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# Solar Sail Technology for Nanosatellites

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**Solar sailing is an attractive means of spacecraft propulsion because it extracts momentum from electromagnetic radiation supplied by the Sun. This allows a solar sail spacecraft to accomplish new classes of missions that would otherwise require a prohibitive amount of propellant. Unfortunately, solar radiation pressure is meager, requiring a large area-to-mass ratio to produce significant accelerations. A solar sailing nanosatellite achieves this with a dramatically reduced mass allowing a smaller sail to generate significant accelerations. This sacrifice of slightly less capability for an immense gain in reduced cost and complexity is the motivation behind Stanfords solar sailing nanosatellite project, SailSat.**

## Nomenclature

| | |
|---|---|
| $\vec{u}_i$ | Incoming photons vector |
| $\vec{u}_r$ | Reflected photons vector |
| $\vec{f}_i$ | Force vector from incoming photons |
| $\vec{f}_r$ | Force vector from reflected photons |
| $\vec{n}$ | Sail normal vector |
| $\vec{f}_{srp}$ | Solar radiation pressure force vector, N |
| $P$ | Solar radiation pressure in Earth's vicinity, N/m$^2$ |
| $\alpha$ | Sail angle of attack |
| $\vec{a}_{srp}$ | Solar radiation pressure acceleration vector, m/s$^2$ |
| $m_s$ | Total spacecraft mass, kg |
| $a_o$ | Characteristic acceleration, mm/s$^2$ |
| $\vec{a}_d$ | Atmospheric drag acceleration vector, m/s$^2$ |
| $\rho$ | Atmospheric density, kg/m$^3$ |
| $C_D$ | Spacecraft coefficent of drag |
| $V$ | Magnitude of spacecraft velocity, m/s |
| $\hat{\vec{v}}$ | Spacecraft velocity unit vector |
| $\vec{T}_{GG}$ | Gravity gradient torque, N m |
| $r$ | Distance from central body, m |
| $\hat{\vec{r}}$ | Spacecraft location from central body unit vector |
| $I$ | Spacecraft moment of inertia matrix, kg m$^2$ |
| $G$ | Gravitational constant, 6.67E-11 m$^3$/kg/s$^2$ |
| $M_{sun}$ | Mass of the sun, kg |
| $\omega$ | Angular acceleration, 1/s$^2$ |
| $\tilde{r}$ | Distance from central body at artificial Lagrange point, m |

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## I. Introduction

Solar sailing is an attractive means of spacecraft propulsion because it does not rely on reaction mass like conventional systems. Instead a solar sail extracts momentum from electromagnetic radiation supplied by an ambient source, the Sun. By removing the restriction of finite reaction mass, a solar sail spacecraft can be propelled by a continuous thrust limited only by the lifetime of the sail itself.[1] This allows a sailcraft to complete many missions that would require a prohibitive amount of propellant otherwise.

Unfortunately, solar radiation pressure is very small, requiring a large area to mass ratio to produce significant accelerations. Standard mission concepts have focused on increasing the sail area to accommodate a large payload. A solar sailing nanosatellite mission concept explores the opposite idea, drastically lowering the mass of the payload and bus to allow for a smaller sail. This paper begins with a brief introduction to solar sailing followed by preliminary designs of a solar sailing nanosatellite, tentatively named SailSat. Next, mission applications in low Earth orbit and beyond are discussed with the aid of Satellite Tool Kit simulation results including the effects of perturbational forces and torques. The paper concludes with an overview of interesting topics in solar sailing research.

