Sunjammer: A Solar Sail Demonstration

Nathan C. Barnes[1] and William (Billy) C. Derbes[2]
L'Garde Inc, Tustin, CA, 92780

Charles J. Player[3]
L'Garde Inc, Tustin, CA, 92780

and
Benjamin L. Diedrich[4]
L'Garde Inc, Tustin, CA, 92780

NASA's newly minted Space Technology Mission Directorate (STMD) is supporting the fabrication of a sail of this design in preparation of a planned 2014 flight. This mission, dubbed Sunjammer, will further advance the potential of propellantless solar sails. The Sunjammer mission is being led by the private company L'Garde Inc. of Tustin, CA. Sunjammer is named after a short story written by Sir Arthur C. Clarke. This ambitious project aims to prove the efficacy of a versatile and scalable solar sail design. The Sunjammer mission is being designed with the following objectives as guidance:

1. Demonstrate segmented deployment of a $1200m^2$ solar sail.
2. Demonstrate attitude control plus passive stability and trim using tip vanes.
3. Execute a navigation sequence with mission-capable accuracy.
4. Fly to and maintain position at a sub-L1 and/or pole sitter positions.

NASA's Space Technology Mission Directorate is providing the necessary leadership and support to sail this flight-ready technology to the launch pad.

[1] President, L'Garde Inc
[2] Chief Engineer, Sunjammer Project
[3] Deputy Project Manager, Sunjammer Project
[4] Mission Designer, Sunjammer Project

Sunjammer Mission Overview

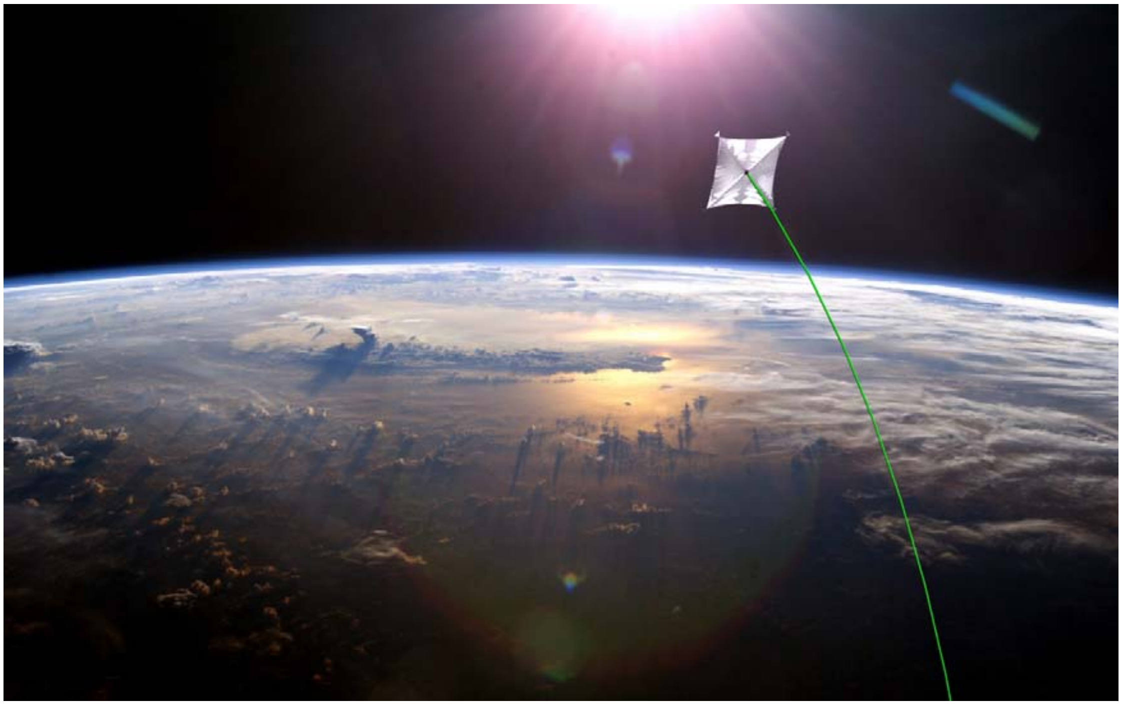

Figure 1. Sunjammer (Artist Rendering)

The Sunjammer mission is built around the desire to fly a sail beyond the bounds of an Earth orbit. Also, the mission is targeted to be low cost. These two constraints drive much of the design of the entire spacecraft. First, in order to achieve the low-cost constraint, this mission is planned as a secondary payload. As a secondary payload, the mission is forced to conform to several regulations and requirements. Specifically, Sunjammer is being designed to meet EELV Secondary Payload Adapter (ESPA) standards. This conformance, among other things, puts volume and mass constraints on the spacecraft.

Launch is scheduled for late 2014 onboard a SpaceX Falcon 9. The insertion trajectory will be sunward, but with slightly less than Earth escape velocity. This necessitates an onboard hydrazine propulsion system to impart enough delta-V to assure Sunjammer does not return to Earth.

