LightSail-1 Solar Sail Design and Qualification

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Abstract

LightSail-1, a project of The Planetary Society, is a Solar Sail Demonstration mission built on the CubeSat platform. Stellar Exploration Inc. designed, built and fully qualified the Solar Sail module for LightSail-1 which includes a boom deployer mechanism that stows a total boom length of 16 meters (4 x 4 meter booms) which are used to deploy a 32-m^2 sail membrane in a 2U package. This design utilizes the rigid TRAC boom developed by AFRL (Air Force Research Laboratory) for deploying and tensioning the membrane that makes up the sail. In order to maximize the size of the solar sail, the boom deployer took on a unique shape to maximize packaging efficiency and achieve an 80:1 deployed to pre-deployed ratio. This paper will discuss the design challenges, unique design features as well system verification for LightSail-1.

Introduction

LightSail-1 is a project of The Planetary Society and is privately funded by members of the organization (Figure 1). The Planetary Society has been a proponent of solar sails for many years and the LightSail program is dedicated to advancing solar sail technology.

The main objective of LightSail-1 is to demonstrate the viability of solar sails by demonstrating a positive change in orbit energy, the ability to manage the orbit energy, and to control the spacecraft under solar sail power. These objectives will be achieved by developing and demonstrating key technologies such as sail deployment and sail material management during flight as well as the control of the spacecraft's attitude.

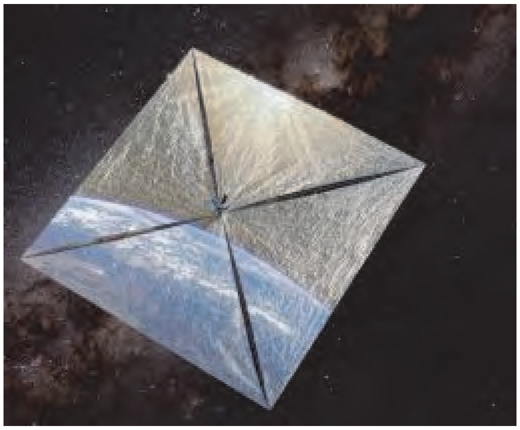

Figure 1. Artist rendering of LightSail-1 (The Planetary Society).

LightSail-1 follows work done for The Planetary Society on another program called COSMOS-1 which was also a solar sail demonstration mission. Unfortunately COSMOS-1 failed to reach orbit due to launch vehicle failure. COSMOS-1 was ~100 kg and had a total sail area of ~600 m^2. This gives COSMOS-1 a solar sail characteristic acceleration (a common metric for evaluating solar sail performance) of 0.047 $^{mm}/_{s}{}^{2}$.

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LightSail-1 Program Requirements

The main requirements and corresponding selected implementation for LightSail-1 are summarized in Table 1. Many of these requirements were derived from COSMOS-1.

Table 1. LightSail-1 requirements.

Requirement	**Selected Implementation**
Low Cost	CubeSat Platform
Greater Performance than COSMOS-1	3U CubeSat (maximum mass = 5 kg) requires 32 m^2 sail
Demonstrate Orbit Energy Change	2 On-board 3 axis accelerometers and optical tracking
Demonstrate Thrust Control	Requires ADCS with 90˚ Slew Maneuver
Image the Sail during/after deployment	2 On-board Aerospace Corporation Cameras

Based on the customer requirements and associated trades it was decided to build LightSail-1 on a 3U CubeSat platform with a 32-m^2 square solar sail achieving a solar sail characteristic acceleration of 0.050 $^{mm}/_{s}{}^{2}$.

LightSail-1 Configuration

The overall spacecraft was divided into three sections that include the avionics section, sail module, and payload section. The avionics section is ~1U and houses the avionics board, the sensor interface board, a transceiver, eight Lithium Polymer batteries and battery control boards, three torque rods, a momentum bias wheel, three single axis MEMS gyros, and a three-axis MEMS accelerometer. The sail module is ~1.5U and includes the sail storage cavity, and boom deployer. The payload section is ~0.5U and contains the deployer spindle drive motor and gear train, a three-axis MEMS accelerometer, a deployable monopole antenna, a deployable panel burn wire mechanism, and a storage compartment for two Aerospace Corporation built cameras mounted to the ends of the deployable panels.

Design Challenges

The following is a list of design challenges to the development of the sail module for LightSail-1.

- How to package the sail and booms in the allowable volume
- How to manage boom strain energy while stowed and during deployment
- How to control the sail deployment
- How to constrain sail material and booms prior to deployment (including during launch)
- How to manage sail material during deployment

It was determined early in the design phase that controlled deployment of the sail would be achieved by driving the deployer spindle that the booms are attached to with a brushless DC motor. Because the booms have a large stored strain energy when fully stowed, a method of constraining the booms while the motor was not energized was required to avoid auto-deployment of the booms. It was decided that this could be achieved by implementing a worm drive that could not be back driven in the gear-train. The worm drive provided the required gear reduction from the motor to the spindle as well as eliminated the need for an additional mechanism to constrain the booms during launch. In order to keep the sail material contained in the sail storage structure the deployable solar cell panels closed over the sail storage module constraining the sail material in place.

Detailed Design

The boom chosen for LightSail-1 is the TRAC boom developed by AFRL because of its packaging efficiency and specific stiffness. These booms were used in NanoSail-D and successfully flown on NanoSail-D2 last year. The TRAC boom consists of two Elgiloy metal strips each formed into a c-shaped curve and laser welded together back-to-back forming an inverted v-shape. The TRAC boom is shown in Figure 2.

