaping strategy is intended to result in zero vibration for a single-DOF damped system after N impulses

Table 4 summarizes the sensors and actuators supporting LightSail ADCS.

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<tr>
<th>Component</th>
<th>Number</th>
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<tr>
<td>Gyros</td>
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<td>Analog Devices</td>
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<td>Magnetometers</td>
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<td>Torque Rods</td>
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<td>Strass Space</td>
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<tr>
<td>Momentum Wheel</td>
<td>1*</td>
<td>Sinclair Interplanetary</td>
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* LightSail-B only

The LightSail-B mission includes a momentum wheel that aids in solar sail maneuvers on orbit to demonstrate orbital inclination change, per an ADCS concept articulated in 2013

![Figure 14. Simulink model for LightSail-B orbital inclination change.](image)

LIGHTSAIL MISSION DESIGN

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.

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 classified Atlas 5 launch opportunities for LightSail A, both targeted for elliptical low-Earth orbits with relatively low perigees and mid-latitude inclinations. Each opportunity involved loading eight P-PODs full of CubeSats into a carrier system developed and provided by the Naval Postgraduate School: the “NPS CuL” system. For integration and tracking, these entire loaded NPS CuL packages were named GRACE and ULTRASat.
Being classified launches, the exact orbit parameters, launch dates and launch times were not divulged to the LightSail team until close to launch time, 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 may lead to some suggested changes).

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.

### 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 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.

A depiction of the Prox-1 spacecraft and its LightSail-B companion is shown in Fig. 15; the Prox-1/LightSail-B mission design is summarized in Fig. 16. 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

![Figure 15. LightSail-B shortly after ejection from Prox-1.](image)
Figure 16. Baseline LightSail-B mission plan in conjunction with the Prox-I mission.

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.

LIGHTSAIL-A INTEGRATION AND TESTING

Starting with the spacecraft in a storage case in mid-2012, the LightSail-A integration and testing effort got started in earnest fall 2013.

Assembly

Responding to actions identified at the Program Assessment Review held in August 2013, the engineering team at Stellar began preliminary de-integration, modification and re-integration and testing of LightSail A (and to a lesser extent LightSail B) in early September 2013, and for about three months completed 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 (e.g., upgrading the Cal Poly v. 2 board to Tyvak’s Intrepid v. 6 board). By early December re-integration of both spacecraft was well along, but neither one was fully ready for end-to-end functional testing.

Functional and Environmental Testing

At the time of the Midterm Program Review (December 16, 2013), LightSail-A mission sequence tests were planned (after final re-integration) starting a few days later, followed by a series of environmental tests scheduled for late January 2014. In parallel with these activities, non-real-time uplink and downlink “thread tests” and a preliminary mission systems test were scheduled to verify the end-to-end data flows with the Cal Poly and Georgia Tech ground systems.

A number of additional actions items, loose ends, FSW issues, testing issues, etc. had cropped up by mid-January 2014, so the various planned end-to-end tests were delayed about a month. Also, during this month decisions were made at the LightSail program level to move overall test planning, FSW development and project coordination from Stellar to Ecliptic, while Spencer would continue to lead overall mission and systems engineering. This transition was completed by mid-February, and shortly after the BenchSat unit was moved from Stellar’s facility to Ecliptic’s Moffett Field office a few blocks away, where Plante and Diaz from Boreal Space and Half Band, respectively, set to work on addressing various FSW issues.

In late February, NASA informed the team that the expected launch date for GRACE would be slipping well into 2015 and that an earlier slot was available with ULTRASat, leading to a LightSail A ship date of August-October 2014 and launch date of February-March 2015. After much discussion within the program, this option was accepted. NASA then assigned LightSail A to its 11th block of CubeSat launches—ElaNa XI—to be launched from Florida aboard an Atlas 5 rocket tapped with inserting the USAF X-37B spaceplane into an elliptical low Earth orbit on a classified mission

By the end of February the ship date had been refined to mid-October to support a March 2015 launch. The integration and testing schedule looked daunting at this time, so the team redoubled efforts to make progress on the over three-dozen open action items, pressing toward the ship date. Most work relating to the LightSail-B spacecraft was put on hold.

