Solar and Drag Sail Propulsion: From Theory to Mission Implementation

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Abstract

Solar and drag sail technology is entering the mainstream for space propulsion applications within NASA and around the world. Solar sails derive propulsion by reflecting sunlight from a large, mirror- like sail made of a lightweight, reflective material. The continuous sunlight pressure provides efficient primary propulsion, without the expenditure of propellant or any other consumable, allowing for very high ΔV maneuvers and long-duration deep space exploration. Drag sails increase the aerodynamic drag on Low Earth Orbit (LEO) spacecraft, providing a lightweight and relatively inexpensive approach for end-of-life deorbit and reentry.

Since NASA began investing in the technology in the late 1990’s, significant progress has been made toward their demonstration and implementation in space. NASA’s Marshall Space Flight Center (MSFC) managed the development and testing of two different 20-m solar sail systems and rigorously tested them under simulated space conditions in the Glenn Research Center’s Space Power Facility at Plum Brook Station, Ohio. One of these systems, developed by L’Garde, Inc., is planned for flight in 2015. Called Sunjammer, the 38m sailcraft will unfurl in deep space and demonstrate solar sail propulsion and navigation as it flies to Earth-Sun L1. In the interim, NASA MSFC funded the NanoSail-D, a subscale drag sail system designed for small spacecraft applications. The NanoSail-D flew aboard the Fast Affordable Science and Technology SATellite (FASTSAT) in 2010, also developed by MSFC, and began its mission after it was ejected from the FASTSAT into Earth orbit, where it remained for several weeks before deorbiting as planned.

NASA recently selected two small satellite missions for study as part of the Advanced Exploration Systems (AES) Program, both of which will use solar sails to enable their scientific objectives. Lunar Flashlight, managed by JPL, will search for and map volatiles in permanently shadowed Lunar craters using a solar sail as a gigantic mirror to steer sunlight into the shaded craters. The Near Earth Asteroid (NEA) Scout mission will use the sail as primary propulsion allowing it to survey and image one or more NEA’s of interests for possible future human exploration. Both are being studied for possible launch in 2017.

The Planetary Society’s privately funded LightSail-A and -B cubesat-class spacecraft are nearly complete and scheduled for launch in 2015 and 2016, respectively. MMA Design launched their DragNet deorbit system in November 2013, which will deploy from the STPSat-3 spacecraft as

an end of life deorbit system. The University of Surrey is building a suite of cubesat class drag and solar sail systems that will be launched beginning in 2015.

As the technology matures, solar sails will increasingly be used to enable science and exploration missions that are currently impossible or prohibitively expensive using traditional chemical and electric rockets. For example, the NASA Heliophysics Decadal Survey identifies no less than three such missions for possible flight before the mid-2020's. Solar and drag sail propulsion technology is no longer merely an interesting theoretical possibility; it has been demonstrated in space and is now a critical technology for science and solar system exploration.

Introduction: A History of Space Sailing

Solar sail propulsion uses sunlight to propel vehicles through space by reflecting solar photons from a large, mirror-like sail made of a lightweight, highly reflective material. Solar sails are highly efficient, using solar photon pressure to provide thrust and perform a wide range of advanced maneuvers, such as to hover indefinitely at points in space, or conduct orbital plane changes more efficiently than conventional chemical propulsion. Solar sails can propel a space vehicle to tremendous speeds – enabling rapid exploration of the outer solar system. Since they are propelled by sunlight, they require no onboard propellant, making them a "propellantless propulsion" system.

Though solar sails have been theoretically possible since the early 20th century, it wasn't until the 1970's until a space mission, to study Halley's Comet, was actually proposed [1]. Unfortunately, the mission was not selected for funding. It was this proposal, however, that began the modern development of solar sail technology which has led to their implementation today.

The Russian Space Agency conducted the first in-space solar sail deployments from a Progress resupply vehicle after it undocked from the Mir Space Station in 1993. Called Znamya, the sail deployment was successful [2]. In 1999, the second Znamya solar sail collided with a deployed spacecraft antenna and was shredded.

The first actual solar sail spacecraft built for flight was The Planetary Society's privately funded Cosmos 1. Unfortunately, it never had a chance to sail, the launch vehicle failed and Cosmos 1 never reached space.