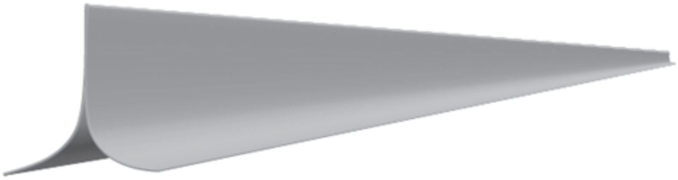

Figure 2. TRAC boom.

The TRAC boom collapses and is then rolled around a drum so it can be stored in an annular space. The TRAC boom has a self-deploying feature due to the stored strain energy in the boom while collapsed and rolled around the drum. This collapsible and rollable feature of the TRAC boom allows it to be stored in a very compact fashion. Due to the constraint imposed on the individual metal strips by the weld bead, the minimum bend radius is driven by the maximum strain of the material.

The sail storage section consists of a section with a wedge shaped cavity cut on each of the four faces. Also included is a hole passed through the center of the section for the routing of the wire harness to connect the avionics board in the top of the spacecraft to the sensors and deployer motor housed in the payload section. This configuration was driven somewhat by the requirement to have P-POD interface rails at least 75% of the overall length of the spacecraft (Figure 3).

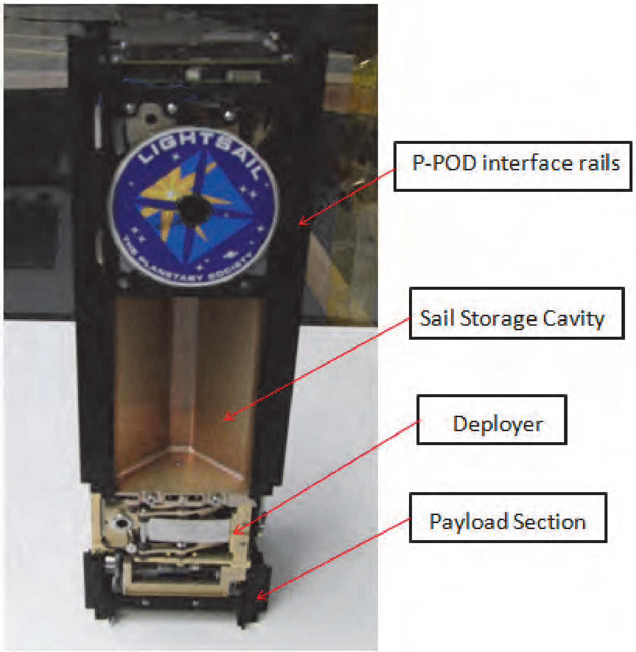

Figure 3. LightSail-1 layout.

The sail folding concept consisted of z-folding the sail in two directions while varying the fold widths from the center to the outside tips to take a wedge shaped cross-section matching the sail storage cavity (Figure 4).

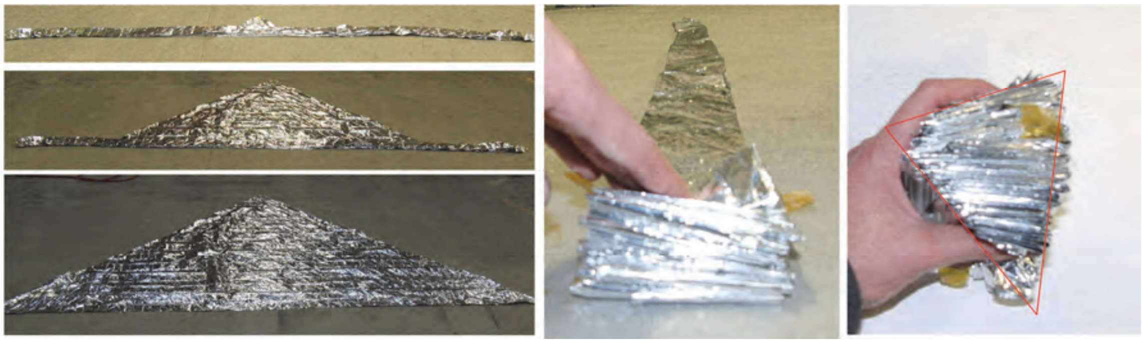

Figure 4. Sail Folding Procedure.

Prototype sails were built to empirically determine the magnitude of the fold height and width tolerances that were required, (and reasonable from a manufacturing standpoint) for the proper fitment into the sail storage cavity.

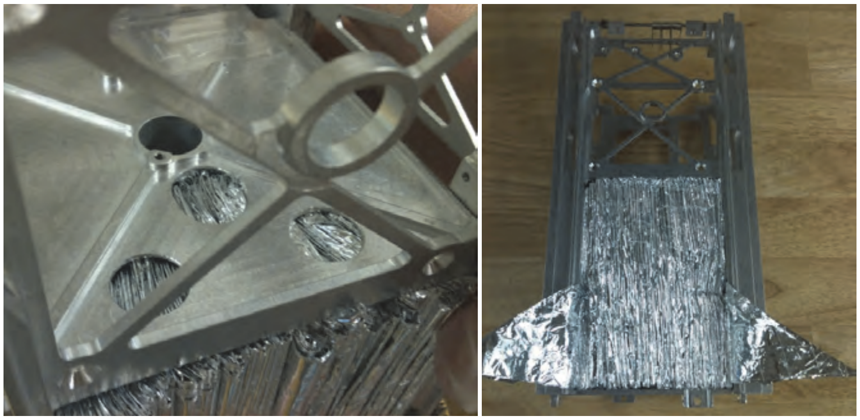

Figure 5. Sail test-fit in engineering structure.