Between early March and early June considerable progress was made on LightSail A, but not without several challenges that had to be addressed by the team:

- March-May: Several design and documentation issues were found with the PIB, and significant changes were made to how the ADCS sensors were read and how the ADSC was controlled, so the PIB design was tweaked and the boards re-spun (twice)
- March-May: Active FSW development and testing continued, focused on refining the overall CONOPS, sequencing logic, file system architecture, beacon telemetry processes, RF communications processes, sail deployment control and ADCS control
• Late May: The new PIB board was tested with the spacecraft at Stellar, followed immediately by limited systems tests and a booms-only test of the sail deployment sequence, which had several issues.
• Plans were finalized for a full-up sail deployment test and “day-in-the-life” test (DITL) for the spacecraft, to be conducted at Cal Poly.
• Final paperwork was filed for a NOAA remote sensing license, and other regulatory and launch-certification paperwork was moved along.

In early May the team, anxious about the looming ship date, was informed that the planned launch date had moved to May 2015, so the ship date was moved to early November 2014—a welcome adjustment.

The DITL test—focused on replicating the deployment sequences for the RF antenna, solar panels and solar sail system—had been planned for early June at Cal Poly, but technical and logistics issues delayed it to mid-June. More anomalies were observed during this test, so after more technical work and FSW modifications another round of tests were conducted at Cal Poly in late June—these went relatively well—and another DITL test was scheduled for late July.

At the program level, two significant developments occurred. In early June TPS ramped up its public coverage of the ongoing LightSail effort, leading to regular status updates on the LightSail-A testing effort16 and a formal announcement in early July about plans for LightSail-B’s launch with Prox-1 in 201517. And, from mid-June on all LightSail testing (-A and -B) was baselined to be at either Ecliptic’s Pasadena offices or at Cal Poly. These developments focused and energized the team to be sure.

Radio issues cropped up in mid-July, including a couple of blown amplifiers, during testing at Cal Poly in advance of the planned DITL test there. Determining the likely root cause of these failures (thought to be a mismatch between the RF antenna and transmitter) took several weeks. Other anomalies were observed with the torque rod behavior. These issues conspired to delay the planned DITL test into mid-August.

The second round of DITL testing planned at Cal Poly for August 20 had to be canceled at the very last hour—with all major LightSail stakeholders (including key donors), the development team and the media present. The principal problem was once again the radio: it wasn’t working. The team regrouped, and with considerable consultation with outside experts and weeks of additional testing determined that the core issue with the radios was traceable to a pin-out change in the v. 6 Intrepid board compared to earlier versions.

Hardware changes were made (and new radios bought and integrated), and a very successful end-to-end mission systems test was completed on September 16. This was followed by a fairly successful DITL test on September 22 and a very successful test (after some FSW tweaks) on October 3 (see Fig. 17). This left less than a month for the team to run LightSail A through its environmental test series.

![Figure 17. LightSail A after a successful DITL test](image)

Updated estimates for the ULTRASat orbit arrived in late September: the perigee would be about 50 km lower than before (~350 km vs. ~400 km). The ship date was also (fortuitously) moved to early December.

Three random vibration tests were completed at Cal Poly in from early October through early November, during which the burn-wire for solar panel deployment broke and other anomalies (e.g., loose screws) were seen. Minor redesigns and rework ultimately rectified these issues, as verified with the final vibe test on November 24. Thermal-vacuum bake-out was completed on November 25, just before the Thanksgiving break. Using LightSail A and BenchSat, final FSW tweaking and testing continued at a hectic pace all through November. The final FSW version was loaded into the spacecraft and locked down on December 1.

A complete Mission Readiness Review involving all parties was conducted and passed on December 3. LightSail A spacecraft integration and testing was declared complete and the spacecraft was cleared for integration into ULTRASat.