NASA again began developing solar sails in the early 2000's. Two different 20 m x 20 m solar sail systems were developed and tested at the Glenn Research Center's (GRC's) Space Power Facility at Plum Brook Station, Ohio [3]. A flight demonstration mission was proposed for flight in 2007, but it was not selected and the technology development again stalled.

In the summer of 2010, JAXA (the Japanese Aerospace Exploration Agency), launched the Interplanetary Kite-craft Accelerated by Radiation Of the Sun, (IKAROS) mission into deep space, becoming the first to demonstrate controlled solar sail propulsion.

That same year, NASA launched the NanoSail-D2, which deployed a 10 m^2 sail in

Earth orbit. Cannibalized from spare parts left over from NASA's 20m x 20m sail ground test program, NanoSail-D2 successfully demonstrated drag propulsion as a viable method for end-of-life spacecraft deorbit.

Missions Enabled By Sails

Solar Sails

Solar sails provide a new capability for delivering science payloads to planetary bodies, small solar system bodies, the outer solar system, non-Keplerian orbits, or a solar polar orbit. Using the continuous low thrust provided by a solar sail, spacecraft can obtain ΔV's that impossible to achieve using chemical or even solar electric propulsion.

The Geostorm mission concept uses a solar sail to position a space weather payload sunwards of the L1 Lagrange point along the Sun-Earth line. Being sunwards of the classic L1 point, the space weather payload will detect coronal mass ejections earlier than is currently possible and potentially double the warning time of impending terrestrial space weather events [4].

A small solar sail may be used to keep a science payload permanently within the Earth's geomagnetic tail. The sail forces the orbit's major axis to precess such that the major axis of the ellipse always points along the Sun-Earth line, with the orbit apogee directed away from the Sun.

Solar sails can be used to create artificial Lagrange Points high above the ecliptic. A sailcraft can be stationed directly over the polar axis of the Earth. An imager located at such an artificial equilibrium position would provide a real-time, hemispherical view of high latitude regions and the poles for climate science [5].

Solar sails work exceptionally well in the inner solar system where sunlight is plentiful. They can propel spacecraft into polar orbits about the Sun first spiraling in toward the Sun to the extent that the thermal properties of the sail will allow. The orbital inclination of the solar sail is then adjusted by directing a component of the photon pressure above and below the orbit plane every half orbit.

Solar sails offer the capability to perform serial rendezvous with multiple Near Earth Objects (NEO's), including asteroids and comets. Taking advantage of a sailcraft not requiring propellant or any sort resupply, a mission can be undertaken to rendezvous or flyby multiple NEO's for as long as the electrical and mechanical systems on the spacecraft remain functional [6].

Sails may also be used to support exploration of planets further from the Sun than the Earth. For example, a solar sail could perform the Earth return portion of a Mars sample return mission, reducing overall launch mass and cost, potentially enabling the project to fly on fewer than the currently planned three launch vehicles. Upon retrieval of a Mars sample canister lofted into Martian orbit by another element of the mission architecture, the sailcraft will begin its low-thrust spiral out of the Martian gravity well.

Scientists have proposed a near-term mission that would use a solar sail to propel a spacecraft into nearby interstellar space. The mission, often called Interstellar Probe (ISP), would use a 160,000 m^2 solar sail with an areal density of less than 1 g/m^2 to achieve a flight time of 20 – 25 years to 250Astronomical Units (AU). The velocity required for such a short flight time would be achieved by having the sail make a very close solar flyby, taking advantage of the increased solar flux and the resulting increased solar photon pressure, to accelerate the sailcraft. The ISP would be instrumented to study the heliopause and the interstellar medium and make a significant penetration into nearby interstellar space, with a minimum goal of reaching 250AU and a desire to reach as far as 400AU before the spacecraft systems cease functioning [7]. A mission like this is called for in NASA's 2012 Heliophysics Decadal Survey – the high-level plan from which NASA plans future science missions [8].

