Solar Sail Propulsion

July 26, 2018

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Science and Technology Office
Within NASA, your acceptance of new technologies depends upon where you sit.
We tend to think of space as being

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 Derive Propulsion By Reflecting Photons

Solar sails use photon “pressure” or force on thin, lightweight, reflective sheets to produce thrust.

Ideal Case
- Sun
- Incident Photons
- Thrust Vector
- Sail
- Sail normal vector
- Reflected Photons
- Sun Angle
Real Solar Sails Are Not “Ideal”

Billowed Quadrant

- Sail
- Incident Photons
- Sun Angle
- Sail "normal vector"
- Reflected Photons

Diffuse Reflection

- Sail
- Incident Photons
- Thrust Vector
- Sun Angle
- Sail normal vector
- Reflected Photons
Thrust Vector Components

- Sail
- F(normal)
- F(total)
- F(tangential)
- Sun Angle
- Sail normal vector
- CM
- M(total)
- Reflected Photons
Solar Sail Trajectory Control

- Solar Radiation Pressure allows inward or outward Spiral
Solar Sails Experience \textbf{VERY} Small Forces

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

  - Solar Force Equivalent at 1 AU
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.
Interplanetary Kite-craft Accelerated by Radiation of the Sun (IKAROS)
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

LightSail-1 (2015)
The Planetary Society
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
Planned Solar Sail Missions (as of July 11, 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
Near Earth Asteroid Scout

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 (20cm X 10cm X 30 cm)
• ~86 $m^2$ solar sail propulsion system
• Manifested for launch on the Space Launch System (EM-1/2020)
• 1 AU maximum distance from Earth

Leverages: combined experiences of MSFC and JPL with support from GSFC, JSC, & LaRC

Target Reconnaissance with medium field imaging
Shape, spin, and local environment

Close Proximity Imaging
Local scale morphology, terrain properties, landing site survey
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
Near Earth Asteroid Scout Mission Overview

**Target Detection and Approach:**
- 50K km, Light source observation

**SKGs:** Ephemeris determination and composition assessment

**Close Proximity Science**
- High-resolution imaging, 10/px over >30% surface
- **SKGs:** Local morphology, Regolith properties

**NEA Reconnaissance**
- <100 km distance at encounter
- 50 cm/px resolution over 80% surface
- **SKGs:** Volume, global shape, spin properties, local environment

**Target Detection and Approach:**
- 50K km, Light source observation
- **SKGs:** Ephemeris determination and composition assessment
NEA Scout Flight System has 3 Main Sections

- Avionics Volume
- Solar Sail and Active Mass Translator
- RCS and Solar Panels
The Flight System

- **HaWK Solar Panel**
  - 3 Strings X2 (MMA)
- **2Ux3U Solar Panel**
  - 3 Strings (TBD)
- **Reaction Wheels (4)**
  - (BCT)
- **Solar Panel Restraints X4**
  - (MMA/TBD)
- **AMT**
  - (MSFC)
- **Sun Sensors**
  - (BCT)
- **Sail**
  - (MSFC)
- **Solar Sail / AMT Controller Board**
  - (MSFC)
- **GSE Connector & Sep. Switches**
  - (COTS)
- **RCS**
  - (TBD)
- **IMU**
  - (Sensonor)
- **Sail Deployer**
  - (MSFC)
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  - (BCT)
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  - (MSFC)
- **Sun Sensors**
  - (BCT)
- **RCS**
  - (TBD)
- **Sail Deployer**
  - (MSFC)
- **2Ux3U Solar Panel and MGA**
  - (TBD)
- **(Hidden) LGA, Sun Sensor**
  - (JPL/BCT)
- **Camera**
  - (JPL)
- **Star Tracker / RW Driver**
  - (BCT)
- **Iris Radio**
  - (JPL)
- **CDH**
  - (JPL)
- **EPS**
  - (TBD)
- **Interface Board**
  - (JPL)
NEAS Configurations

- Stowed in Dispenser
- Configuration before sail deployment
- Ejection, before panel deployments
- Sail deployed
Deployed Solar Sail

School Bus

Folded, spooled and packaged in here

6U Stowed Flight System
Problems and Challenges

- NEA Scout’s center of mass (CM) and center of pressure (CP) are not collinear with the estimated thrust vector. This creates a disturbance torque. Furthermore, the CP is fore of the CM, creating a naturally unstable vehicle and necessitating an active control mechanism.

- Little mass and volume available. This challenge is compounded by the vehicle’s total mass (14 kg) and volume (6 Liters) requirement. The AMT was originally given 250 grams and a volume of 226 x 105 x 17 mm (400 cc). This volume and mass will include: an X-Y translation stage, thermal controls, limit switches, and a wire harness. The wire harness must pass through the AMT and survive exposure to deep space environments.
AMT Overview

Nominal State

Trimmed State

KEY

Thrust

CP
CM
Disturbance
Torque
On Schedule to Deliver Spacecraft
Concept of Operations Overview

- **Launch (SLS EM-1)**: 4 days
- **Sail Characterization**: 42 days
- **Target Scan Imaging**: 2766 days
- **Recon**: 2764 days
- **Proximity**: 810 days

**Lunar Fly-by 1**
- De-tumble
- Initial Health Check
- ~10 m/s dv to target 1st lunar fly-by

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

**Target Search and Approach**
- ~1-2 additional lunar flybys to target departure
- Additional targeting possible for off-nominal launch dates
- Instrument calibration at Moon

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

**Data Downlink**
- <1 AU Earth dist.
- ~1 kbps DTE (34 m DSN)
- On-board science processing

**Proximity**
- Slow target flyby
- Full success criteria addressed

**High Resolution Imaging** (10 cm/pixel)

**Instrument Calibration**

**Earth**
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

Toward Higher Performance Beamed Energy Propulsion
My Real Motive…

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

- **Areal Density (Sail Mass/Sail Area)**

**Near-term Sails**
- 2010 - 2015
- 3 – 5 m DIA
- TECH DEV

- NanoSail-D
- LightSail
- InflateSail/CubeSail

**Mid-term Sails**
- 2015 - 2025
- TECH DEV

- 5 to 100 m DIA
  - □ = 10 g/m²
- 1000-km DIA
  - □ = 0.1 g/m²

**INTERSTELLAR PROBE**
- 2025 - 2050
- TECH DEV

- 500 - 800-m DIA
  - □ = 1 - 2.5 g/m²

- 1-km DIA
  - □ = 0.1 g/m²

- 4-km DIA
  - □ = 0.1 g/m²

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

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Solar Sails: A Step Toward the Stars

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