The design of the sail was such that it had a slight interference fit in the sail storage cavity for sail management purposes during deployment. The idea being that each fold would be pulled out of the sail storage cavity one by one as the booms were deployed while the rest of the folded sail material was held in place. This would insure that the sail material would not billow from the cavity and potentially tangle around a deploying boom or get caught in the deployer and fail to deploy properly (Figure 6).

Figure 6. Sail behavior during deployment.

The sail-to-boom connection is made using metal grommets in the sails and booms with split rings and extension springs in series as shown in Figure 7. The extension springs are required to maintain an appropriate tension in the sail during thermal cycling.

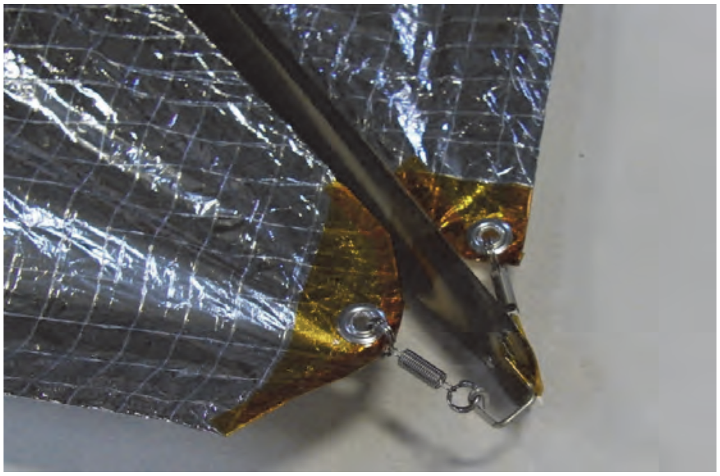

Figure 7. Sail to Boom connection feature.

Deployer Design

The deployer has four main functions: (1) Provide an attachment point to the boom to react all deployment loads (2) Protect the booms from yield due to strain (3) Store the 4m TRAC booms within the CubeSat allowable cross-section, (4) Provide smooth unrestrained deployment of the TRAC booms and Sail material.

The deployer is made up of a simply supported spindle mounted between two plates that the booms are attached to. The booms are clamped to the spindle and held with two stainless steel #4-40 bolts. This feature provides the attachment point for the booms and takes all the boom reaction loads. The spindle and clamp are machined with a flare at the bottom so as to not completely pinch the booms while mounted to the spindle. This increases the area moment of inertia of the boom over the pinched configuration providing a better boom root condition. The spindle flanges constrain and protect the booms from contacting any non-moving surfaces during deployment. The spindle with flanges and clamps are shown in Figure 8.

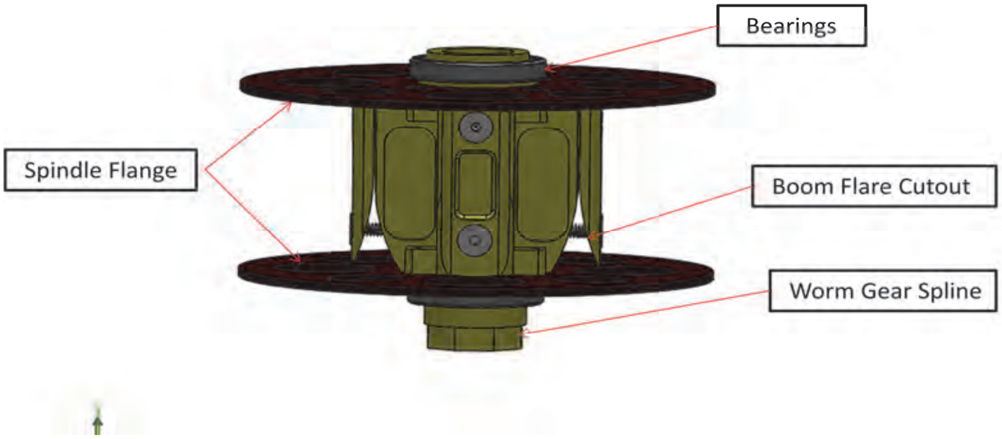

Figure 8. Spindle with boom clamps and flanges.

The rest of the deployer assembly contains four Tensioner Assemblies that are arranged between the two plates 90˚ from each other as well as multiple Delrin rollers mounted near the four corners, and four flexure clamp assemblies mounted adjacent to the Delrin Boom Exit Guides. These components are shown in Figure 9.