Follow on missions, taking robotic spacecraft ever deeper into interstellar space have also been proposed. For example, the Focal mission would use a solar sail to carry a telescope to the solar gravity focus at approximately 550 – 1000 AU [9]. A massive object, like the Sun, curves space time in its vicinity. As a result, light from a distant background source propagating through space time around the Sun is bent – acting like a lens. This lensing effect can magnify distant objects, allowing a telescope placed there to study distant objects that would otherwise not be visible. The next logical evolutionary step would be a mission to the inner Oort Cloud, a spherical cloud of asteroids and comets that is thought lie 1000AU - 50,000AU from the Sun. Each would require a progressively larger and more capable solar sail; all of these sails appear to be an extrapolation from current sail technology.

The next step, using a solar sail to travel to another star, will require an enormous increase in capability and is significantly beyond today's state-of-the-art technology; but the first steps are being taken that may one day enable such missions.

Drag Sails

The growth of orbital debris in LEO has resulted in the need for future spacecraft to remove themselves from orbit within a few years of their end of life so they will not pose a collision risk to future spacecraft in similar orbits. To avoid the cost and complexity of a conventional chemical propulsion system to provide an active, de-orbit propulsion maneuver, passively increasing a spacecraft's aerodynamic drag may provide an attractive alternative. A drag sail, one that provides ΔV through interacting with the tenuous atmosphere remaining at LEO altitudes is sufficient to deorbit some spacecraft residing there.

It is important to note that at the altitudes in which drag sails are effective, the aerodynamic drag forces substantially exceed any solar photon pressure that would enable meaningful propulsion by solar sailing. It is therefore not likely that combination drag and solar sails will be feasible or practical.

IKAROS and NANOSAIL-D Paved the Way

JAXA launched the IKAROS on May 21, 2010 as a secondary payload on the Venus climate orbiter AKATSUKI mission. IKAROS successfully deployed on June 9, 2010 and a small deployable camera was used to photograph the sail craft as shown in Figure 1.

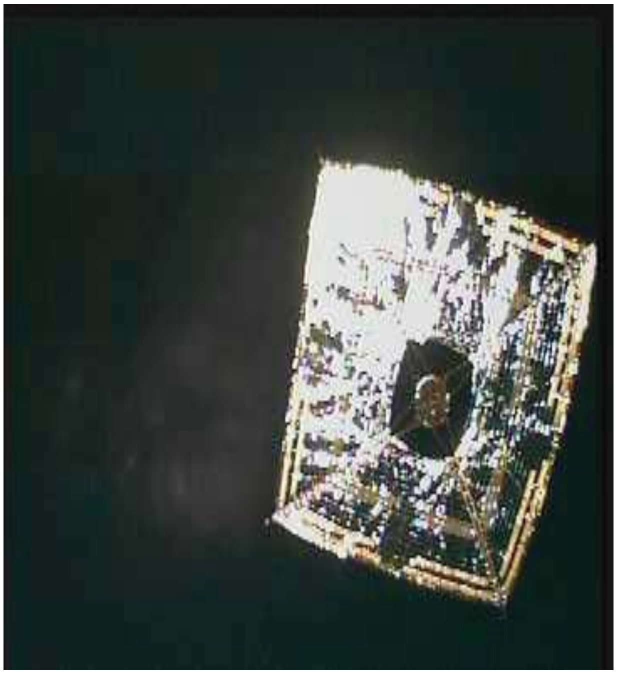

Figure 1. Solar-sailing IKAROS in the interplanetary space.

In December 2010 IKAROS successfully passed by Venus showing an accumulated acceleration of 100 m/s [10]. As shown in Figure 2, the spacecraft weighs approximately 300kg and consists of four 7.5 μ sail quadrants which deploy using centrifugal force to a 14 meters square sail with the total mass of the sail system equal to 16kg [11]. Several unique features of IKAROS include

- Thin film solar cells attached directly to certain areas of the membrane. They generate almost 500W. The area ratio is 5%.
- Steering device: 72 variable reflectance elements, approximately 70U thick, are located near the tips of the membrane [12]. As shown in Figure 3, they can be used to control the spin direction and provide attitude control.

