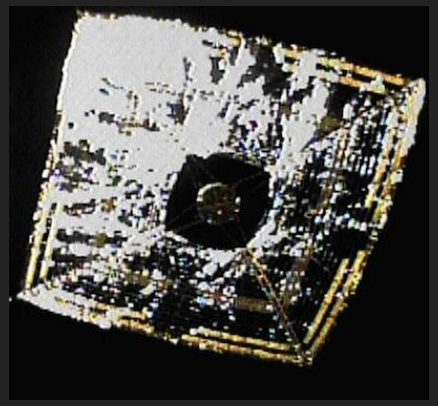
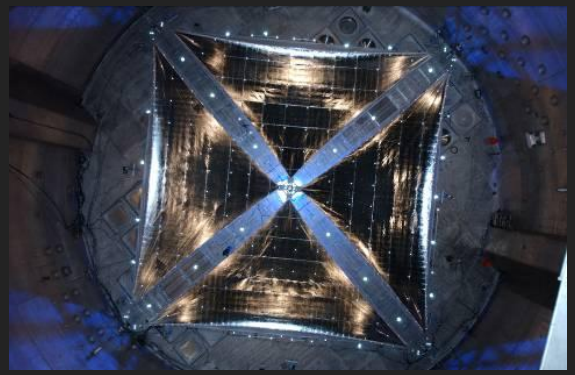
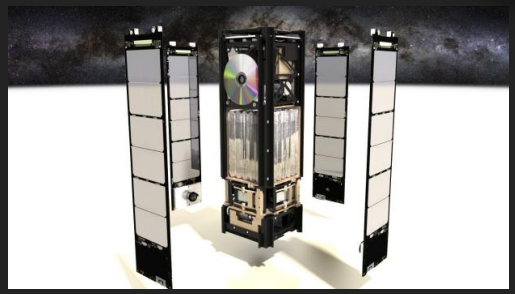


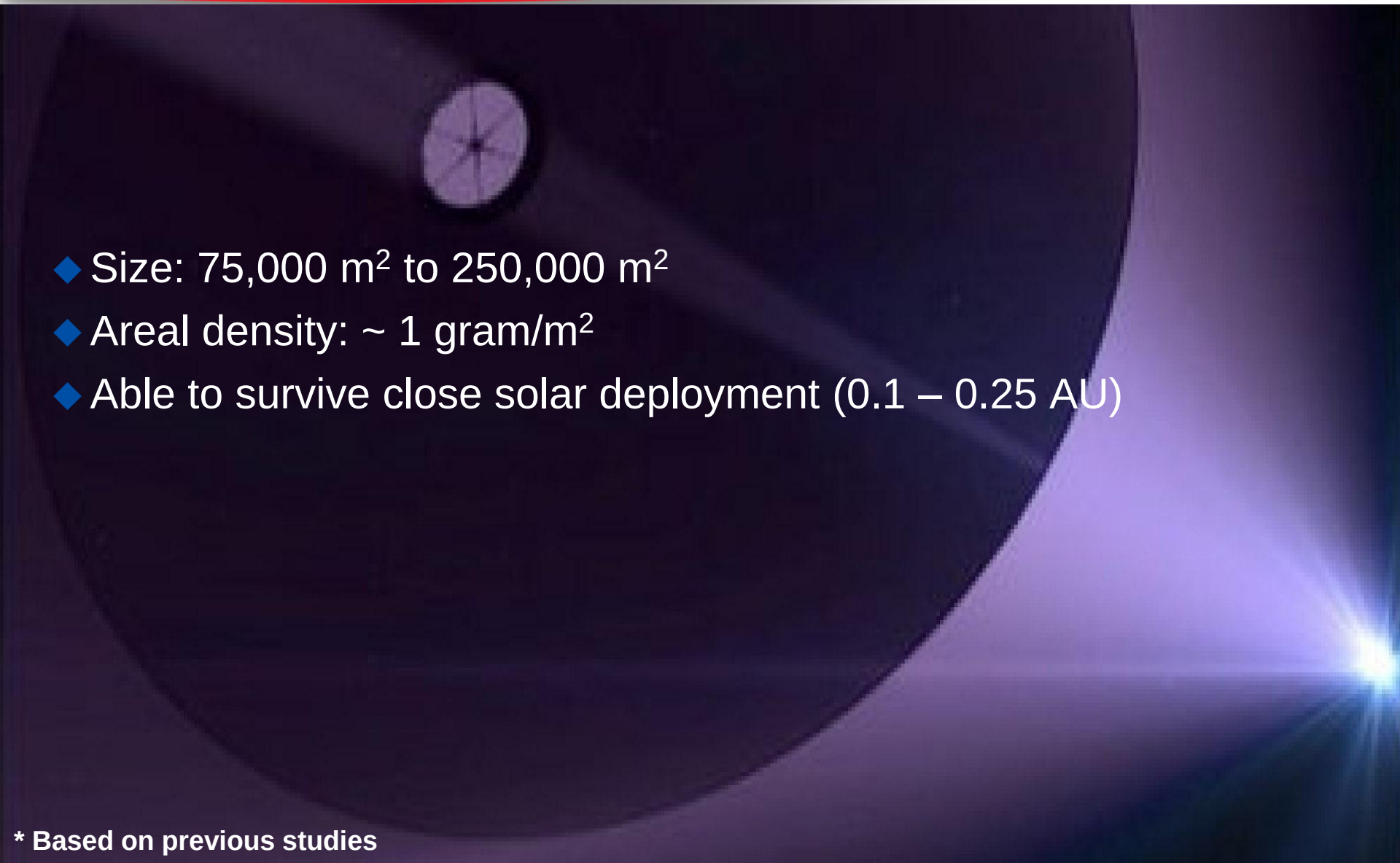
Solar Sails for Exploration of the Interstellar Medium

