Solar Sails for Spacecraft Propulsion

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We tend to think of space as being big and empty…
Can we use the environments of space to our advantage?
How does a solar sail work?

Solar sails use photon “pressure” or force on thin, lightweight reflective sheet to produce thrust.
• **Photons carry Momentum**
  
  $p = h\nu/c$
  
  - $h = $ Planck’s, $\nu = $ frequency, $c = $ speed of light

• **Force generated on Reflective Surface**
  
  - Resultant force approximately perpendicular to surface
  
  - The bigger the surface, the more the force
  
  - Can “steer” sail by changing pitch angle $\alpha$

• **Small, but potentially Constant Acceleration**
  
  - Potentially unlimited “delta $V$”
  
  - Allows some otherwise impossible orbits
Solar Sails Provide Low Thrust Propulsion

Solar Photon Pressure (R=0.9)

Pressure (N/m²²) vs Distance to Sun (AU)

Energy: \[ W = \frac{L}{4\pi r^2} \]
Pressure: \[ P = \frac{W}{c} \]
\[ W_e = 1368 \text{ W/m}^2 \]
\[ P_e = 9.15 \times 10^{-6} \text{ N/m}^2 \]
Net Force Drops with Increasing Pitch Angle

- For a 100 kg sailcraft, 100 m x 100 m square sail:

- Force (maximum, perp. to sun, perfect/flat reflector)
  - 0.09 N

- Acceleration (maximum)
  - $0.92 \times 10^{-3} \text{ m/s}^2$ (0.9 millimeters/sec$^2$)

- Force decreases with increasing pitch angle ($\theta_i$ or $\theta_n$)

$$\bar{f}_{tot} = 2P_i A(\cos \theta_i)^2 \hat{n}$$

Solar Sail Total Force (Thrust) Vs. Sun-Incidence Angle
(For a 100 x 100 meter perfect sail @ 1 A.U.)
Solar Sails Experience VERY Small Forces

- Force on a 100 m x 100 m square sail:

Solar Force Equivalent at 1 AU

10,000 m² (two football fields)
Solar Sail Trajectory Control

- Solar Radiation Pressure allows inward or outward Spiral

![Diagram showing solar sail trajectory control](image)
Potential Solar Sail Applications
(A Partial List!)

- NEA Reconnaissance & Small Body Science
- Earth Pole Sitting
- Rapid Outer Solar System Exploration and Escape
- Heliophysics & Out of the Ecliptic Science
- Toward Higher Performance Beamed Energy Propulsion
Echo II 1964
Solar thrust effect 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

When folded, satellite was packed into the 41-inch diameter canister shown in the foreground.
Znamya (Space Mirror)

- Russian experiment that flew on Progress after undocking from Mir Space Station in 1993.
- Purpose was to reflect sunlight onto the ground from space.
- A 20-meter diameter sail was successfully deployed.
- A 5-km spot illuminated Europe from France to Russia moving at 8 km/sec.
- Follow-on mission flew but was damaged during deployment.

• 100 kg spacecraft
• 8 triangular sail blades deployed from a central hub after launch by the inflating of structural tubes.
  • Sail blades were each 15 m long
  • Total surface area of 600 m²
• Launched in 2005 from a Russian Volna Rocket from a Russian Delta III submarine in the Barents Sea:

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Rocket Failed
NASA Ground Tested Solar Sails in the Mid-2000’s
Nasa space technology Demo (2009)

Planned to be a space flight demonstration of the solar sail developed and tested as part of the ground sail test program.
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Canceled
Mission Description:
• 10 m² sail
• Made from tested ground demonstrator hardware
NanoSail-D1 Flight (2008)

Launch:

• Falcon-1, flight 3
• Kwajalein, Missile Range
• Primary payload: Air Force PnPSat
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- Falcon-1, flight 3
- Kwajalein, Missile Range
- Primary payload: AFRL PnPSat
- Secondary P-POD payloads (2)

Rocket Failed
Nanosail-D2 Mission Configuration (2010)

3U CubeSat: 10 cm X 10 cm X 34 cm
- Deployed CP-1 sail: 10 m² Sail Area (3.16 m side length)
- 2.2 m Elgiloy Trac Booms
- UHF and S-Band communications

PPOD Deployer (Cal-Poly)

NSD-001 NSD-002

NanoSail-D
(Aluminum Closeout Panels Not Shown)

Spacecraft Bus (Ames Research Center)

Bus interfaces
Actuation
Electronics (MSFC/UAH)

Boom & Sail Spool (ManTech SRS)

AFRL Satellite (Trailblazer)

Stowed Configuration

Adapter

Ride Share Adapter (Space Access Technology)

PreSat (ARC)

HSV-1

NanoSail-D (MSFC)

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NanoSail-D (MSFC)
Interplanetary Kite-craft Accelerated by Radiation of the Sun (IKAROS)

Liquid crystal device power was off.

