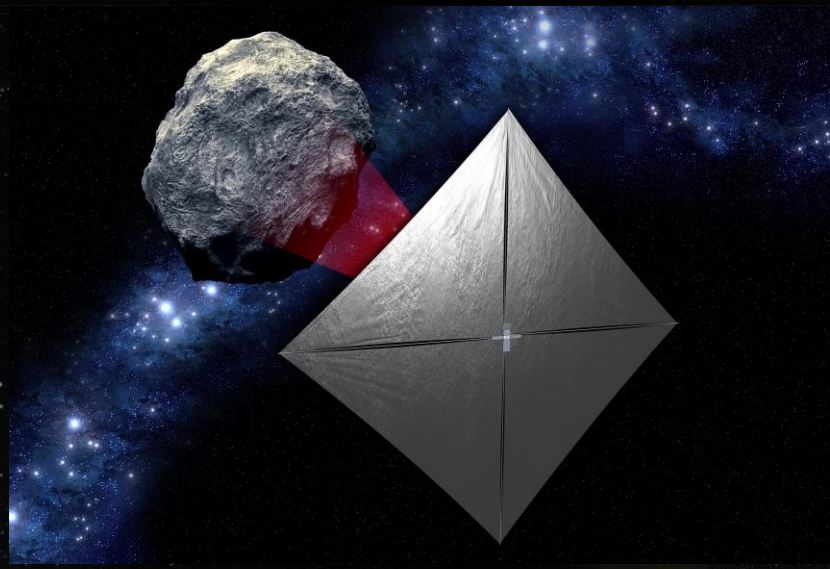
National Aeronautics and Space Administration

Solar Sail Propulsion for Interplanetary Small Spacecraft

Les Johnson
NASA MSFC

FISO Telecon 3-25-15



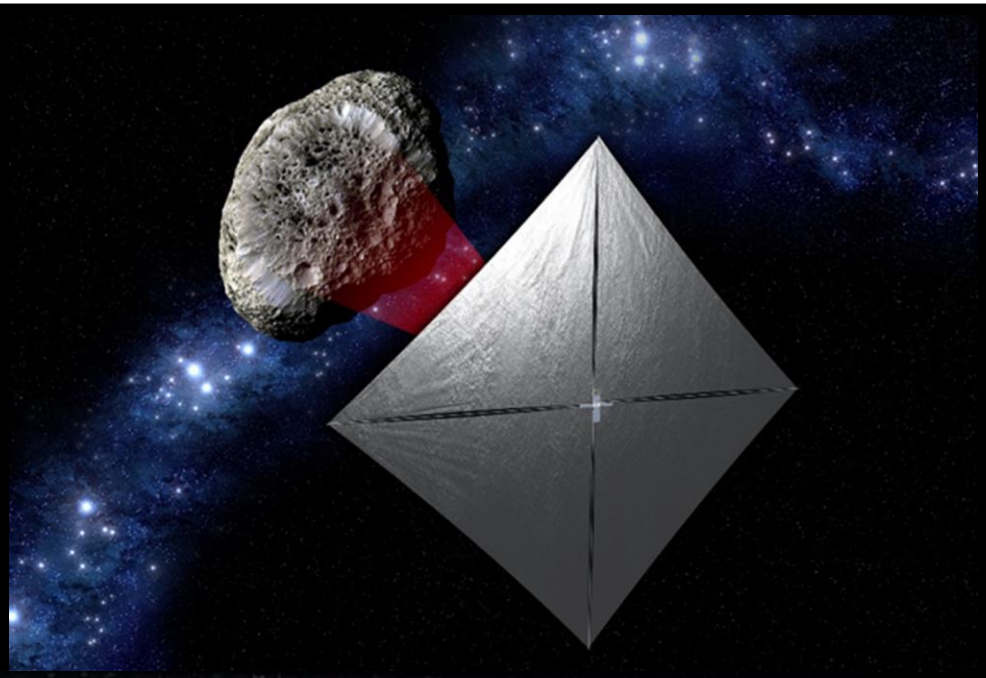
SLS EM-1 Secondary Payloads

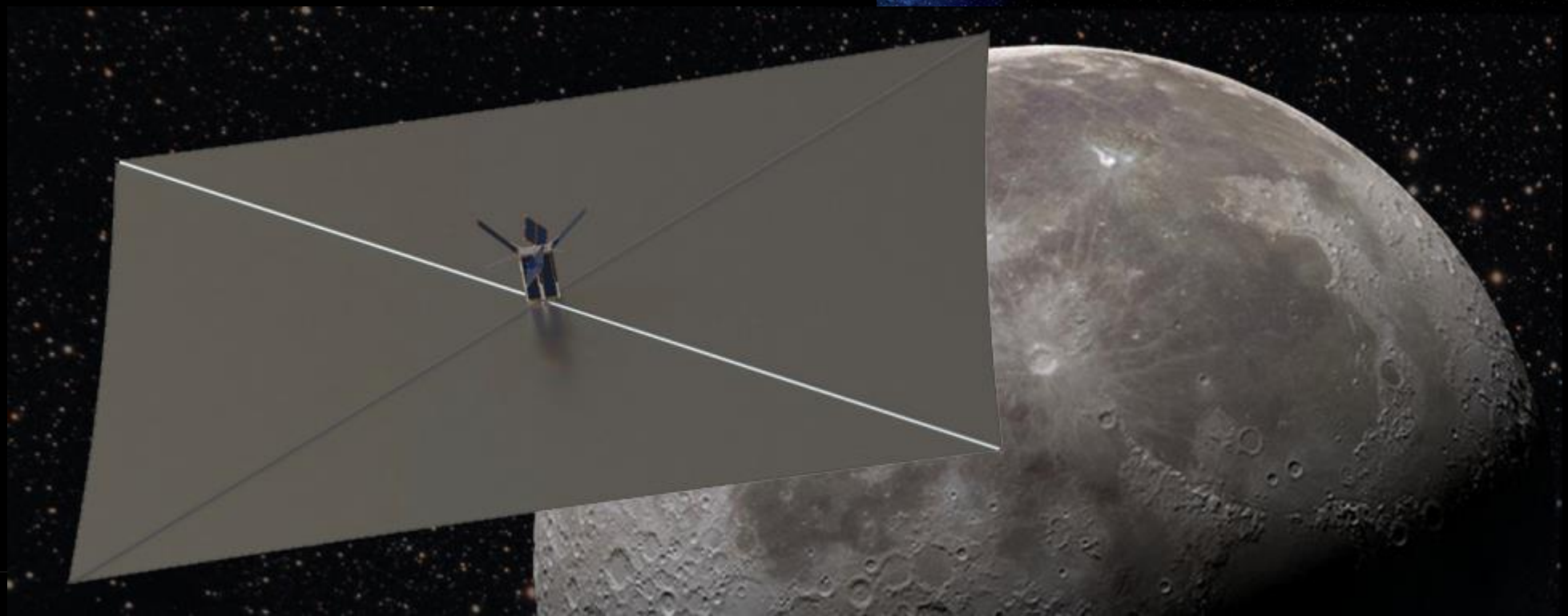
- **HEOMD's Advanced Exploration Systems (AES) selected 3 cubesats for flight on SLS EM1**
- **Primary selection criteria:**
  - Relevance to Space Exploration Strategic Knowledge Gaps (SKGs)
  - Life cycle cost
  - Synergistic use of previously demonstrated technologies
  - Optimal use of available civil servant workforce

Payload *NASA Centers*	**Strategic Knowledge Gaps Addressed**	**Mission Concept**
BioSentinel ***ARC**/JSC* 	**Human health/performance in high-radiation space environments** • Fundamental effects on biological systems of ionizing radiation in space environments	Study radiation-induced DNA damage of live organisms in cis-lunar space; correlate with measurements on ISS and Earth
Lunar Flashlight ***JPL**/MSFC* 	**Lunar resource potential** • Quantity and distribution of water and other volatiles in lunar cold traps	Locate ice deposits in the Moon's permanently shadowed craters
Near Earth Asteroid (NEA) Scout ***MSFC**/JPL* 	**Human NEA mission target identification** • NEA size, rotation state (rate/pole position) **How to work on and interact with NEA surface** • NEA surface mechanical properties	Flyby/rendezvous and characterize one NEA that is candidate for a human mission

