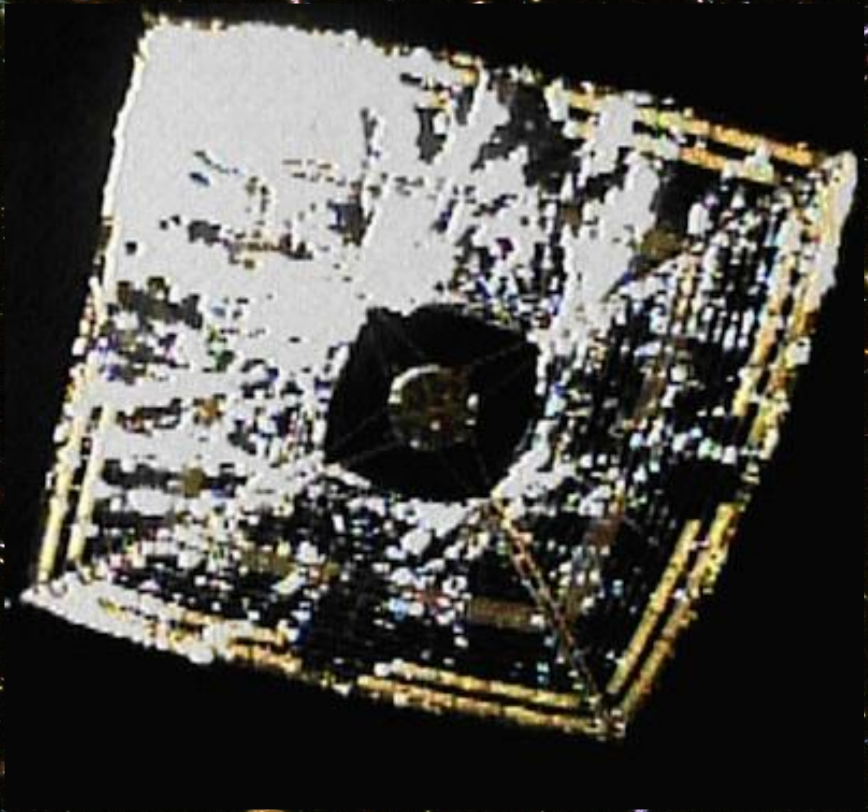
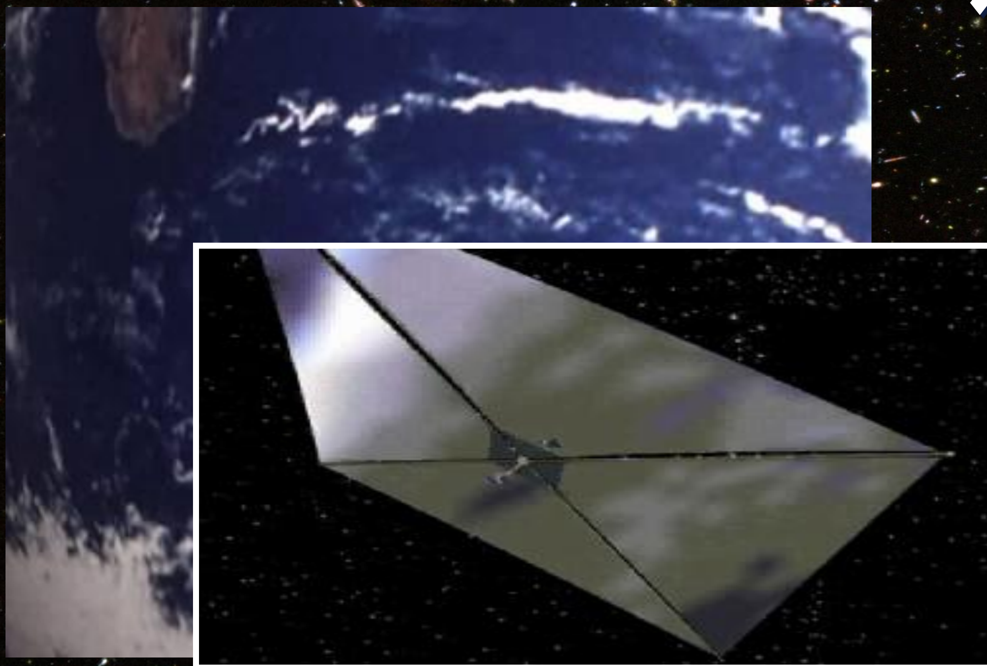
Solar Sail Propulsion

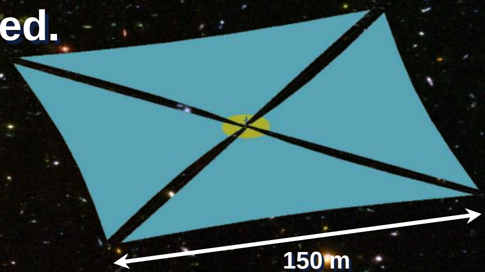


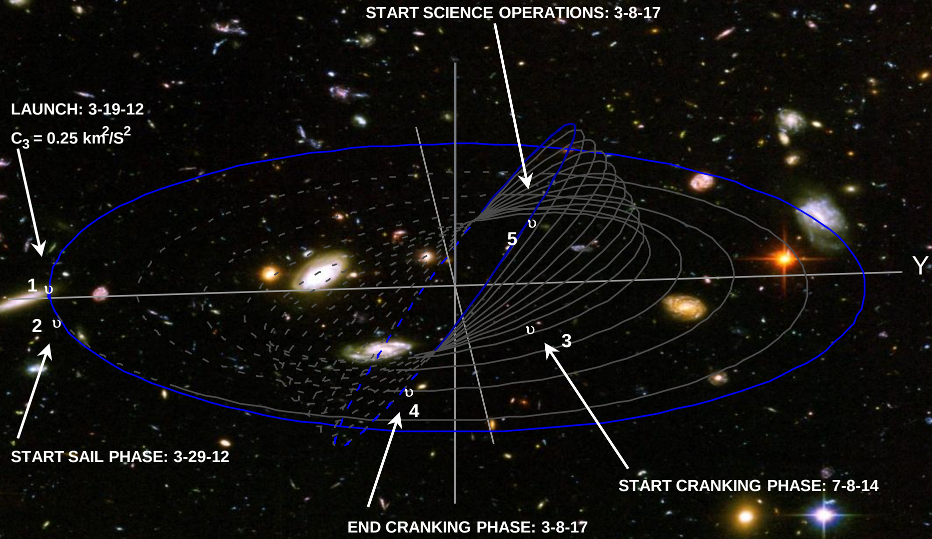
Les Johnson
NASA Marshall Space Flight Center