Approximately two hours after this burn, sail deployment will begin. This process will take up to two more hours. The Sunjammer spacecraft is split into two distinct portions: the sailcraft and the carrier. The sailcraft is the portion of the spacecraft that will perform the solar sail demonstration after being boosted to earth escape. The carrier is the portion of the spacecraft that is expendable, and so will be jettisoned after deployment of the sailcraft, more than doubling the characteristic acceleration. Figure 2 shows the assembled spacecraft and the separated sailcraft and carrier, as well as the jettison simulation.

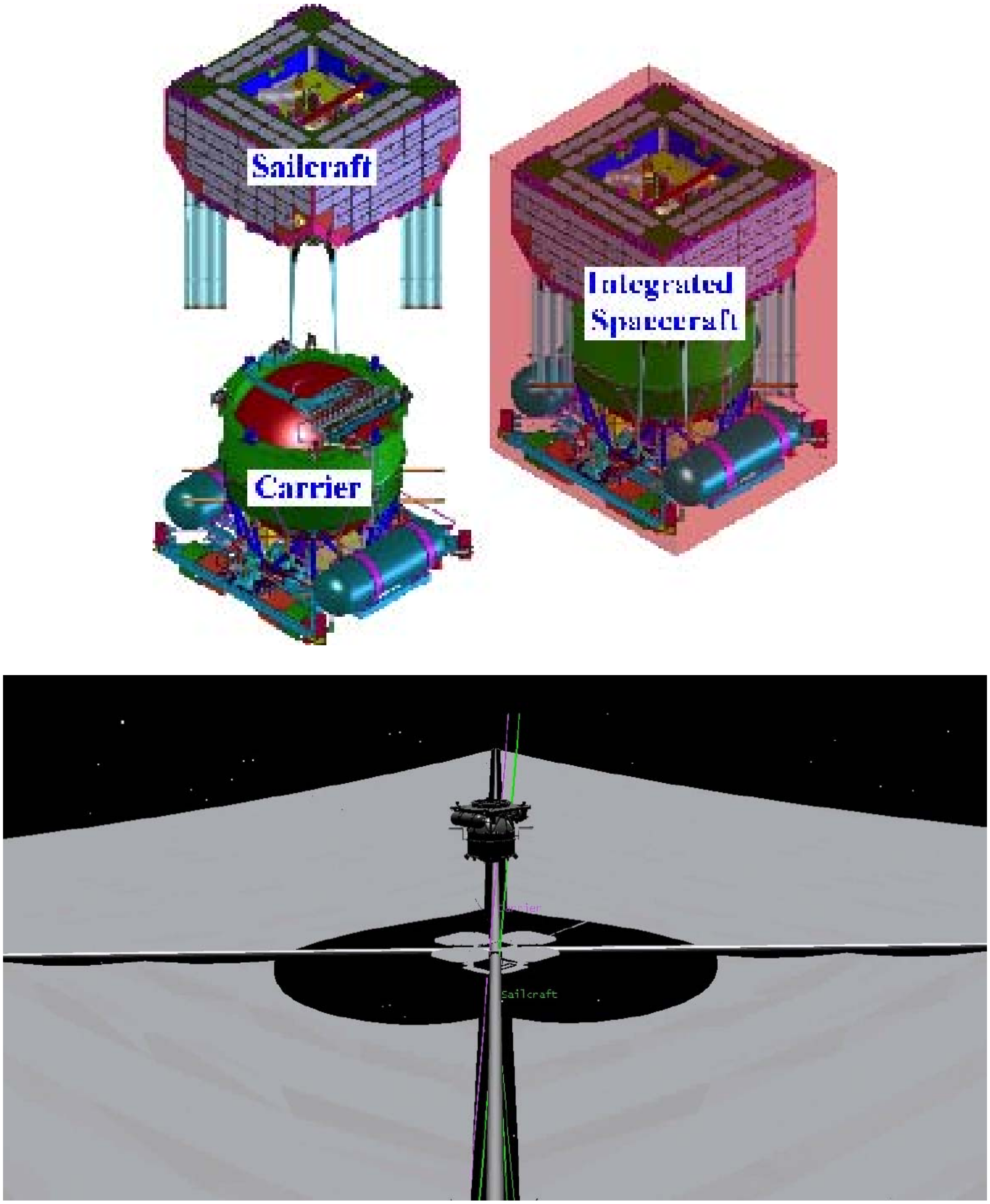

Figure 2. Packaged Sailcraft and Carrier, and Jettison Simulation

The operational sailcraft will be 1200 m^2 with a characteristic acceleration of approximately 0.25 mm/s^2. Deployment to a functional state will satisfy NASA's first requirement. An deployed overview is shown in Figure 3.