## II. Solar Sailing

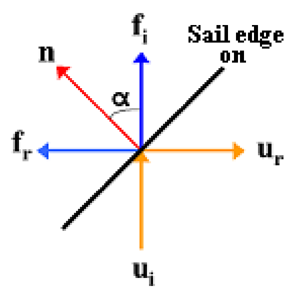


**Figure 1. Solar sailing forces resulting from incoming and reflected photons**

Solar sails derive their propulsive force from solar radiation pressure, photons of light from the sun. These photons, though massless, carry momentum that impart a force on anything they strike. In figure 1, the incoming photons travel in the direction of $u_i$ and strike the sail producing the force $f_i$. Solar sails are reflective so the photons bounce away in the direction of $u_r$. This also produces a force, $f_r$, to conserve momentum. The ideal solar sail is 100% reflective so the two forces are equal and sum together to give a total force in the direction of the sail normal, $\vec{n}$. The general equation for the force on an ideal solar sail is

$$\vec{f}_{srp} = 2PA\cos^2\alpha\,\vec{n} \tag{1}$$

$$P = 4.67 \times 10^{-6}\ \mathrm{N/m^2} \tag{2}$$

where $P$ in equation 2 is the solar radiation pressure in the Earth's vicinity. This term varies with the inverse square of the spacecraft's distance from the Sun; as the spacecraft gets closer to the Sun, the radiation pressure gets larger. $A$ is the sail area while $\alpha$ is the angle the sail normal makes with the direction of the incoming photons. The factor of two comes from the addition of the two equal forces, $f_i$ and $f_r$.[2]

As can be seen from equation 1, a solar sail must have a very large area to produce a sizable force. Fortunately, the size of the force is not what matters for solar sailing spacecraft, it's the acceleration as given by

$$\vec{a}_{srp} = \frac{\vec{f}_{srp}}{m_s} = 2P\left(\frac{A}{m_s}\right)\cos^2\alpha\,\vec{n} \tag{3}$$

Equation 3 shows that a large area to mass ratio is required to produce a large acceleration due to solar radiation pressure. In fact, the characteristic acceleration is directly proportional to this ratio and is defined as the acceleration the sail would produce at 1 AU with the sail oriented perpendicular to the incoming photons ($\alpha = 0$):

$$a_o = 9.34 \times 10^{-3}\left(\frac{A}{m_s}\right)\mathrm{mm/s^2} \tag{4}$$

It is the largest acceleration the sail can produce at 1 AU. Typical values for characteristic acceleration are on the order of 0.1 to 1 mm/s$^2$.

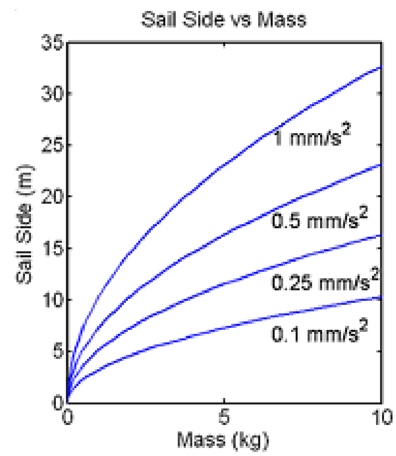


**Figure 2. Constant characteristic acceleration curves for a square solar sail show reduced sail size requirement for reduced mass. A solar sailing nanosatellite takes advantage of this property.**

The characteristic acceleration offers a useful way for comparing two solar sailing spacecraft. Two sailcraft with the same characteristic acceleration can perform the same maneuvers and would always tie in a race regardless of their individual masses and areas. Figure 2 illustrates that when the total mass of the spacecraft is reduced, the curves of constant characteristic acceleration converge. A solar sailing nanosatellite exploits this feature. By drastically reducing total mass, a solar sailing nanosatellite only requires a modestly sized sail to produce significant accelerations. A smaller sail should be easier to manufacture, package, deploy, and maintain compared to the larger sails used in typical solar sail mission designs. The larger sails are often a necessity to produce the desired acceleration given some massive payload. With the vast reduction in mass of viable scientific payloads, this is no longer required.

To use a solar sail to change an orbit, one must articulate the sail with respect to the sun to direct the force into a desired direction. This can be done, for example, by displacing the center of mass from the center of pressure thereby causing the force due to solar radiation pressure to create a torque.