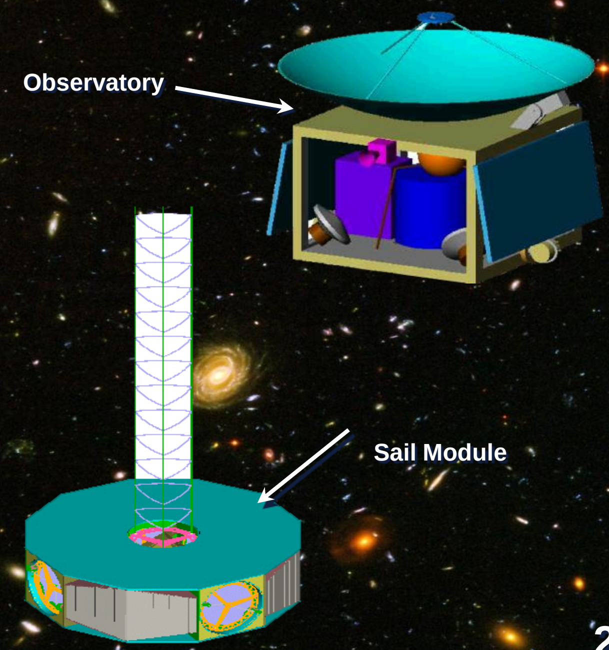
Solar Sails

- Solar sails use photon “pressure” or force on thin, lightweight reflective sheet to produce thrust. Sails can open up new regions of the solar system to accessibility for important science missions, with no propellants required.



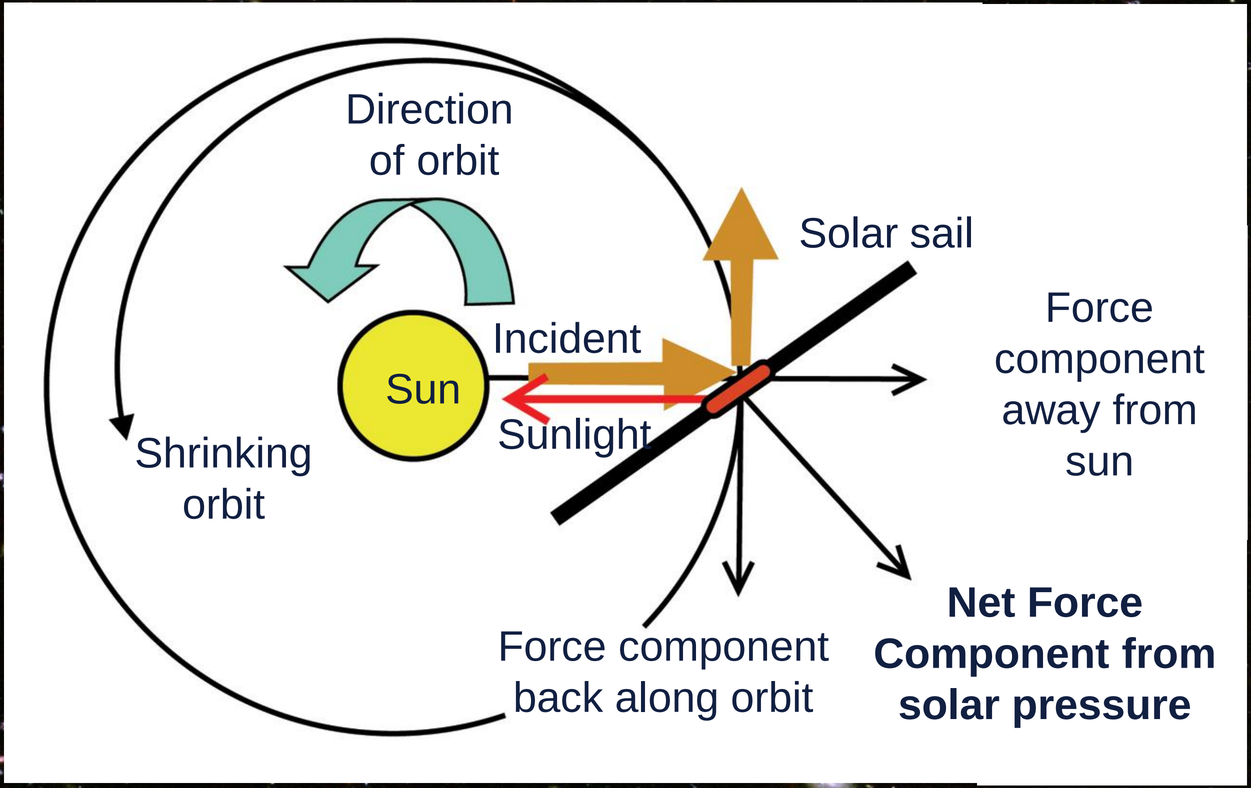






Solar Sails

Propulsion from Photon Momentum Exchange



Reflecting the photons forward along the direction of motion slows the spacecraft down.

An example of how a solar sail propulsion can change orbits

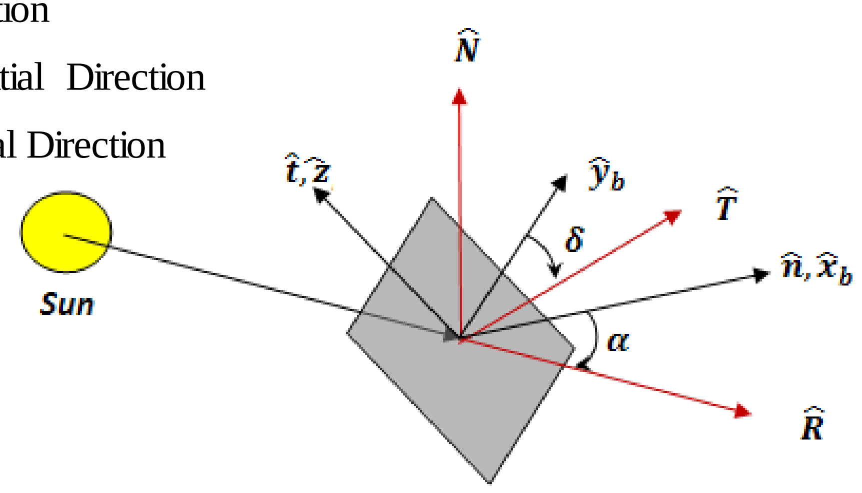
Solar Sail Control Angles

- **Thrust vector is dependent on two angles**
  - Cone Angle (α) (a.k.a. Sun Incidence Angle)
  - Clock Angle (δ)