**Launch Integration**

The NPS CuL integration and certification process was managed by a consortium of Cal Poly, Tyvak and SRI via a contract with the NRO’s Office of Space Launch. LightSail-A-to-P-POD integration (Fig. 18) was completed at Cal Poly on January 14, 2015, but only after the spacecraft was sent back to Ecliptic for the addition of stiffener frames to each deployable solar panel. (Measurements of the overall spacecraft...
dimensions slightly violated the P-POD spec for allowable 3U CubeSat size because the solar panels were bowed outward a slight amount.) The final mass of LightSail A came in at 4.93 kg—within the maximum allowed 5.0 kg.

Soon after successful P-POD integration the LightSail-A package was delivered to the Naval Postgraduate School in Monterey, California, where it was integrated into the ULTRASat Cul Lite box on January 22 (Fig 19). After undergoing an additional vibration test and final checkouts, ULTRASat was then certified ready for launch and arrived at the launch site in Florida in early March, ready for integration with the Atlas 5, then scheduled for launch no earlier than May 6.

**Operations Readiness Tests (ORTs)**

Mission Director Dave Spencer articulated a notional ORT series in late 2013, but it wasn’t until a realistic launch date solidified that the details were worked out. Spencer held a kickoff meeting on March 30 to baseline the ORT plan: ORT-1 would rehearse the sequence of events from P-POD ejection through initial acquisition of LightSail-A telemetry, while ORT-2 would rehearse the sequences for solar panel deployment and solar sail deployment. These half-day tests were scheduled for early April and mid-April, respectively, first with a non-real-time ‘tabletop review’ to get roles, responsibilities and procedures straight followed shortly after by a real-time execution of the planned mission sequences, plus all-hands debrief.

Both ORTs were held on schedule, and in general quite successful. The principal surprise was that an error in the (long ago-frozen) FSW was revealed that essentially locked up the ADCS control routines after 4 sec of their starting—after a reboot, say. (The error was attributable to a single line of ADCS code in the PIB with one character in it that was misplaced in the code sequence by three lines during the final hectic days of November, 2014.) After such a restart, a snapshot of key ADCS parameters like gyro rates would be captured in telemetry, but the ADCS algorithms themselves would not be operable.

Diagnosing the root cause of this anomaly took several weeks (until after ORT-2) and was a major disappointment after so much work had gone into refining the ADCS approach months before, but the spacecraft was out of reach and no late FSW updates were possible, so the team had to live with it—for LightSail A, anyway.

On April 10, Atlas 5 manufacturer ULA announced that the launch was slipping two weeks, to May 20, “to resolve unspecified issues with the payload.” The extra two weeks allowed for more thinking about the PIB code bug and how to deal with it, and more extensive BenchSat tests were run to characterize the effects of the bug. An ORT-3 was proposed for early May, but Spencer opted to defer this in favor of a through rehearsal of launch-day activities, which was held on May 18. Between the BenchSat tests and the final mission rehearsal, the team was convinced that the PIB bug would not interfere with the any of the mission-critical deployments, the imaging or the telecommunications planned for LightSail A.

**Launch and Orbit Insertion**

The Atlas 5/X-37B launch with ULTRASat aboard was launched right on time at 11:05 am EDT on May 20, inserting the X-37B into the desired elliptical orbit (as it
turns out, 356 km x 705 km and 55° inclination). LightSat A—in the last of the eight ULTRASat P-PODs to be actuated—was ejected into its own orbit two hours after launch, at 1:05 pm EDT.

**Early Mission Operations**

Telemetry data from LightSail 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 s—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 (from the busy time in November) that was not caught during testing and 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.) LightSail A fell completely silent for days, in spite of 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 LightSail A.)

After consulting with other CubeSat operators familiar with the class of avionics on LightSail, it was generally agreed that the only hope for LightSail 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: LightSail 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 ASAP.

- 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 up linking 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 dumped in favor of diligent FSW rebooting, which was working well. Commands tasking each camera to snap a test image were successfully sent on May 31, so panel and sail deployments was 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. 20). 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.