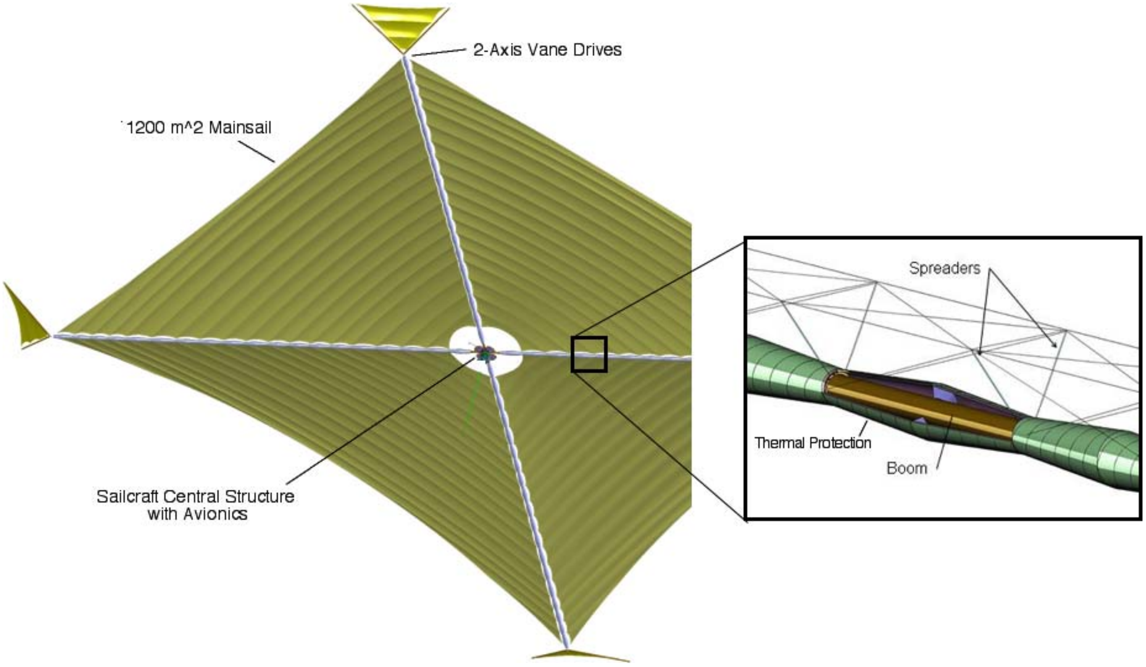

Figure 3. Major Components of the Deployed Sailcraft

Within six days of launch the sail will be calibrated for the moments that affect attitude control, then the thrust that affects navigation. The ability to retrim to new passively stable attitudes off-normal to the sunline will have been demonstrated as part of fulfilling NASA's attitude control requirements.

For the next 30 days the sail will navigate to demonstrate and fulfill the navigation requirements specified by NASA.

At this point, L'Garde desires to continue the mission to fly the sail near L1 and finally to a sub-L1 location, to stationkeep.

Along the way, the onboard magnetometer and plasma detector will be measuring particles from the Sun and comparing the results with NOAA's Advanced Composition Explorer. These important instruments are being provided by the UK Space Agency and will be instrumental in demonstrating the usefulness of solar sails in this particular application.

After six months, the sail will be recalibrated to demonstrate that it can still be controlled and navigated in the presence of degradation.

Deployment

A camera boom will be deployed first, then the vanes, then the mainsail.

All deployments are driven by L'Garde's telescopic boom deployment technology. The four mainsail booms, for example, are tapered such that they can be folded in on themselves. When pressurant is introduced, the boom deploys linearly, base-first, in a controlled and structurally stable manner, folded segment by folded segment, repeatably. The boom folding also allows rings fixed to the boom to be exposed such that the sail membrane quadrants may be attached to the boom periodically along the boom length, so the booms take the sail along for the ride. There are line management devices for the spreader system lines, and membrane management devices to keep the quadrant deploying orderly, stripe-by-stripe. A deployment in progress showing the booms pulling out the managed sail quadrants is seen in Figure 4.

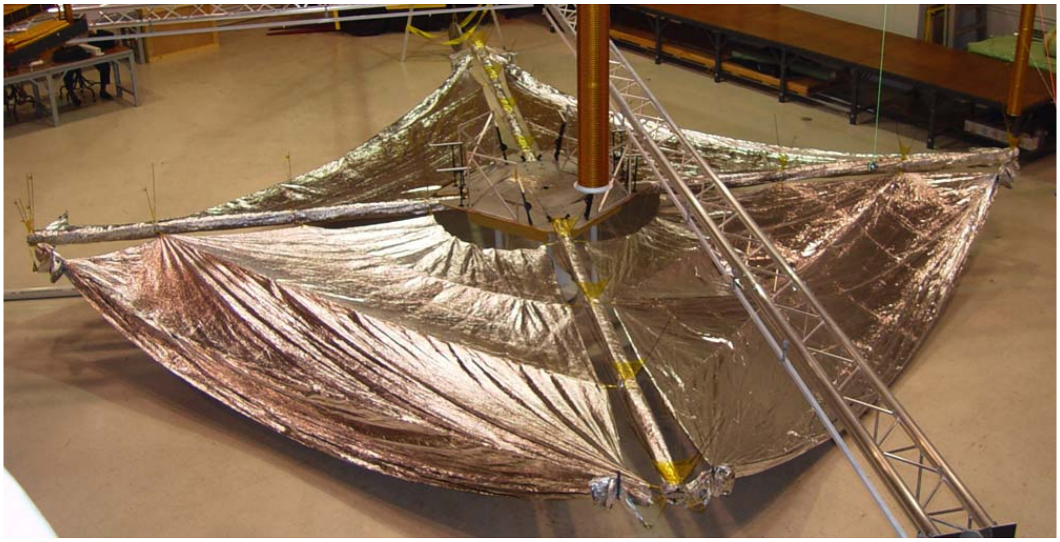

Figure 4. 10m ISP Deployment in Progress

The Sunjammer design relies on L'Garde's inflatable rigidizable technology in the sail structure. The booms are warmed before deployment to make them flexible enough to deploy. Once fully extended, the heaters are turned off and the booms allowed to cool below the glass-transition temperature of their composite matrix, under the protection of the thermal protection system. Now rigid, the booms will be intentionally vented to prevent gas-jet moments due to micrometeoroid strikes. The combination of this boom with its sunside spreader system makes an efficient scalable beam.