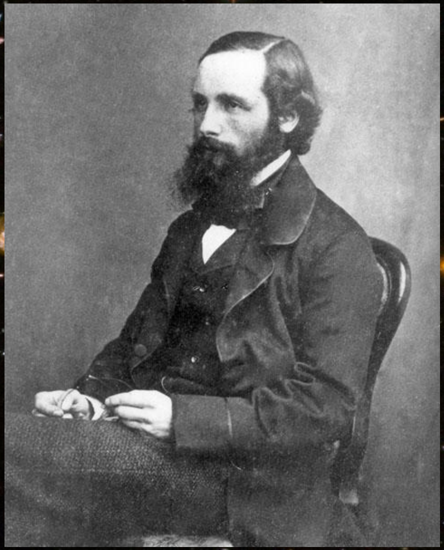
$\hat{R}$ - Radial Direction

$\hat{T}$ - Orbit Tangential Direction

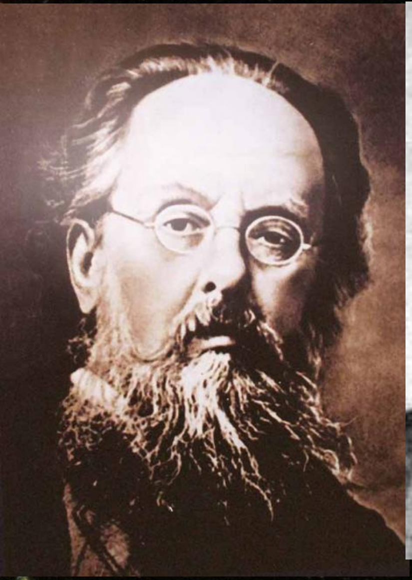
$\hat{N}$ - Orbit Normal Direction



Solar Sailing Is Not A New Idea



- **James Clerk Maxwell (England), who developed the modern theory of electromagnetism in the 1860's, proved that light could exert pressure.**



- **Konstantin Tsiolkovsky (Russia) first discussed solar sailing; Fridrickh Tsander (Russia) wrote in 1924, "For flight in interplanetary space I am working on the idea of flying, using tremendous mirrors of very thin sheets, capable of achieving favorable results."**

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.

Spherical shape has no solar pressure torques – enabling direct observation of thrust effects without regard to spacecraft attitude

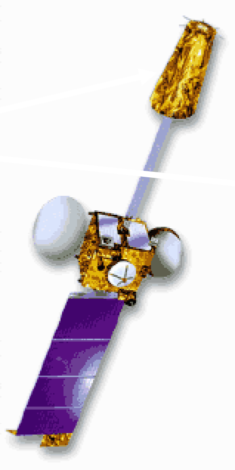
When folded satellite is packed into the 41-inch diameter canister shown in the foreground

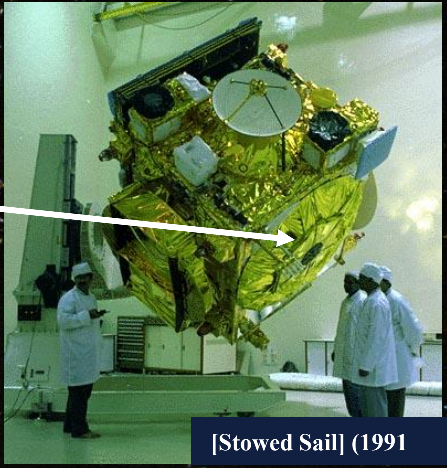
Solar Sail Technology History

Used Since 1962

- Solar Sailing was initially developed at JPL as a measure to save the Mariner 10 mission which had lost a large portion of its propellant margin when the star tracker locked on to floating debris instead of Canopus. The mission went on to flyby Venus and three encounters with Mercury. Its successful implementation on that mission led to it being declared a mature technology, ready for application to future NASA missions in 1978.
- Several Comsats (e.g. INSAT 2E) operating today in GEO use solar pressure to unload momentum wheels or offset solar torques on asymmetric solar arrays.
- Chosen for Halley Comet Rendezvous in 1985, it was replaced by a chemical rocket in phase B due to launch date/window pressure
- Joint NASA/NOAA/USAF proposal to NMP ST5 fell in the 11th hour when USAF/NASA/NOAA partnership collapsed
- Planetary society launched a flight experiment and a full system on converted Russian Volna sub-launched missiles. Unfortunately both boosters had stage separation failures.
- 2010: JAXA launches the world's first true solar sail on a journey past Venus.
- 2011: NASA launches a subscale "drag sail" into Low Earth Orbit.

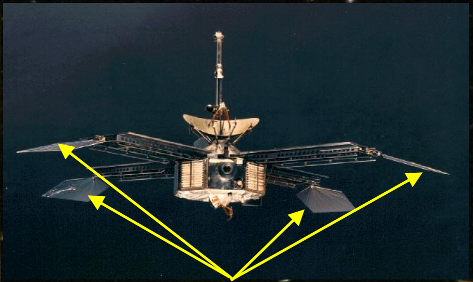
Mariner 10: "the solar sailing technique for conservation of attitude control gas was improvised successfully and thereby qualified as a technique for use in future missions." – Bruce Murray, Flight to Mercury, Columbia University Press 1977, page 142.