**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 placed into June 5.

With the regular FSW reboots, gyro rate updates were coming in at a good pace (Fig. 21), and had leveled out at ~2x the original tip-off rates. Panel deployment commands were sent early in the morning Cal Poly time on June 3, and subsequent beacon packets indicated successful deployment 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 the 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 useable 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. 8) which captured the rather complex battery fault-protection mechanisms, suspecting that LightSail-A’s power subsystem was hunkered down in that chart somewhere. The team discussed blasting commands to the spacecraft to turn components ON—and also 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 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 reattaching 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 serving as backups.

There was another reason for pressing all-out with sail deployment: gyro rates were at over 20 °/s—a now about the long Z axis—and rapidly increasing by almost 6 °/s per day (Fig. 21). By Sunday morning they would be triple what they were just days before. LightSail A was becoming a spinning dart.

**Solar Sail Deployment**

Telemetry from the first good Sunday morning (June 7) pass looked good across the board, so the team was directed 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 (Fig. 21), 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 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 rapid spin rate was causing spurious communications.

For the next Cal Poly pass 90 min. later, an excellent pass, it was decided to try it again, only send both commands 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 2 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. 22). 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.”

![Figure 22. Two minutes of motor count telemetry.](image)

**Sail Imaging**

Telemetry from the Monday morning (June 8) passes gave all indications that the sails were fully deployed or nearly out. The gyro rates dropped to nearly zero (Fig. 21), and all other subsystems looked fine.

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. 23). 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. 23)

![Figure 23. Progression of first deployed sail images.](image)

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. 24). It was disseminated globally by TPS and social media outlets shortly after.

![Figure 24. Full image of deployed sail.](image)

With the primary mission objectives accomplished, 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.

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 the morning of June 14.

PLANNING FOR THE LIGHTSAIL-B MISSION
The 25-day LightSail-A mission occurred between May 20 and June 14, 2015, and was declared a success by TPS CEO Bill Nye 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.

Due to the cut-off date for this paper, however, the detailed mission assessment is not available for inclusion herein. The mission summary above should be considered as mission highlights and not a definitive treatment of the material. More mission detail—including key lessons learned—will be provided at the 2015 August Conference on Small Satellites in Logan, Utah.

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 launch, would likely slip from mid-2015 to sometime in 2016. A year later this did occur, and as of this writing the expected launch date is mid-2016, suggesting a LightSail-B ship date of early December 2015. This is the date the team is working toward.

Serious planning for the LightSail B mission started with a thorough review and discussion of mission objectives held at The Planetary Society in Pasadena on December 5, 2014, two days after LightSail A was cleared for launch on ULTRASat. All co-authors of this paper were involved in this meeting (Fig. 27) as were the leaders of TPS. With the LightSail-A mission over, another similar LightSail-B planning meeting is scheduled for early July, 2015.

Figure 27. LightSail program technical leadership after the 2014 LightSail-B planning meeting. (l to r: Wong, Munakata, Foley, Díaz, Ridenoure, Plante, Stetson, Spencer.)

LightSail-B final flight software development will be completed fall 2015, followed by completion of final system integration, system-level testing by December and Prox-1 integration activities—LightSail-B-to-P-POD and P-POD-to-Prox-1—in early 2016.

ACKNOWLEDGMENTS
The LightSail program so far formally spans across six years, and is expected to continue for at least another year or two. Many people and organizations have been directly involved with the technical execution of the program, still more have served in various supporting roles, and many thousands of others have provided funding. It would be a significant challenge if not impossible to list them all.

But certainly Lou Friedman deserves credit for keeping the vision of a solar sailing demonstration mission like LightSail alive since at least 1976, and especially since the humbling disappointments of the Cosmos-1 attempts in 2001 and 2005.

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 and during several mission ORTs. Cal Poly Prof. John Bellardo provided essential leadership and direction during the ORTs and on console during mission ops.

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. We’ll nail it on LightSail B!

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 >18,000 donors to its LightSail Kickstarter campaign (kicked off on May 12) for actually funding these missions. Their support was essential.

REFERENCES
4. For more information see The Planetary Society’s website: http://planetary.org/.