The sail area is built from 5µm Kapton. During previous efforts Kapton of this gauge was unavailable. However, the promise of projects like this has incited DuPont to invest in developing Kapton of sufficiently low thickness as to be credible for use in large solar sail projects. They are now marketing this film for other applications, a technology spinoff.

This design and deployment technique was matured by L'Garde through the execution of several programs including the NASA In-Space Propulsion (ISP) efforts. The major thrust of that program was scalability, both in deployment and the resulting structure. The "stripe-net" sail suspension (Greschik, Ref. 5) imparts the lowest loads possible to the beams, and together with the resulting periodic follower loading on the beam makes for a scalable structural architecture. A scaling of approximately four times was demonstrated in ISP, to the largest size that can fit in the largest vacuum chamber in the world, and Sunjammer will demonstrate another factor of four in space (Figure 5).

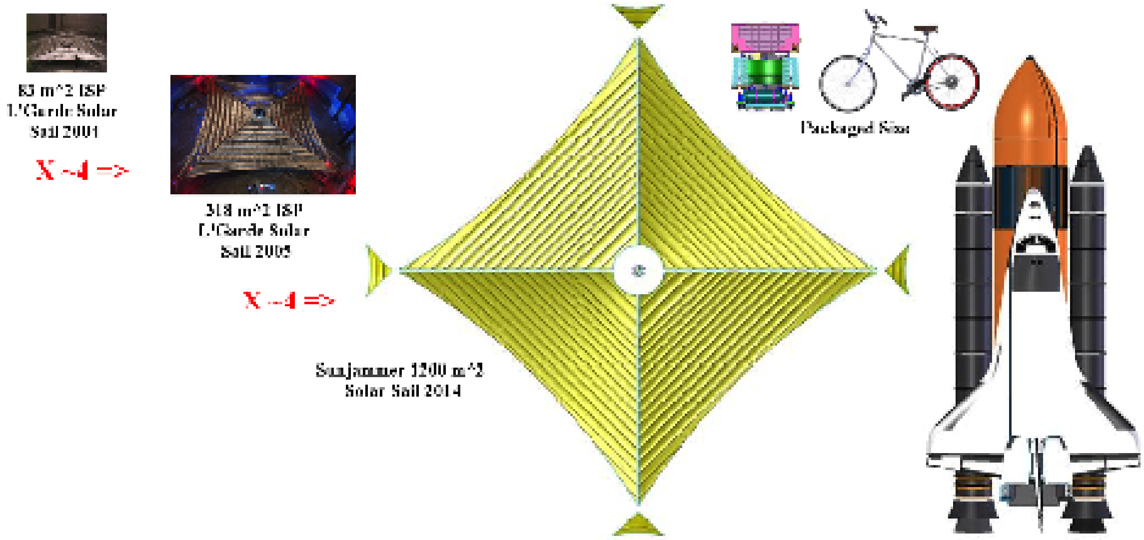

Figure 5. Scaling from ISP Deployments

The deployment will be viewed via cameras on a six-meter boom deployed sunward of the sail. There may be sponsorship logos painted on the sail surface. Carrier jettison will also be viewed, possibly from a camera on the fly-away carrier itself, which would give spectacular views of the deployed sail and Earth behind from a standoff distance.

Attitude Calibration

Sunjammer will be equipped with four vanes at the tip of the mainsail beams, each with two axes of control, "Twirl" and "Cant." With eight degrees of freedom, there are several possible ways to control attitude, but L'Garde will use a simple and safe method, and demonstrate basic backup modes.

The vanes will rely on the same technology as the sail area. The use of vanes makes the Sunjammer design truly propellantless. This will be an important feature to future mission planners who envision ultra-long solar sail flights.

All sails possess passive static stability about the two axes normal to the sunline. In addition to the familiar "drag" stabilization due to the center of mass (CM) being forward of the "center" of pressure (CP), the effectively shuttlecocked shape of the sail due to sail billow also provides stability. This can be greatly enhanced by canting the vanes antisunward, as illustrated in Figure 6.