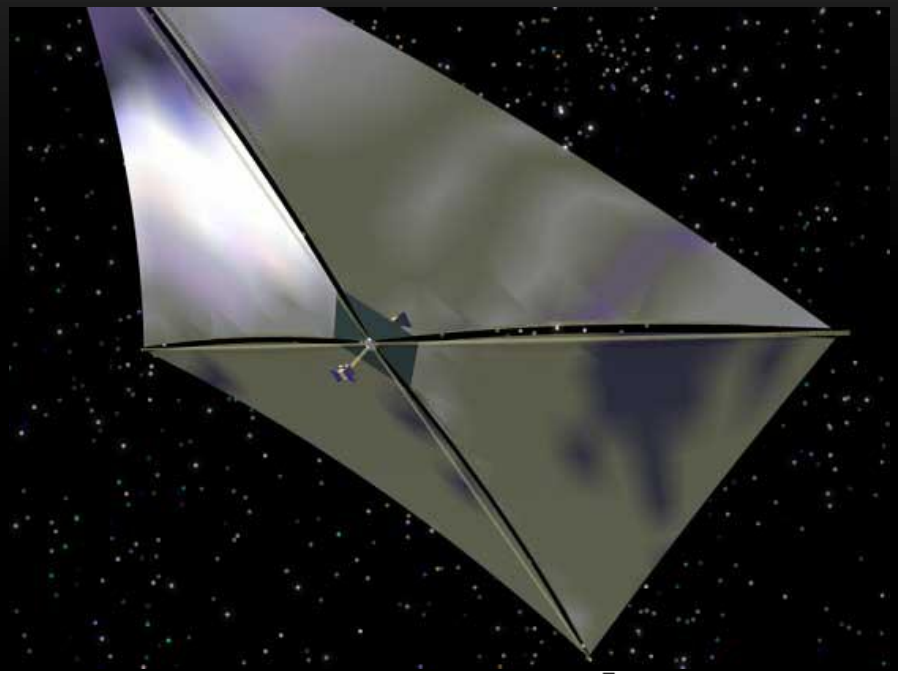
NEA Scout and Lunar Flashlight

Both Use Solar Sail Propulsion and 6U CubeSats

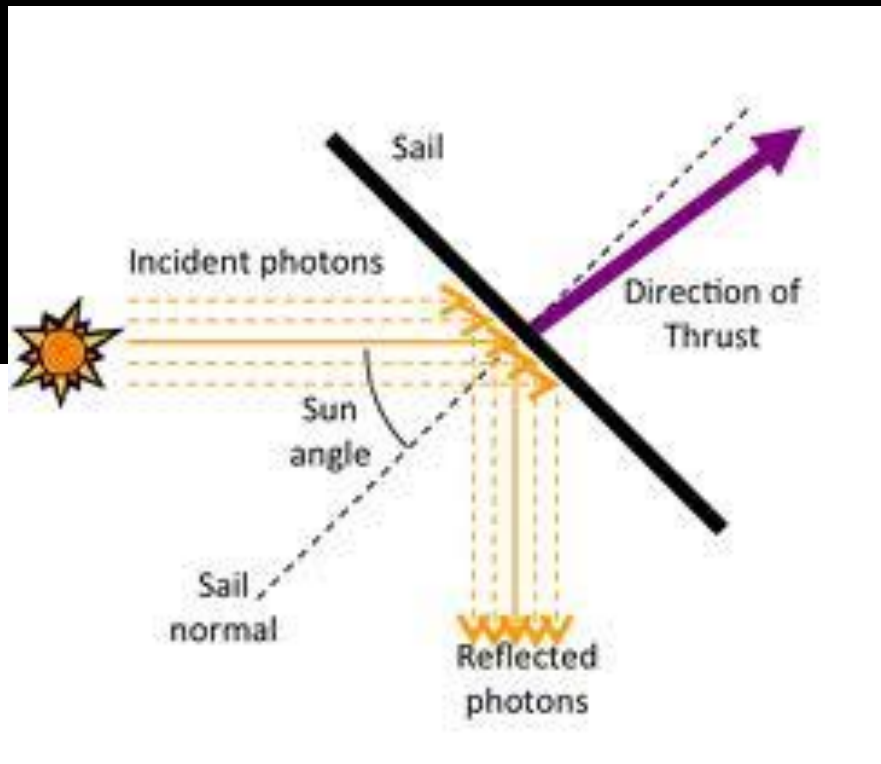


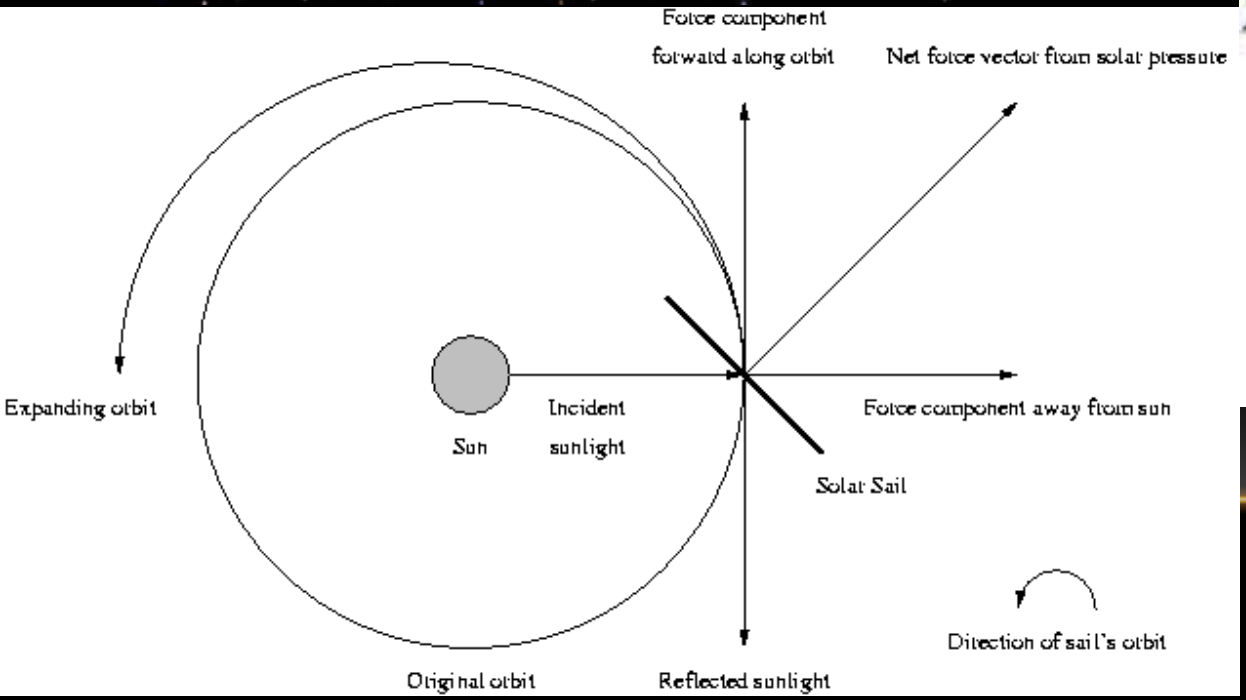


HOW DOES A SOLAR SAIL WORK?



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





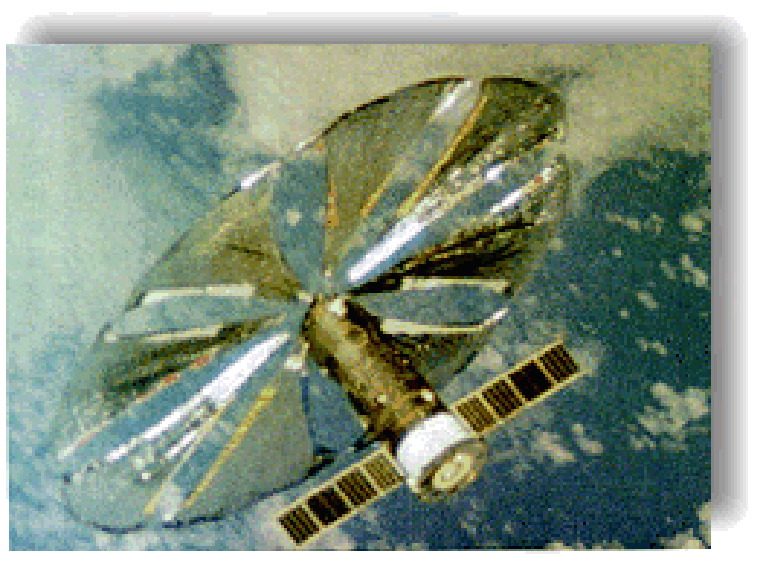
ECHO II 1964

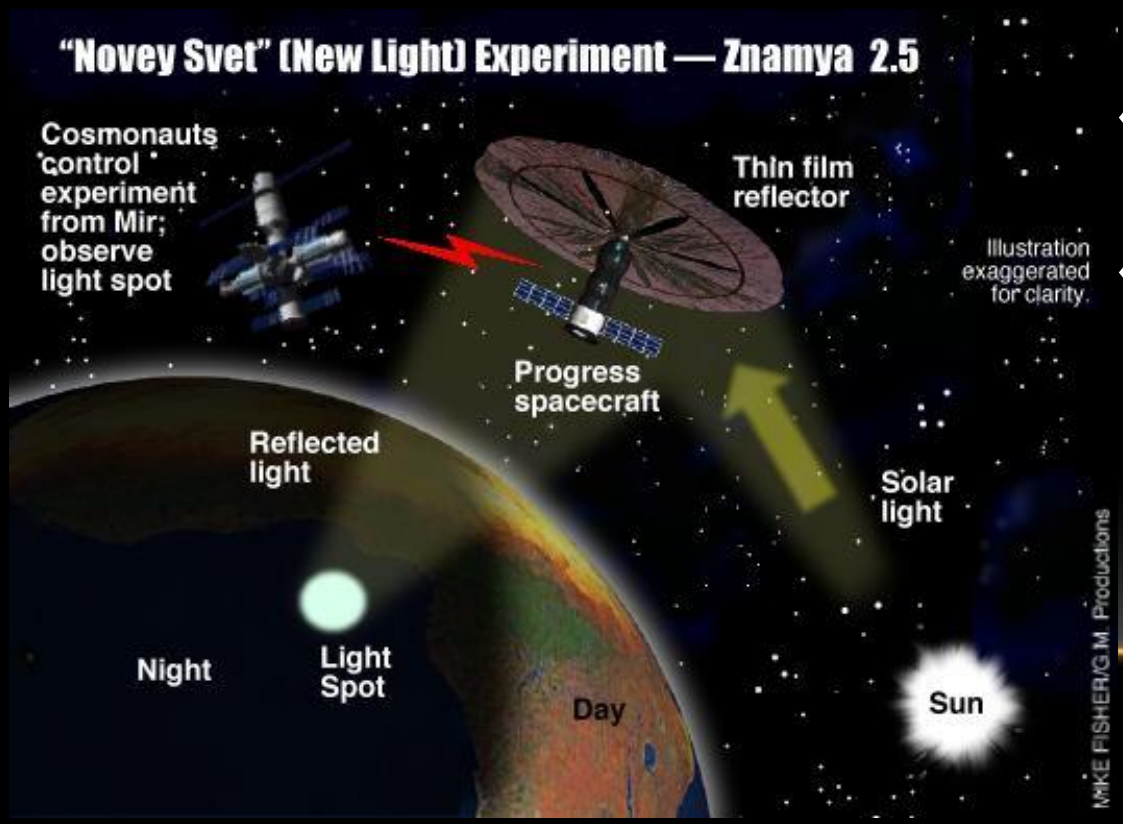
SOLAR THRUST AFFECT ON SPACECRAFT ORBIT

- 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

When folded, satellite was packed into the 41-inch diameter canister shown in the foreground.

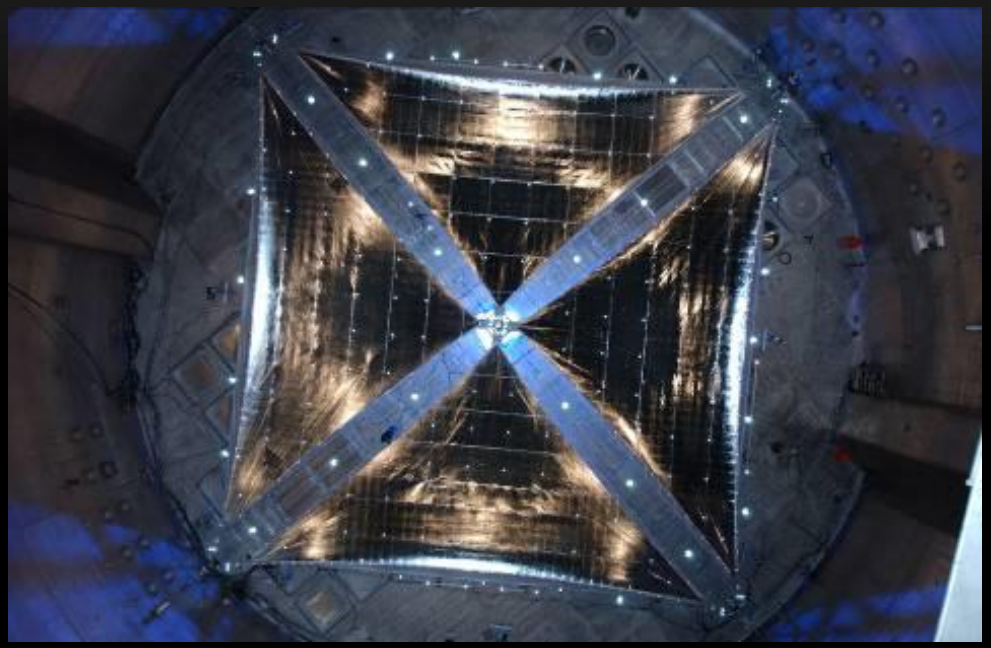
Znamya (Space Mirror)





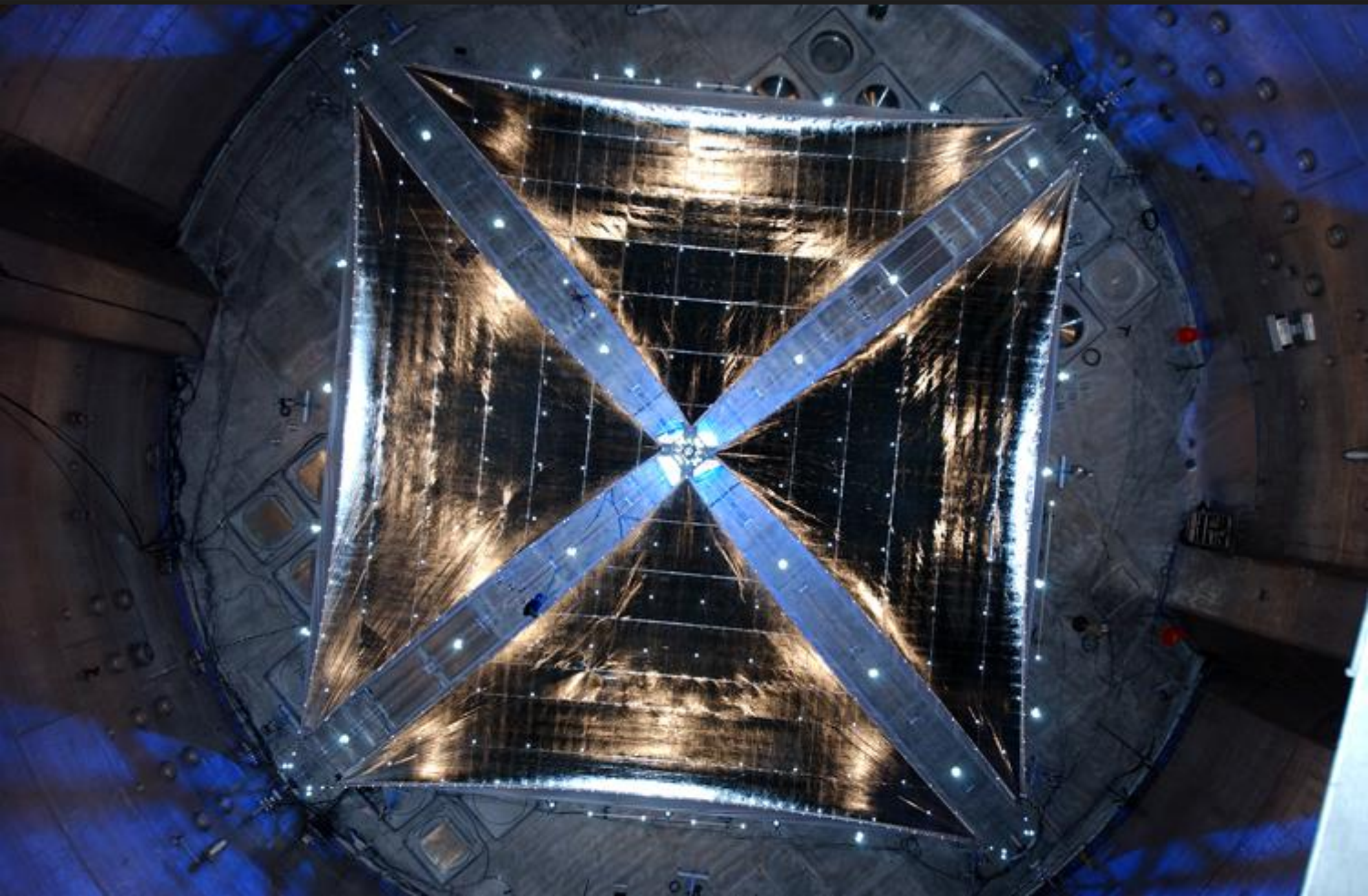
- Russian experiment that flew on Progress after undocking from Mir Space Station in 1993.
- Purpose was to reflect sunlight onto the ground from space.
- 20-m diameter sail successfully deployed
- 5-km spot illuminated Europe from France to Russia moving at 8 km/sec.
- Follow-on mission flew, but was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

