Solar Sail Propulsion

Les Johnson
NASA Marshall Space Flight Center
Solar Sails

Solar sails use photon “pressure” or force on thin, lightweight reflective sheet to produce thrust. Sails can open up new regions of the solar system to accessibility for important science missions, with no propellants required.
Solar Sails
Propulsion from Photon Momentum Exchange

An example of how a solar sail propulsion can change orbits.

Reflecting the photons forward along the direction of motion slows the spacecraft down.
Solar Sail Control Angles

- Thrust vector is dependent on two angles
  - Cone Angle ($\alpha$) (a.k.a. Sun Incidence Angle)
  - Clock Angle ($\delta$)

\[ \hat{R} - \text{Radial Direction} \]
\[ \hat{T} - \text{Orbit Tangential Direction} \]
\[ \hat{N} - \text{Orbit Normal Direction} \]
Solar Sailing Is Not A New Idea

- James Clerk Maxwell (England), who developed the modern theory of electromagnetism in the 1860’s, proved that light could exert pressure.

- Konstantin Tsiolkovsky (Russia) first discussed solar sailing; Fridrickh Tsander (Russia) wrote in 1924, “For flight in interplanetary space I am working on the idea of flying, using tremendous mirrors of very thin sheets, capable of achieving favorable results.”
Echo II 1964
solar thrust affect on spacecraft orbit

• 135-foot rigidized inflatable balloon satellite
• laminated Mylar plastic and aluminum
• placed in near-polar Orbit
• passive communications experiment by NASA on January 25, 1964.

Spherical shape has no solar pressure torques — enabling direct observation of thrust effects without regard to spacecraft attitude

When folded satellite is packed into the 41-inch diameter canister shown in the foreground
Solar Sail Technology History

Used Since 1962

Solar Sailing was initially developed at JPL as a measure to save the Mariner 10 mission which had lost a large portion of its propellant margin when the star tracker locked on to floating debris instead of Canopus. The mission went on to flyby Venus and three encounters with Mercury. Its successful implementation on that mission led to it being declared a mature technology, ready for application to future NASA missions in 1978.

Several Comsats (e.g. INSAT 2E) operating today in GEO use solar pressure to unload momentum wheels or offset solar torques on asymmetric solar arrays.

Chosen for Halley Comet Rendezvous in 1985, it was replaced by a chemical rocket in phase B due to launch date/window pressure.

Joint NASA/NOAA/USAF proposal to NMP ST5 fell in the 11th hour when USAF/NASA/NOAA partnership collapsed.

Planetary society launched a flight experiment and a full system on converted Russian Volna sub-launched missiles. Unfortunately both boosters had stage separation failures.

2010: JAXA launches the world’s first true solar sail on a journey past Venus.

2011: NASA launches a subscale “drag sail” into Low Earth Orbit.
Geostorm: Solar Storm Warning
Use a solar sail to achieve a non-Keplerian orbit near the sun-earth line, twice as far from the earth as the current warning system, NOAA’s Advanced Composition Explorer (ACE) at the $L_1$ point.

Geostorm will double the warning time to enable the reconfiguration and securing of space systems (and ground electrical power grids) to avoid:

- Complete or partial loss of HF & satellite communications
- Degraded navigational and geo-locational capability
- False returns on ATC and early warning radars
- Satellite system disruption and lock problems

Geostorm, being propellantless, could result in a significantly longer spacecraft lifetime.
Pole Sitter Mission

- Continual coverage of the polar regions with no propellant usage!
- Altitudes ranging from 0.75 million km to 3.5 million km, depending on sail performance and inclination chosen.
Pole Sitter Spacecraft

- Constantly above an Earth pole
- Continuous hemispheric view of the pole
- New vantage point for telecommunications satellites and Earth observing satellites
Solar Sail Asteroid Rendezvous Mission
(rendezvous with 3 NEO’s in 6 years):

Departure: Aug 2017

Candidate asteroids visited:

<table>
<thead>
<tr>
<th>NEO</th>
<th>Date</th>
<th>Observation Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999 A010</td>
<td>Mar 2019</td>
<td>35 days</td>
</tr>
<tr>
<td>Apophis</td>
<td>Dec 2021</td>
<td>30 days</td>
</tr>
<tr>
<td>2001 QJ142</td>
<td>July 2023</td>
<td>30 days</td>
</tr>
</tbody>
</table>