January 2015





The Sails We Need*



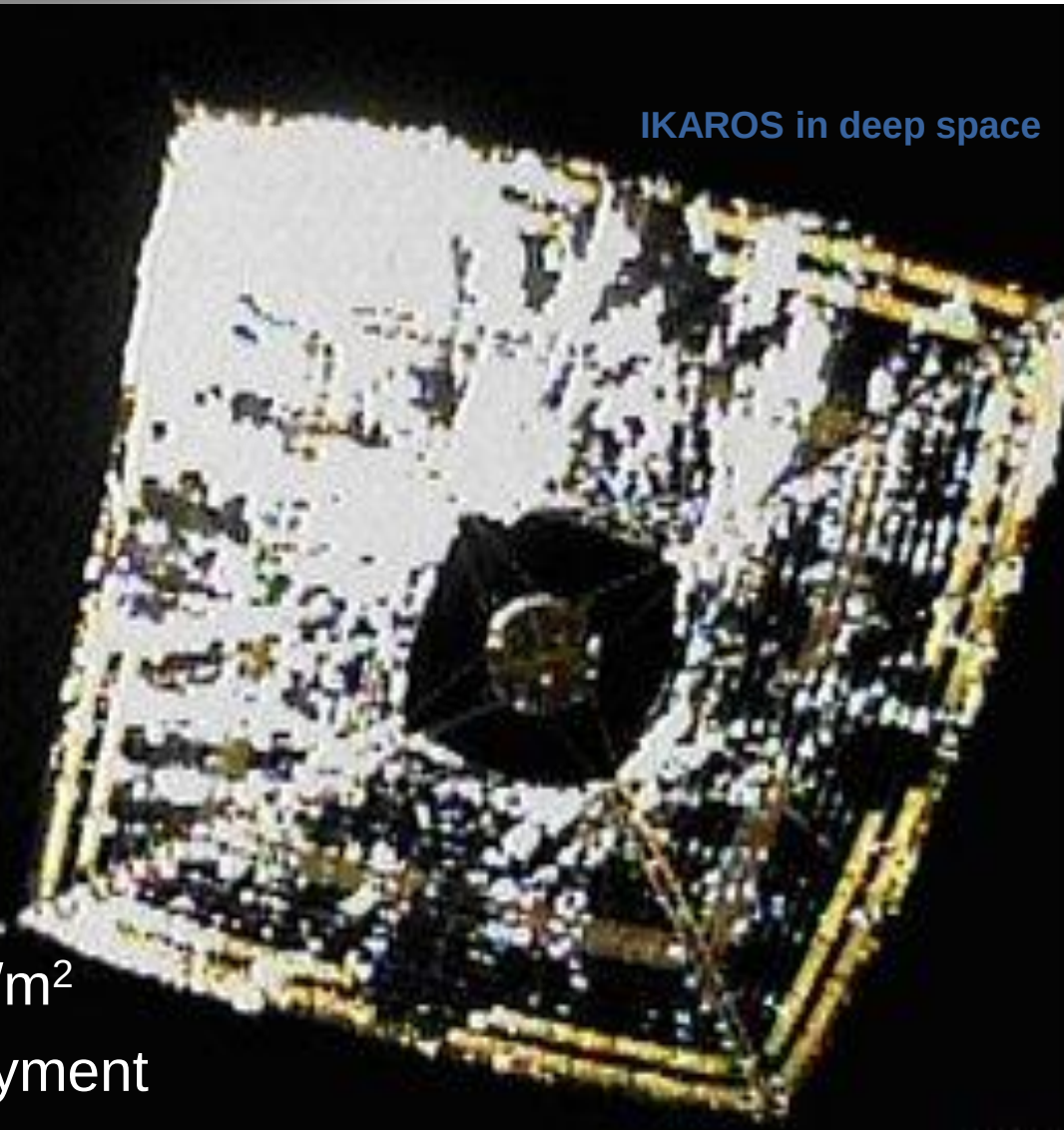
- Size: 75,000 m^2 to 250,000 m^2
- Areal density: ~ 1 gram/m^2
- Able to survive close solar deployment (0.1 – 0.25 AU)

*** Based on previous studies**

The Sails We Have are not close to what we need

NanoSail-D as seen from the ground

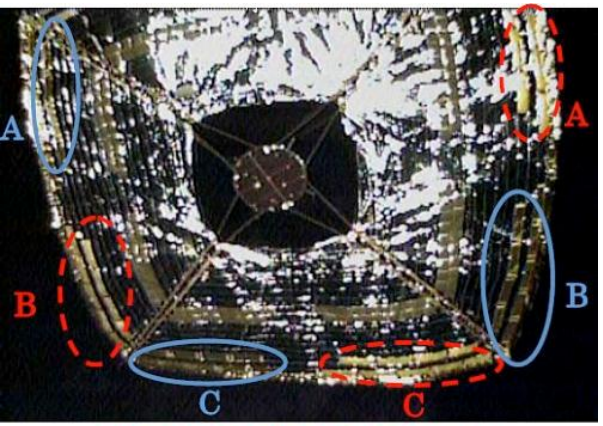
IKAROS in deep space

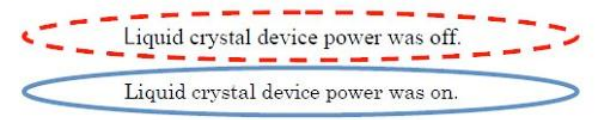


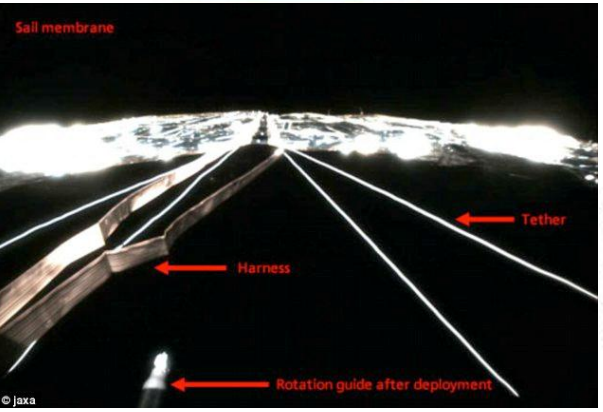
- Size: ~100 m^2 to ~200 m^2
- Areal density: 25 - 300 gram/m^2
- Able to survive 0.5 AU deployment