NASA GROUND TESTED SOLAR SAILS IN THE 2000'S



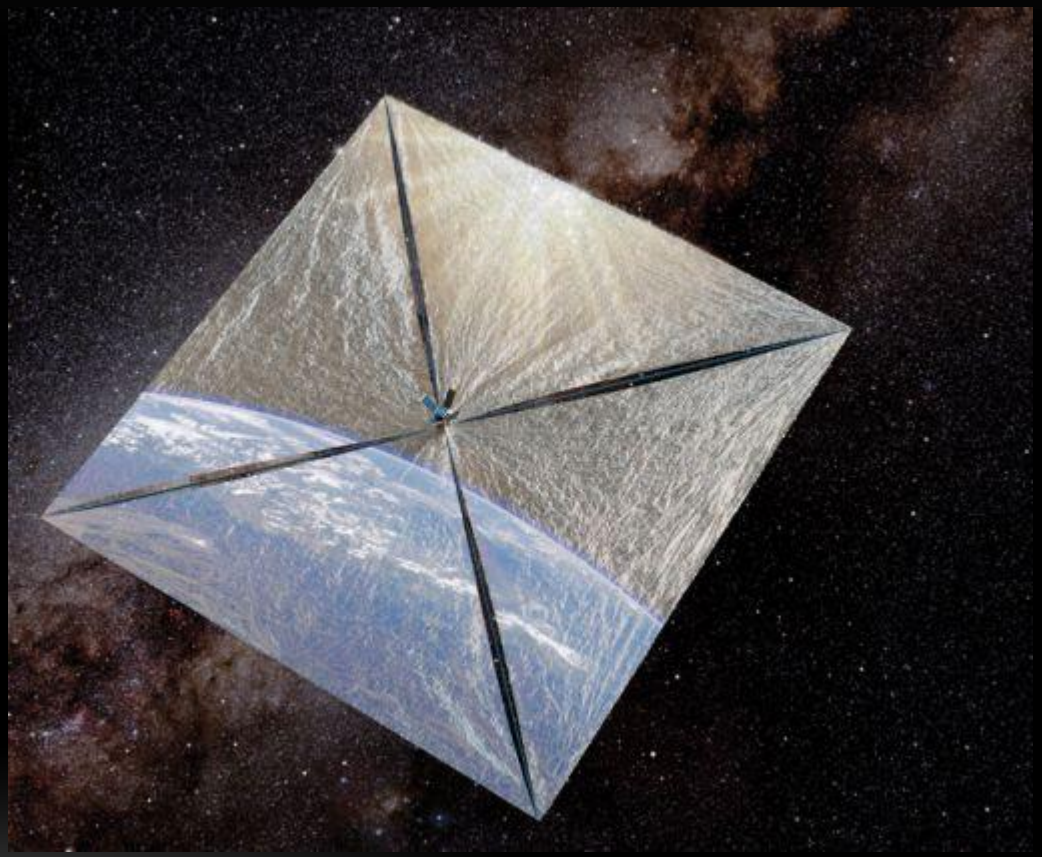
- Two solar sail technologies were designed, fabricated, and tested under thermal vacuum conditions in 2005:
  - 10 m system ground demonstrators (developed and tested in 2004/2005)
  - 20 m system ground demonstrators (designed, fabricated, and tested)
- Developed and tested high-fidelity computational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

NASA'S 400 SQ. METER SOLAR SAIL DEMONSTRATOR IN GROUND TEST



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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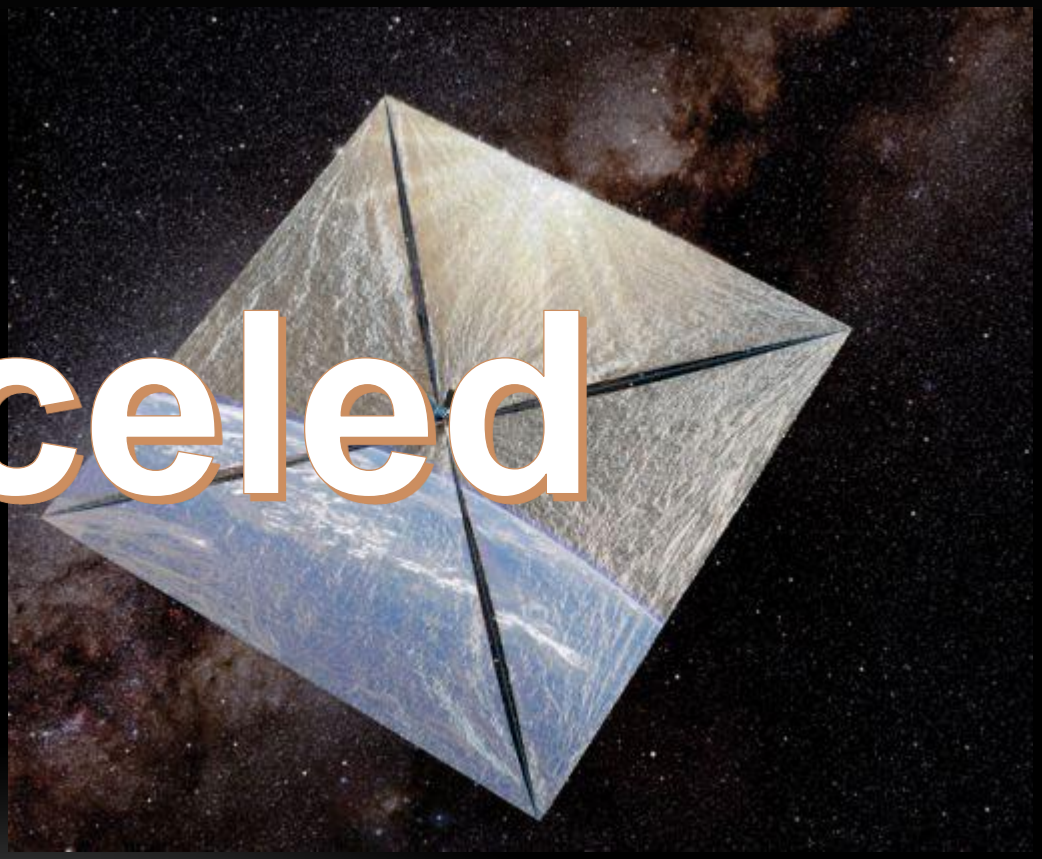
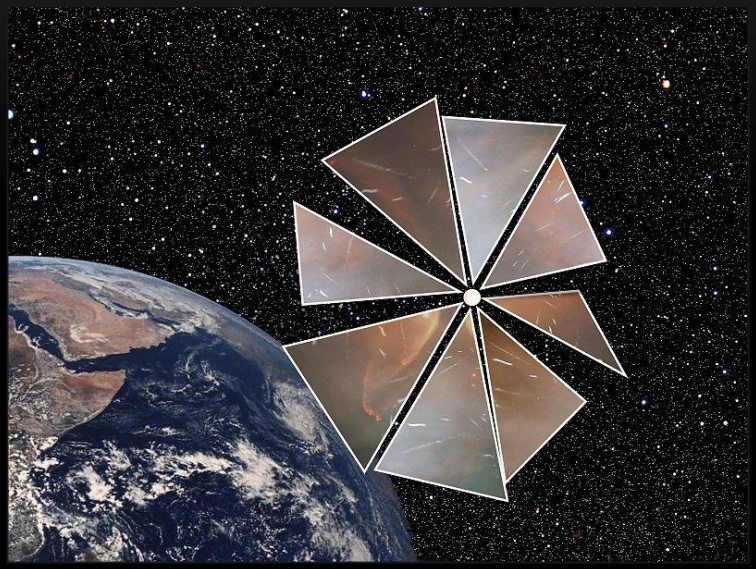
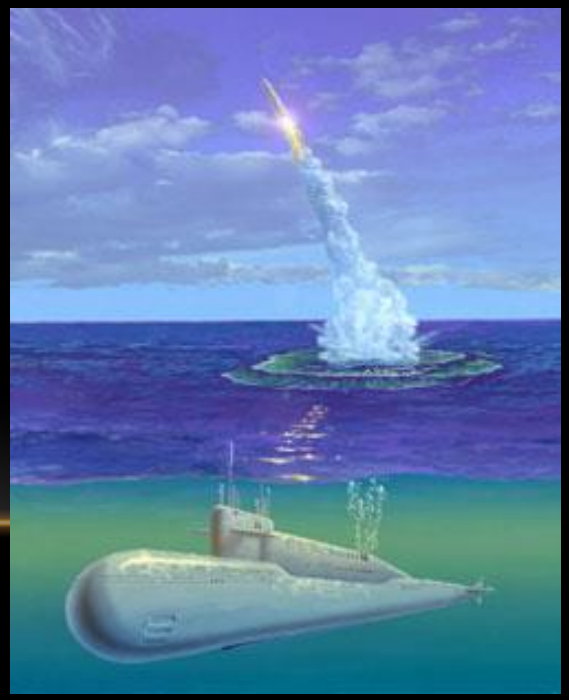


Canceled

THE PLANETARY SOCIETY'S COSMOS-1 (2005)

- 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 square meters
- Launched in 2005 from a Russian Volna Rocket from a Russian Delta III submarine in the Barents Sea:





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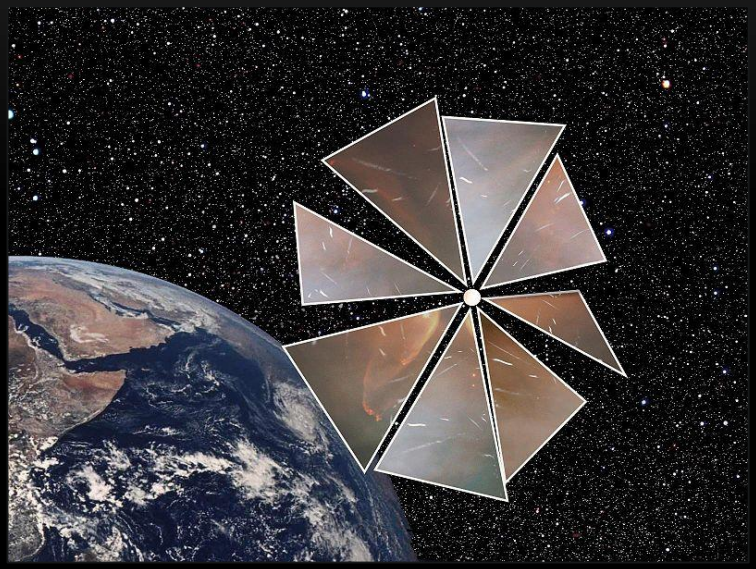
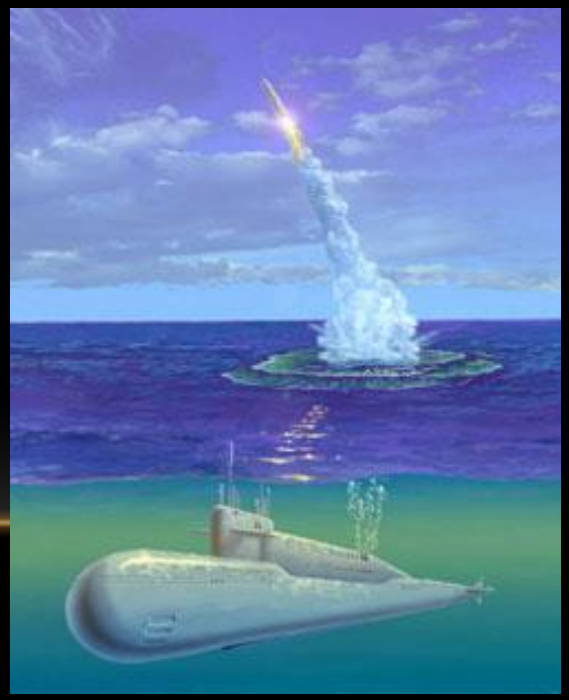
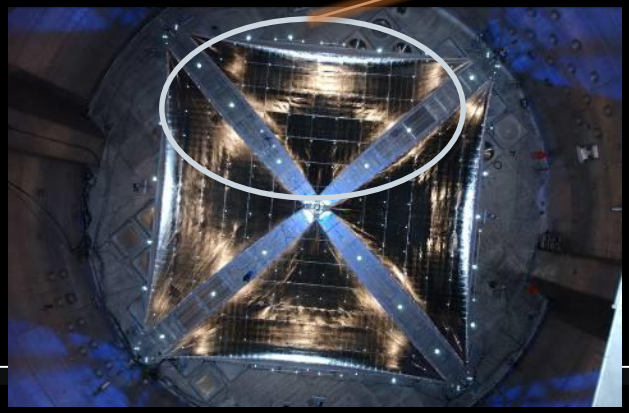