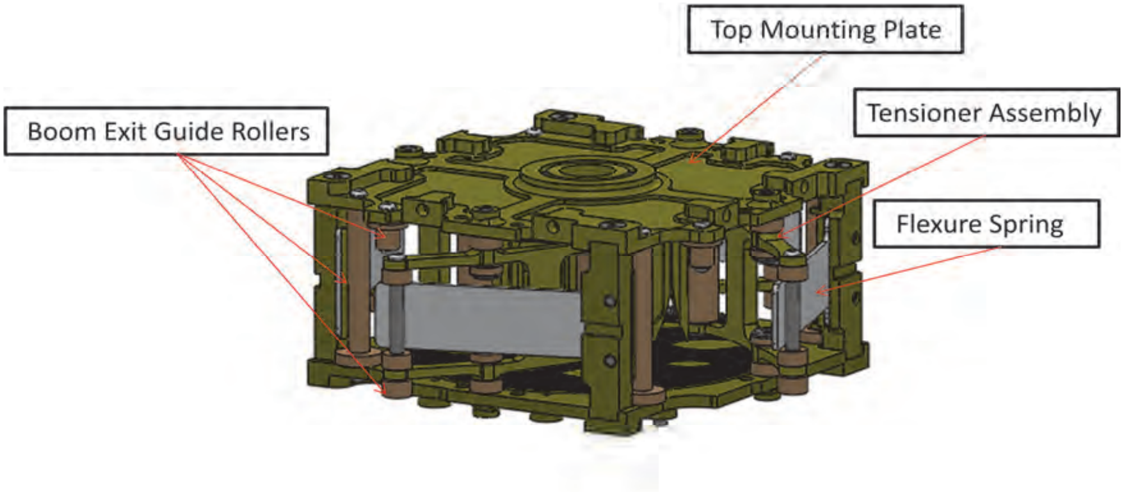

Figure 9. The deployer assembly with booms not shown.

As mentioned above, the booms require the application of a normal force to first collapse the boom into its pinched configuration and then to force the boom to roll around the drum. This is accomplished with the tensioner which uses the reaction force of a deflected cantilever flat spring against the flexure contact pin. The force on the flexure contact pin produces a moment on the tensioner body which pivots around two shoulder screws with Delrin bushings. This moment is reacted at the Boom Roller causing a normal force against the boom wrap. The flexure spring passes though the space between the shoulder screws and contacts the contact pin mounted in the tensioner. Standoff rollers are used to isolate the boom wrap from the metal tensioner body and shoulder screw heads. The tensioner assembly is shown in Figure 10.

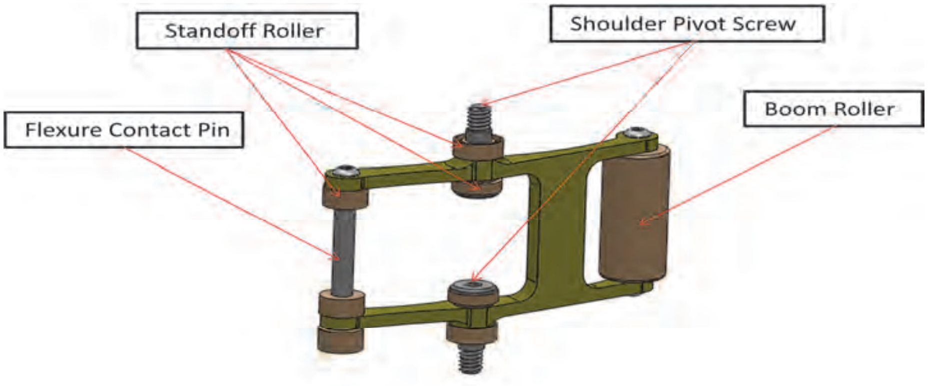

Figure 10. Tensioner Assembly.

Figure 11 shows a top view of the deployer in the fully deployed configuration with the top plate and spindle flange transparent, and the booms not shown for clarity. This fully deployed configuration refers to the state when the booms are just beginning to be rolled around the spindle to be stowed, or at the end of deployment.

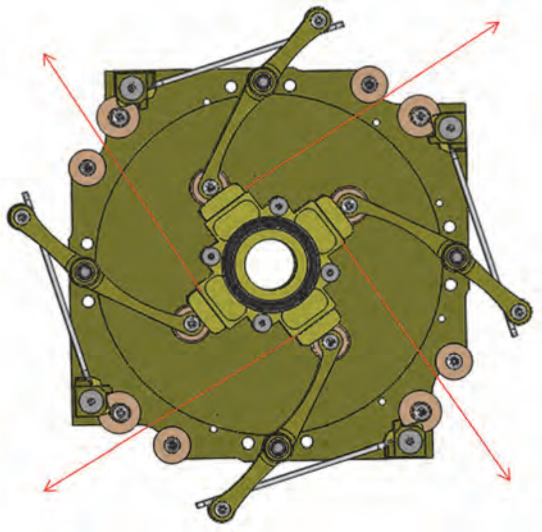

Figure 11. Tensioner orientation at full boom deployment with the flexure springs in the relaxed state (red arrows indicate the path of the booms).

As the booms are wound around the spindle, the increasing outside diameter of the boom wrap pushes the contact roller on the tensioner outward increasing the deflection of the flexure spring. As the boom wrap thickness reaches its maximum outside diameter and the flexure spring reaches its maximum deflection, the tensioner assembly is stowed within the CubeSat allowable cross-section as shown in Figure 12.

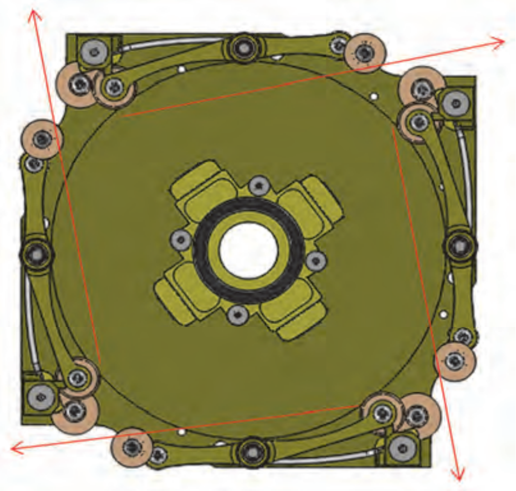

Figure 12. Tensioner orientation for stowed booms with flexure spring at maximum deflection (red arrows indicate the path of the booms).