• Ground Rules:
  • Use existing spacecraft and components
  • Use existing instruments
  • Use NASA-developed sail technology

• Solar Sail Spacecraft Launch Mass: 328.6 kg
• Mass at destination: 228.4 kg
• Cost: $175M, plus launch vehicle and ops
Missions From Earth

Mission Elapsed Time (Years) vs. Characteristic Acceleration mm/s²

- 2000 SG344
- 1999 AO10
- Apophis
- 2009 CV

Note: Launch window constrained between January 1, 2017 to January 1, 2020
Solar Sail Comet Chaser

• Use the unique capabilities of a solar sail to study the life cycle of a comet within the inner solar system

  • Place science spacecraft in a propulsive co-orbit with a comet

  • Acquire the comet between the orbits of Mars and Jupiter

  • Follow the comet through perihelion and as far out as possible
Studying the Sun: L-1 Diamond

- 4 solar sails could provide continuous observations of the sun.
**Solar Far-Side Sentinel**

- Farside Sentinel is 1 of a 6 spacecraft mission to study 1) the acceleration and transport of SEPs and 2) the initiation and evolution of CMEs and interplanetary shocks in the inner heliosphere.
- Will provide a major advancement toward the future ability to forecast space weather events.
- Far side observations hold promise as an indicator of upcoming earth side activity
- With opposition orbit the sun blocks earth communication
- Options include two satellites in ecliptic or 1 solar sail orbiting above the sun
- Solar sail enables high degree of flexibility in orbits and mission ops
Solar Sail Cargo Ships

- Fleets of propellantless solar sails could be the cargo ships of the future
- (Operating within the inner solar system – near the sun)
Solar Sails Enable Interstellar Travel
The first mission to beyond the Heliopause
- 250 AU minimum
- Reach 250 AU within 20 years from launch
- 15-20 AU/year target velocity

Two propulsion concepts considered
- BASELINE: Solar Sails (via close solar approach)
- OPTION: Nuclear Electric (fission reactor)
- REJECTED: All Chemical with Gravity Assists

Sail Requirements
- 500 - 800 meters diameter
- 1 g/m² density
- Survivable to T=3000K for close solar approach

Science Objectives
- Explore the nature of the interstellar medium and its implications for the origin and evolution of matter in our Galaxy and the Universe.
- Explore the influence of the interstellar medium on the solar system, its dynamics and its evolution
- Explore the impact of the solar system on the interstellar medium as an example of the interaction of a stellar system with its environment
- Explore the outer Solar System in search of clues to its origin, and to the nature of other planetary systems.

The Heliopause is a barrier where charged particles from the sun cannot go beyond because cosmic rays from deep space force them back.

Carbon fiber µ-truss fabric
(1 gm/m², 2 mm thick)
Interstellar Probe Flight Configuration

Fully Deployed Sail
Very Large Solar Sails With A Very Close Solar Approach May Enable Interstellar Travel

- 100-km class sail unfurled at less than 0.2 AU may enable a trip to the nearest star in under 1000 years.

- 1000 years ago…
  - China was the world's most populous empire. By the late 11th century, the Song Dynasty had a total population of some 101 million people, an average annual iron output of 125,000 tons/year
  - The Islamic world was experiencing a Golden Age and continued to flourish under the Arab Empire
  - Leif Ericson landed in North America
  - Oslo Norway was founded and lots of wars were fought in Europe

- We have recorded history going back 1000 years and will likely know to turn on the radio to listen for the probe “calling home.”
Near-Term Solar Sail Applications Lead to Interstellar Capability with Laser Sails

- Solar Powered
- Laser Powered

\[ \delta = \text{Areal Density (Sail Mass/Sail Area)} \]

**Near-Term Sail Demo**
- 40 - 70-m DIA
  - \( \delta = 20 \text{ g/m}^2 \)

**Mid-Term Sail Demo**
- 100-m DIA
  - \( \delta = 10 \text{ g/m}^2 \)

**Geostorm**
- 67-m DIA
  - \( \delta = 15 \text{ g/m}^2 \)
  - (8 \( \mu \)m film)

**Advanced Sail Demo and/or Heliosphere Science**
- 1-km DIA
  - \( \delta = 1 - 2.5 \text{ g/m}^2 \)

**Interstellar Medium Exploration**
- 4.5 LY
  - Interstellar Probe Flyby
- 40 LY
  - Interstellar Probe Rendezvous

**Tech Dev**
- Interstellar Probe
- Europa Landers
- Comet Sample Return
- Oort Cloud
- Solar Polar Imager
- Mercury Orbiter
- Non-Keplerian Earth Orbits