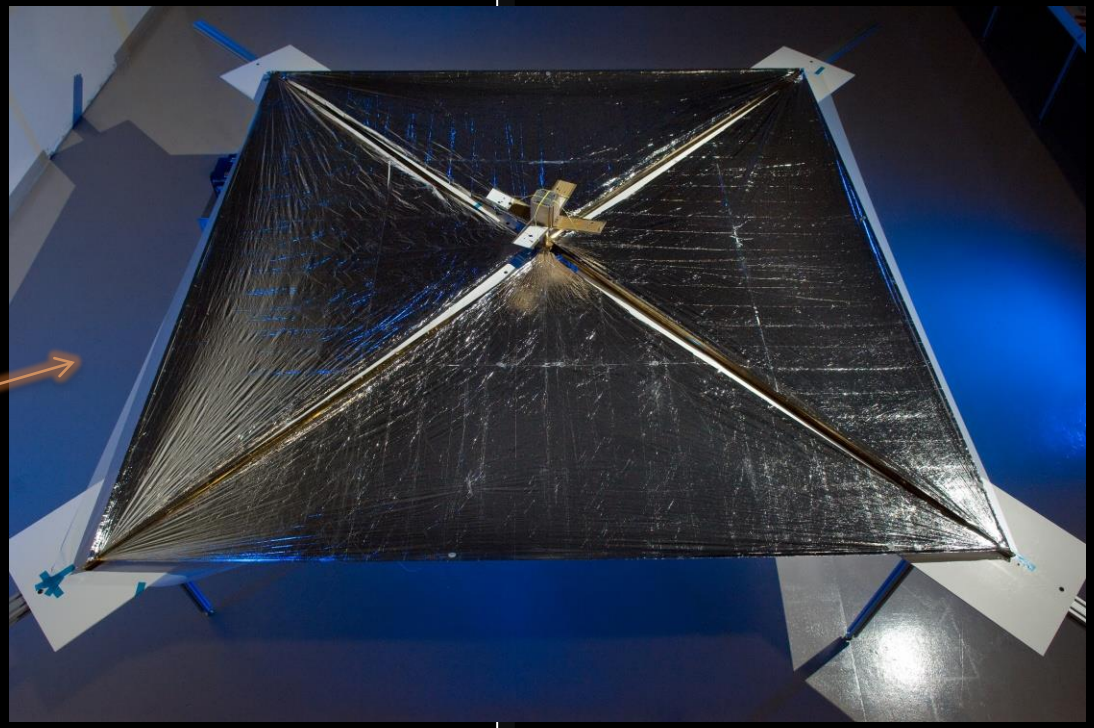


Rocket Failed

NANOSAIL-D DEMONSTRATION SOLAR SAIL

- Mission Description:
  - 10 m^2 sail
  - Made from tested ground demonstrator hardware

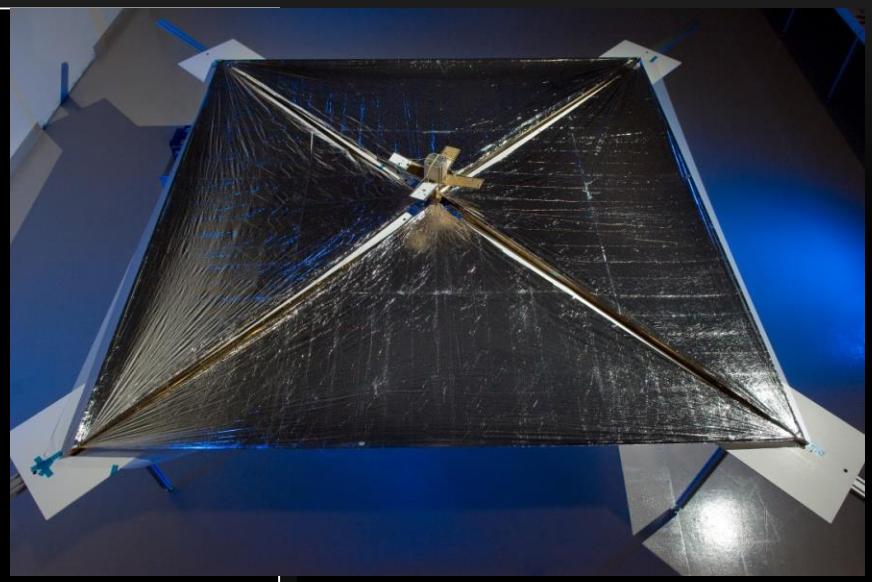




NANOSAIL-D1 FLIGHT (2008)

Launch

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



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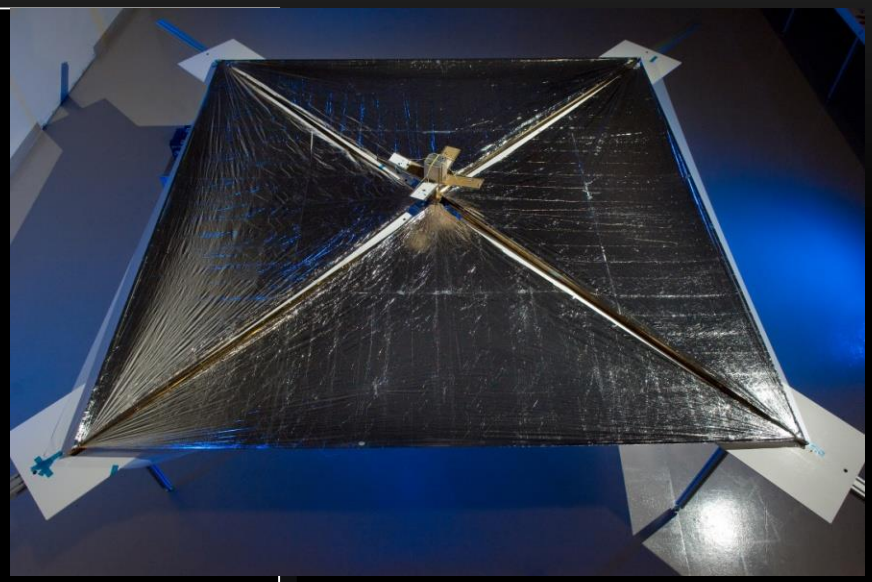
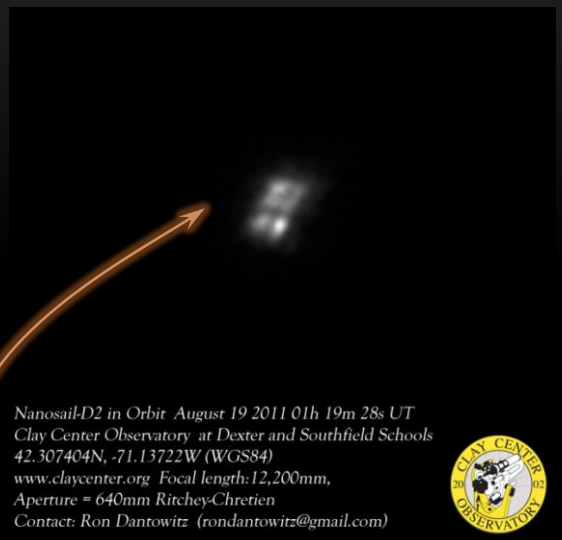
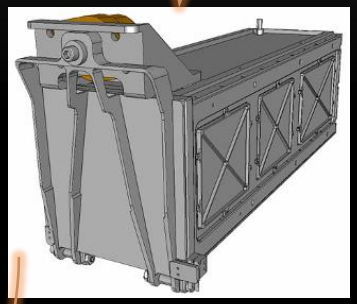


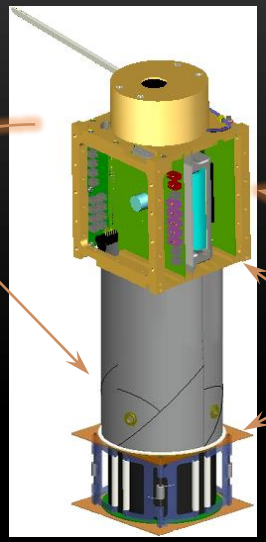
Rocket Failed

NANOSAIL-D2 MISSION CONFIGURATION (2010)





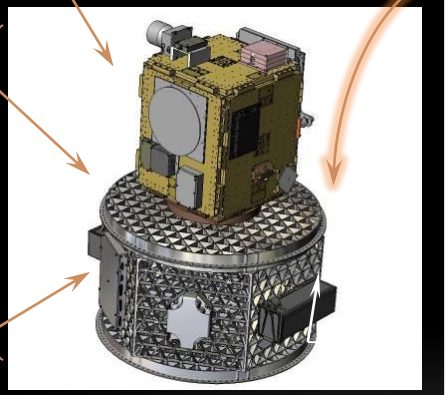
PPOD Deployer
(Cal-Poly)



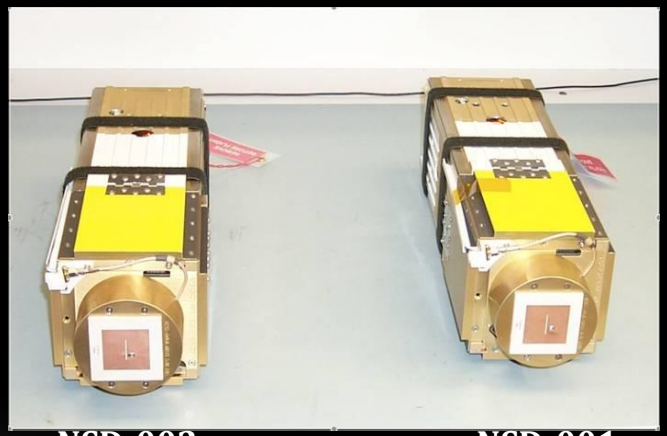
NanoSail-D
(Aluminum Closeout Panels Not Shown)

Stowed Configuration

HSV-1



Ride Share Adapter
(Space Access Technology)

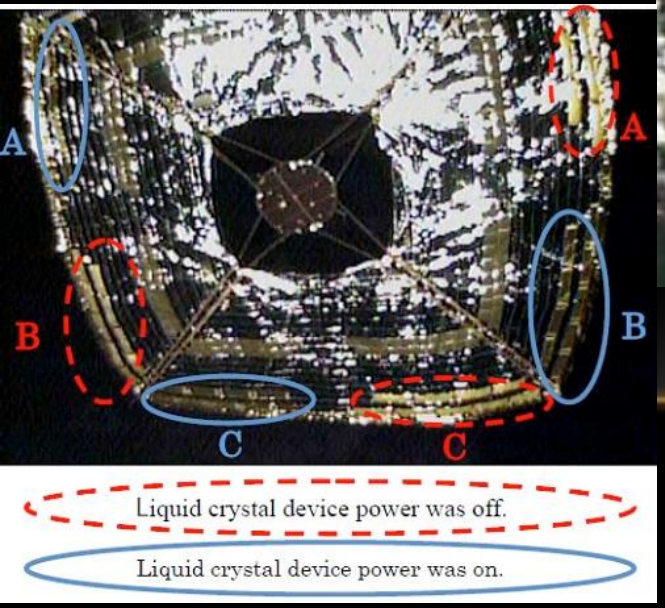


NSD-002 **NSD-001**

- 3U Cubesat: 10 cm X 10 cm X 34 cm
- Deployed CP-1 sail: 10 m^2 Sail Area (3.16 m side length)
- 2.2 m Elgiloy Trac Booms
- UHF and S-Band communications

Nanosail-D2 in Orbit August 19 2011 01h 19m 28s UT
Clay Center Observatory at Dexter and Southfield Schools
42.307404N, -71.13722W (WGS84)
www.claycenter.org Focal length:12,200mm,
Aperture = 640mm Ritchey-Chretien
Contact: Ron Dantowitz (rondantowitz@gmail.com)

Interplanetary Kite-craft Accelerated by Radiation of the Sun (IKAROS 2010)