The best direction to apply the force for a desired orbit change is not entirely obvious. Consider a solar sailing spacecraft orbiting the sun at some initial radius. To increase that radius, the sail normal would be angled to give a component of force along the velocity direction. One might assume that simply directing the force away from the Sun would be the best strategy. This is not the case because in order to increase orbital radius, one must increase orbital energy. This is done by directing some component of force in the direction of velocity. In this case, the sail is doing work on the orbit.

The converse also holds. Directing some component of force in the direction opposite of velocity will do negative work on the orbit and decrease the orbital energy. This in turn shrinks the orbital radius. In standard sailing terminology, sailing against the wind is called tacking, so it is no surprise that the solar sailing community has adopted it to describe sailing towards the Sun. To change the other orbital elements, one must know how a perturbing force affects that element. This information is given by the Gauss form of the Lagrange Planetary Equations, but is beyond the scope of this paper.[3]

## III. SailSat

The solar sailing nanosatellite group at Stanford University has only begun to scratch the surface in terms of design. There are many ways to design a solar sailing spacecraft, see figure 3, but, unfortunately, no one knows the best way to do so. All of the design types have their own strengths and weaknesses. Initial designs of SailSat have adopted the square sail design supported by four deployable booms as shown in figure 4. This design is much easier to control than the heliogyro or spinning sail types, however, it is slightly more difficult to deploy because it must rely on unfurling booms rather than centripetal acceleration to support the sail.

In the stowed configuration, SailSat will conform to the triple CubeSat standard, $30 \times 10 \times 10$ cm$^3$, to be


**Figure 3. The three main sail design types are square, heliogyro, and spinning disk. SailSat will likely use a square sail design for its simplicity.**

easily deployed from California Polytechnic State University's Poly Picosatellite Orbital Deployer (P-POD).[4] When given the command to deploy the sail, hinged solar panels similar to those found on a previous Stanford satellite, QuakeSat,[5] could be released allowing the sail support booms and sail to unfurl. Previous design studies on drag sails at Stanford have shown that rolled up strips of carpenter's tape work well for stowage and self deployment of smaller sails. Figure 5 shows the deployed drag sail made from a mylar camping blanket.

In addition to solar sail designs, there are also many sail materials to choose from. The most common are

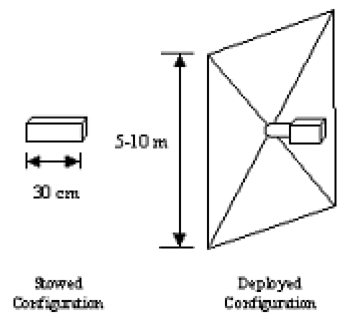


**Figure 4. SailSat initial conceptual design in the stowed and deployed configuration - Not to scale**

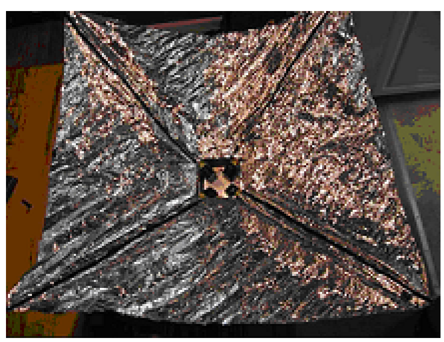

**Figure 5. 0.58 $m^2$ drag sail deployment prototype made from a mylar survival blanket. Stowed volume: 5 $\times$ 10 $\times$ 10 $cm^3$**

very thin aluminized Mylar or Kapton films with areal densities of around 7 $g/m^2$ and 12 $g/m^2$ respectively. SailSat is planned to use a film similar to Kapton called CP1, which has an areal density of 5 $g/m^2$. CP1 is a polyimide that can incorporate both a highly reflective surface and rip stop properties in a large area film with a thickness of about 2.5 microns.[6] The company that produces CP1, SRS Technologies, has offered the solar sailing nanosatellite group samples of their material for testing, prototyping, and space qualification.