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

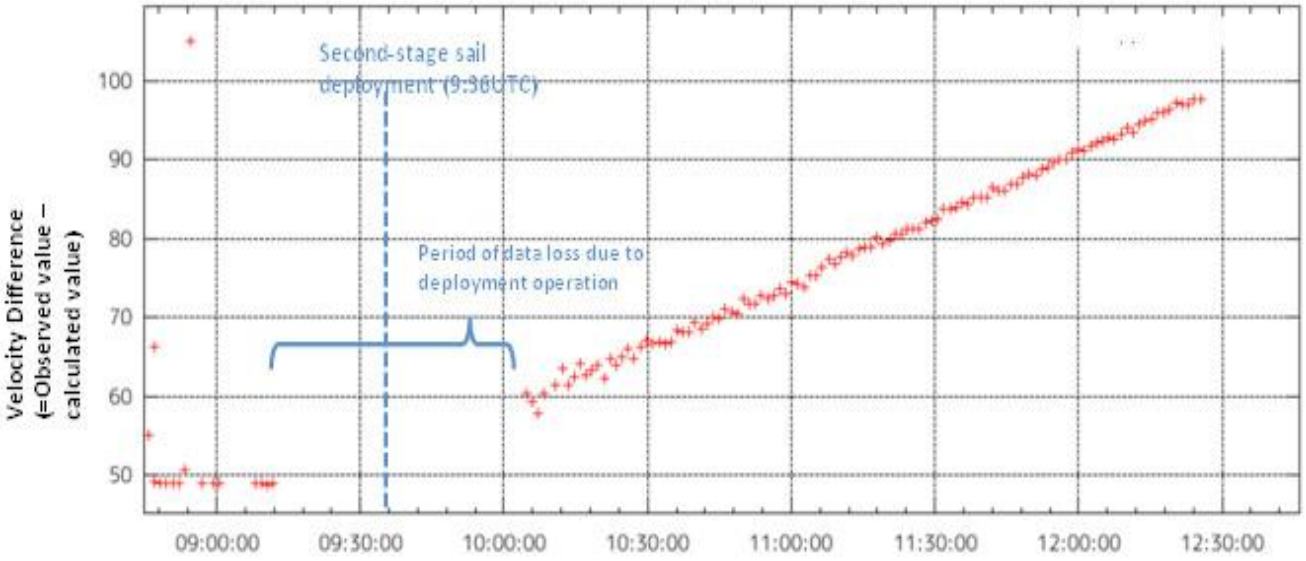
- **IKAROS was launched on May 21, 2010**
- **IKAROS has demonstrated deployment of a solar sailcraft, acceleration by photon pressure, and attitude control.**
  - **Deployment was by centrifugal force**







Configuration / Body Diam.	1.6 m x Height 0.8 m (Cylinder shape)
Configuration / Membrane	Square 14 m and diagonal 20 m
Weight	Mass at liftoff: about 310 kg