SUNJAMMER SOLAR SAIL DEMONSTRATION MISSION

83 m² ISP L'Garde Solar Sail 2004

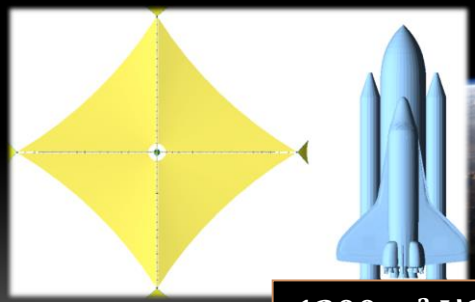
318 m² ISP L'Garde Solar Sail 2005

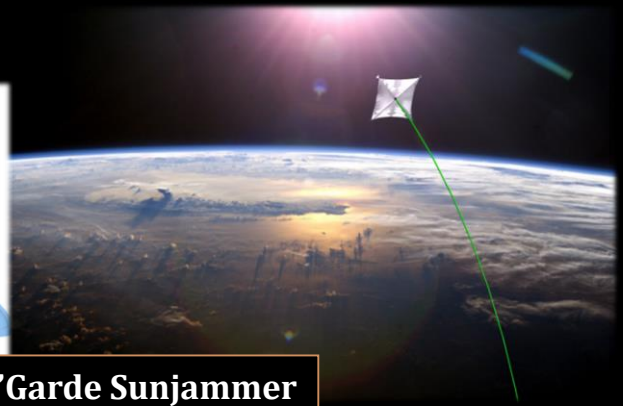
Design Heritage:

- 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





1200 m² L'Garde Sunjammer

SUNJAMMER SOLAR SAIL DEMONSTRATION MISSION

83 m² ISP L'Garde Sola
2004

31 m² ISP L Sol
2005

Canceled

Design Heritage:

- Cold Rigidization Boom Technology
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- Aluminized Sun Side
- High Emissivity Eclipse Surface
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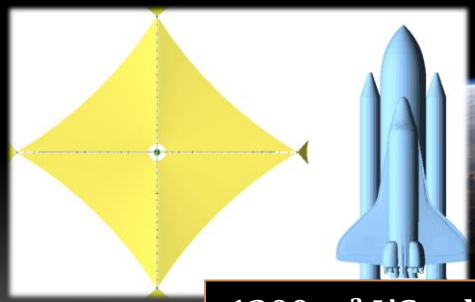
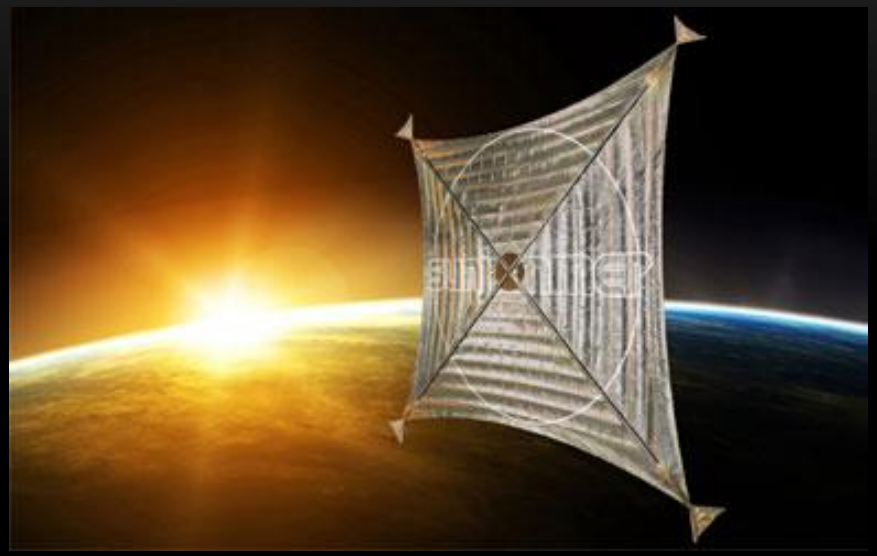
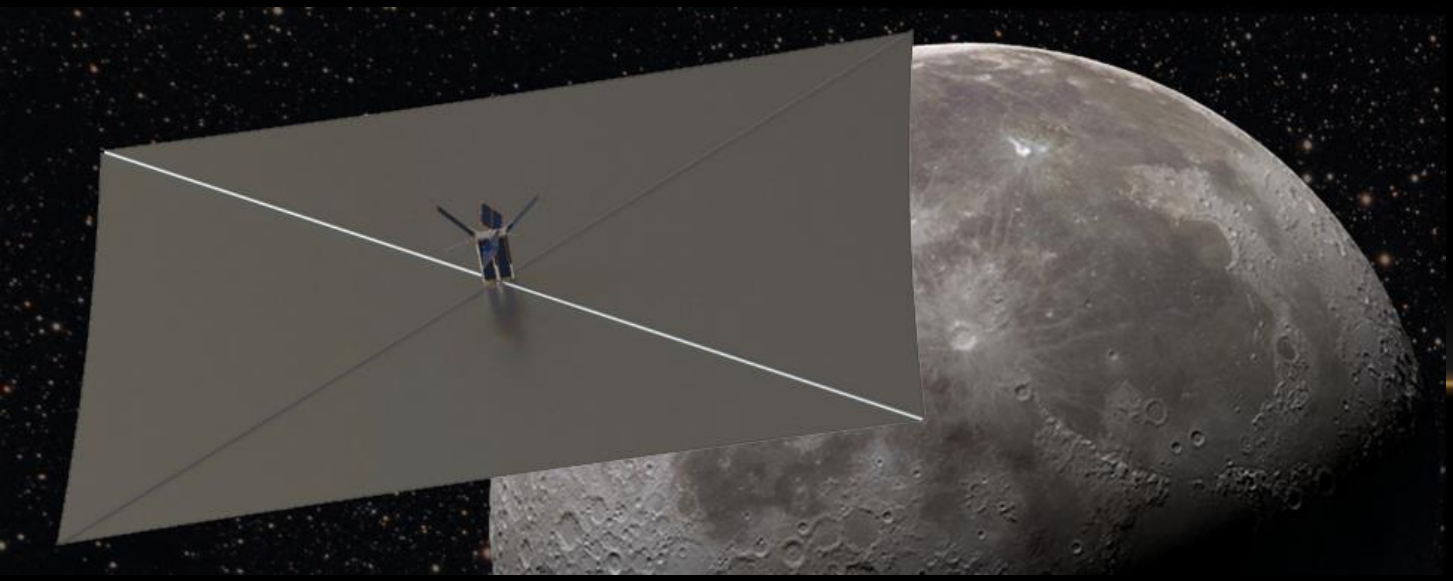


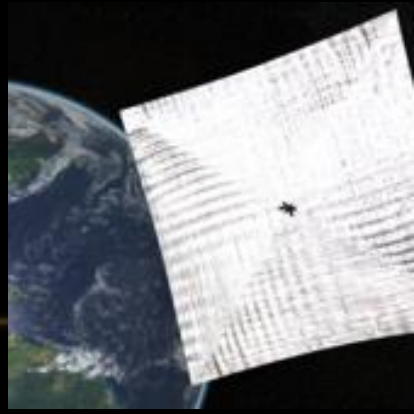
1200 m² L'Garde Sunjammer Launch
2015

SOLAR SAILS TODAY – MANY MISSIONS PLANNED

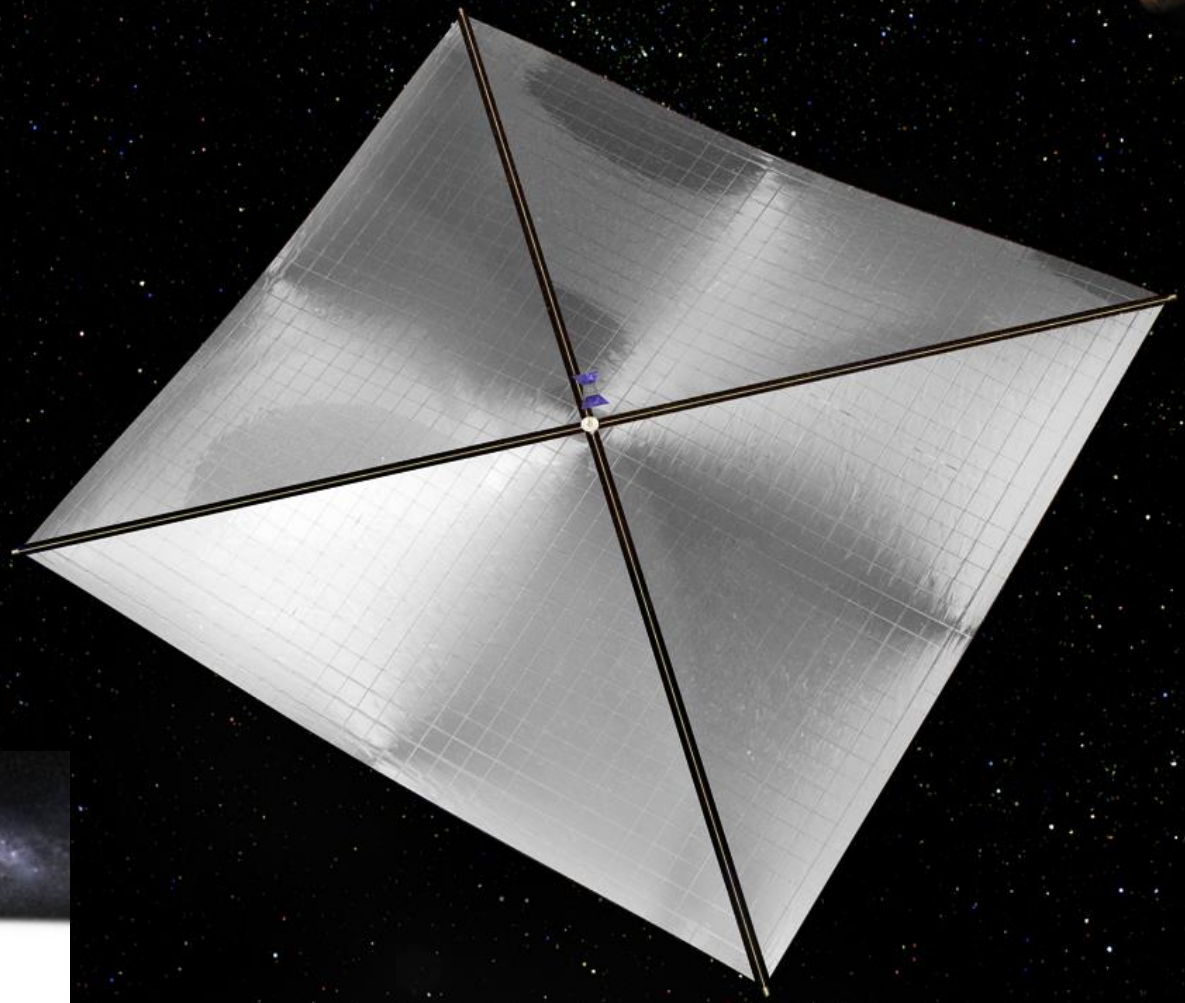


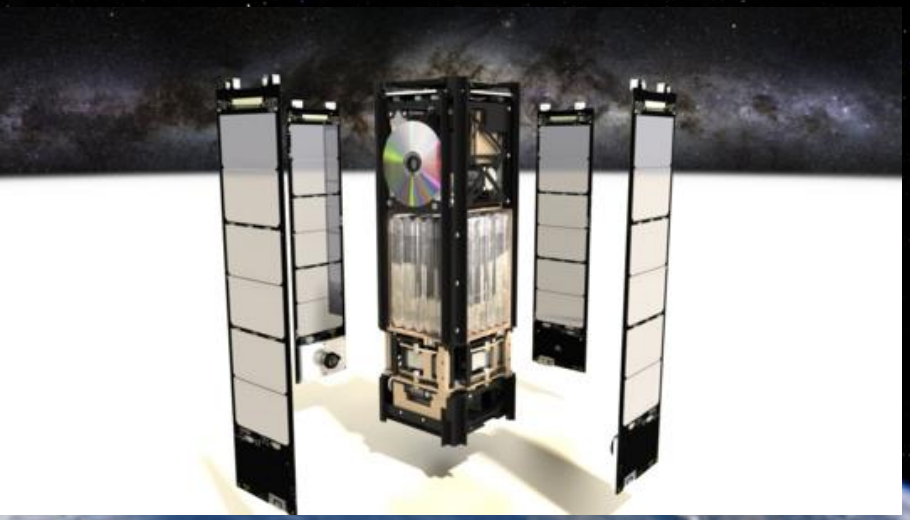
- NASA's *NEA Scout* and *Lunar Flashlight*
- The Planetary Society's *LightSail-A* and *LightSail-B*
- The University of Surrey's *CubeSail*, *DeorbitSail*, and *InflateSail*





LIGHTSAIL-A AND -B (THE PLANETARY SOCIETY)





- 3U Cubesat design
- Sail Material: aluminized 4.5 micron Mylar film
- 32 square meters solar sail area fully deployed
- LightSail-A (2015) and LightSail-B (2016)

UNIVERSITY OF SURREY'S INFLATESAIL

- **InflateSail** is an <u>inflatable</u>, <u>rigidizable</u> sail for flight in Low Earth Orbit:
  - 3U CubeSat with deployed sail area of 10 m^2
  - Sail supported by bistable booms
  - Inflation is driven by Cool Gas Generators (CGG): low system mass, long lifespan