Other materials under consideration are curved thin film shells produced by Mevicon, Inc. The films are a bit thicker than their standard counterparts, but they make up for this with inherent stiffness due to curvature, compact roll stowage, deterministic self deployment, and self rigidization.[7] The shells are spherically curved so that they are self supporting even in 1-g. This combined with self deployment would greatly reduce the requirements of the sail support structure, potentially reducing its mass enough to compensate for the thicker material. Samples of Mevicon's material have been donated to the group and are pictured in figure 6.

**Figure 6. Mevicon's thin film shells are self supporting in 1 g and roll into thin cylinders for compact stowage.**

There are several options still under consideration for the design of SailSat. The solar sailing nanosatellite group's current activities include building prototypes of deployment mechanisms in the sizes we are interested in, testing available materials for deployability and survivability, and performing trade studies to choose the best design. These tasks will continue into the next school year as part of Stanford's satellite design course.

## IV. Solar Sail Missions

### A. Low Earth Orbit

In addition to what is best structurally, SailSat's design will be very mission dependent. SailSat's first mission, in one to two years, is targeted to be a low-cost technology demonstration mission in low Earth orbit to test deployment, sail survivability, and the sail control system. This is a necessary first step to prove the feasibility of our design before attempting more exotic missions beyond LEO.

A sail deployment test is required because it is a single of point failure for all solar sailing missions, a fact that makes any mission planner nervous. Several space agencies have tested the deployment of large gossamer space structures. Most recently the Japan Aerospace Exploration Agency, JAXA, deployed solar sails from sounding rockets, see figure 7. In our case, SailSat has an advantage over typical solar sailing spacecraft because it is attempting to deploy a much smaller sail.

**Figure 7. JAXA deploying a clover shaped solar sail in August 2004**

Once the sail is deployed, we would like to monitor its health in the harsh environment of space. Solar UV radiation would act to destroy the plastic substrate of the solar sail material, while the solar wind could cause a charge difference between the front and back of the sail that could result in a damaging discharge. Additionally, the vast ranges of temperatures in space could cause thermally-induced structural failure. To combat these effects, the sail material should be chosen based on good UV resistance, the front and back surfaces should be in electrical contact, and the orbit should be chosen to limit thermal cycles.

Also micrometeorite impacts could puncture the sail requiring rip stops to prevent large tears.[2] SailSat at first will have no way of repairing damage due to the space environment, so our only recourse is to monitor the sail and plan accordingly for the next mission. SailSat will have cameras to capture the sail's deployment and image the sail throughout the mission. Also, the sail's performance will give information about its health based on how much acceleration it is generating.

After deployment, testing of the sail control system will begin; SailSat will start sailing. For a LEO mission, control torques to change the sail's orientation with respect to the Sun are planned to be applied through magnetic torque coils and momentum wheels. This will keep system complexity low and enable orientation of the sail in the Earth's shadow. Ideally, SailSat will be in a terminator orbit, meaning the spacecraft is always in the Sun, allowing the sail to generate continuous thrust. This thrust will be used to shrink and grow SailSat's orbital radius, while slightly perturbing the orbital plane to maintain the terminator orbit.

The sail controller will also have to deal with perturbational forces and torques caused by non-spherical Earth, atmospheric drag, gravity gradient, and gravitational forces of the Moon and Sun. Some of these forces can be useful. For instance, the effect of a non-spherical Earth is to precess the right ascension of the ascending node, which can be used to help maintain the terminator orbit. The equation for atmospheric drag is given by

$$\vec{a}_d = -1/2\rho \left( C_D \frac{A}{m_s} \right) V^2 \,\hat{\vec{v}} \tag{5}$$

It always acts in the opposite direction of velocity, so energy is always removed from an orbit. Below approximately 700 km, the atmospheric density, $\rho$, is large enough to make the acceleration from atmospheric drag overwhelm any accelerations produced by a solar sail; in effect, the solar sail becomes a drag sail. Above this altitude it is possible to produce acceleration from the solar radiation pressure that are greater than those from drag, allowing a sailcraft to boost its orbit even higher.