The “rocker-arm” configuration of the tensioner allows for very compact packaging by taking up area around the boom wrap and not protruding past the allowable CubeSat cross-sectional area while in the stowed configuration. The deployer and elegant design of the TRAC boom resulted in a deployed to pre-deployed ratio of 80:1 since the packaged cross-section is 0.1 m x 0.1 m and the deployed boom length, tip to tip, is 8 m.

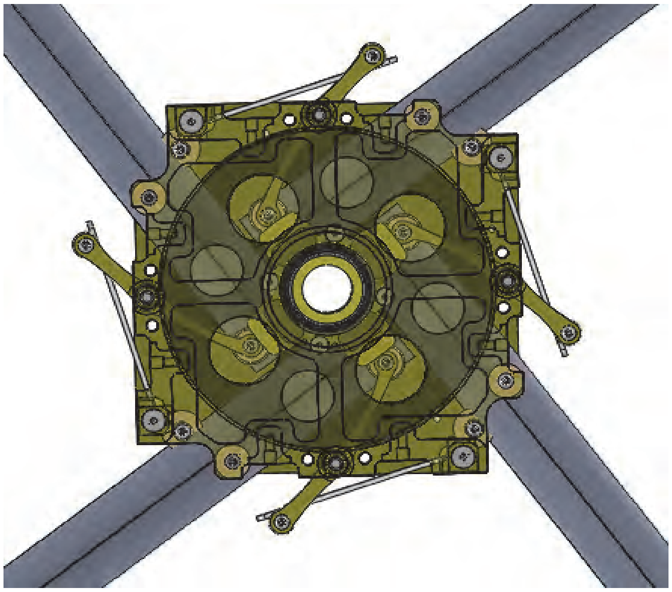

Figure 13. Deployer with top plate and flanges transparent to show booms in fully deployed configuration.

Development testing of the boom deployer assembly consisted of measuring the drive motor current required to deploy the booms while varying parameters within the deployer including the flexure spring rate, and coefficient of friction between adjacent boom wraps. This testing revealed a strong correlation between the required motor drive current required to deploy the booms and (1) the coefficient of friction between the adjacent boom wraps, and (2) the flexure spring thickness. It was discovered that a large coefficient of friction was desired between adjacent boom wraps because a higher axial force could be transferred from the drive motor through the boom wrap to the deployed length of the boom. Since the sails had a slight interference fit with the sail storage cavity a small axial force was imparted on the booms in order to pull the sail material out of the cavity and unfold it. Initially this axial force would cause ballooning of the boom wrap inside of the deployer. This ballooning was controlled with a higher spring rate on the flexure spring which exerted a larger normal force on the boom wrap keeping it contained. This was critical for achieving reliable deployment of the sail.

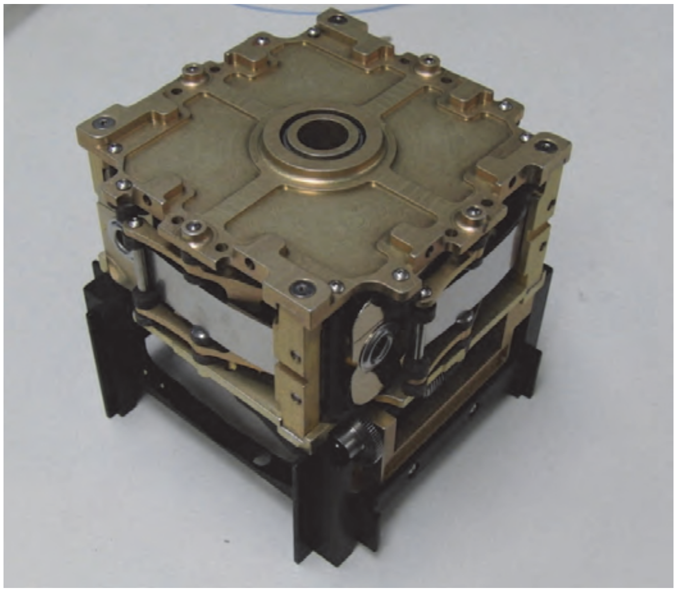

Figure 14. Flight deployer and payload assembly in fully stowed configuration.

Figure 14 shows the deployer and payload section in the flight configuration with the booms fully stowed. Figure 15 shows the spacecraft fully assembled (with engineering deployable solar cell panels).

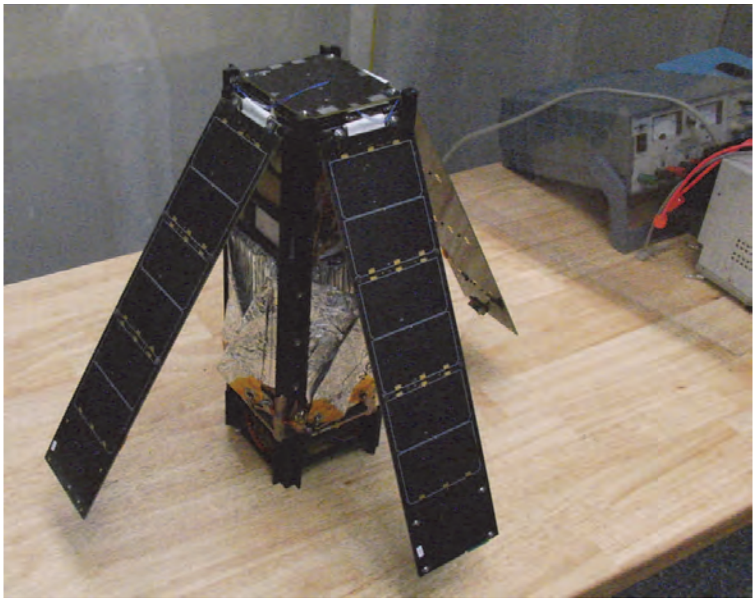

Figure 15. LightSail-1 fully assembled.