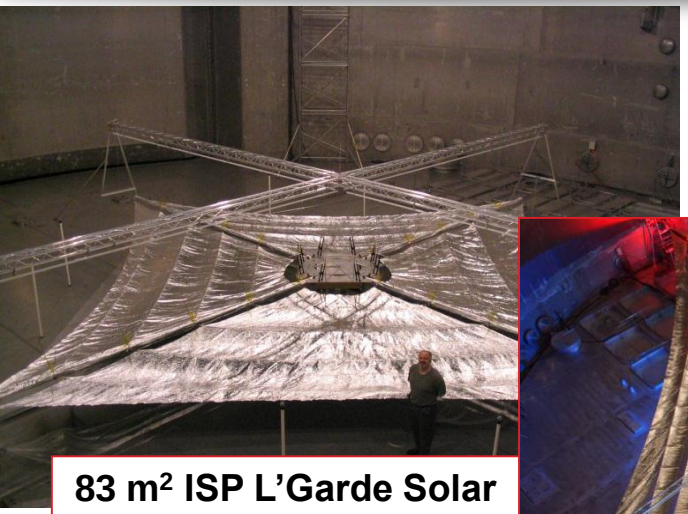


IKAROS' Selfies

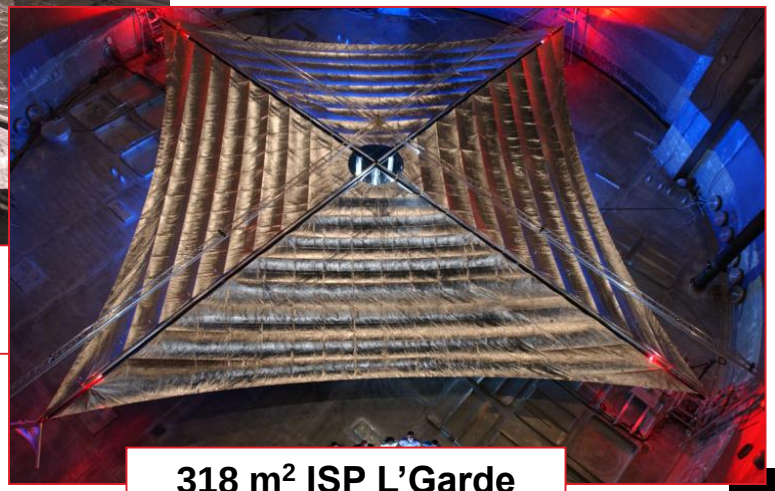
NASA's Sunjammer Canceled

Design Heritage

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



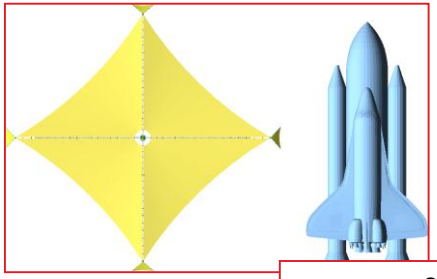
83 m^2 ISP L'Garde Solar Sail 2004



318 m^2 ISP L'Garde Solar Sail 2005

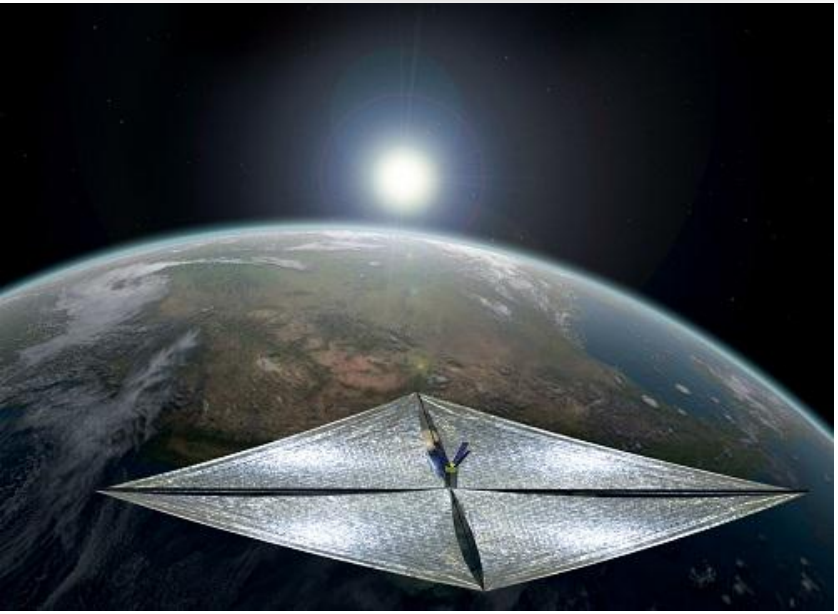
Design Features

- High Density Packagability
- Controlled Linear Deployment
- Structural Scalability
- Propellantless Operation
- Meets Current Needs

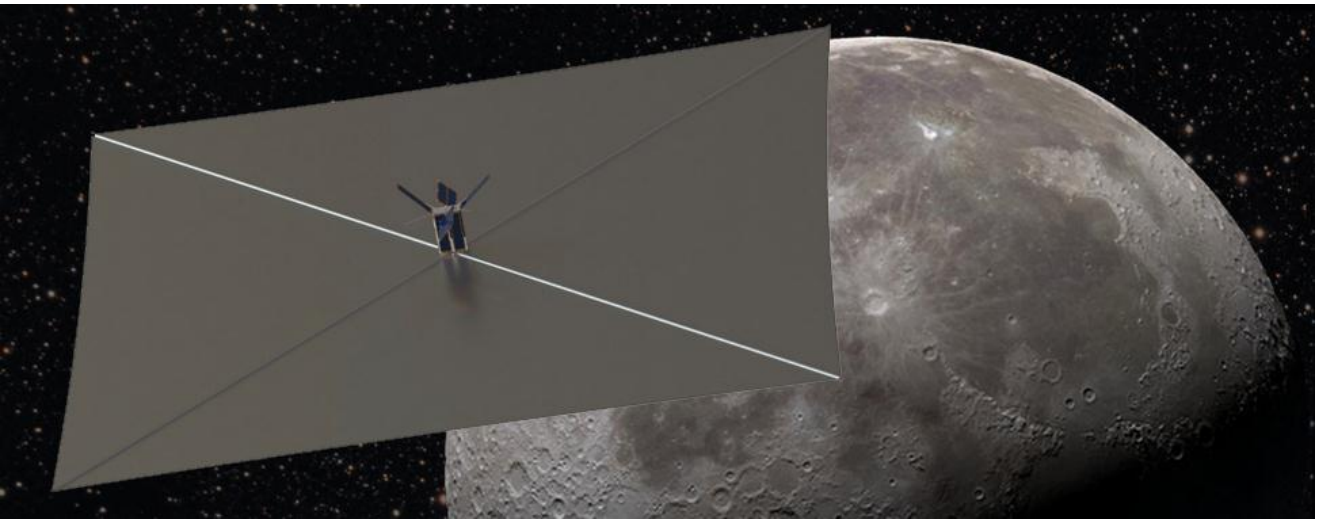


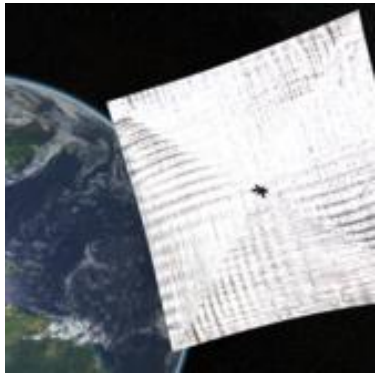
1200 m^2 L'Garde Sunjammer Mission Concept