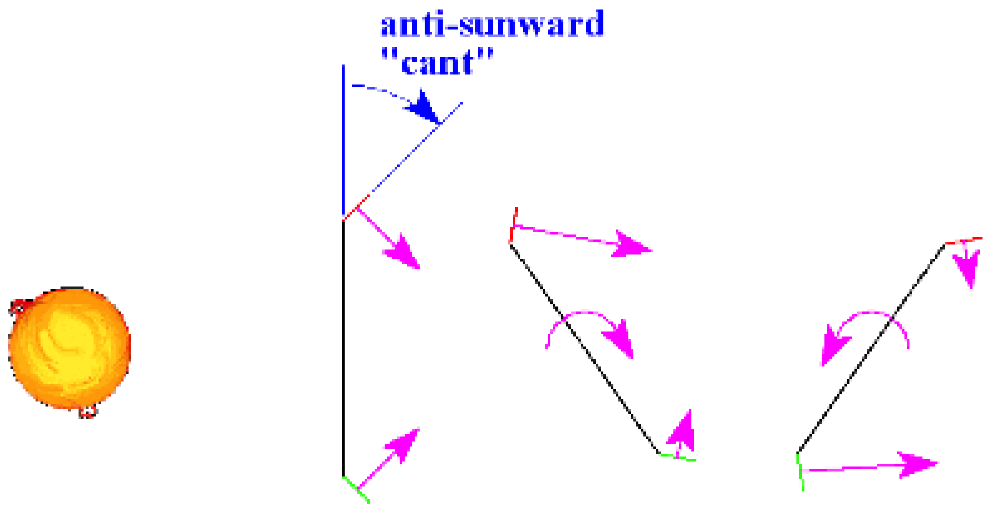

Figure 6. Restoring Moments due to Vane Cant or Mainsail Shuttlecock

(Vanes Set to Trim the Sail at Sunline-Normal)

By changing the vane cant angles, the sail can be retrimmed to an attitude off-normal to the sunline, as shown in Figure 7. This is similar to retrimming aircraft pitch using elevator trim tabs.

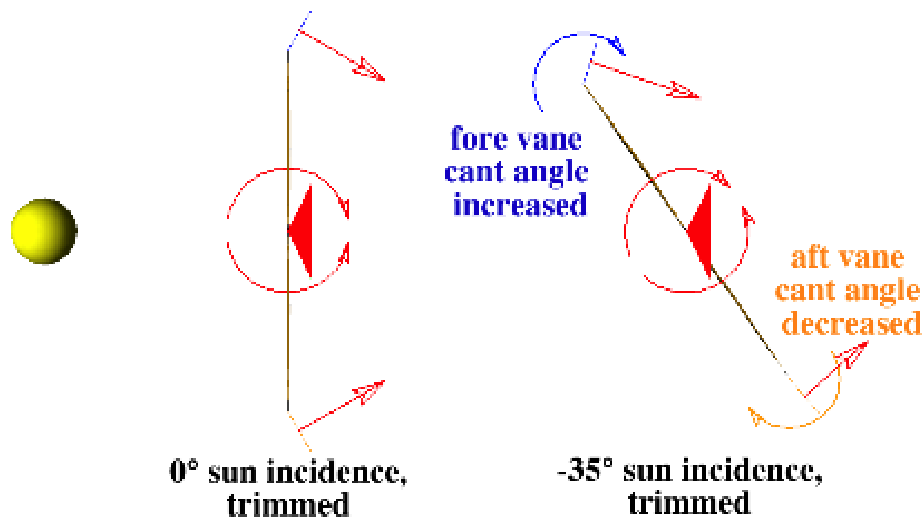

Figure 7. Retrim to Passively Stable 35° Sun Incidence Using Vane Cant Angles

There can be no passive stability about the sunline, so more spacecraft-like methods must be used to maneuver in "Top" and actively stabilize that angle. Two opposing vanes are twirled about the mainsail boom axes to produce a "windmill" torque, as shown in Figure 8.

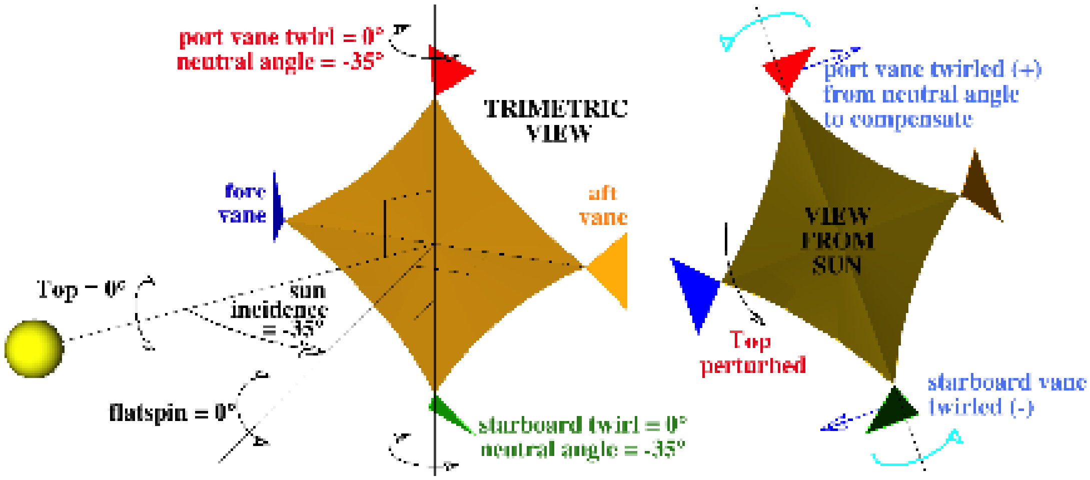

Figure 8. Differential Vane Twirl to Windmill the Sail about the Sunline

In order to perform these maneuvers, the restoring moments on the mainsail at the desired attitude must be known so that vane angles can be calculated to overcome them. The sail shape is gridded, each little element a flat plate to which is applied an elementary solar force model for its particular angle to the sun (Figure 9). The forces from all these elements are integrated to determine the total forces and moments on the mainsail.