**Travel Within Solar System:** Days to Weeks
- 1000-km DIA
  - \( \delta = 1 \text{ g/m}^2 \)
Interstellar Light Sail Concept

INTERSTELLAR FLYBY

Laser (1.5µm)
Transmitter Optics

100 km Diameter

1000 km Diameter

2 L.Y.

Coast Rest of Way to Star

INTERSTELLAR RENDEZVOUS

Laser (0.5µm)
Transmitter Optics

300 km Diameter

6 L.Y.

2nd Stage (300 km Dia.) Stops at Star

1st Stage (1000 km Dia.) Accelerated Out of System

• Advantages
  • Perform interstellar missions in < 50 years
  • Only competitor is antimatter
  • Use as a solar sail once in orbit about target
  • Use solar power satellite as driver for robotic flybys

• Disadvantages
  • Very high laser / microwave powers (0.1-1,000 TW)
  • Very large optics (100-1,000 km)

• Far-term concept, but one of the few ways to do "fast" interstellar missions
Laser Sails Are BIG

LightSail for 40 LY Rendezvous Mission
- 100 Year Trip Time
- 0.2 gees Max Accel.
- 936 km Dia
- 3,000 TW Beam

LightSail for 4.5 LY Rendezvous Mission
- 20 Year Trip Time
- 0.2 gees Max Accel.
- 117 km Dia
- 47 TW Beam

Beamed-Energy Transmitter Array
- 1,000 km Dia
- 1 μm Wavelength

Courtesy: Robert Frisbee
Types of Sail Designs

Square Sail

Spinning Disk Sail

Heliogyro
Spinning Solar Sail
Deployment Sequence

Launch Configuration
- Sail
- Deployment Module
- Marmom Clamp
- Belly Band

Boom Deployment and Spacecraft Spin-up
- Cold Gas Thrusters
- Boom

Gore Deployment Using Centrifugal Force
- Gore

Continued Gore Deployment
- Gore

Final Gore Deployment Achieved
- Spacecraft

Unfurl Sail
- Sail Gore

Sail Fully Deployed
Solar Sail Technology – Many Players

- NASA developed 80m class solar sail propulsion systems to ~TRL-5/6 in the mid-2000’s and will test one in space ~2015
- JAXA is flying a 14m solar sail in deep space
- NASA tested in space the NanoSail-D subscale solar sail prototype
- The Planetary Society’s LightSail-1 will fly this year
Technology Area Status:

- **Two solar sail technologies were designed, fabricated, and tested under thermal vacuum conditions in 2005:**
  - 10 m system ground demonstrators were developed and tested in 2004/2005.
  - 20 m system ground demonstrators designed, fabricated, and tested
- Developed and tested high-fidelity computational models, tools, and diagnostics.
- Multiple efforts completed: materials evaluation, optical properties, long-term environmental effects, charging issues, and assessment of smart adaptive structures.
10, 20, and 40-m Solar Sail Systems
ATK Solar Sail Development

Technical Team:
- ATK (Goleta, CA) systems engineering & coilable booms
- Nexsolve (Huntsville, AL): Sail manufacture & assembly
- LaRC (Hampton, VA) Sail Modeling & Testing
- MSFC (Huntsville, AL) Materials Testing

Overall Strategy
- Leveraged New Millennium Program ST 7 Phase A Design Concept
  - Improve performance with Ultra-Light Graphite Coilable booms
    - Sail membrane, AL coated 2.5 µm CP1, compliant border, 3 point attach
  - Thrust Vector Control uses sliding masses along boom with spreader bars and micro-PPT at mast tip
ATK Solar Sail Development, Continued

- **Operating Temperature**
  - 16°C at .98 au

- **First Natural Frequency**
  - 0.02 Hz

- **Stowed Package**
  - 1.5 m dia. by 0.53 m

- **System Mass:**
  - 108 kg (w/ contingency)