System Validation

System validation consisted of full-scale sail deployment tests before and after random vibration testing, and TVAC testing while monitoring the drive motor current as the performance metric. Cold full-scale sail deployment tests while monitoring motor drive current were conducted as well to verify cold deployment performance. In order to conduct sail deployment tests a method of off-loading was required to simulate a zero-g environment. This was accomplished by building a deployment table to support the weight of the booms and sail during testing. The table is shown in Figure 16 and features removable panels in order to access the spacecraft while the sail and/or booms are deployed.

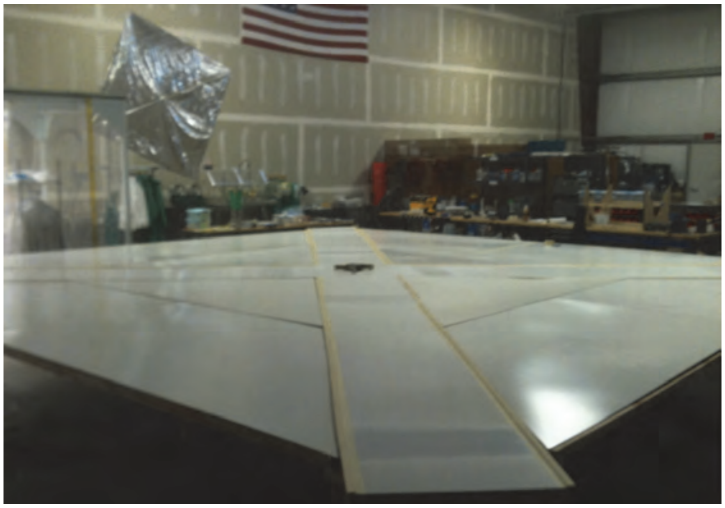

Figure 16. Sail deployment table.

Random Vibration Testing

Random Vibration tests were conducted to validate the structural design of the spacecraft and also to validate the deployer mechanism design. The random vibration test would also be used to validate the worm drive locking feature. Figure 17 shows LightSail-1 on the vibration table at Cal Poly.

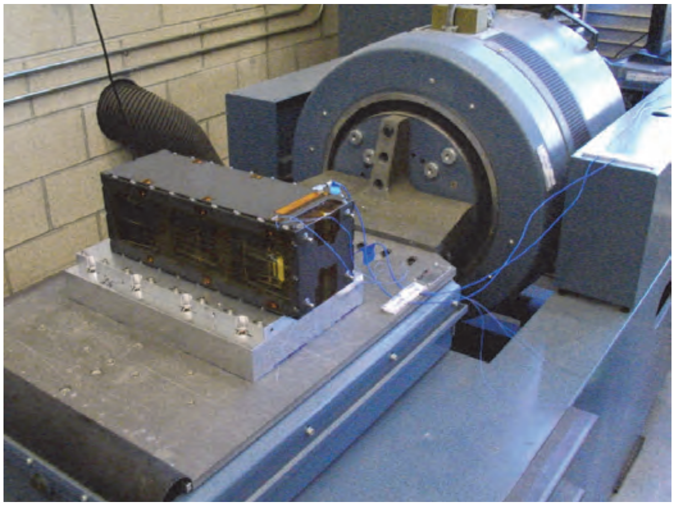

Figure 17. LightSail-1 during random vibration testing at Cal Poly.

The structure and worm drive locking feature performed well. The worm drive locking feature was verified by observing that the spindle orientation had not changed after random vibration testing by lining up reference marks on the spindle and deployer top plate before random vibration testing. If the reference marks lined up after random vibration testing it confirmed that the spindle was held fixed by the worm drive, which is what occurred.

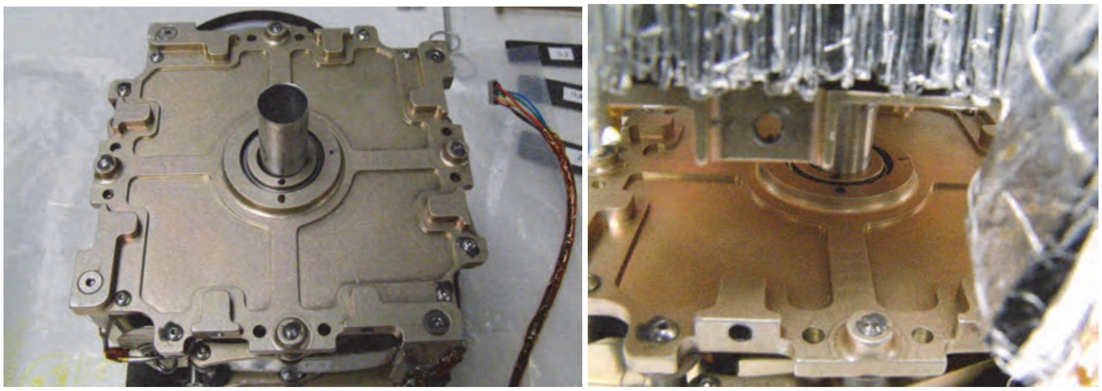

Figure 18. Spindle reference marks before (left) and after (right) random vibration testing.