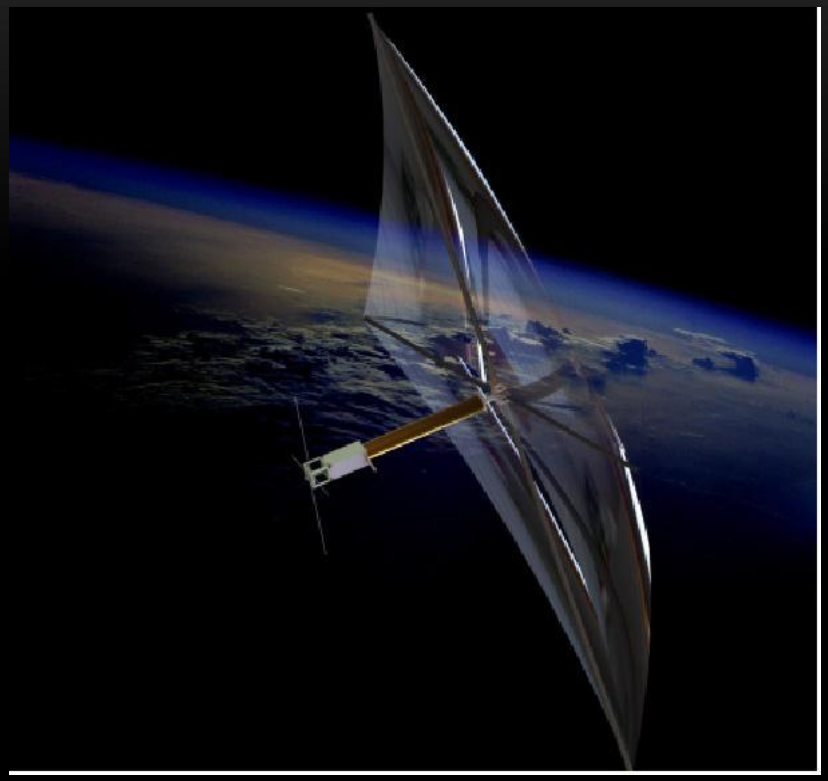


***Fig. 1**: InflateSail design concept*

***Fig. 2**: 80 mg CGG* George C. Marshall Space Flight Center

SURREY SPACE CENTRE

CGG technologies COOL GAS GENERATOR

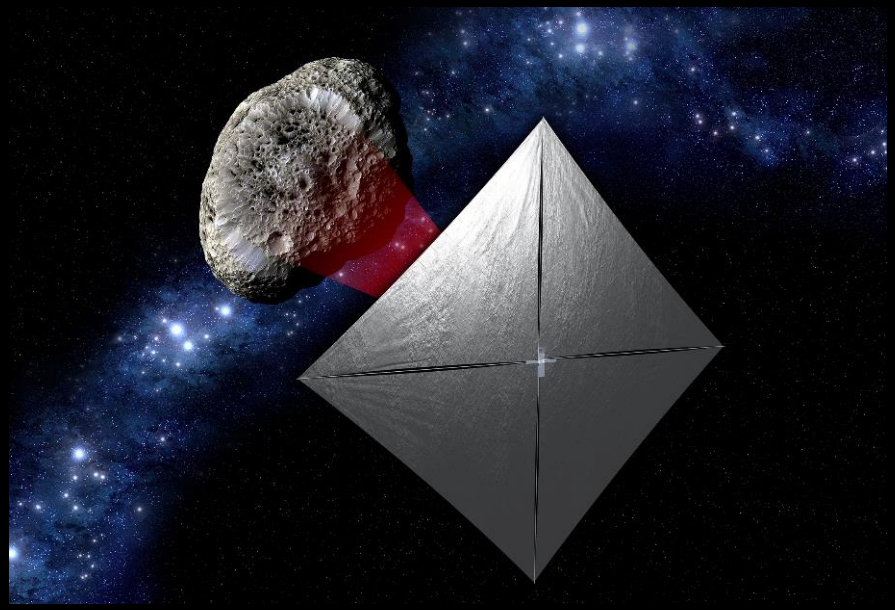
ASTRIUM AN EADS COMPANY

UNIVERSITY OF CAMBRIDGE

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

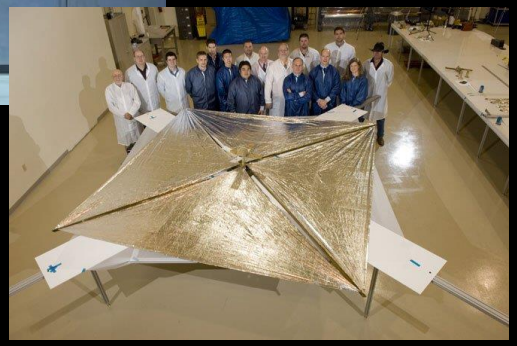


Key Spacecraft & Mission Parameters

- 6U cubesat (20 cm X 10 cm X 30 cm)
- ~85 m^2 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

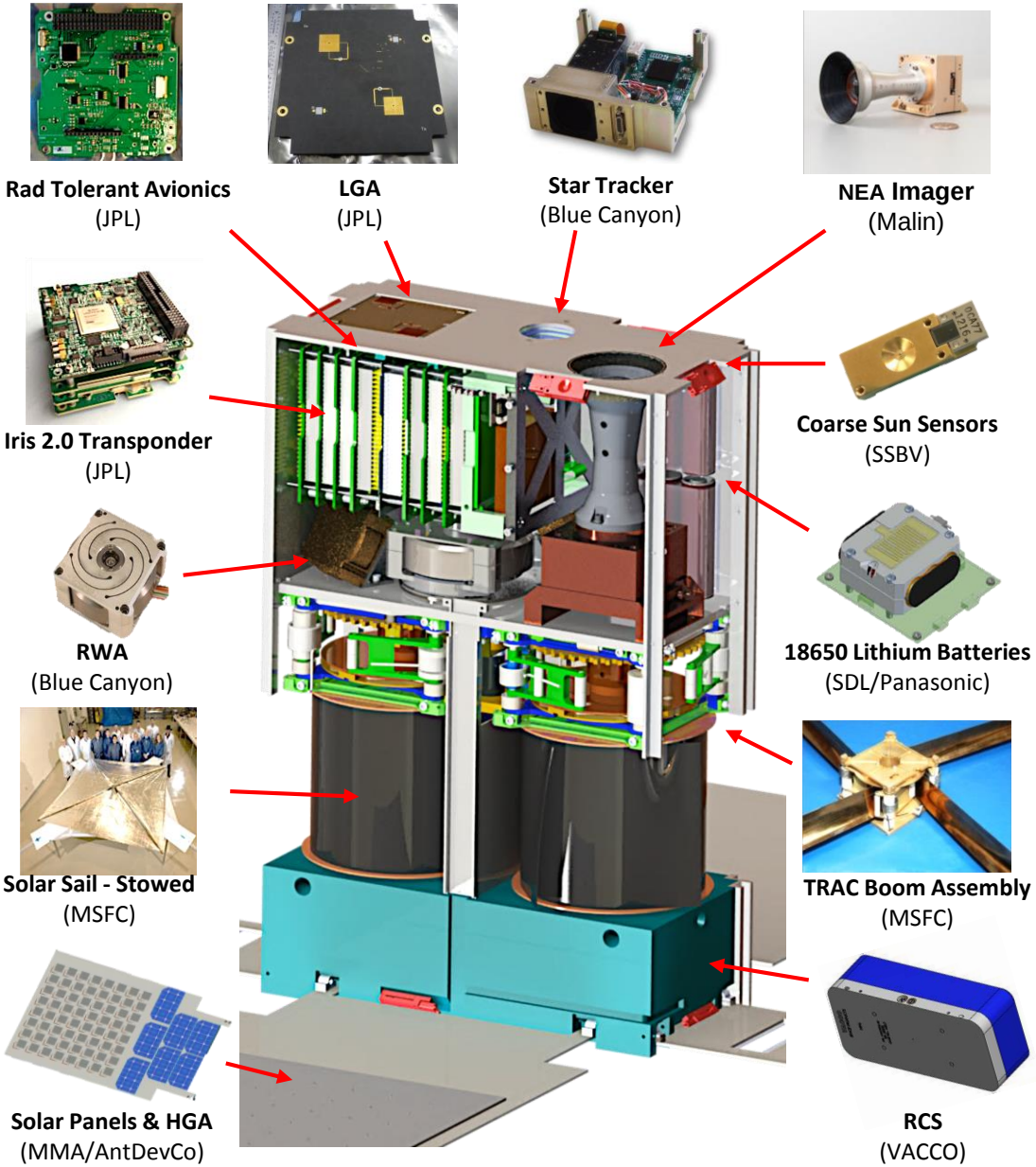
Solar Sail Propulsion System Characteristics

- ~ 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 w/NFOV optics • Static color filters (400-900 nm)
Mechanical & Structure	• "6U" CubeSat form factor (~10x20x30 cm) • <12 kg total launch mass • Modular flight system concept
Propulsion	• ~85 m^2 aluminized CP-1 solar sail (based on NanoSail-D2)
Avionics	• Radiation tolerant LEON3-FT architecture
Electrical Power System	• Simple deployable solar arrays with UTJ GaAs cells (~35 W at 1 AU solar distance) • 6.8 Ah Battery (3s2p 18650 Lithium Cells) • 10.5-12.3 V unregulated, 5 V/3.5 V regulated
Telecom	• JPL Iris 2.0 X-Band Transponder; 2 W RF SSPAs; supports doppler, ranging, and D-DOR • 2 pairs of INSPIRE-heritage LGAs (RX/TX) • 8x8 element microstrip array HGA (TX) • ~500 bps to 34m DSN at 0.8 AU
Attitude Control System	• 15 mNm-s (x3) & 100 mNm-s RWAs • Zero-momentum slow spin during cruise • VACCO R134a (refrigerant gas) RCS system • Nano StarTracker, Coarse Sun Sensors & MEMS IMU for attitude determination



