Solar Sail Propulsion

July 26, 2018

Les Johnson
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 use photon “pressure” or force on thin, lightweight, reflective sheets to produce thrust.
Real Solar Sails Are Not “Ideal”

Billowed Quadrant

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

Diffuse Reflection

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

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

• Solar Radiation Pressure allows inward or outward Spiral
Solar Sails Experience **VERY** Small Forces

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

  ![Diagram showing force comparison with coins at 1 AU](image)

  - 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.
Interplanetary Kite-craft Accelerated by Radiation of the Sun (IKAROS)

Liquid crystal device power was off.

Liquid crystal device power was on.
<table>
<thead>
<tr>
<th>Mission</th>
<th>Agency</th>
<th>Type</th>
<th>Mass</th>
<th>Deployment</th>
<th>CubeSat Size</th>
<th>Sail Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>NanoSail-D (2010)</td>
<td>NASA</td>
<td>Earth Orbit</td>
<td>315 kg</td>
<td>Deployment Only</td>
<td>10 m²</td>
<td>3U CubeSat</td>
</tr>
<tr>
<td>IKAROS (2010)</td>
<td>JAXA</td>
<td>Interplanetary</td>
<td>196 m²</td>
<td>Full Flight</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CanX-7 (2016)</td>
<td>Canada</td>
<td>Earth Orbit</td>
<td>&lt;10 m²</td>
<td>Deployment Only</td>
<td></td>
<td></td>
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<tr>
<td>InflateSail (2017)</td>
<td>EU/Univ. of Surrey</td>
<td>Earth Orbit</td>
<td>10 m²</td>
<td>Deployment Only</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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 m² 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 1991VG (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:**
500K 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

**Reference stars**
Target

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

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

- **Lunar Fly-by 1**
  - Minimum Ops, Periodic Tracking
  - Rehearsal of science activities

- **Lunar Fly-by 2+**
  - Sail deployment
  - Sail characterization
  - Maneuver to 2nd lunar flyby

- **Cruise**
  - On-ground eclipse
  - On-board science processing

- **Target Search and Approach**
  - Minimum science success criteria addressed
  - Target Scan Imaging (Image Stacking)
  - Imaging of the resolved target

- **Target**
  - (SNR > 5)
  - Ref stars

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

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

- **Target Distance**
  - <50,000 km

- **Target Reconnaissance**
  - <28 km

- **Earth-Moon Departure**

- **Cruise**

- **Search/Approach**

- **Recon**

- **Proximity**

- **Downlink**

- **Deployment**

- **Earth**
Potential Future Solar Sail Applications
(A Partial List!)

- NEA Reconnaissance & Small Body Science
- Heliophysics & Out of the Ecliptic Science
- Earth Pole Sitting
- Rapid Outer Solar System Exploration and Escape
- Toward Higher Performance Beamed Energy Propulsion
My Real Motive…

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

<table>
<thead>
<tr>
<th>Distance (km)</th>
<th>Areal Density (g/m²)</th>
</tr>
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<tbody>
<tr>
<td>1 – 5</td>
<td>10</td>
</tr>
<tr>
<td>500 – 800</td>
<td>1 – 2.5</td>
</tr>
<tr>
<td>1 – 2.5</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>0.1</td>
</tr>
</tbody>
</table>

- **NEA Scout**
- **Solar Polar Imager**
- **NON-KEPLERIAN EARTH ORBITS**
- **INTERSTELLAR PROBE**
  - **2025 - 2050**
  - **4.5 LY INTERSTELLAR PROBE FLYBY**
  - **40 LY INTERSTELLAR PROBE RENDEZVOUS**

- **MID-TERM SAILS**
  - **2015 - 2025**
  - **500 – 800-m DIA**
  - **1-km DIA**
  - **4-km DIA**

- **TECH DEV**
  - **INTERSTELLAR MEDIUM EXPLORATION**
  - **NEAR-TERM SAILS**
    - **2010 - 2015**
    - **3 – 5 m DIA**

- **NanoSail-D**
- **LightSail**
- **InflateSail/CubeSail**

- **Chemical Rocket Limit**
- **Nuclear Rocket Limit**
Solar Sails: A Step Toward the Stars

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