While the structure performed well and the worm drive locking feature was validated, it was observed that the booms were pulled inside the deployer ~10 mm during the random vibration test. It was determined that the boom wrap was allowed to balloon slightly due to some compliance in the flexure spring/tensioner assembly. This was solved by packaging the booms in such a way that the tensioner was completely bottomed out against a hard stop while the boom wrap was pulled tight. Additionally, a pin was added to the tip of each boom to act as a hard stop to not allow the boom to retract into the deployer.

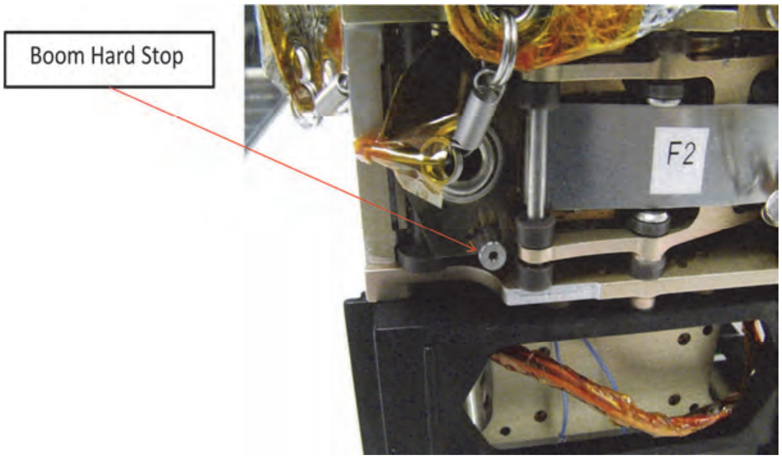

Figure 19. Boom hard stop.

Following the implementation of the above mentioned solutions the random vibration test was repeated to validate the design with full scale sail deployment tests conducted before and after random vibration testing. The deployment tests were successful with no significant difference in the motor drive current between the two deployment tests.

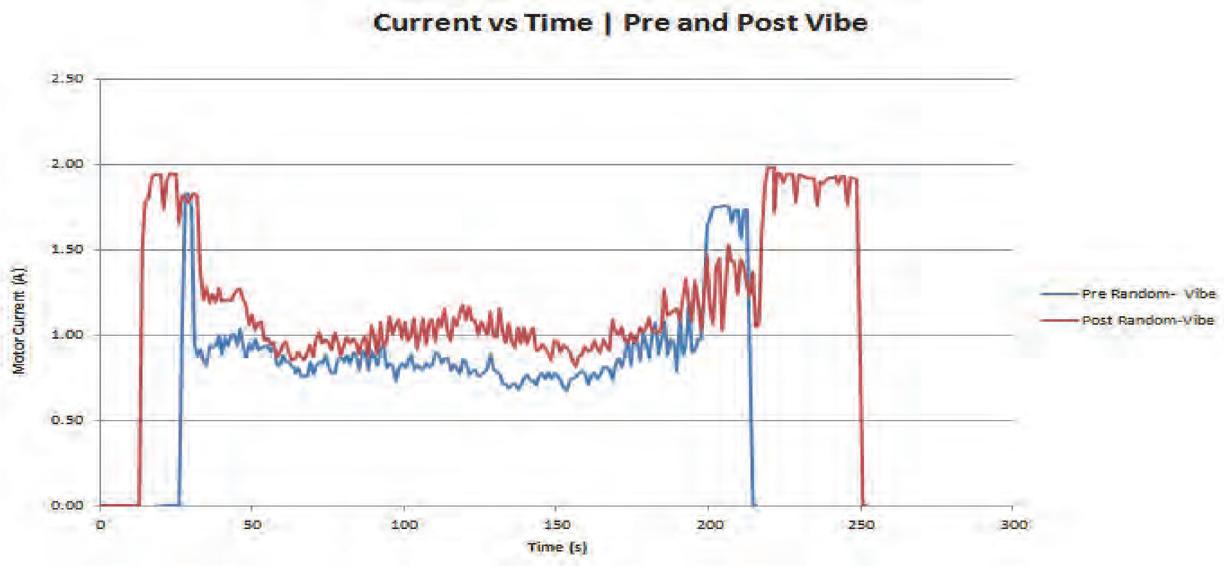

Figure 20. Drive motor current plot for Pre and Post Random Vibration deployment tests.