- **Characteristic acceleration**
  - 0.76 mm/s²
  - 0.34 mm/s² with 130 kg SC

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**CoilABLE Mast Linear Mass:** ~ 70 g/m

- **Stowed**
  - CoilABLE Mast Linear Mass: ~ 70 g/m

  - Ø20-in. (50.5 cm)
  - 18.7-in.-tall (<0.55% of length)

- **Sail Thickness:**
  - 2.5 μm CP1

- **Cut-Away of Stowed Package**
CoilAble Mast Heritage

- Able Engineering Company Established in 1975 (called ATK Space Systems at the time of the demo)
  - 30 CoilAble systems had been flown to date
  - A phenomenal Stiffness to Weight ratio, High Dimensional Stability, Robust deployment, and Compact Stowage
- Recent flight mast designs
  - Mars Pathfinder (1999) 1-meter boom: 130 g/m
  - IMAGE spacecraft (2000) 10-meter booms: 93 g/m
- 100% Product Success Rate With No On-Orbit Failures

LACE | ISP | ST8

- Stowed
  - 100-m
  - Ultra-Light
  - CoilABLE
Nexolve Solar Sail Membrane Features

Membrane Design:
4-quadrant planar sail
- Compliant Border interface between edge cable and membrane
  - Shear insensitive, Cord/Material CTE mismatch insensitive
  - Thermal Gradient insensitive

Sail Material:  CP1 Polyimide
- High Operating Temperature (>200°C)
- UV Stable
- Essentially Inert
- Soluble (Wet Process), modifiable with variety additives - improve conductivity and thermal properties
- 2.5 micron polyimide
- Flight Proven --- flying on Numerous GEOCOM satellites

Sail Construction Methods:
A gossamer film construction similar to gusseted, reflective blankets flying on numerous GEOCOM satellites
- Scalable Construction Methods --- current system >20m
- Adhesive less Bonding Methods --- eliminates sticking and contamination risks.
ATK Sail Deployment

Scalable Square Solar Sail

The S^4 System
L’Garde Solar Sail Development

Technical Team:
- L’Garde, Inc. (Tustin, CA) systems engineering and inflatable truss
- Ball Aerospace & Tech Corp. (Boulder, CO) mission eng. & bus design
- LaRC (Hampton, VA) sail modeling & testing
- JPL (Pasadena, CA) mission planning & space hazards

Overall Strategy
- Concept Leveraged ST-5 Phase A design concept and Team Encounter experience
  - Sail membrane, AL coated 2 µm Mylar attached with stripped net
  - Lightweight Boom With Sub-Tg Rigidization
  - 4 Vane Thrust Vector Control
**Beam Characteristics**

Load bearing longitudinal uni-directional fibers
- Fibers impregnated with resin (rigid below -20°C)
- 0.48 AU design requires greater fiber density to withstand loads from the increased solar flux

**Spiral wrap**
- Stabilizes longitudinal fibers
- Allows over-pressurization for deployment anomalies

**Bonded Kapton bladder and Mylar**
- Encapsulation "skin" carries shear
- Aircraft fuselage like structure

**Beam Structure**
- Sail structure is stressed for solar loading in one direction for mass efficiency
- Truss system comprised of mostly tension elements, minimal rigid components
- Highly mass efficient, ~36g/m linear density

Stowed 7 m boom (~.5 m)  
Deployed 7 m boom
Net/Membrane Sail

Net/Membrane Sail Schematic

Net Membrane

- Sail is supported by a low CTE net with additional membrane material added to allow for thermal compliance
- Sail properties effect local billow between net members only, global sail shape is stable

Advantages

- Net defines the overall sail shape, not the membrane
- Stability and geometry of the sail is effectively decoupled from membrane properties
- Sail shape, and hence thrust vector, sailcraft stability and performance, are predictable and stable
- No high local stress concentrations in the sail, loads are transferred though the net, not the membrane
- Very scalable, larger net/membrane sails simply add additional net elements to control overall shape
L’Garde 20-m System Ground Demonstrator

- Sail Membrane
- Tip Vane
- Vane Mechanism
- Tip Mandrel
- Inflatable Beams
L’Garde Inflatable Sail Deployment
Solar Sail Subsystem Development

Solar Sail Spaceflight Simulation Software (S5)
Developed an integrated simulation and analysis software tool for optimal design of solar sail trajectories and for evaluation of guidance navigation and control strategies.