Also of concern in low Earth orbit is the effect of gravity gradient torque given by

$$\vec{T}_{GG} = \frac{3\mu}{r^3} \hat{\vec{r}} \times \left( I \hat{\vec{r}} \right) \tag{6}$$

It has been demonstrated that this torque can overwhelm attitude control systems on standard solar sailing spacecraft in LEO unless particular orbits and sail orientations are selected.[8] We are still looking into how this torque scales down to nanosatellite proportions. It is possible that when acting on a much smaller sail, the gravity gradient disturbance torque can be managed by properly sized magnetic torque coils and momentum wheels. Third body gravitation has a measurable effect, but it typically affects only long-term changes in the orbital elements.

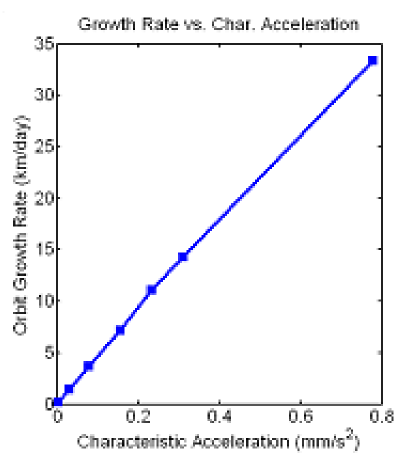


**Figure 8. Orbit growth rate vs characteristic acceleration for initial 800 km terminator orbit with near optimum sail pointing strategy**

A Satellite Tool Kit (STK) simulation was run for an 800 km altitude terminator orbit using solar sailing spacecraft with varying characteristic accelerations. At each time step, the sails were oriented in such a way as to maximize the component of force in the velocity direction. The systems were propagated using a seventh order Runge-Kutta-Fehlberg integrator with eighth order error control including the effects of non-spherical Earth, atmospheric drag, and third body gravitation. Absolute and relative error tolerances were $10^{-9}$ and $10^{-12}$ respectively. From these simulations, orbital growth rate was estimated from observed secular variation in the semi-major axis. These results are plotted in figure 8, and are roughly linear.

This means that in terms of orbital growth, ten days with a characteristic acceleration of 0.1 mm/s$^2$ would equal one day with a characteristic acceleration of 1 mm/s$^2$. Since time is not a factor in this simple demonstration mission, SailSat can exploit this feature and reduce the size of the sail even more. If SailSat's total mass were 5 kg and it could deploy a 5 $x$ 5 m$^2$ sail, its characteristic acceleration would be a modest 0.05 mm/s$^2$ allowing it to boost an orbit roughly 1.5 km/day. This is more than enough to verify that the control system can orient the sail and make a controlled orbit change.

A successful solar sail mission would raise solar sail's technology readiness level (TRL) to seven meaning a system prototype has been demonstrated in a space environment. Raising the TRL level would boost mission planner's confidence in solar sails and perhaps inspire other follow up missions. By using donated sail material, COTS parts, and student labor, SailSat would do all this and more for relatively low cost.

### B. Geosail

The next logical step is a space weather mission in the Earth's geomagnetic tail, typically referred to as Geosail or Solar Kite.[9] The Earth's geomagnetic tail comes about from the interaction between the solar wind and the Earth's magnetic field and rotates about one degree per day to always remain along the Earth-Sun line. A drawing of the geomagnetic tail appears in figure 9.