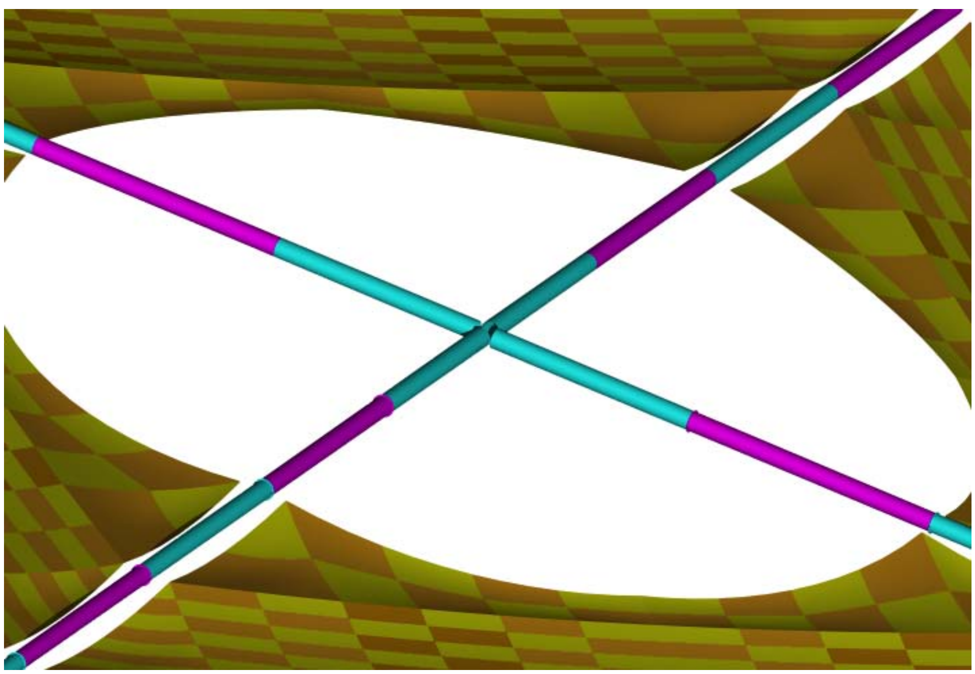

Figure 9. Sail Grid Consisting of Elemental Flat Plates

If the mainsail were simply modeled as a perfectly reflecting flat plate, there would be no restoring moments at all. If the "drag" force due to an imperfectly reflecting sail is introduced, the moment due to CM-CP offset would appear, but this may be minor compared to the effect of mainsail billow. The sail shape must therefore be captured, and as this shape is affected by bending of this gossamer structure, structural analysis must be included as well. One other significant shape effect to consider is "photoflexibility." Because the forces on an elemental piece of sail material are a function of solar attitude, as the sail flexes in response to pressure, the forces change, so the flexing must be recalculated, iteratively.

L'Garde has calculated these moments, but recognizes that as this is a gossamer structure, there will be bias moments due to imperfect balancing and shimming, as well as residual deployment effects. Sunjammer's vanes are oversized to overcome both mainsail restoring moments and estimated bias moments, with margin. Post-deployment, the sail will be calibrated using onboard attitude determination to determine the real moments vs. attitude, providing vane trim tables for the practical onboard control of the sailcraft. This attitude calibration will demonstrate the attitude accuracy required by NASA.

Thrust Calibration

Thrust calibration will follow, using ground ranging measurements. While shape effects have a major impact on attitude control, they have far less effect on thrust and navigation. What is most important is surface quality – wrinkles. This effect is captured in the elemental solar force model used by L'Garde, which differs from the frequently seen optical model.

The optics model of solar force due to reflection is flawed for two reasons:

1. The optics model separates reflected light into specular and diffuse components, and adds the resulting solar forces as scalars. However, the definition of what is "specular" in optics is actually arbitrary and restrictive (+/- 6° or +/-10° of the specular reflection line), and the resulting forces from rays reflected all about the specular reflection line, all useful to propulsion, add as vectors, not scalars.

2. The diffuse reflectance is symmetric about the specular reflection line; not about the surface normal, as is assumed in optics. In fact, there is a little more scattered forward of the specular reflection line than backward. Visibly, wrinkling simply facets the material (Figure 10). It doesn't make it diffuse. This is evidenced by the fact that total reflectivity doesn't change much even for heavily wrinkled samples.

It is possible to use the optics model on a flat plate to do trajectory simulations by assuming a mirror-high value of specularity, but when actual data for wrinkled sail membranes under pragmatically low stress is used, the optics model predicts a poorly performing sail, while actually adding force vectors from the same data shows quite good performance.