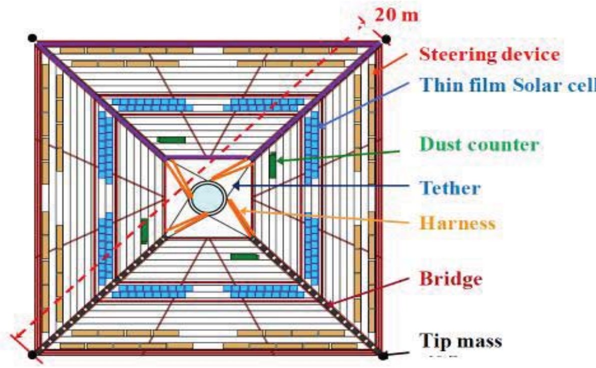

Figure 2. IKAROS overall configuration.

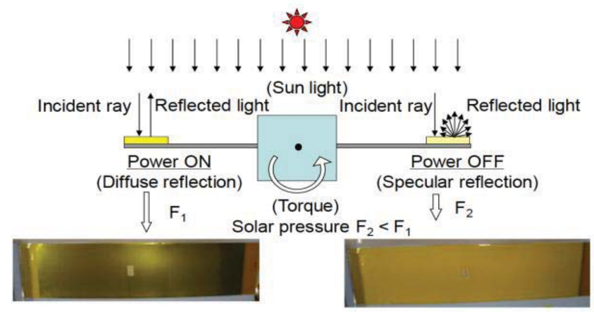

Figure 3. Variable reflectance polyimide patches that change from reflective to specular when a voltage is applied.

In the summer of 2008, NASA engineers began development of cubesat that would deploy a sail in Low-Earth-Orbit (LEO). The NanoSail-D project was formalized in a collaboration between NASA's Ames Research Center (ARC) and Marshall Space Flight Center (MSFC) with a goal completing development of the flight hardware in less than four months. The team successfully developed two flight units that were subsequently delivered to the SpaceX facility in the Kwajalein Atoll. NanoSail-D1 was integrated into their Falcon-1 rocket for its third test flight. Unfortunately, the rocket failed and the sail never had a chance to deploy in space [13]. The second unit, NanoSail-D2, was placed in storage until a second flight opportunity was obtained about a year later.

NanoSail-D2 was launched inside MSFC's FASTSAT HSV-1 satellite. FASTSAT was successfully placed into a 650km orbit, 72° inclination, on November 19th, 2010. NanoSail-D2 was eventually ejected from the FASTSAT on January 19th, 2011. As designed, three days later the sail was automatically deployed. NanoSail-D2 orbited the earth for approximately 240 days, slowly descending due to aerodynamic drag within the upper atmosphere. It finally deorbited in the fall of 2011. Analyses predicted that without the sail, the NanoSail-D2 cubesat would orbit the earth for another 20-25 years [14].

The NanoSail-D project was a success in many ways. The rapid development led to a very robust, simple sail deployment mechanism. The collaboration of ARC and MSFC on this project allowed the reuse of the backup GeneSat electronics which were slightly modified for NanoSail-D. When it was ejected from FASTSAT, NanoSail-D2 was the first NASA cubesat to be successfully ejected from a minisatellite in orbit. This accomplishment has shown the potential for future satellites to deploy a local constellation flying together.

In addition, NanoSail-D2 was the first cubesat to deploy a sail in earth orbit. Additionally, in conjunction with the other scientific instruments on FASTSAT, NanoSail-D2 was used as a test article for these instruments' upper atmospheric research. During its orbital lifetime, NanoSail-D2 was also visible to ground observers in many parts of the world.

The relevance of the NanoSail-D2 mission will be directly measured by its impact to future missions and implementation of its demonstrated technology. Because of its simple, robust design, several other groups have developed similar solar sail deployment mechanisms. LightSail-A, developed by Stellar Exploration for The Planetary Society, utilizes the same type of deployment mechanism.