Many Small Missions Planned

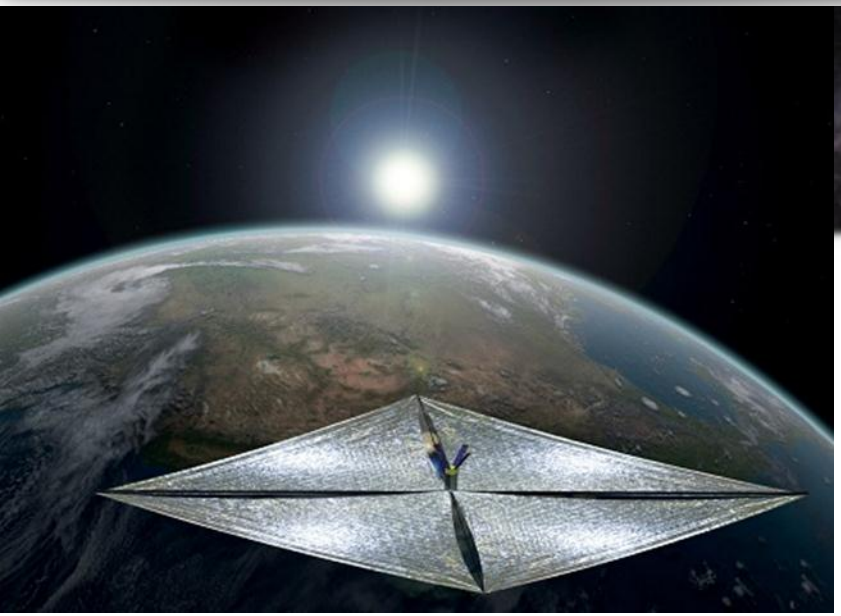


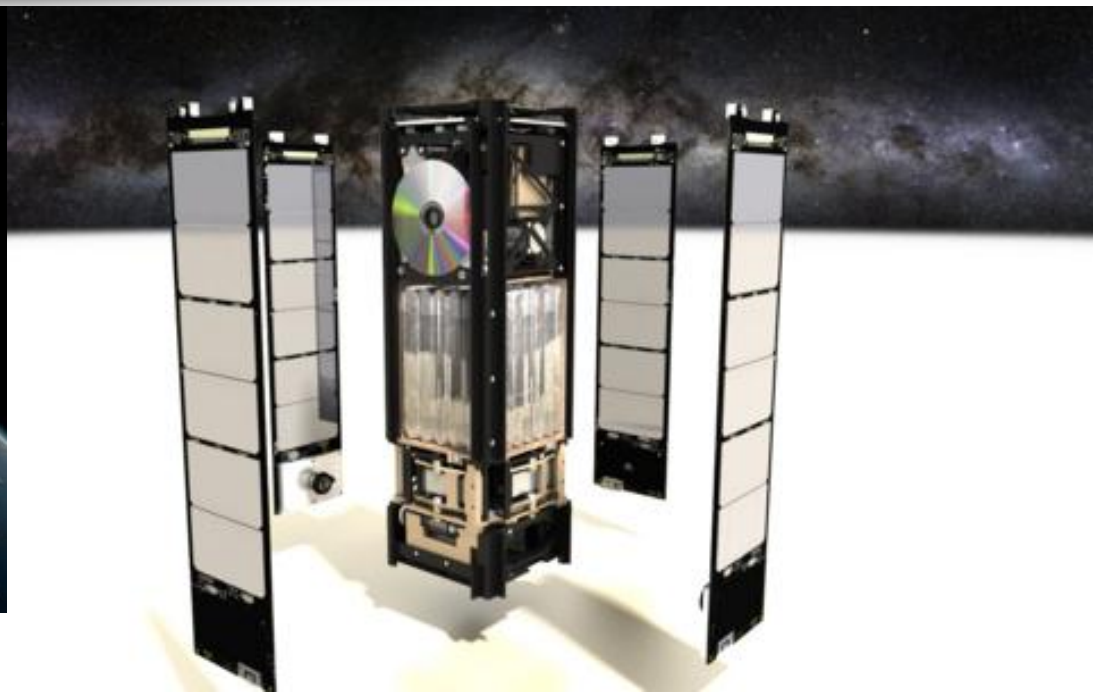
- NASA's *NEA Scout* and *Lunar Flashlight*
- The Planetary Society's *LightSail-A* and *LightSail-B*
- The University of Surrey's *CubeSail*, *DeorbitSail*, and *InflateSail*
- ESA and DLR's *Gossamer 1* and *Gossamer-2*





LightSail-A and -B

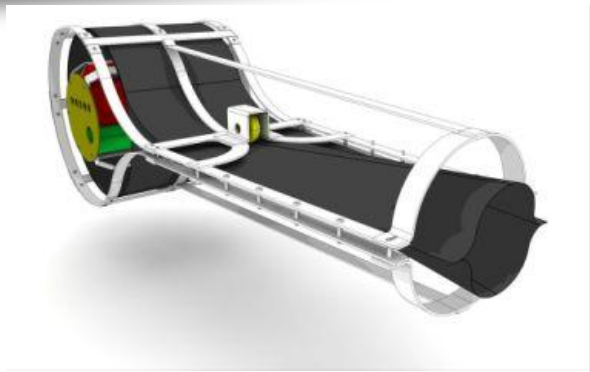




- 3U Cubesat design
- Sail Material: aluminized 4.5 micron Mylar film
- 32 square meters solar sail area fully deployed
- LightSail-A (2015) and LightSail-B (2016)

ESA's Gossamer 1-2-3

- Gossamer-1:
  - Demonstration of the safe deployment of a 5m x 5m solar sail in a 320km Earth orbit.