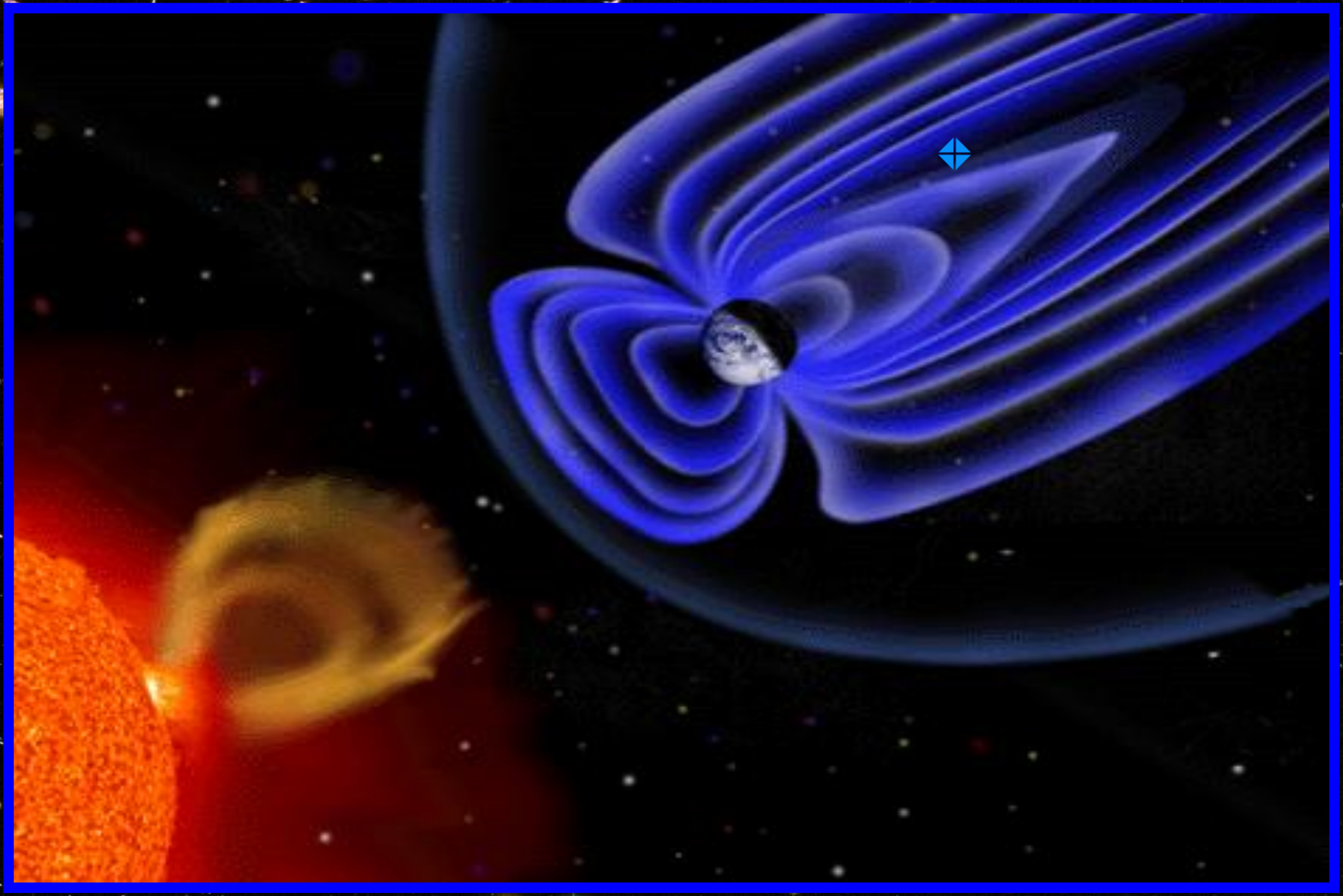
[Stowed Sail] (1991

Mariner 2 Dacron Solar Sail (1962)



solar sails on Mariner IV (1964)

Geostorm: Solar Storm Warning



The Geostorm Mission

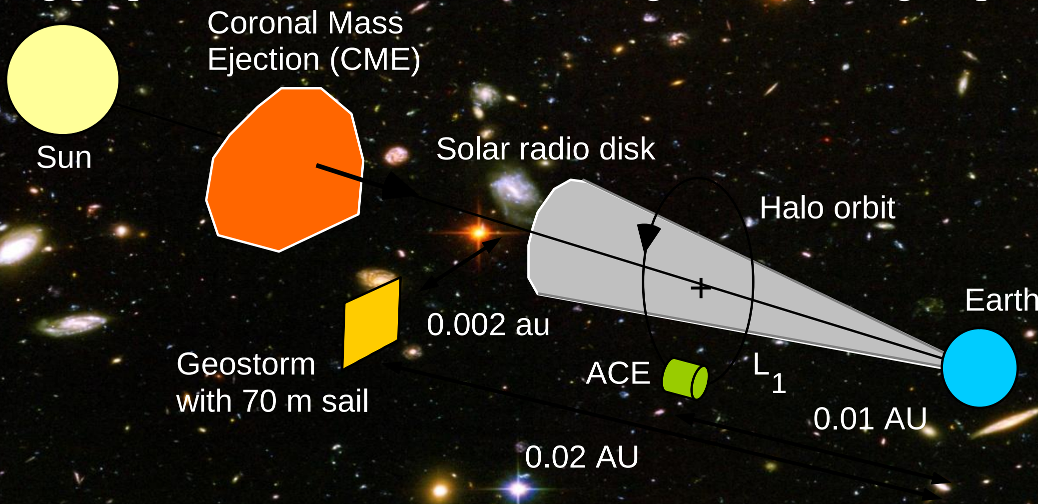
Warning Earth of Impending Coronal Mass Ejections

Use a solar sail to achieve a non-Keplerian orbit near the sun-earth line, twice as far from the earth as the current warning system, NOAA's Advanced Composition Explorer (ACE) at the L_1 point

Geostorm will double the warning time to enable the reconfiguration and securing of space systems (and ground electrical power grids) to avoid:

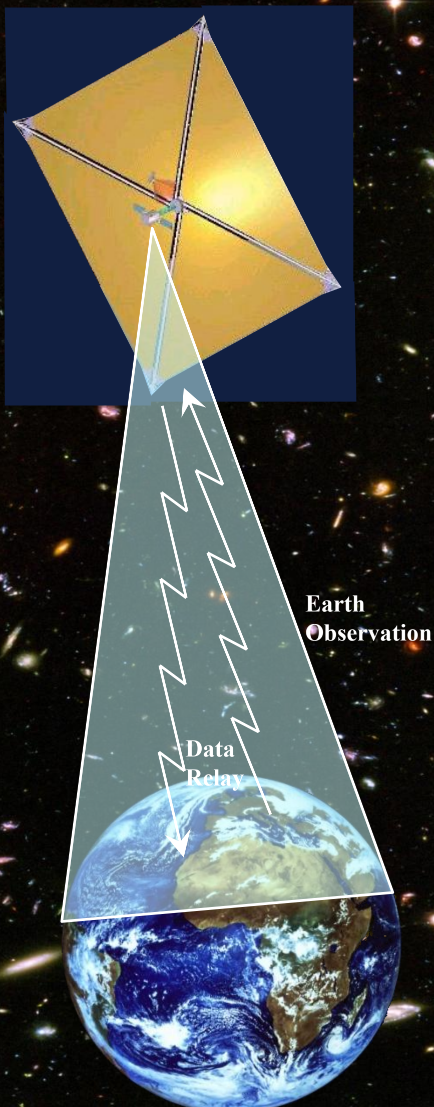
- Complete or partial loss of HF & satellite communications
- Degraded navigational and geo-locational capability
- False returns on ATC and early warning radars
- Satellite system disruption and lock problems

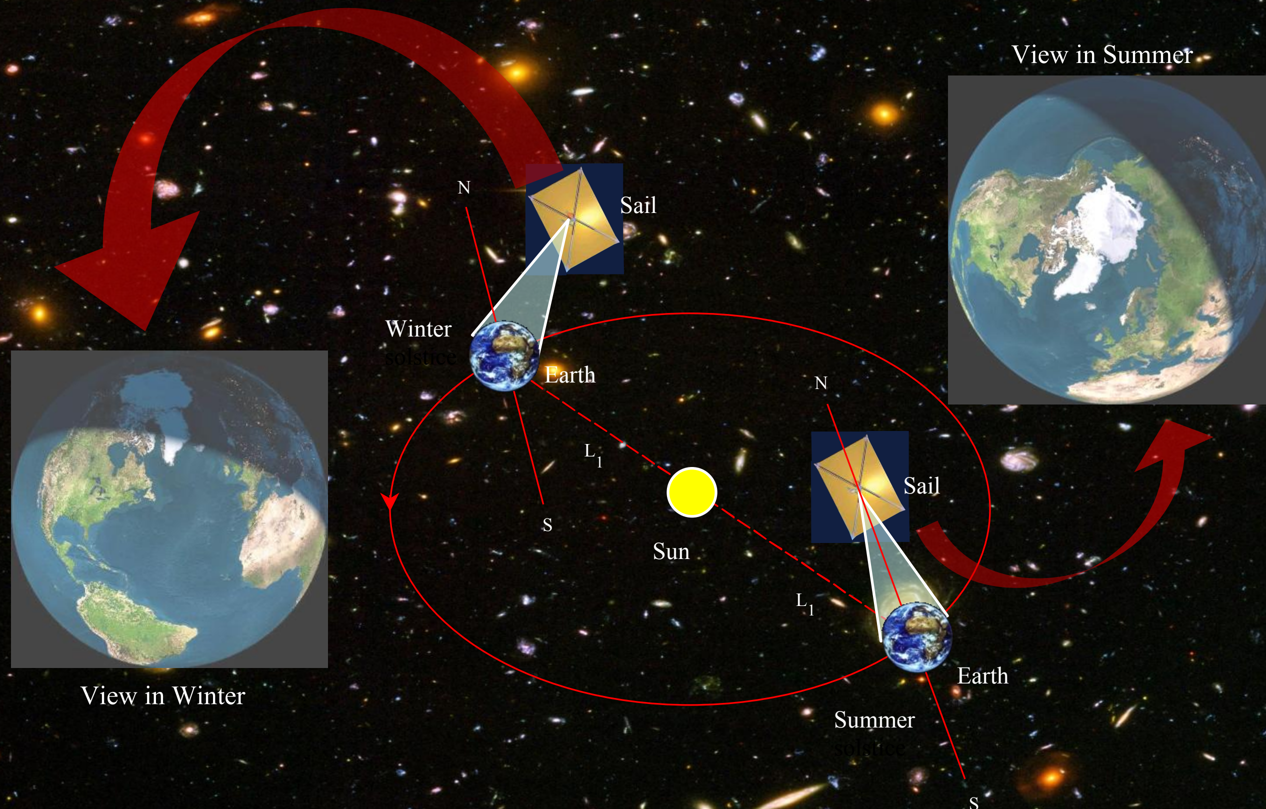
Geostorm, being propellantless, could result in a significantly longer spacecraft lifetime