Planned Demonstrations and Missions

The L'Garde Sunjammer mission will see the development and flight of a 1200 m2 solar sail [15]. The preliminary design calls for the sail to be boosted to Geostationary Transfer Orbit (GTO) as a secondary payload. Once Sunjammer (the sailcraft is named after a short story by Arthur C. Clarke) is released from the booster vehicle, it will perform a propulsive burn and boost itself to an Earth escape orbit. Upon reaching this trajectory, the sail will be deployed and the demonstration mission will begin. For the next 30 days the sail will navigate to demonstrate and fulfill navigation requirements. Sunjammer will fly the sail near L1 and finally to a sub-L1 location. Along the way, an onboard magnetometer will be measuring magnetic field and comparing the results with NOAA's Advanced Composition Explorer. It is hoped that these measurements will foster the infusion of this technology into the space weather monitoring community.

The L'Garde design utilized their patented inflation deployed, sub-Tg rigidized booms and is based on development work funded under the NASA In-Space Propulsion Program in the early 2000's [16]. Figure 4 is the L'Garde 20 m system at the Plum Brook 100 ft. diameter vacuum chamber. The sails are constructed from aluminum coated Kapton with an integral ripstop feature. The sails transferred loads to the beams through a novel "stripped net" architecture that resulted in a lightweight beam design and low tensile stresses in the sail membrane. The L'Garde design has articulated tip vanes for attitude control. Rotation of the tip vane offsets the location of the center of radiation pressure from the center of mass and induces torques to provide roll, pitch and yaw control. L'Garde has also utilized a staging concept where components such as the inflation system and bus interface are discarded once they are no longer needed to ensure the lightest sail craft possible.

Figure 4. L'Garde 20 m System

The Planetary Society's LightSail program is a near-term demonstration of Cubesat solar sailing. By merging solar sail propulsion with the very low-cost and universally available Cubesat architecture, LightSail will help to establish a new paradigm for low-cost space exploration. Sail-propelled cubesats can in principle access virtually any destination in the inner solar system with a limited but increasingly capable sensor suite, and can play an important role for initial characterization or reconnaissance in advance of larger more sophisticated spacecraft. They also hold the promise of making solar system missions accessible to universities and other organizations for whom such projects have previously been unaffordable.

LightSail has been under development for nearly five years and is completely funded by members and donors of The Planetary Society. As of mid-2014, the spacecraft hardware and software are essentially complete and preparing to enter full system and environmental test. The program consists of two missions that taken together will fully validate Cubesat solar sail deployment and control, with the prospect of adding other more capable missions as the program progresses.

The two LightSail spacecraft are virtually identical: Each is based on a 3-U CubeSat architecture and contains a square solar sail measuring approximately 5.6 m on a side for a total sail area of about 32 m2. The sail is divided into quadrants, each of which is linked to a TRAC boom for deployment. Total spacecraft mass is less than 5 kg. The table below summarizes important parameters of both missions.

Table 1 Mission Parameter

	LightSail-A	LightSail-B
Launch	Apr 2015 (Atlas 5 piggyback)	Apr 2016 (Falcon 9H piggyback)
Objective	Sail system validation	Orbit raising/control, sail performance
Planned orbit	380 x 750 km (est.)	~700 km circular
Duration	~ 2 weeks	~ 2 months
Attitude control	Torque rod system	Torque rods plus momentum wheel
Data return	On-board images of deployed sail	High-res stand-off imaging via Prox-1

LightSail-A will launch in April 2015 as a secondary payload on an Atlas V, with launch funded by NASA's ELaNa (Educational Launch of Nanosatellites) program. The planned altitude is too low for actual solar sailing due to atmospheric drag, but sufficient to allow a demonstration and validation of the sail deployment system and characterization of coarse attitude control using the magnetic torque system. On-board cameras will document sail deployment and provide at least one good image of the fully deployed sail. Expected orbital lifetime after sail deployment is less than two weeks, which is more than sufficient for these limited validation objectives.

LightSail-B will launch in April 2016 on a Falcon 9H, in this case mated to the Prox-1 spacecraft being developed by students at the Georgia Institute of Technology. Prox-1 is a demonstration of proximity operations and autonomous navigation technologies funded by the US Air Force. Once in Earth orbit, LightSail-B will be released by Prox-1 and the two spacecraft will fly in formation for a period of several months. During that time, LightSail-B will deploy its solar sail and conduct a series of maneuvers to demonstrate precise attitude control and orbit modification by use of solar pressure, while Prox-1 circumnavigates LightSail-B and acquires high-resolution images of the sail and its deployment system. This will further characterize the performance of the sail and the integrated CubeSat platform, and the stand-off imaging from multiple perspectives will provide unique and important information about the behavior and control of sail systems in space.