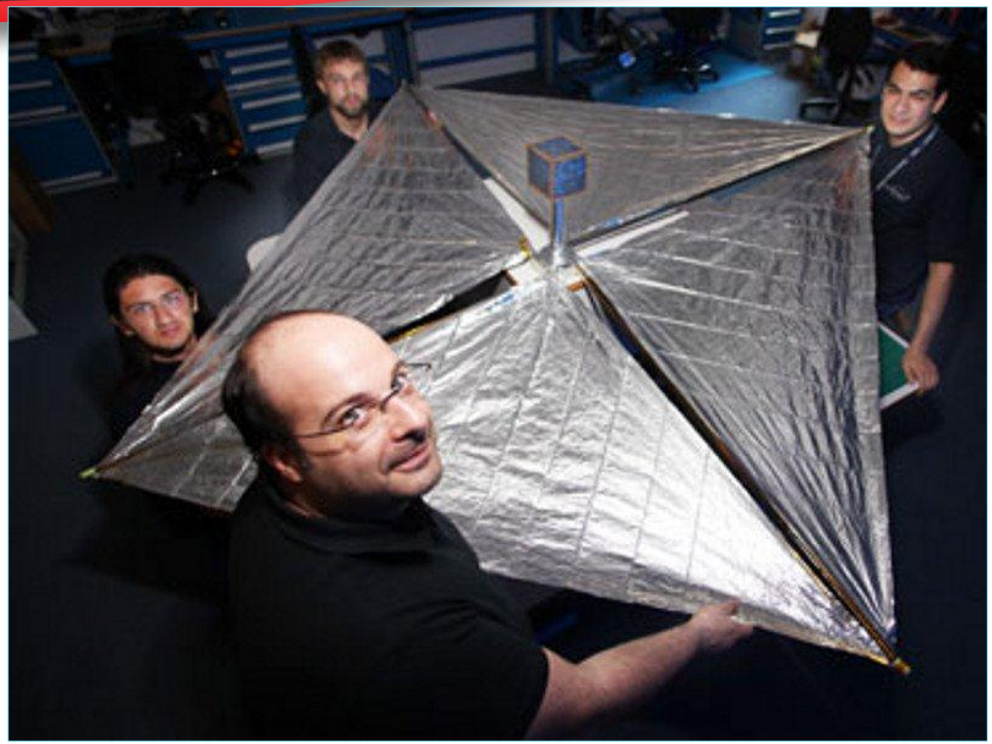


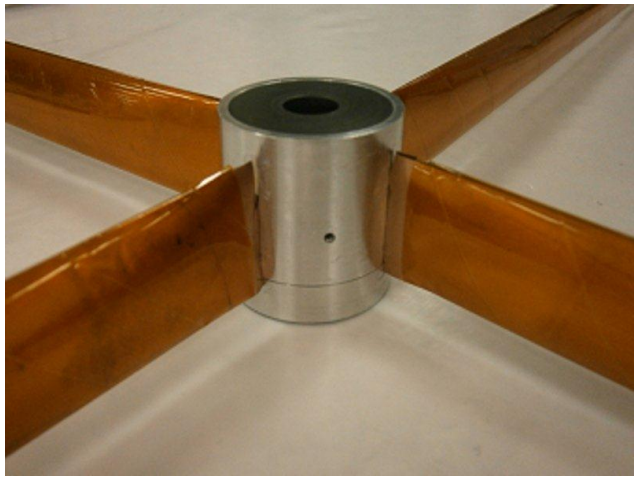
DLR Boom Deployment Mechanism

- Gossamer-2:
  - Deployment of a 20m x 20m solar sail in a 500km Earth orbit.
- Gossamer-3:
  - Deployment of a 50m x 50m solar sail in a > 10.000km Earth orbit.

University of Surrey's CubeSail

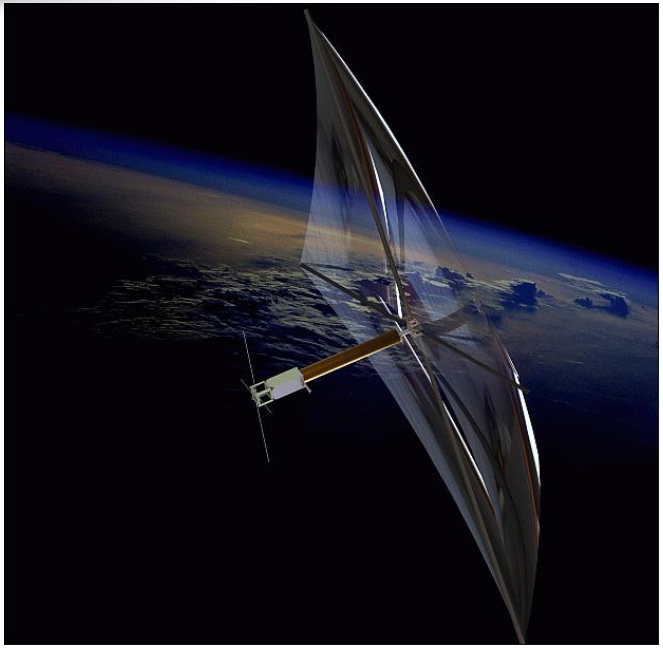
- 25 m^2 solar sail / drag sail
- 700 km sun-synchronous orbit





University of Surrey's InflateSail

- **InflateSail** is an inflatable, rigidisable sail to be flown in Low Earth Orbit.
- 3U CubeSat with deployed sail area of 10 m^2
- Sail supported by CFRP bistable booms.
- Inflation is driven by Cool Gas Generators (CGG): low system mass, long lifespan.