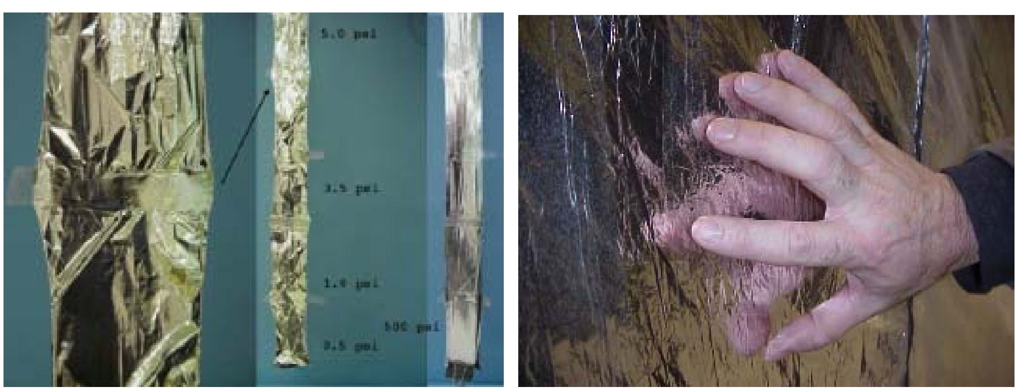

Figure 10. Wrinkles at Various Stress Levels

Seeking a better measure of the propulsive performance of wrinkled films, L'Garde in 2001 had material samples, some more wrinkled than others, tested for bi-directional reflectance (BDR) under zero stress. Forces from each individual ray reflected into the hemisphere above the sample were added as vectors. L'Garde developed a mathematical technique to boil the hundreds of data points at any solar incidence angle down to just two values, "Propulsive Reflectivity" (Rp) and "Propulsive Zenith" (Θp) (Figure 11). The resulting data indicates that despite the wrinkled appearance of the material, very good propulsive performance is attained.

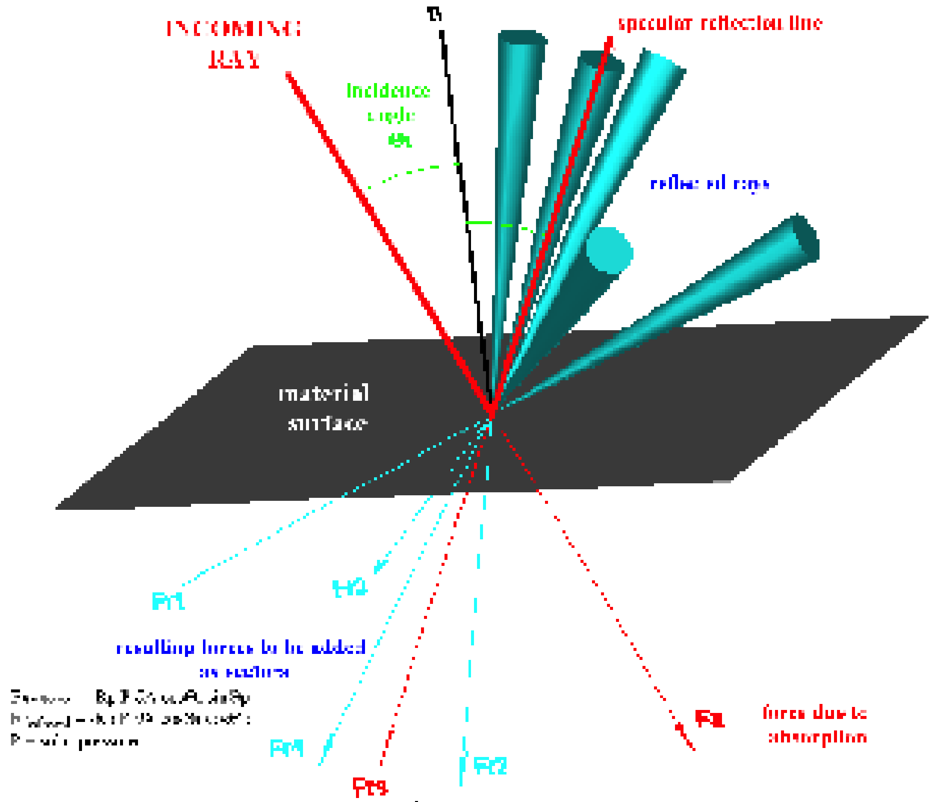

Figure 11. L'Garde's Reflected Solar Force Model is a Vector Summation of BDR Data

L'Garde theorizes that propulsive reflectivity Rp is fairly constant with incidence angle, and that propulsive zenith Θp, which must be zero at zero incidence, varies from actual incidence Θi only mildly with increasing incidence angle, due to forward scattering. We call on interested experimenters to take bi-directional reflectance data on sail films at other incidence angles.

Total forces are summed from the elemental flat plates in the gridded model of the shaped sail. Because there will be coating and wrinkle variations throughout the sail which cannot be fully evaluated, the sail thrust must be calibrated on-orbit. This will allow better navigation solutions, starting with the 30 day NASA-required navigation sequence immediately following calibration.