Optical Diagnostic System (ODS)
Developed a ground integrated instrumentation package to allow measurement of sail shape, tension and temperature; boom & sail vibration modes and stress; and deployment monitoring.
Material Testing
Characterized engineering performance of candidate SS materials at .5 and 1 AU, gauging material property tolerances after exposure to simulated mission-specific charged-particle and micrometeoroid environments.

Development of a Lightweight Robust SACS and a Software Toolkit for Solar Sails
Developed of a highly integrated, low cost, low mass, low volume, and low power attitude determination and control system and develop a high-fidelity multi-body modeling and simulation software toolkit.
Solar Sail Subsystem Development—cont.

**Sail Charging Analysis**
Developed environmental and sail configuration models and design guideline criteria for solar sails. Conduct laboratory assessment of potential for destructive charging fields and arcing events within the sail and surrounding environment.

**Smart Adaptive Structures**
Identified nonlinear mechanism for existing 40 meter coilable boom. Assess potential for control structures interactions.
TRL Assessment Process Flowchart

On-Orbit Environment
Launch Environment
Ground Environment

Relevant Environment Definition

Solar Polar Imager
Heliostorm

Initial Application Missions

Technology Readiness Level (TRL) Definitions/Requirements

TRL 1-9

Technology Readiness Level (TRL) Assessment

Technology Gaps

TRL Determination

L’Garde
ATK

System Ground Demonstrator (SGD)
Design, Analyses, Fabrication, Testing
(10 Meter and 20 Meter)

TRL Assessment Tool

Technology Assessment Group (TAG)
**TRL Assessment Methodology**

**ATK 20M System**
- Central Structure
- Masts
- Beams
- Sails

**L'Garde 20M System**
- ACS
- Central Structure
- Masts
- Beams
- Sails

**Identify Solar Sail Major Subsystems**
- Sails
- Masts/Beams

**Assess System TRL (6)**

**Assess Component/Subsystem TRL (3-5)**

**System Subsystems**
- Components
- Materials & Coatings
- Integrated Rigging
- Grounding Straps
- Stowed Net

**L'Garde 20M System**
- Beams
- Insulation
- End Caps
- Support System & Rings
- Cafe Grade

**ACS**
- Vane Mount Mechanism
- Vane Rotation Mechanism
- Control Wiring
- Software
- Doors & Actuators
- S/C Interface
## TRL Assessment Results Comparison

<table>
<thead>
<tr>
<th>Vendor</th>
<th><strong>Post 10M</strong></th>
<th><strong>Post 20M</strong></th>
<th><strong>Post 10M</strong></th>
<th><strong>Post 20M</strong></th>
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<td>TRL 5</td>
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<tr>
<td>ATK</td>
<td>76%</td>
<td>89%</td>
<td>60%</td>
<td>86%</td>
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<tr>
<td>L’Garde</td>
<td>75%</td>
<td>84%</td>
<td>68%</td>
<td>78%</td>
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</table>
NanoSail-D Demonstration Solar Sail

- **Mission Description**
  - 10 m² sail
  - Made from tested ground demonstrator hardware
**NanoSail-D Mission Configuration**

**Stowed Configuration**
- **Spacecraft Bus (Ames Research Center)**
- **Bus interfaces Actuation Electronics (MSFC/UAH)**
- **NanoSail-D (Aluminum Closeout Panels Not Shown)**
  - **Boom & Sail Spool (ManTech SRS)**
- **PPOD Deployer (Cal-Poly)**

**Ride Share Adapter**
- **Space Access Technology**
- **AFRL Satellite (Trailblazer)**

**NanoSail-D**
- **NSD-001**
- **NSD-002**

- **3U Cubesat: 10cm X 10cm X 34cm**
- **Deployed CP-1 sail: 10 m² Sail Area (3.16 m side length)**
- **2.2 m Elgiloy Trac Booms**
- **UHF & S-Band communications**
- **Permanent Magnet Passive Stabilization**

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- **Permanent Magnet Passive Stabilization**
Solar Sail Propulsion is a Near-Term Priority NASA Technology