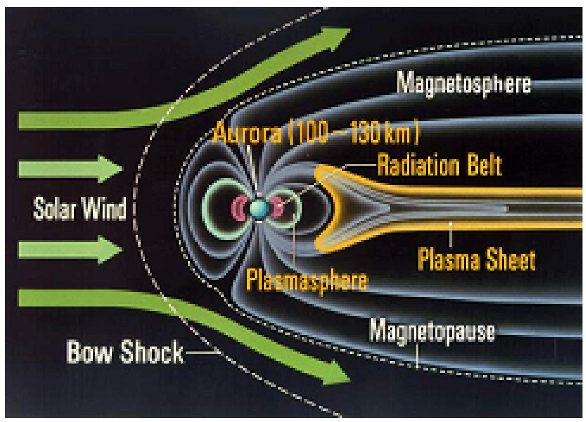


**Figure 9. Solar wind blows the Earth's magnetic field away from the sun producing the geomagnetic tail.**

Measurements of the environment inside the geomagnetic tail are quite important to the space physics community, but the rotation of the tail makes year-round measurements impractical for a conventional spacecraft, which generally has an inertially fixed orbit. The spacecraft would have to artificially precess its orbit one degree per day by using propellant to create a continuous low thrust or an ever present series of high impulsive thrusts. On the other hand, a solar sail is ideally suited for generating the continuous low thrust required to precess an orbit 0.9856 deg/day to match the rotation of the geomagnetic tail thus enabling year-round measurements.[10]

The required characteristic acceleration for sun-synchronous apse line precession is only dependent on the desired orbit's apogee radius and perigee radius. For a scientifically interesting $11 \times 23$ Earth radii elliptical orbit, a characteristic acceleration of only 0.11 mm/s$^2$ is required.[9] This acceleration can be achieved by a three kg sailcraft with a square sail that is six meters on a side. Relevant sensors such as magnetometers, plasma detectors, and PIE detectors exist with sizes and power requirements small enough to fit on a nanosatellite in addition to standard bus systems. Those for the Solar Kite mission were chosen with mass less that 0.85 kg and power consumption under five watts.[9]

An STK simulation was run for this mission using the sailcraft described above. The same integrator and perturbing forces were used as before for the LEO simulation, but the absolute and relative error tolerances were both increased to $10^{-8}$ to limit integration time. The orbit was propagated for 100 days with the solar sail precessing the apse line to remain sun-synchronous. The results are illustrated in figure 10. The picture was taken from STK at the start of the simulation in a view from the north pole looking downward. During the simulation, the Earth's shadow, hence the Earth-Sun line, sweeps around counter-clockwise while the apse-line of the orbit follows.

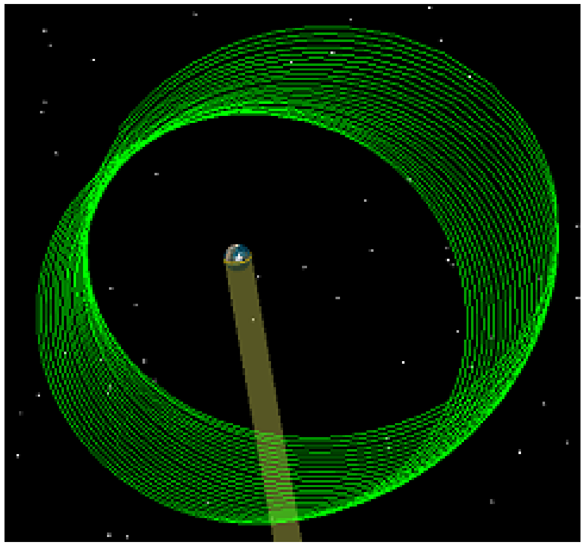

**Figure 10. With the proper sail orientation, the argument of perigee can be precessed to be in sync with the Earth-Sun line. This continuous orbit perturbation would require far too much fuel for a conventional spacecraft.**

In the simulation, the sail was programmed to reorient itself every 15 minutes using the Accessibility and Deficit (AnD) blending method.[11] This method calculates the optimal pointing direction based on how far orbital elements are perturbed from their desired values. This steering method reduces the required characteristic acceleration slightly, but requires knowledge of position and velocity. Another benefit of the geosail orbit is that an entirely passive steering method can be used to maintain it. Simply aligning the sail normal with the Sun vector ($\alpha = 0$) causes the necessary precession of the apse line while producing no long-term variation in the other elements. This alignment can be maintained passively if the spacecraft's center of mass is closer to the sun than the sail's center of pressure.