SURREY SPACE CENTRE

CGG technologies COOL GAS GENERATOR

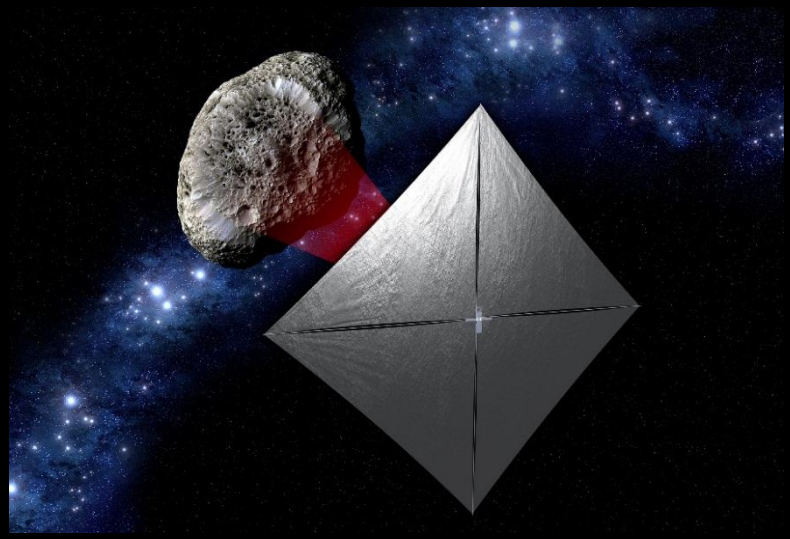
ASTRIUM AN EADS COMPANY

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

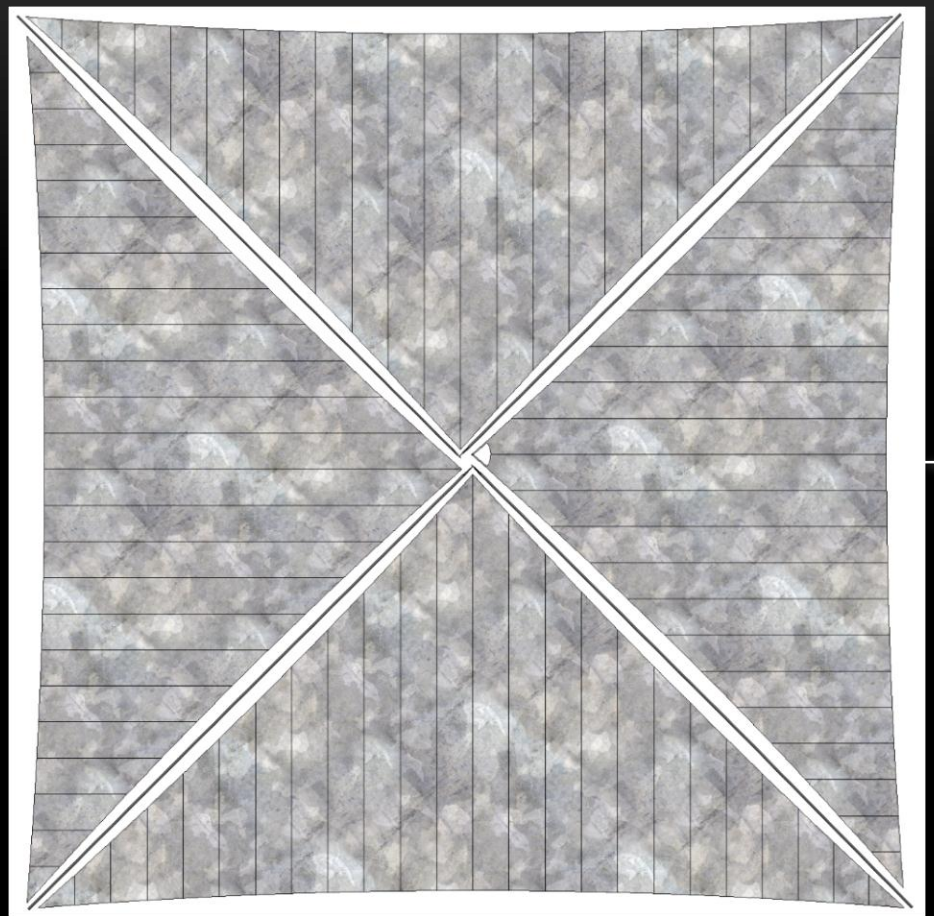
- 6U cubesat (20 cm X 10 cm X 30 cm)
- ~85 m^2 solar sail propulsion system
- Manifested for launch on the Space Launch System (EM-1/2017)
- Up to 2.5 year mission duration
- 1 AU maximum distance from Earth

Solar Sail Propulsion System Characteristics

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

NEA SCOUT SAIL APPROXIMATE SCALE

Deployed Solar Sail



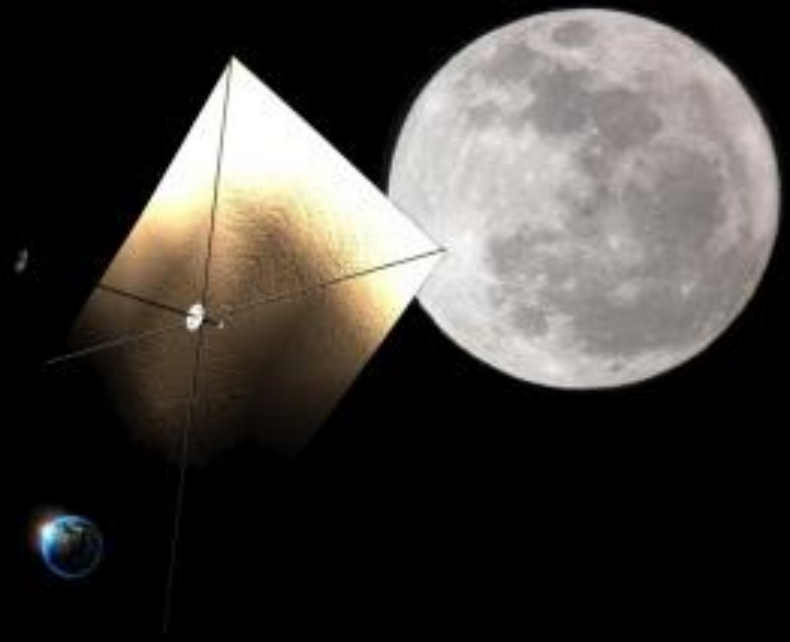
School Bus

Human

6U Stowed Flight System

Folded, spooled and packaged in here

Lunar Flashlight



- 85 m^2 solar sail
- Interplanetary 6U Cubesat

Solar Sail Performance Data

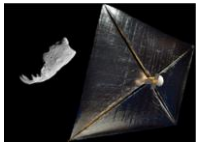
Spacecraft	A/m [m^2/kg]*
IKAROS - JAXA	1.3
Nanosail-D – NASA	2.2
Cosmos 1 – The Planetary Society	5.7
LightSail® - The Planetary Society	7.0
Lunar Flashlight/NEA Scout - JPL	8.0
Sunjammer Developed	22
JPL NIAC Study	368
JPL Near ISM Mission Study	700
JPL Halley Comet Rendezvous Design	711