Pole Sitter Mission

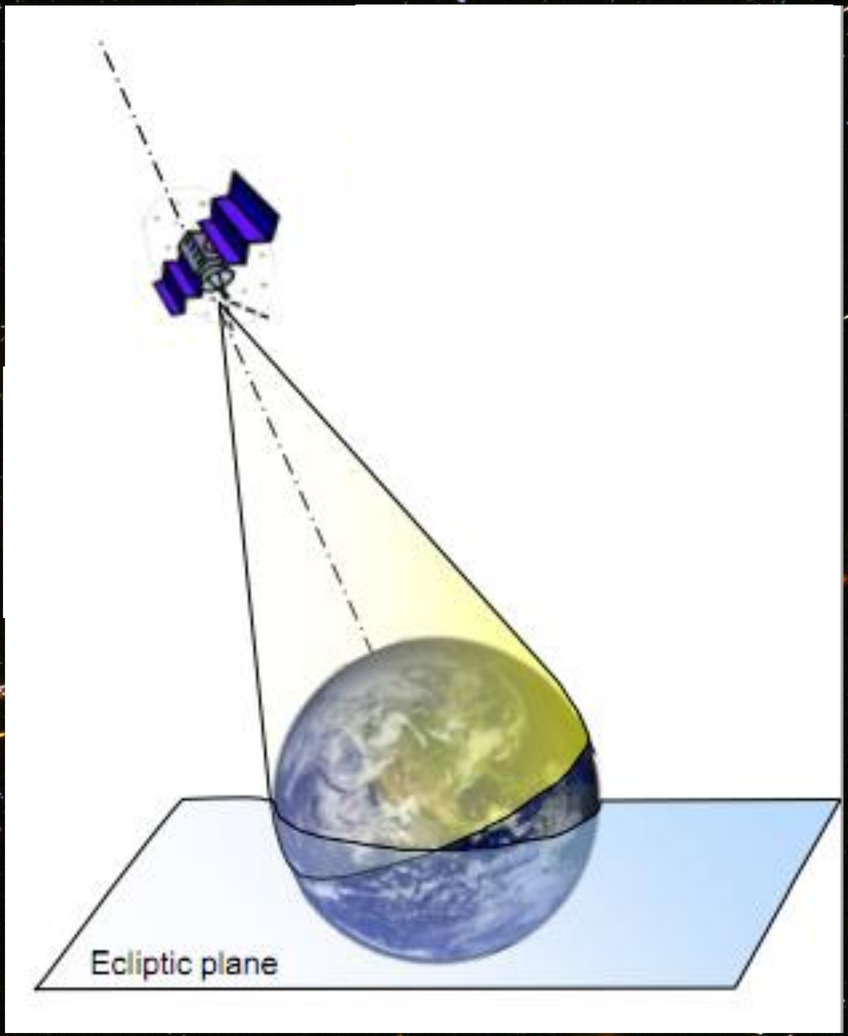
- Continual coverage of the polar regions with no propellant usage!
- Altitudes ranging from 0.75 million km to 3.5 million km, depending on sail performance and inclination chosen





Pole Sitter Spacecraft

- Constantly above an Earth pole
- Continuous hemispheric view of the pole
- New vantage point for telecommunications satellites and Earth observing satellites