## C. Geostorm

The constant acceleration produced by a solar sail can be used to put the spacecraft in a non-Keplerian orbit; the sailcraft does not orbit like a standard spacecraft. An example of this is using the sail to create artificial Lagrange points. There are five points in every two body system where the gravitational accelerations from both bodies cancel with the centripetal acceleration from rotation. These are called Lagrange points.[12] A properly oriented solar sail can create entire artificial Lagrange surfaces where the gravitational accelerations and centripetal accelerations are canceled by the acceleration from the sail.

When any spacecraft is in a circular orbit about the Sun, the gravitational acceleration and the centripetal acceleration exactly cancel:

$$\frac{GM_{sun}}{r^2} = \omega^2 r \tag{7}$$

Imagine the same spacecraft keeping the same angular velocity, $\omega$, but reducing the distance from the Sun, $\tilde{r} < r$. In this case, the gravitational acceleration on the left hand side of equation 7 increases, while the centripetal acceleration on the right hand side decreases leaving the equation unbalanced. If the spacecraft had a solar sail, it could direct the acceleration away from the Sun to re-balance the equation:

$$\frac{GM_{sun}}{\tilde{r}^2} = \omega^2 \tilde{r} + a_{srp} \tag{8}$$

Thus, solar sails can orbit the sun at a lower radius while maintaining an angular velocity that satisfies equation 7 for a higher radius. This is the key mechanism for creating an artificial Lagrange point.

In the Earth-Sun system, L1 is the Lagrange point between the two bodies. Near L1, local accelerations are quite small (since gravitational and centripetal accelerations have almost canceled), so even a modest solar sail can use the trick above to create an artificial L1 much closer to the sun. For instance, a solar sail with a characteristic acceleration of 0.25 mm/s$^2$ can push this artificial L1 point twice as close to the Sun as normal.[1] This particular vantage point is extremely useful to the space weather community and is the desired orbit for the Geostorm mission.

Located twice the distance sunward as L1, the Geostorm mission would act as an early warning system for dangerous coronal mass ejections that can disrupt the Earth's magnetosphere, cause power outages, damage satellites, and even harm astronauts. Because it is an unstable Lagrange point and due to radio interference from the Sun, satellites are not stationed exactly at L1. Instead they enter a halo orbit about L1. For these same reasons, the Geostorm mission requires a halo orbit about the artificial Lagrange point. The Geostorm orbit, along with that of the Advanced Composition Explorer, or ACE, is pictured in figure 11.[13]

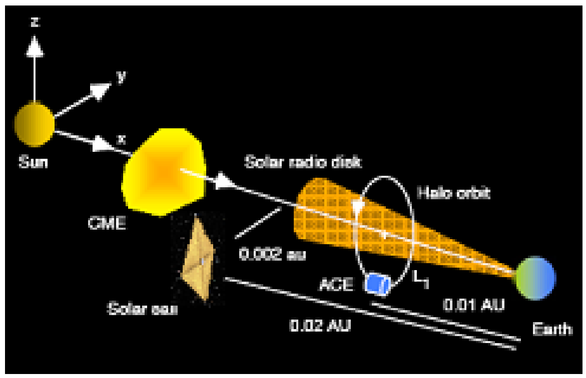


**Figure 11. The Geostorm mission requires the solar sailing spacecraft to enter a halo orbit between the Earth and the Sun much closer to the Sun than L1.**

Because of moderate sail requirements and large scientific impact, the Geostorm mission seems like another logical next step beyond either the Geosail or the LEO demonstration missions. It can in turn be used as a stepping stone for even more advanced missions, such as visits to near Earth asteroids or the inner planets. These missions, including Geosail and Geostorm, are long term goals for the solar sailing nanosatellite group, but our first focus is on a LEO demonstration mission.