NEA Scout Approximate Scale

Deployed Solar Sail

School Bus

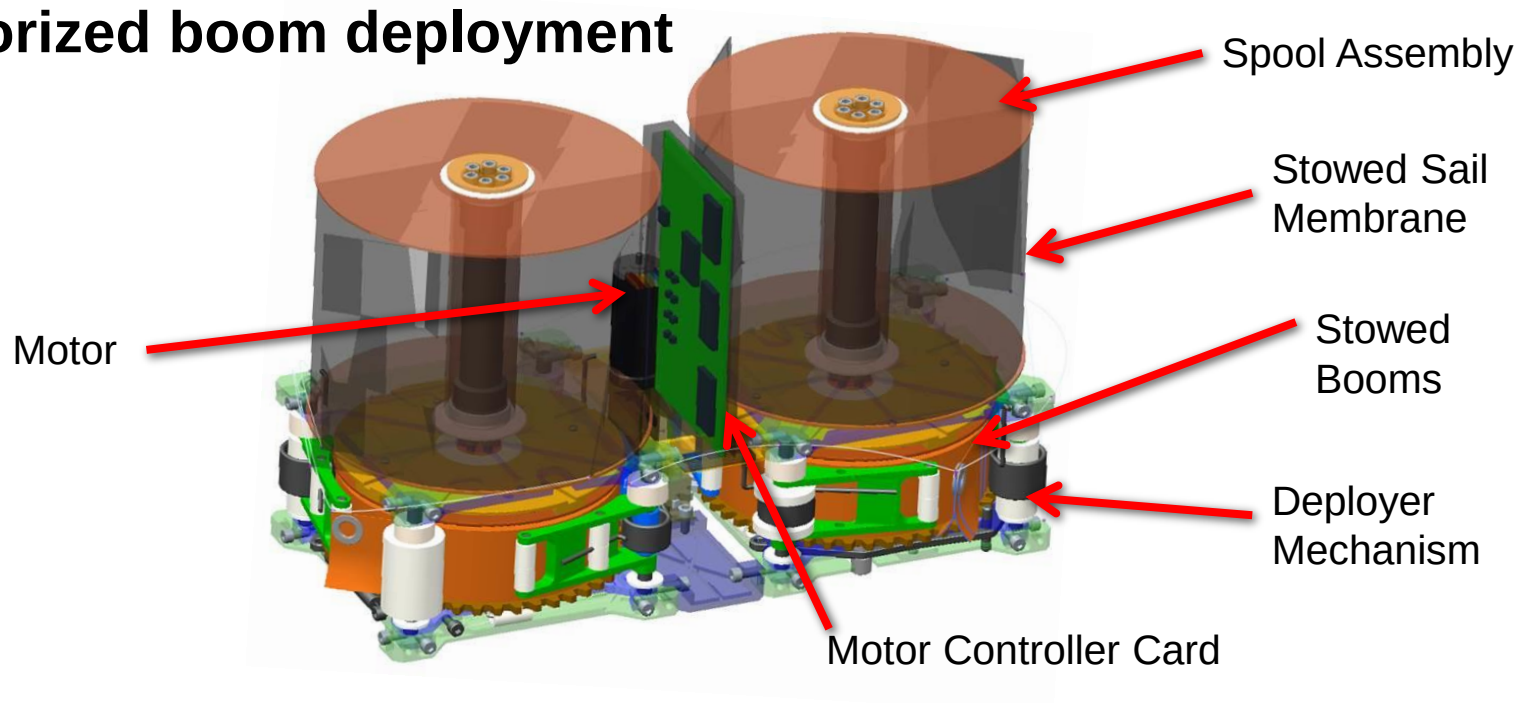
Human

6U Stowed Flight System

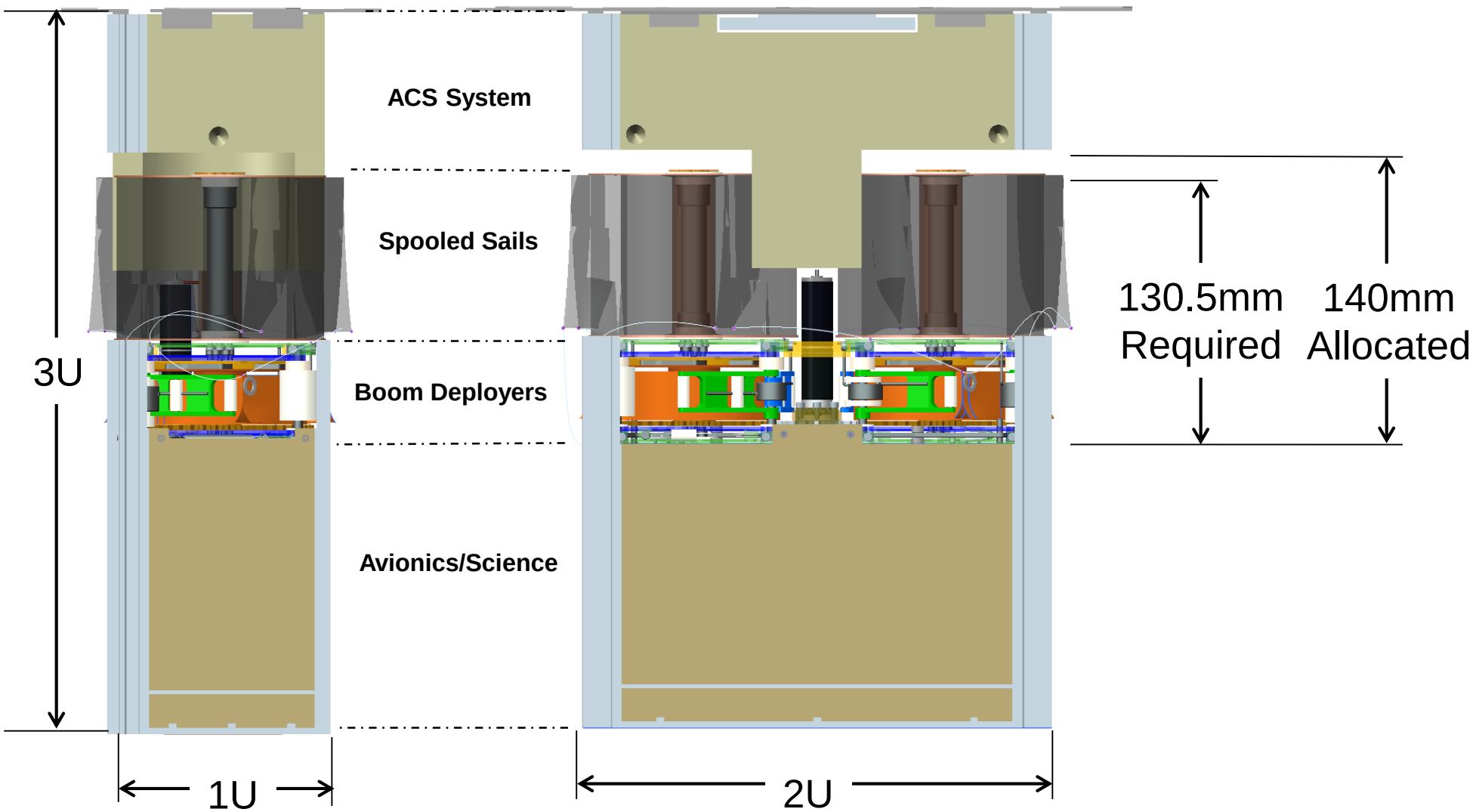
Folded, spooled and packaged in here

Solar Sail Mechanical Description

- 4 quadrant sail
- 85 m2 reflective area
- 2.5 micron CP1 substrate
- Z folded and spooled for storage
  - 2 separate spools with 2 sail quadrants folded onto each
- 4 7-meter stainless steel TRAC booms coiled on a mechanical deployer
  - 2 separate deployers and each deployer releases 2TRAC booms
  - Motorized boom deployment



Solar Sail Volume Envelope

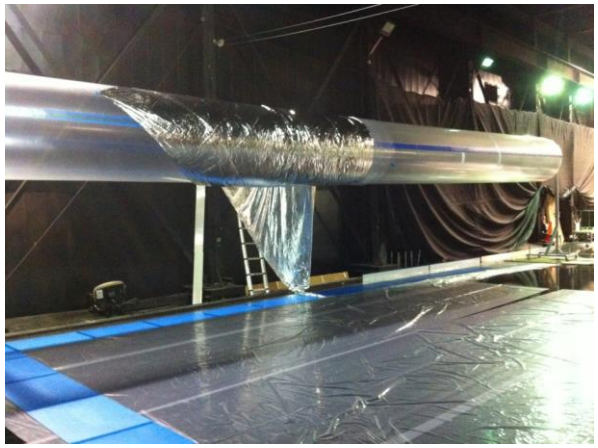


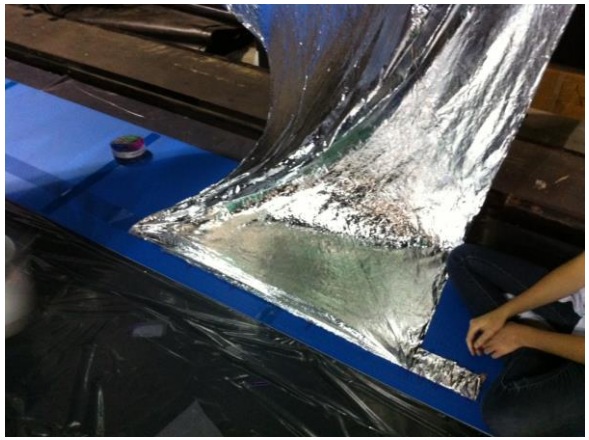
Sail Packing Efficiency

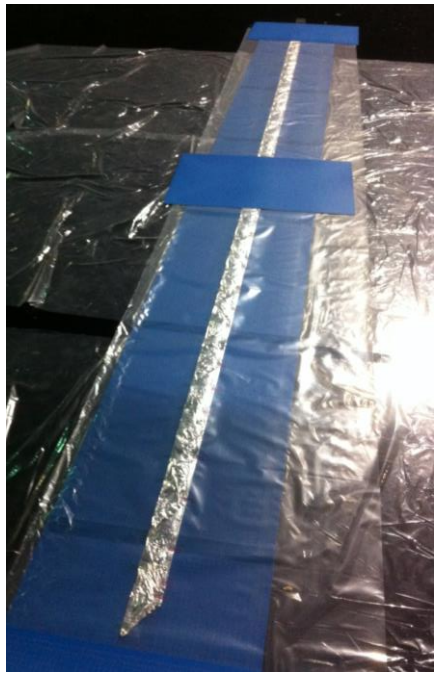
Calculated Value:

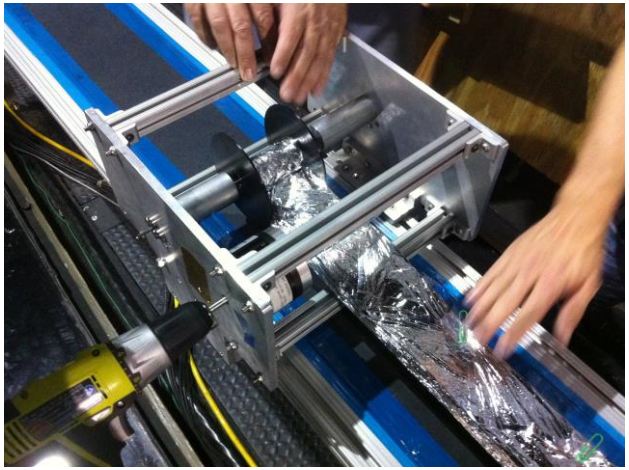
- Fabricated 2 flight size 10m sails from existing 20m CP1 sail.
- Z-folded and spooled 2 sail quadrants onto the hub.
- Calculated new packing efficiency to be **27.5 %**

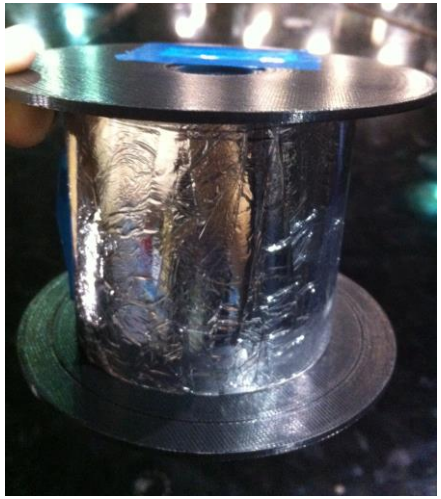
Higher percentage results in tighter packaging and thus more volume margin for design space.