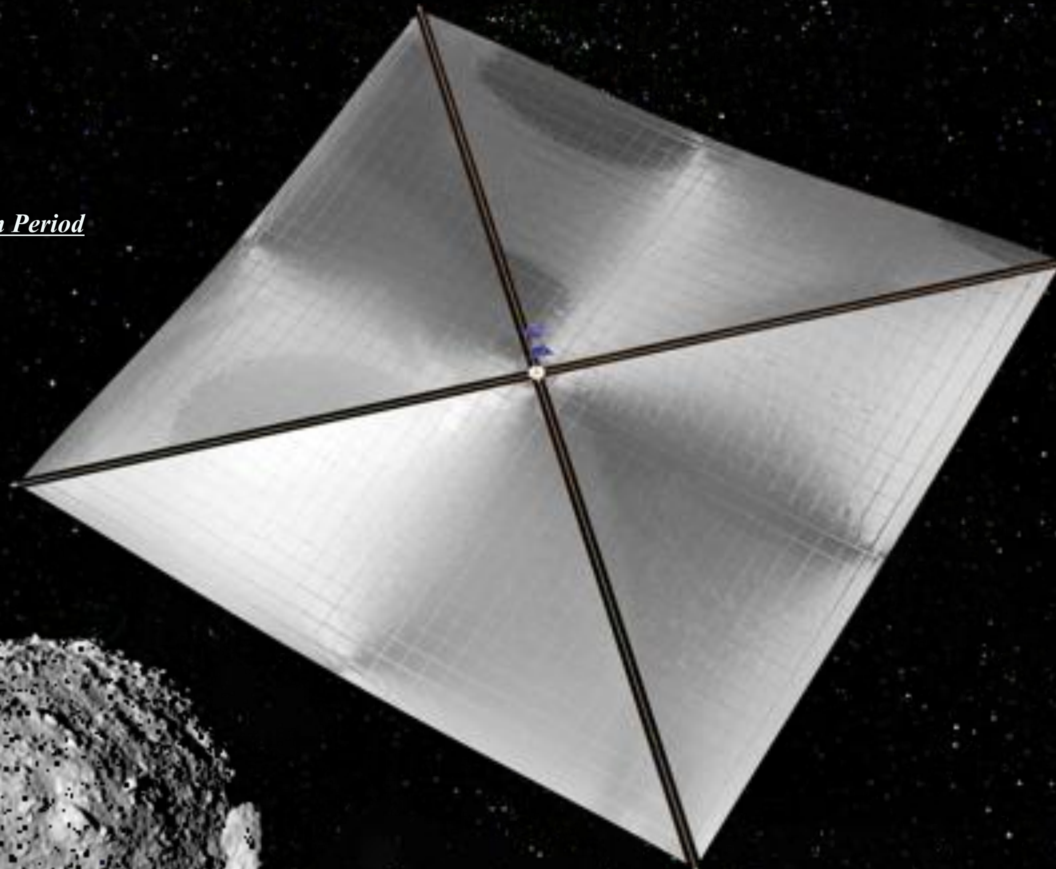


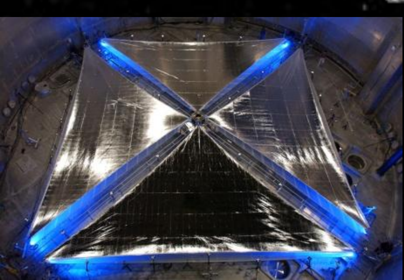
Solar Sail Asteroid Rendezvous Mission
(rendezvous with 3 NEO's in 6 years):

Departure: *Aug 2017*

Candidate asteroids visited:

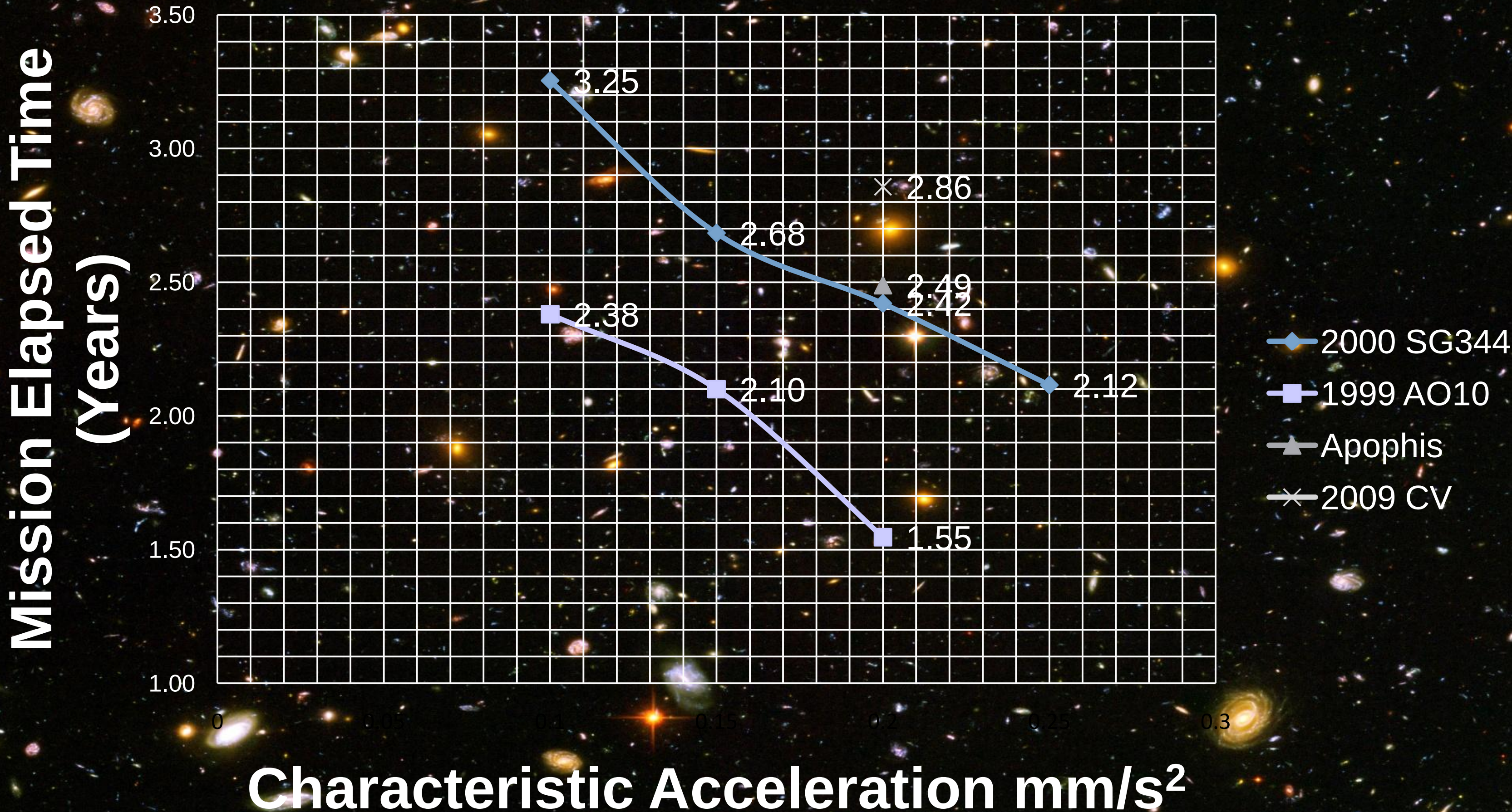
NEO	Date	Observation Period
1999 A010	Mar 2019	35 days
Apophis	Dec 2021	30 days
2001 QJ142	July 2023	30 days





- ***Ground Rules:***
  - ***Use existing spacecraft and components***
  - ***Use existing instruments***
  - ***Use NASA-developed sail technology***
- ***Solar Sail Spacecraft Launch Mass:*** *328.6 kg*
- ***Mass at destination:*** *228.4 kg*
- ***Cost:*** *$175M, plus launch vehicle and ops*

Missions From Earth



Note: Launch window constrained between January 1, 2017 to January 1, 2020

Solar Sail Comet Chaser

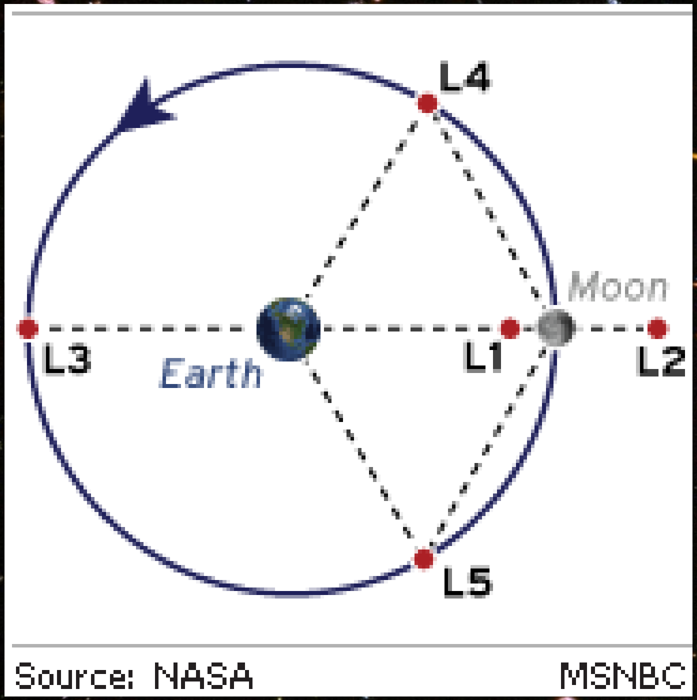
- Use the unique capabilities of a solar sail to study the life cycle of a comet within the inner solar system