<table>
<thead>
<tr>
<th>Rank</th>
<th>Description</th>
<th>Priority</th>
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<tbody>
<tr>
<td>1</td>
<td>Power Processing Units (PPUs) for ion, Hall, and other electric propulsion systems</td>
<td>N</td>
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<tr>
<td>2</td>
<td>Long-term in-space cryogenic propellant storage and transfer</td>
<td>M</td>
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<tr>
<td>3</td>
<td>High power (e.g. 50–300 kV) class Solar Electric Propulsion scalable to MW class Nuclear Electric Propulsion</td>
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<tr>
<td>4</td>
<td>Advanced in-space cryogenic engines and supporting components</td>
<td>M</td>
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<tr>
<td>5</td>
<td>Developing and demonstrating MEMS-fabricated electrospay thrusters</td>
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<tr>
<td>6</td>
<td>Demonstrating large (over 1000 m²) solar sail equipped vehicle in space</td>
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<tr>
<td>7</td>
<td>Nuclear Thermal Propulsion (NTP) components and systems</td>
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<tr>
<td>8</td>
<td>Advanced space storable propellants</td>
<td>M</td>
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<tr>
<td>9</td>
<td>Long-life (&gt;1 year) electrodynamic tether propulsion system in LEO</td>
<td>N</td>
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<tr>
<td>10</td>
<td>Advanced In-Space Propulsion Technologies (TRL &lt;3) to enable a robust technology portfolio for future missions.</td>
<td>F</td>
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</table>

* From NASA Office of Chief Technologist Draft In-Space Propulsion Systems Roadmap Technology Area 02
Interplanetary Kite-craft Accelerated by Radiation Of the Sun (IKAROS)

- IKAROS was launched on May 21, 2010
- The Japan Aerospace Exploration Agency (JAXA) began to deploy the solar sail on June 3, 2010.
- IKAROS has demonstrated deployment of a solar sailcraft, acceleration by photon pressure and attitude control
  - Deployment was by centrifugal force
  - Sail membrane is 7.5 mm thick

<table>
<thead>
<tr>
<th>Configuration / Body Diam.</th>
<th>1.6 m x Height 0.8 m (Cylinder shape)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Configuration / Membrane</td>
<td>Square 14 m and diagonal 20 m</td>
</tr>
<tr>
<td>Weight</td>
<td>Mass at liftoff: about 310 kg</td>
</tr>
</tbody>
</table>
LightSail-1 (The Planetary Society) Status

- **Cubesat design**
  - 4.5 kg
  - Two 2-megapixel cameras
  - Four sun sensors
  - Six accelerometers for measuring solar acceleration

- **Sail Material:** aluminized 4.5 micron Mylar film

- 32 square meters solar sail area fully deployed
The LightSail-1 Spacecraft

- **Trac Booms (4)**
- **Sail (4)**
- **Avionics Package**
  - C&DH Board
  - Power Regulation
  - Transceiver
  - Payload interface Board
- **Sun Sensor (4)**
- **Battery**
- **Torque Rod (3)**
- **Sail Deployment Mechanism**
- **Whip Antenna**

Other components:
- **Solar Panels (10)**
- **Cameras (2)**
- **3 axis Accelerometer (2)**
- **Momentum Wheel**
- **Single Axis Gyro (3)**
- **Solar Sail Storage (4)**
- **3 axis Accelerometer (2)**
LightSail-1
Concept of Operations

Drift away from primary vehicle, eject from PPOD, deploy whip antenna, 3 axis stabilization. Solar panel deployment followed by Solar Sail (Sail deployment video stored for downlink).

Sun Synchronous Orbit 824 km, inclined 98°

Delta 7920-10
Secondary launch with NPP (June 2011)
Vandenberg AFB

Sail uses sun energy to gain orbit energy (up to $4.29 \times 10^{-5} \text{ m/s}^2$ when "on"). 3 - 4 week mission life.

9.6 Kbps 437 MHz downlink FSK.
Acceleration data and 2 camera images/day

Command and Control from Cal Poly and Ga. Tech and other ground stations as appropriate

Amateur Optical trackers to provide position data
Solar Sail Technology Status

- JAXA has taken solar sail propulsion to TRL-7
- NASA plans a deep space solar sail mission in ~2015
- Cubesat scale sails are a mature technology for selected applications