## V. Research Topics

Solar sailing is an exciting subject because there are many areas of active research. For instance, globally optimum (minimum time) transfer trajectories for many mission scenarios are still unknown. It is actually quite difficult to answer the question: "How do I get from this orbit to the next in minimum time?" It does not appear to be a convex optimization problem: the search space for transfer trajectories is plagued with local optima, solutions that are better than those similar to them, but are still not the best. One method uses a genetic algorithm and a neural network to cleverly traverse the search space. This mechanism for searching is called an evolutionary neurocontroller, and it has found trajectories that take much less time than those previously thought to be optimal.[14] Even so, globally optimal solutions are highly desired to quantify suboptimality.

Others have abandoned global optimality to instead focus on practicality. The AnD blending method mentioned in the Geosail section is only locally optimal, but would be very easy to implement onboard the spacecraft.[11] It requires knowledge of the current and desired orbits and a set of user defined weights to help the blending method. These weights can require some in depth knowledge of solar sail orbits and the blending method is simply a weighted sum. The author of this paper is currently modifying the AnD blending method to use weighted least squares. This method was applied to the Geosail orbit and was found to reduce the required characteristic acceleration greatly. This implies a more efficient use of the sail.

Attitude control is another area of active research, and it is generally separated from trajectory control due to the differing timescales. Nevertheless, a sailcraft must be able to orient itself with respect to the Sun in order to change its orbit thus the two are coupled. The most common method for attitude control is to displace the center of mass from the center of pressure. The force from solar radiation pressure acts at the center of pressure, which causes a torque if this point is not at the center of mass. Some designs displace the center of mass directly by manipulating the mass distribution of the spacecraft, while others displace the center of pressure by changing the configuration of the sail. See references[15] or[16] for more information.

Another way is to use thrusters at the edges of the sail, or, as in the case of the LEO demonstration mission described previously, magnetic torque coils could be used. There is no best way, and most methods require very complicated controls. Eventually attitude and trajectory control will merge because some "optimal" trajectories require impossible amounts of control authority. This merger is another area of research.

Additionally, attitude control and trajectory control will have to deal with realistic sail conditions. The first solar sail is not going to be ideal. It's not going to reflect 100% of the incoming photons, it's going to have wrinkles and cracks, and it's going to billow in the light like a terrestrial sail billows in the wind. All of these effects need to be quantified into a realistic sail model,[17] and then accounted for.

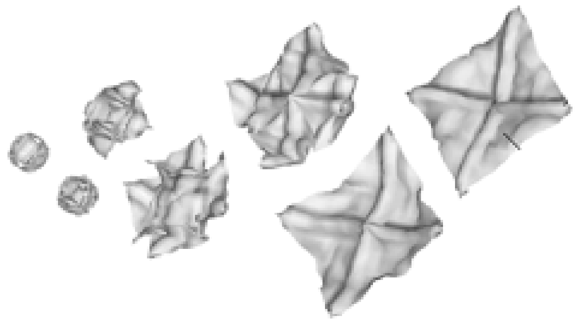

**Figure 12. Solar Kite's inflation simulation**

Finally, sail deployment is an active topic because, unfortunately, no one knows the easiest and most reliable way to deploy a sail. Some prefer the standard square sail supported by four booms, while others favor the spinning sails that rely on centripetal acceleration. Others use inflatable booms that rigidize in the space environment as illustrated in figure 12.[9] The method of deployment feeds back heavily into overall sail design and attitude control.

# VI. Conclusion

With the miniaturization of worthwhile scientific payloads, solar sailing nanosatellites may become the most viable platforms for solar sailing in the near future. By decreasing total mass, a much smaller sail can produce significant accelerations. The solar sailing nanosatellite group at Stanford University hopes to demonstrate this concept with a solar sail mission in low Earth orbit within one to two years. This mission will be a stepping stone to more exotic missions with particular interest to those dealing with space weather. In addition to being a unique and elegant form of propulsion, solar sailing also has many active areas of research to keep graduate students busy. It's a very exciting time for solar sails.

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