The University of Surrey's CubeSail, DeorbitSail and InflateSail are additional cubesat class sail demonstrations that will fly within the next few years. The 5 m x 5 m CubeSail, with a total mass of around 3 kg, will demonstrate demonstrate the solar sailing and end-of-life deorbiting using the sail membrane as a dragsail. The CubeSail will demonstrate solar sailing by changing the inclination within its ~700 km sun-synchronous orbit. At the end of its lifetime, the CubeSail will change orientation and point its sail along the velocity vector. The increased cross sectional area will cause rapid descent [17].

DeorbitSail, like NanoSail-D and DragNet will show that large sail membranes can effectively be used to deorbit spacecraft at the end of their useful life.

InflateSail, a 3-U cubesat scheduled to launch on the QB50 mission demonstrate rigidization of an inflatable sail structure in orbit [18]. InflateSail is to have a total area of ~10 m2 using a 3-m diameter inflatable torus frame that stretches the sail film by a series of equidistant cords. The torus is to be suspended from the satellite bus by three inflatable booms as shown in Figure 5.

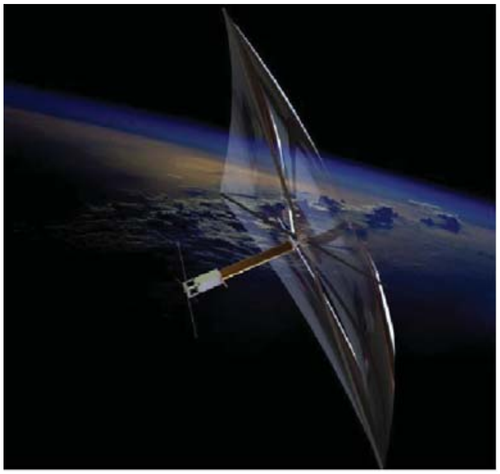

Figure 5. The University of Surrey's InflateSail will demonstrate inflatable sail technology on a cubesat.

Based on the technology developed for NanoSail-D, NASA recently selected for study two 6U cubesat missions for possible flight in 2017. The first, Lunar Flashlight, will study the ice deposits in the Moon's permanently shadowed craters using its solar sail as a mirror to steer sunlight into shaded craters from a polar low lunar orbit. Lunar Flashlight, if approved, will fly on the Space Launch System (SLS) Exploration Mission 1 (EM-1) mission and will accomplish its flight mission within approximately two years of launch. The primary instrument will be a four band-point spectrometer. The solar sail will be allocated the mid-2U stowage volume within the 6U spacecraft bus. After ejection from SLS, the spacecraft will detumble and perform a lunar flyby. Within the first 3 days, and after the first lunar flyby, the solar sail will be deployed for a 160 day trajectory before getting captured by the moon. Once the spacecraft is captured by the moon, Lunar Flashlight will use the sail to trim its orbit and begin science operations.

The second mission being studied is the Near Earth Asteroid Scout (NEAS). NEAS will perform a slow flyby of a NEA within about two years of launch and is also manifested for launch on the SLS EM-1 mission. The primary instrument payload will be an imaging camera to collect data regarding the physical properties of the NEA. Like Lunar Flashlight, the solar sail will be stowed near the center of the spacecraft structure with a volume allocation of approximately 2U. The deployed sail area will be approximately 80 m2 has a tentative mass allocation of 2.5 kg. Once ejected from the SLS, the NEAS will perform systems checkout and then subsequently deploy the solar sail (nominally within 3-4 days after launch). The solar sail will provide the primary source of flight system ΔV. If the spacecraft is still functioning after the flyby, an extended mission to visit a different NEA will be considered.

SUMMARY

Solar and drag sail propulsion are now engineering reality. Several technology demonstration and implementation missions have flown or are planned for flight within the next few years. With these flights comes the opportunity to mature the technology to the next level of performance, allowing future ambitious space missions heretofore considered impossible to implement become a reality.

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