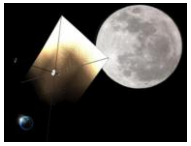
* Calculated using the total spacecraft mass (not just the sail subsystem)

Business As Usual (Best Case!) Expectations for Sails

85 m^2
30 g/m^2 (sail system)

NEA Scout
Lunar Flashlight
ATP 2014
2017 – 2020





32 m^2

LightSail A/B
2015 / 2016

THE NEED

- Size: 75,000 m^2 to 250,000 m^2
- Areal density: ~ 1 gram/m^2
- 0.1 – 0.25 AU Deployment

2015 **2020** **2025** **2030**

Business As Usual (Best Case!) Expectations for Sails

85 m^2
30 g/m^2 (sail system)

NEA Scout
Lunar Flashlight
ATP 2014
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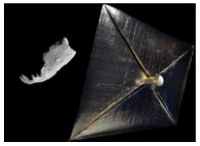
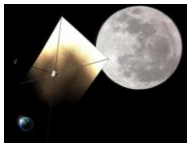
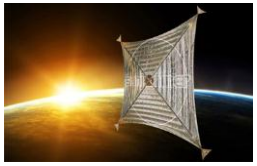


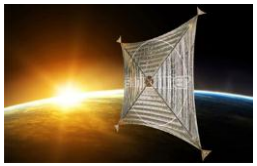


32 m^2

LightSail A/B
2015 / 2016



Tech Demo 1
30 g/m^2 1500 m^2
ATP 2017
2020 Flight



Tech Demo 2
20 g/m^2 10,000 m^2
ATP 2023
2026 Flight

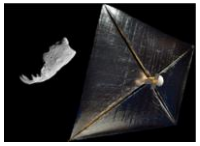
THE NEED
- Size: 75,000 m^2 to 250,000 m^2
- Areal density: ~ 1 gram/m^2
- 0.1 – 0.25 AU Deployment

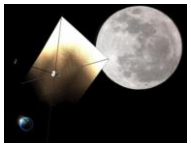
2015 **2020** **2025** **2030**

Business As Usual (Best Case!) Expectations for Sails

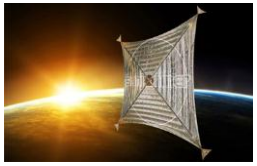
LightSail A/B
2015 / 2016
32 m^2

NEA Scout
Lunar Flashlight
ATP 2014
2017 – 2020
85 m^2
30 g/m^2 (sail system)

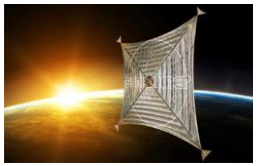




Tech Demo 1
30 g/m^2 1500 m^2
ATP 2017
2020 Flight



Tech Demo 2
20 g/m^2 10,000 m^2
ATP 2023
2026 Flight



We cannot meet the goal

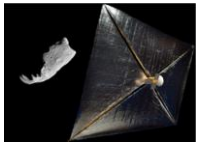
THE NEED
- Size: 75,000 m^2 to 250,000 m^2
- Areal density: ~ 1 gram/m^2
- 0.1 – 0.25 AU Deployment

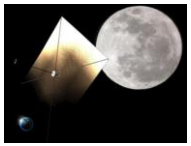
REALITY
- *Sunjammer* cancellation is huge setback
- Sail are not a priority in NASA Tech Roadmaps
- Even if support is strong, we cannot meet the goal by 2030

2015 2020 2025 2030

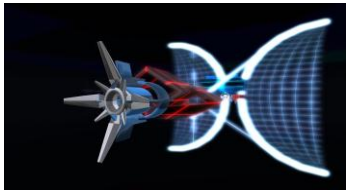
Alternative Sail Future Seek a Breakthrough

NEA Scout
Lunar Flashlight
ATP 2014
2017 – 2020





LightSail A/B
2015 / 2016



Tech Demo 100,000 m^2
ATP 2023
2026 Flight

THE NEED
- Size: 100,000 m^2 to 250,000 m^2
- Areal density: < 1 gram/m^2
- <0.1 AU Deployment

LEAPFROG
- Continue incremental sail development
- Focus on innovative materials, packaging and deployment
  - UV evaporative materials
  - High temperature tolerance
  - Alternate stabilization and deployment approaches
  - In Space Fabrication (SpiderFab)

- Aggressive materials R & D
- Alternate deployment technology
- Beamed energy R & D

2015 2020 2025 2030

Items to trade for more capable solar sails (1/2)

- Traditional Large Sail Technology Development
  - Big square sails (Sunjammer, ATK)
  - Gyula Greschik's Space Tow
  - Ultrasail heliogyro or ribbon sails
  - High temperature materials and structures
- Lightweight sails
  - Reduce support structure
  - Spinning ala IKAROS
  - R&D into adding spin rate control
  - Tent of reflective control material
  - Shape deformation to create pinwheel effect
  - Inflatable booms to deploy sail, vent from tips to spin, deflate to form tethers or detach altogether

Items to trade for more capable solar sails (2/2)

- Lightweight sails
  - Electrostatic structures: http://hanspeterschaub.info/research-EIMS.html
  - Minimal sail film
  - Sublimating sail support film
  - Heavy plastic support film that detaches from minimal sail film
  - Electrostatic charging to repel sail film from backing
  - Start with sail design optimized for in-space use without regard for folding and deployment
  - High strength fiber triangular mesh with metal-only sail films held by foil springs to corners of mesh
  - Add deployment and deployment hardware separation system
  - In-space manufacturing to optimize mass & size
  - Continuous 3D printed structures or sail membranes
  - Sail materials shipped up in bulk and robotically assembled