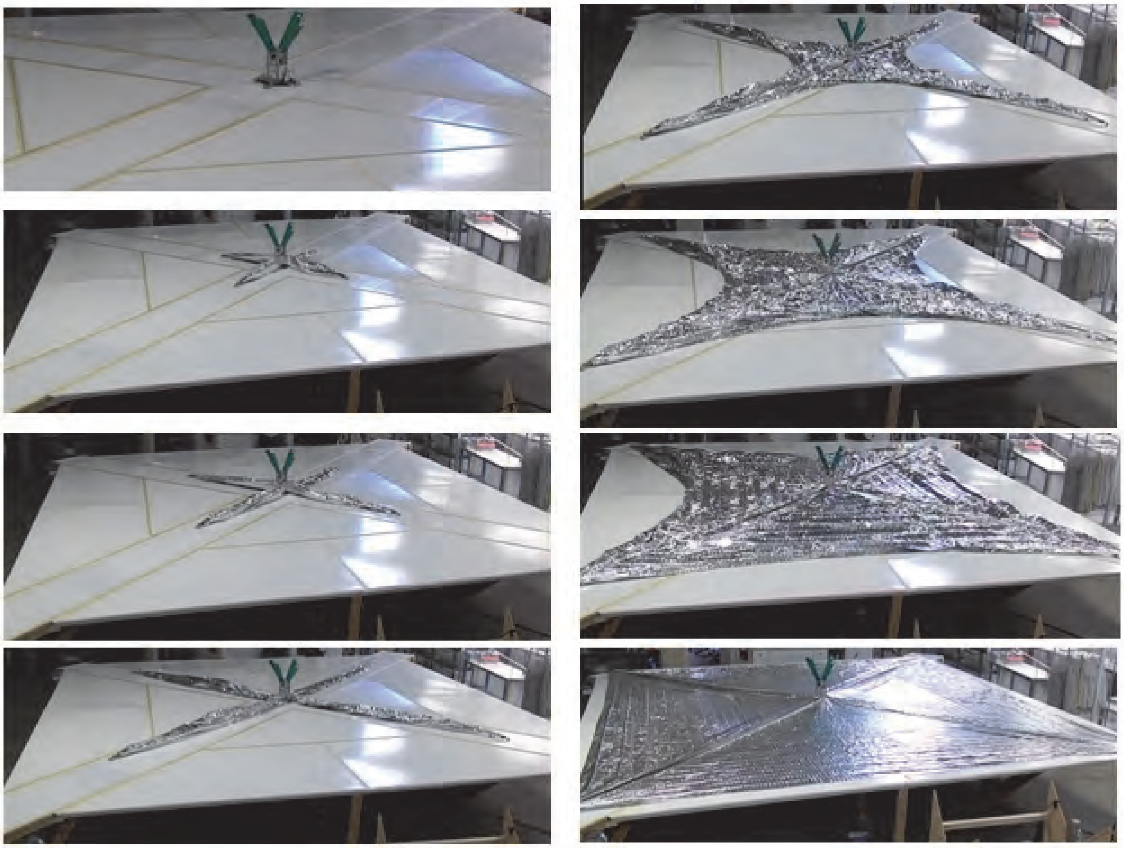

Figure 21. Sail deployment test.

Cold Deployment Testing

Cold deployment testing consisted of cooling only the deployer and booms to a prescribed temperature and then deploying only the booms while monitoring the drive motor current and comparing that with the current required to deploy the booms at room temperature. It was decided to focus on the deployer mechanism and booms, without the sail, because the sail behavior was not expected to change significantly over the temperature range being tested and because of the difficulty controlling moisture in a laboratory environment (without a vacuum chamber). The moisture in the system needed to be carefully controlled since the cold testing was conducted below freezing and the introduction of ice in the system could limit the performance of the deployer. The cold testing was performed by flowing cold nitrogen vapor into a container housing the deployer with small cutouts for the booms to pass through until the deployer assembly reached the appropriate temperature after which the booms were deployed. The drive motor current was monitored during cold deployment testing for comparison with room temperature deployment data. The deployer was qualified down to -6˚C where it was well within the allowable motor current margin.

Many full-scale deployment tests have been conducted on the engineering model hardware for development. Full-scale "acceptance" deployment tests will be conducted on the flight hardware including before and after random vibe and TVAC. As of this writing the flight unit TVAC test has not been completed. These flight hardware tests are held to a minimum because of degradation of the sail material during re-folding of the sail after deployment testing. However up to 6 deployment tests on a set of sails is reasonable without significant degradation.

Conclusion

The result of work done on the LightSail-1 program is a fully qualified 32-m^2 solar sail packaged in a ~1.5U volume with a mass <3 kg (4.6 kg total spacecraft mass). The boom deployer assembly has a deployed to post deployed ratio of 80:1. It is planned to launch LightSail-1 by the end of 2012.

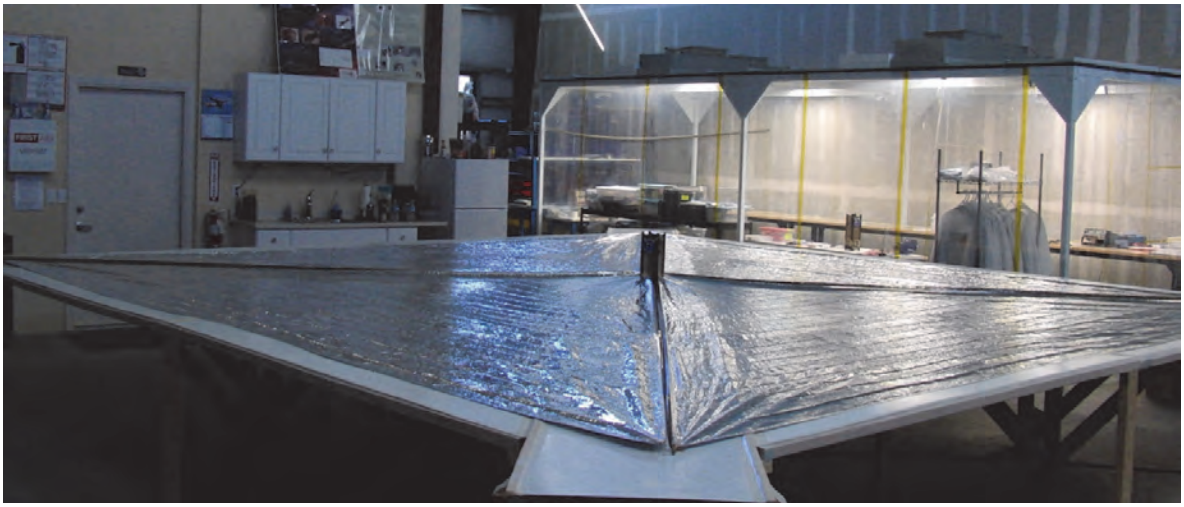

Figure 22. LightSail-1 fully deployed in the lab at Stellar Exploration.

Acknowledgments

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