Solar Sails: Traveling the Solar System (and Beyond!) with Sunlight

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We tend to think of space as being \textit{big and empty}...
Space is NOT Empty. We can use the environments of space to our advantage
Just As Sailing Ships Can Use the Momentum of the Wind
Spacecraft Can Use the Momentum of Sunlight
Solar sails use photon “pressure” or force on thin, lightweight, reflective sheets to produce thrust.

![Solar Sail Diagram](image-url)
Photons Have Momentum
Which Can Be Imparted to the Solar Sail

- Photons carry Momentum
  \[ p = \frac{hv}{c} \]
  - \( h \) = Planck’s, \( v \) = 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
Real Solar Sails Are Not “Ideal”

Billowed Quadrant

Diffuse Reflection
Thrust Vector Components

- F(normal)
- F(total)
- F(tangential)
- CM (Center of Mass)
- Reflected Photons
- Sun Angle
- Sail normal vector
- Sail

CP (Center of Pressure)
Solar Sail Trajectory Control

Solar Radiation Pressure allows inward or outward Spiral

Original orbit

Expanding orbit

Shrinking orbit

Sail

Force
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)
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, the 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.
- 20-m diameter sail successfully deployed.
- 5-km spot illuminated Europe from France to Russia moving at 8 km/sec.
- Follow-on mission flew, but was damaged during deployment.
Space Sail Missions Flown (as of July 11, 2018)

NanoSail-D (2010) NASA
- Earth Orbit Deployment Only
- 3U CubeSat
- 10 m²

IKAROS (2010) JAXA
- Interplanetary Full Flight
- 315 kg Smallsat
- 196 m²

- Earth Orbit Deployment Only
- 3U CubeSat
- 32 m²

CanX-7 (2016) Canada
- Earth Orbit Deployment Only
- 3U CubeSat
- <10 m²

InflateSail (2017) EU/Univ. of Surrey
- Earth Orbit Deployment Only
- 3U CubeSat
- 10 m²
Interplanetary Kite-craft Accelerated by Radiation of the Sun (IKAROS)

Liquid crystal device power was off.

Liquid crystal device power was on.
Planned Solar Sail Missions (as of Sept. 28, 2018)

CU Aerospace (2018)  
Univ. Illinois / NASA

Earth Orbit  
Full Flight

3U CubeSat  
20 m²

LightSail-2 (2018)  
The Planetary Society

Earth Orbit  
Full Flight

3U CubeSat  
32 m²

Near Earth Asteroid Scout (2020)  
NASA

Interplanetary  
Full Flight

6U CubeSat  
86 m²
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-1/2019)
• 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
Baseline Target Asteroid: 1991 VG

- Diameter ~ 5 - 12 meters
- Rotation period between a few minutes and less than 1 hour
- Unlikely to have a companion
- Unlikely to retain an exosphere or dust cloud
  - Solar radiation pressure sweeps dust on timescales of hours or day

Near-Earth Asteroid 1991 VG (marked with green lines) on 2017 May 30. This is a composite of several images obtained with the ESO VLT. The images have been combined in 7 stacks tracking the position of the asteroid, resulting in the object appearing as 7 dots as it moves in front of the background stars. The stars appear trailed due to the motion of the asteroid during each series. Credit Hainaut/Micheli/Koschny
NEA Scout Approximate Scale

Deployed Solar Sail

School Bus

Folded, spooled and packaged in here

6U Stowed Flight System
The AMT will move one portion of the NEA Scout relative to the other. This translation of mass will alter the inertial properties of the vehicle and align the CP and CM.
System Performance:
0.07 mm/sec^2
25 g/m^2
NEA Scout Flight System has 3 Main Sections

- Avionics
  - Volume
- Solar Sail and Active Mass Translator
- RCS and Solar Panels
NEAS Configurations

Stowed in Dispenser

Configuration before sail deployment

Ejection, before panel deployments

Sail deployed
AMT Overview

**Nominal State**

**Trimmed State**

![Diagram showing AMT in Nominal and Trimmed States]

**KEY**

- Thrust
- CP
- CM
- Disturbance
- Torque

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NASA’s Near Earth Asteroid Scout
Full Scale Successful Deployment
NEA Scout Hardware Ready for Integration
NEA Scout: Concept of Operations Overview

- SLS EM-1 Launch
  - L+4 days: Sail Characterization
  - L+47 days: Instrument Calibration

- Separation from SLS
  - De-tumble
  - Initial Health Check
  - ~10m/s dV to target 1st lunar flyby

- Lunar Fly-by 1
  - ~1-2 additional lunar flybys to target departure
  - Additional targeting possible for off-nominal launch dates
  - Instrument calibration @Moon

- Cruise
  - Minimum Ops, Periodic Tracking
  - Rehearsal of science activities

- Target Search and Approach
  - Target Scan Imaging (Image Stacking)
  - Imaging of the resolved target
  - Target (SNR > 5)
  - Ref stars

- Target Reconstruction
  - Minimum science success criteria addressed
  - Sub-pixel imaging of target
  - On-board image co-adding to achieve detection SNR
  - Ephemeris and color addressed

- Slow target flyby
  - Full success criteria addressed
  - <1 AU Earth dist.
  - ~1 kbps DTE (34 m DSN)
  - On-board science processing

- Data Downlink
  - Proximity

- Earth-Moon Departure
  - L+764 days
  - C/A = L+784 days
  - L+810 days

- Deploy

- Earth-Moon Departure

- Cruise

- Search/Approach

- Recon

- Proximity

- Downlink
Potential Future 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
Earth Observation
Data Relay
Toward Higher Performance Beamed Energy Propulsion
My Real Motive…
Going to the Stars!

Solar Powered
- NanoSail-D
- LightSail
- InflateSail/CubeSail

Laser Powered

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

INTERSTELLAR PROBE
2025 - 2050

INTERSTELLAR MEDIUM EXPLORATION

• INTERSTELLAR PROBE
• EUROPA LANDERS
• COMET SAMPLE RETURN

40 LY INTERSTELLAR PROBE RENDEZVOUS

4.5 LY INTERSTELLAR PROBE FLYBY

INTERSTELLAR PROBE FLYBY

40 LY INTERSTELLAR PROBE FLYBY

• OORT CLOUD

4-km DIA
\( \square = 0.1 \text{ g/m}^2 \)

1-km DIA
\( \square = 1 - 2.5 \text{ g/m}^2 \)

500 - 800-m DIA
\( \square = 1 \text{ g/m}^2 \)

5 to 100 m DIA
\( \square = 10 \text{ g/m}^2 \)

MID-TERM SAILS
2015 - 2025

NEAR-TERM SAILS
2010 - 2015
3 – 5 m DIA

Chemical Rocket Limit
Nuclear Rocket Limit

\( \square = \text{Areal Density (Sail Mass/Sail Area)} \)
Solar Sails: A Step Toward the Stars

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