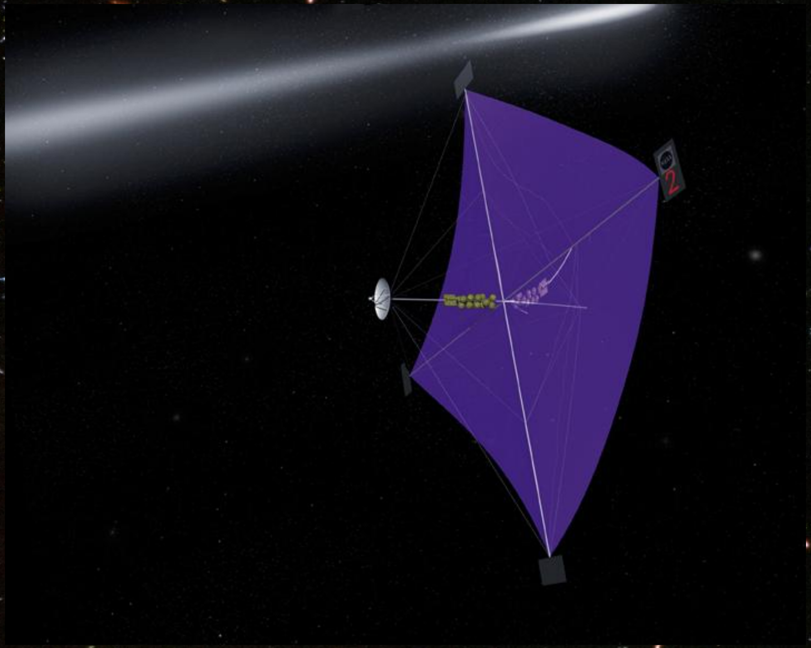
    - Place science spacecraft in a propulsive co-orbit with a comet

    - Acquire the comet between the orbits of Mars and Jupiter

    - Follow the comet through perihelion and as far out as possible

Studying the Sun: L-1 Diamond





- 4 solar sails could provide continuous observations of the sun

Solar Far-Side Sentinel

• Farside Sentinel is 1 of a 6 spacecraft mission to study 1) the acceleration and transport of SEPs and 2) the initiation and evolution of CMEs and interplanetary shocks in the inner heliosphere.

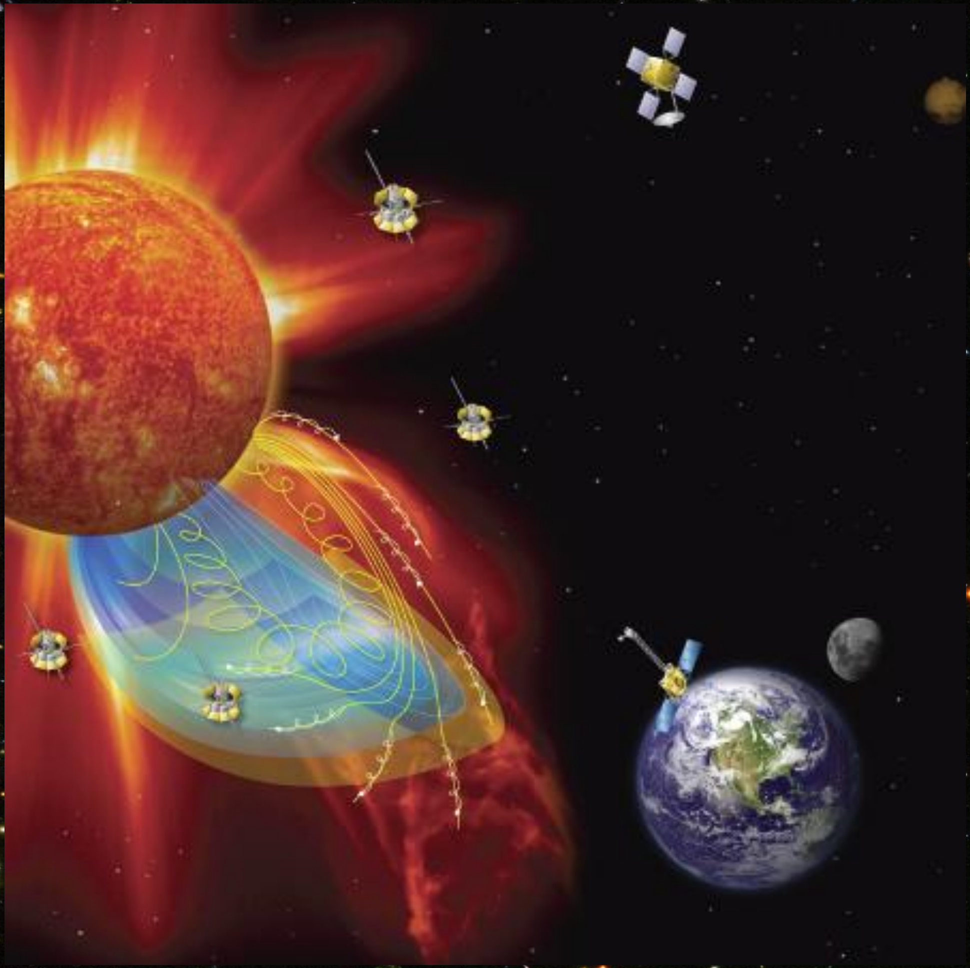
• Will provide a major advancement toward the future ability to forecast space weather events.

• Far side observations hold promise as an indicator of upcoming earth side activity

• With opposition orbit the sun blocks earth communication

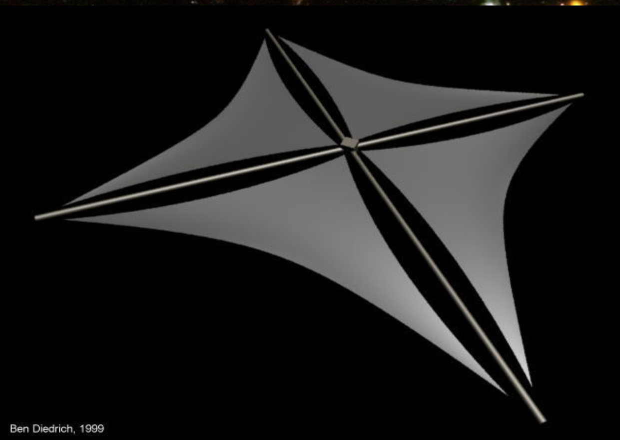
• Options include two satellites in ecliptic or 1 solar sail orbiting above the sun