Liquid crystal device power was on.
Sunjammer Solar Sail Demonstration Mission

Design Heritage:
- Cold Rigidization Boom Technology
- Distributed Load Design
- Aluminized Sun Side
- High Emissivity Eclipse Surface
- Beam Tip Vane Control
- Spreader System Design

Design Features:
- High density packagability
- Controlled linear deployment
- Structural scalability
- Propellantless operation
- Meets current needs
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83 m² ISP L’Garde Solar Sail 2004
318 m² ISP L’Garde Solar Sail 2015
1200 m² L’Garde Sunjammer Launch 2015
Lightsail-A (The planetary society)

32 m²
No active ‘sailing’
3U cubesat
Solar Sails TODAY – Many Missions Planned

- NASA’s NEA Scout
- The Planetary Society’s LightSail-B
- The University of Surrey’s CubeSail, DeorbitSail, and InflateSail
- University of Illinois’ CubeSail
The Near Earth Asteroid Scout Will

- Image/characterize a NEA during a slow flyby
- Demonstrate a low cost asteroid reconnaissance capability

Key Spacecraft & Mission Parameters

- 6U cubesat (20 cm X 10 cm X 30 cm)
- ~86 m² solar sail propulsion system
- Manifested for launch on the Space Launch System (EM-1/2017)
- Up to 2.5 year mission duration
- 1 AU maximum distance from Earth

Solar Sail Propulsion System Characteristics

- ~ 7.3 m Trac booms
- 2.5µ aluminized CP-1 substrate
- > 90% reflectivity
Flight System Overview

**Mission Concept**
Characterize a Near Earth Asteroid with an optical instrument during a close, slow flyby

**Payload**
Malin Space Science Systems ECAM-M50 imager

**Mechanical & Structure**
“6U” CubeSat form factor (~10x20x30 cm)

**Propulsion**
CP-1 solar sail (based on NanoSail-D2)

**Avionics**
Radiation tolerant LEON3-FT architecture

**Electrical Power System**
Simple deployable solar arrays

**Telecom**
JPL Iris
2 pairs of INSPIRE-heritage LGAs (RX/TX)
8x8 element microstrip array HGA (TX)
Near Earth Asteroid (NEA) Scout
**InflateSail** is an **inflatable**, rigidizable sail for flight in Low Earth Orbit:

- 3U CubeSat with deployed sail area of 10 m²
- Sail supported by bistable booms
- Inflation is driven by Cool Gas Generators (CGG): low system mass, long lifespan

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**Fig. 1:** InflateSail design concept

**Fig. 2:** 80 mg CGG  
George C. Marshall  
Space Flight Center
The University of Illinois at Urbana-Champaign (UIUC), working with NASA MSFC, NSF, and CU Aerospace, built the flight hardware for a CubeSat-based 20 m² solar sail orbit raising demonstration mission.

Selected for flight under the NASA CubeSat Launch Initiative.
Continuous Polar Observations

Sailcraft over the polar regions of the Earth
Sail tilted so the light pressure from the sunlight reflecting from it is exactly equal and opposite to the gravity pull of the Earth.
Interstellar Probe

Deploy a large (>10,000 m$^2$) solar sail near the sun to enable travel 5X faster than Voyager

Goal: Reach 250 Astronomical Units within 20 years of launch
Ground to space laser illumination of a solar sail to impart measurable $\Delta V$
My Real Motive…

- **Solar Powered**
- **Laser Powered**

Areal Density (Sail Mass/Sail Area)

**INTERSTELLAR MEDIUM EXPLORATION**

**INTERSTELLAR PROBE** 2025 - 2050

- **4.5 LY INTERSTELLAR PROBE FLYBY**
- **40 LY INTERSTELLAR PROBE RENDEZVOUS**

**TECH DEV**

**INTERSTELLAR PROBE MEDIUM EXPLORATION**

- **1-km DIA** $\leq 0.1$ g/m$^2$
- **4-km DIA** $\leq 0.1$ g/m$^2$

**NEAR-TERM SAILS** 2010 - 2015

- **3 – 5 m DIA**

**MID-TERM SAILS** 2015 - 2025

- **5 to 100 m DIA** $\leq 10$ g/m$^2$

**TECH DEV**

- **NEA Scout**
- **Solar Polar Imager**
- **NON-KEPLERIAN EARTH ORBITS**

**TECH DEV**

- **INTERSTELLAR PROBE**
- **EUROPA LANDERS**
- **COMET SAMPLE RETURN**

**TECH DEV**

- **OORT CLOUD**

**TECH DEV**

- **NanoSail-D**
- **LightSail**
- **InflateSail/CubeSail**
Solar Sails: A Step Toward the Stars

Honoring the late Dr. Robert Forward, the ‘father’ of laser beamed energy propulsion