There is also a requirement to recalibrate the sail after six months. The intention is not to isolate the reason for any degradation, but rather to demonstrate that the sail can still be flown in the presence of degradation. This is true as well of the initial attitude and thrust calibrations. There is not instrumentation to determine why the sail is different than predicted, nor is there a requirement to validate our predictive models, but calibration will allow us to better demonstrate attitude control and navigation despite these differences.

Flyout and Other Extended Operations

L'Garde intends to operate the spacecraft for 1 year. After the completion of this one year flight, the ultimate infusion goal is to hand over operation of the spacecraft to an interested party. The spacecraft can then be used directly by another organization to demonstrate its capabilities. NOAA is one infusion partner with L'Garde. Possible activities include extended stationkeeping, polesitting, and transfers.

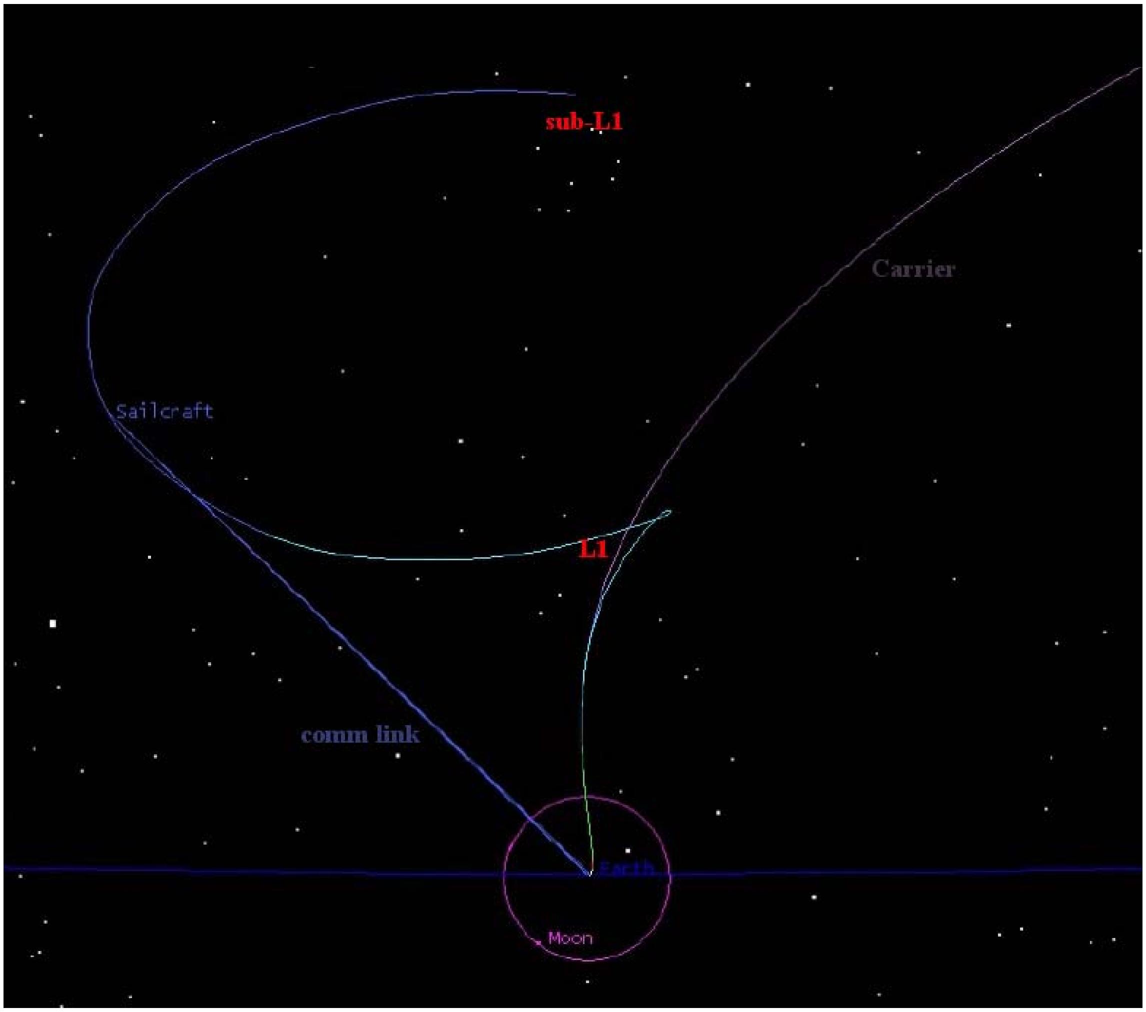

Figure 12. Flyout to Sub-L1

Conclusion

The L'Garde built Sunjammer, with its planned 2014 launch, will fully demonstrate the propellantless propulsion potential of solar sails. Upon completion of this Technology Demonstration Mission (TDM) flight, mission planners will have a flight-proven scalable solar sail design with which to build operations around. The technologies required for future larger sail missions will be demonstrated in this single mission. This relatively inexpensive mission will greatly advance the solar sail technology that NASA has already invested in. It will provide NASA and the USA with a solar sailing technology and capability that is second to none.

NASA's Space Technology Mission Directorate is providing the necessary leadership and support to sail this flight-ready technology to the launch pad.

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