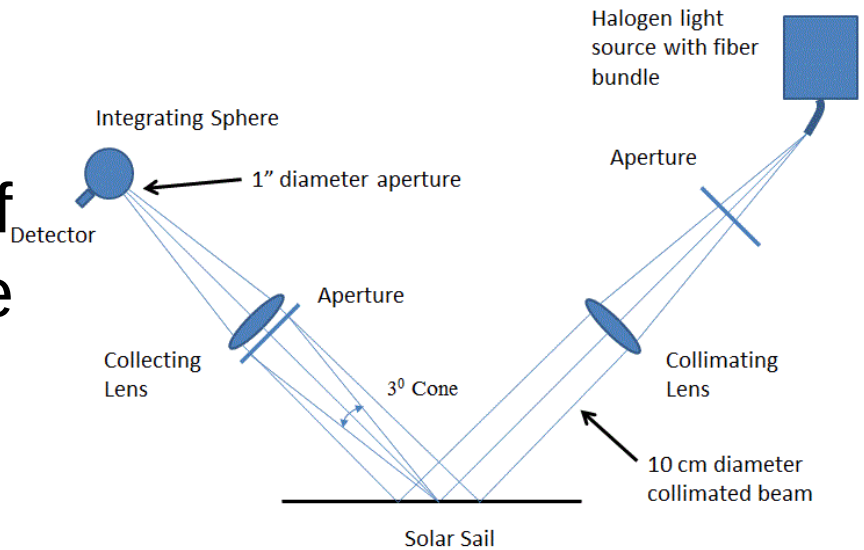


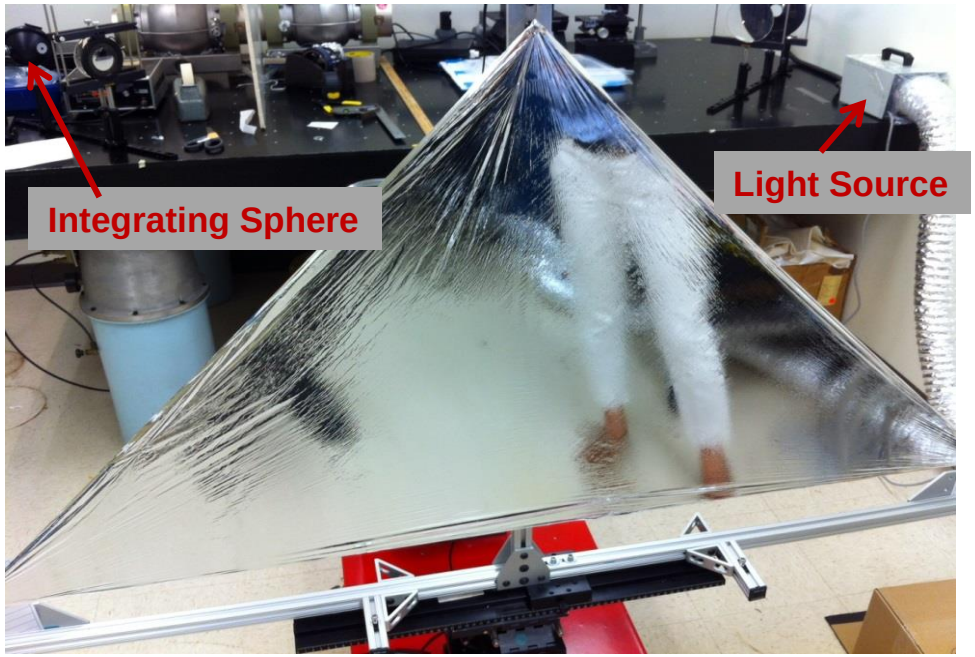


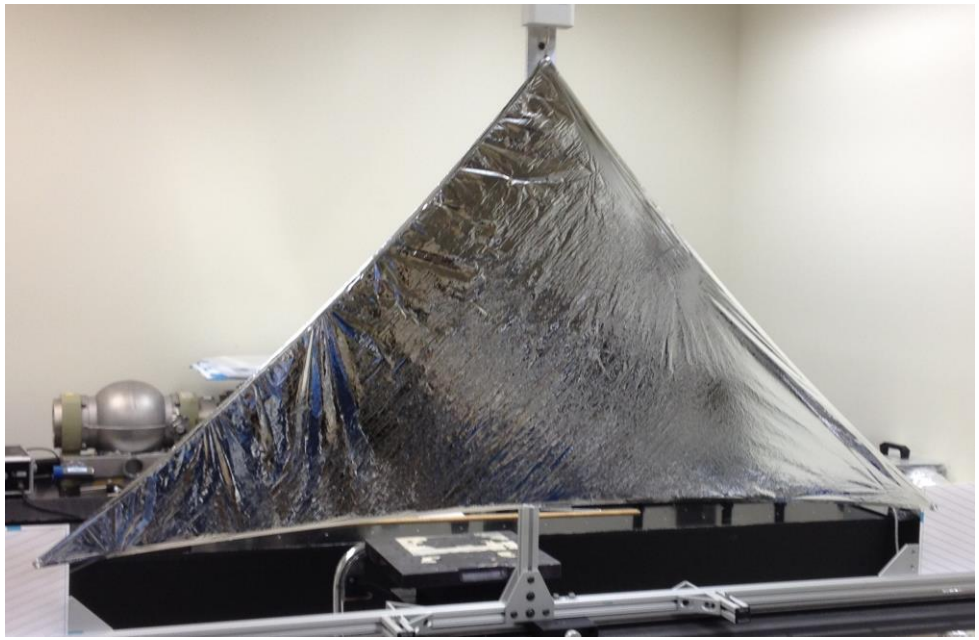
Surface Illumination Test

Lunar Flashlight Requires Surface Illumination:

- Determine the capabilities of the solar sail in regard to the amount of light that the sail can reflect into the desired 3 degree cone onto a surface.

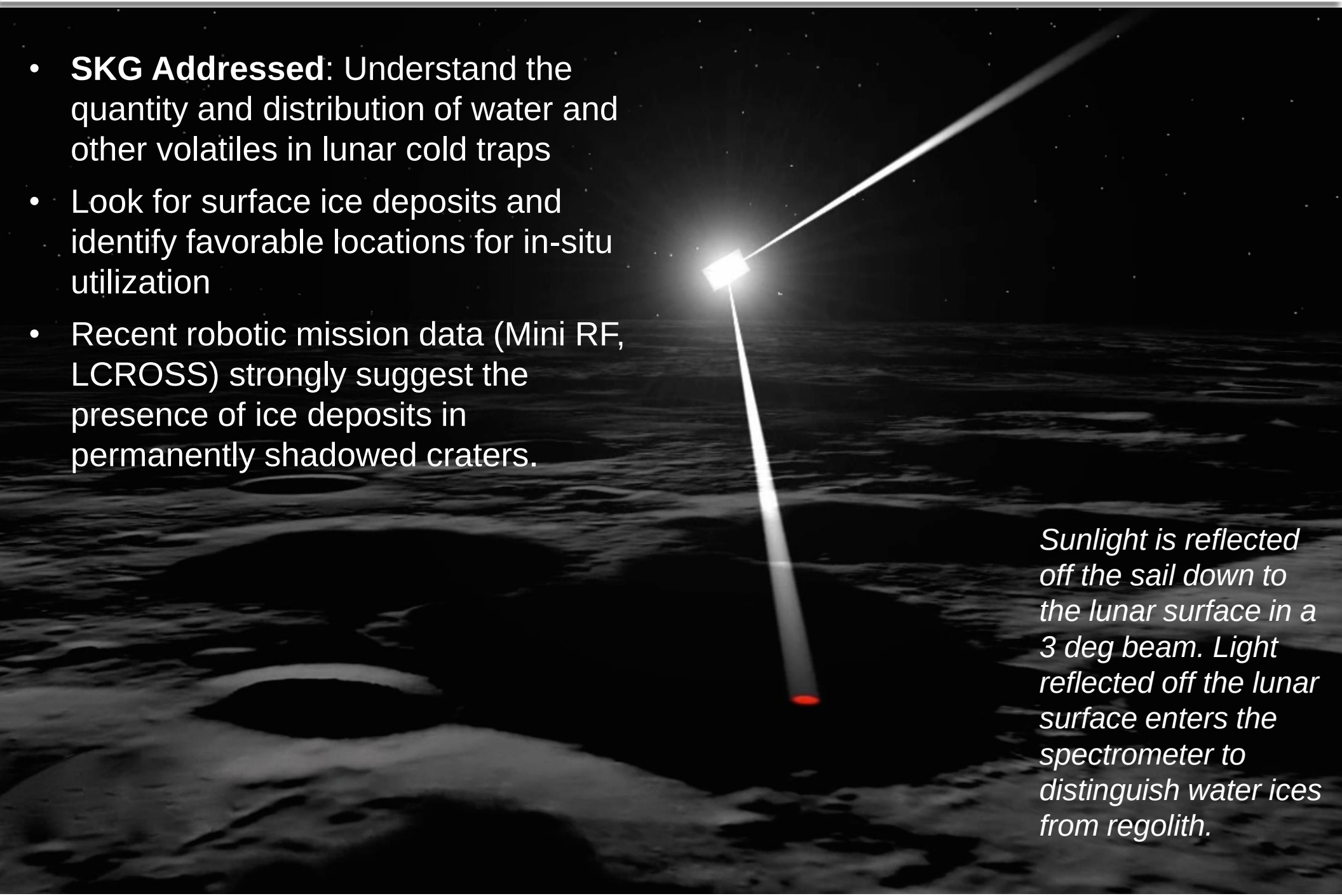






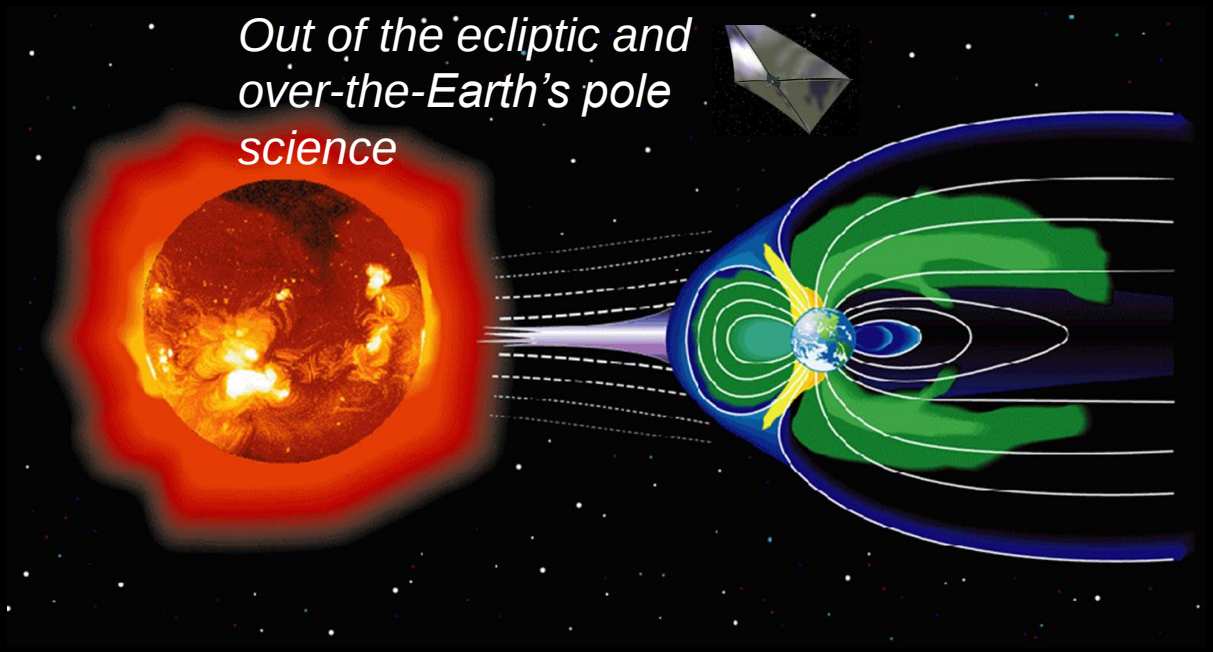
Lunar Flashlight

- **SKG Addressed**: Understand the quantity and distribution of water and other volatiles in lunar cold traps
- Look for surface ice deposits and identify favorable locations for in-situ utilization
- Recent robotic mission data (Mini RF, LCROSS) strongly suggest the presence of ice deposits in permanently shadowed craters.

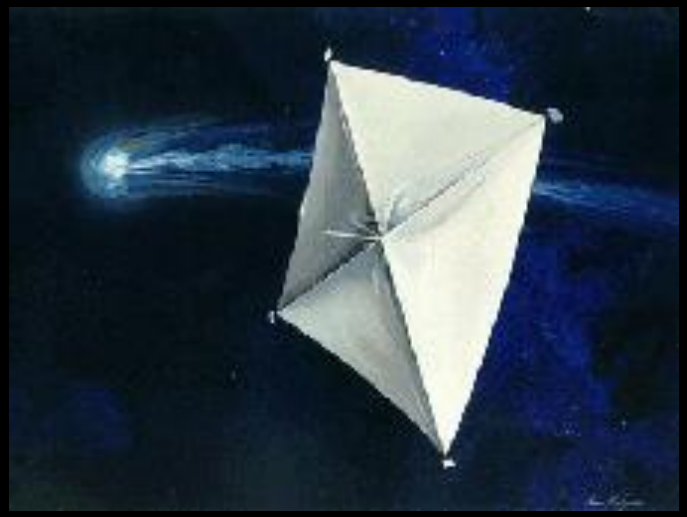


Sunlight is reflected off the sail down to the lunar surface in a 3 deg beam. Light reflected off the lunar surface enters the spectrometer to distinguish water ices from regolith.

What Next?

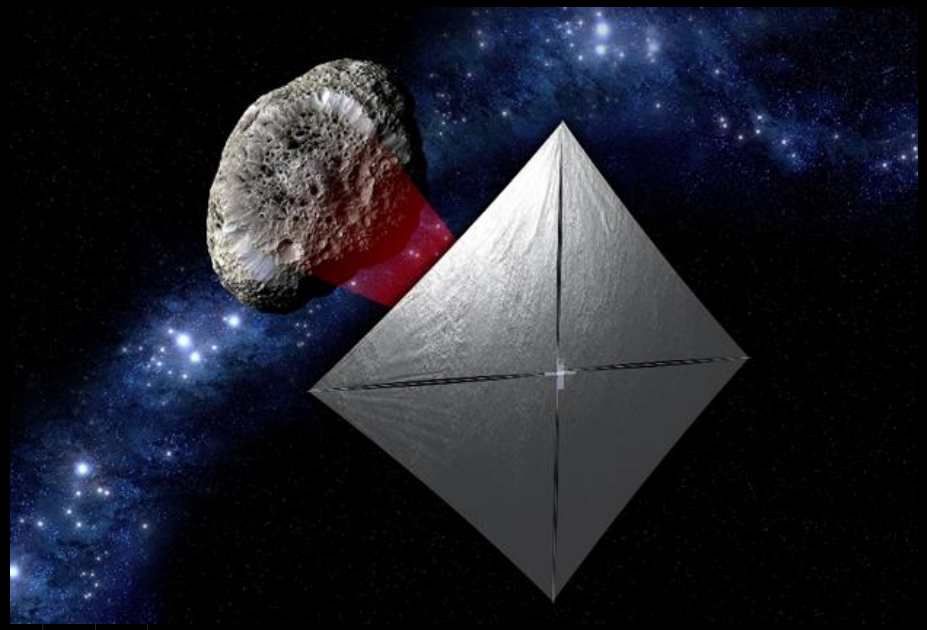


Out of the ecliptic and over-the-Earth's pole science



Comet rendezvous

Multiple NEA reconnaissance



Solar storm warning