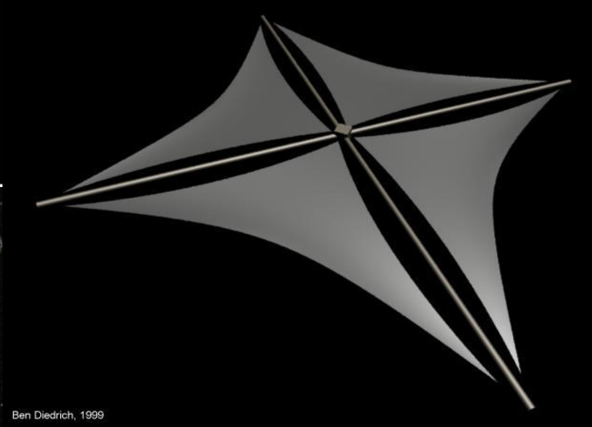
• Solar sail enables high degree of flexibility in orbits and mission ops



Solar Sail Cargo Ships

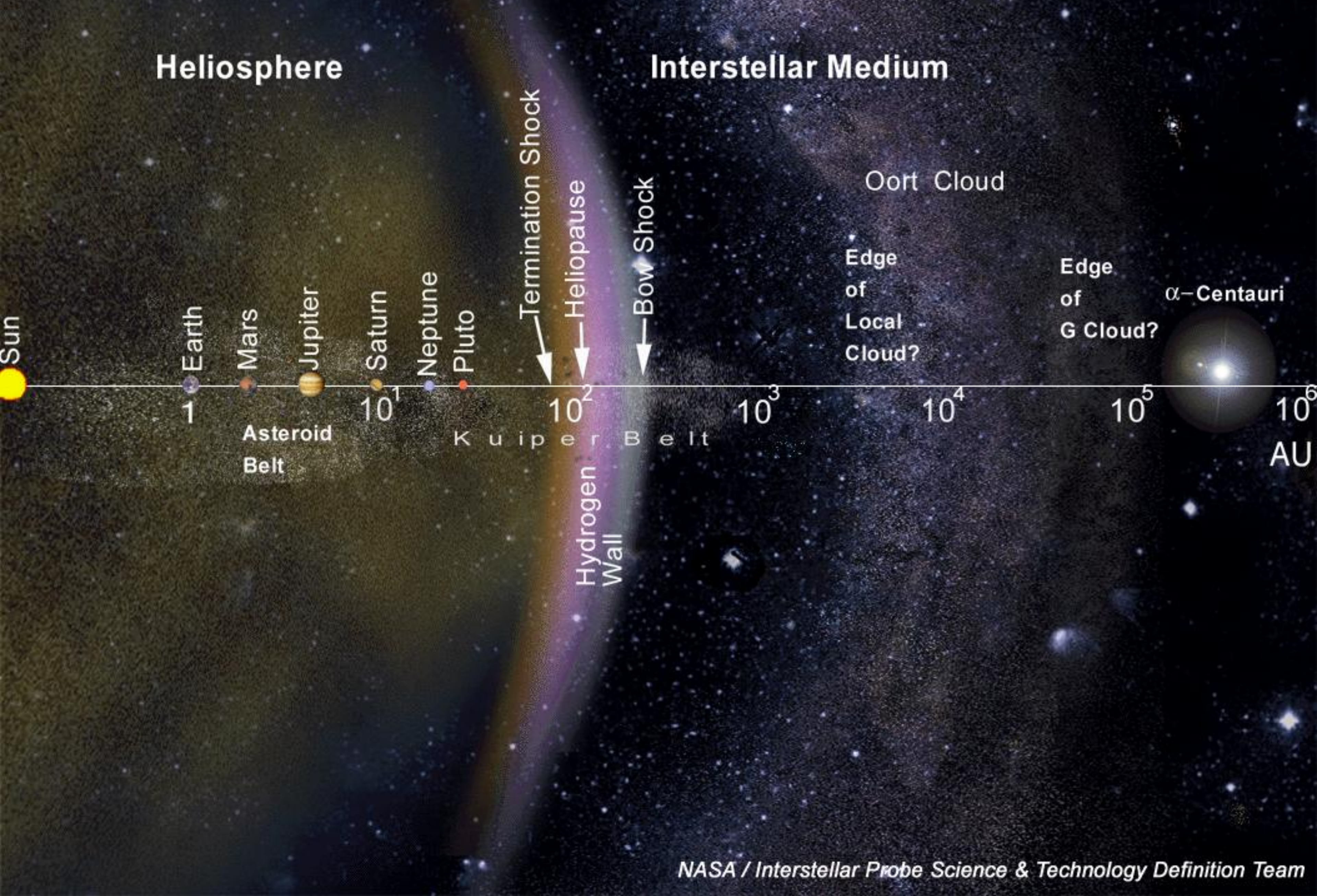
- Fleets of propellantless solar sails could be the cargo ships of the future
- (Operating within the inner solar system – near the sun)



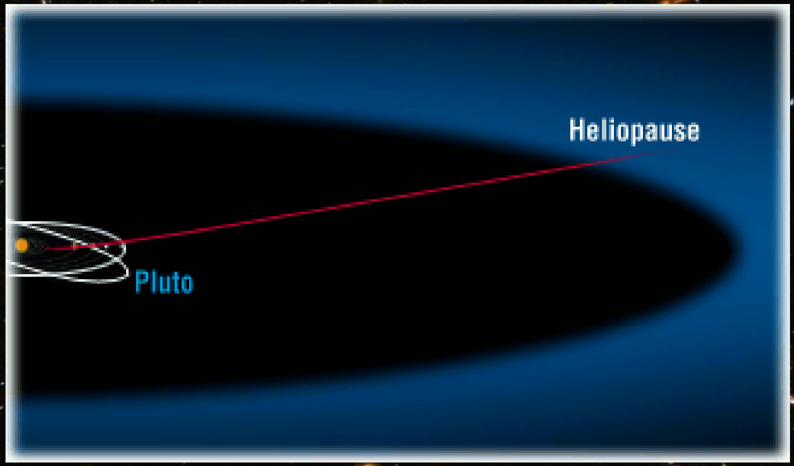


Solar Sails Enable Interstellar Travel

Our Solar Neighborhood



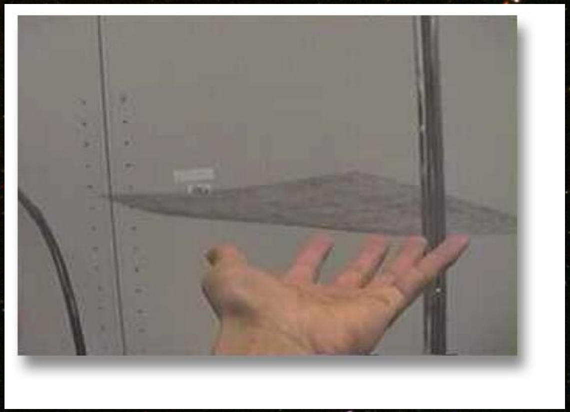
Solar Sail Propulsion for the Interstellar Probe Mission



The Heliopause is a barrier where charged particles from the sun cannot go beyond because cosmic rays from deep space force them back.

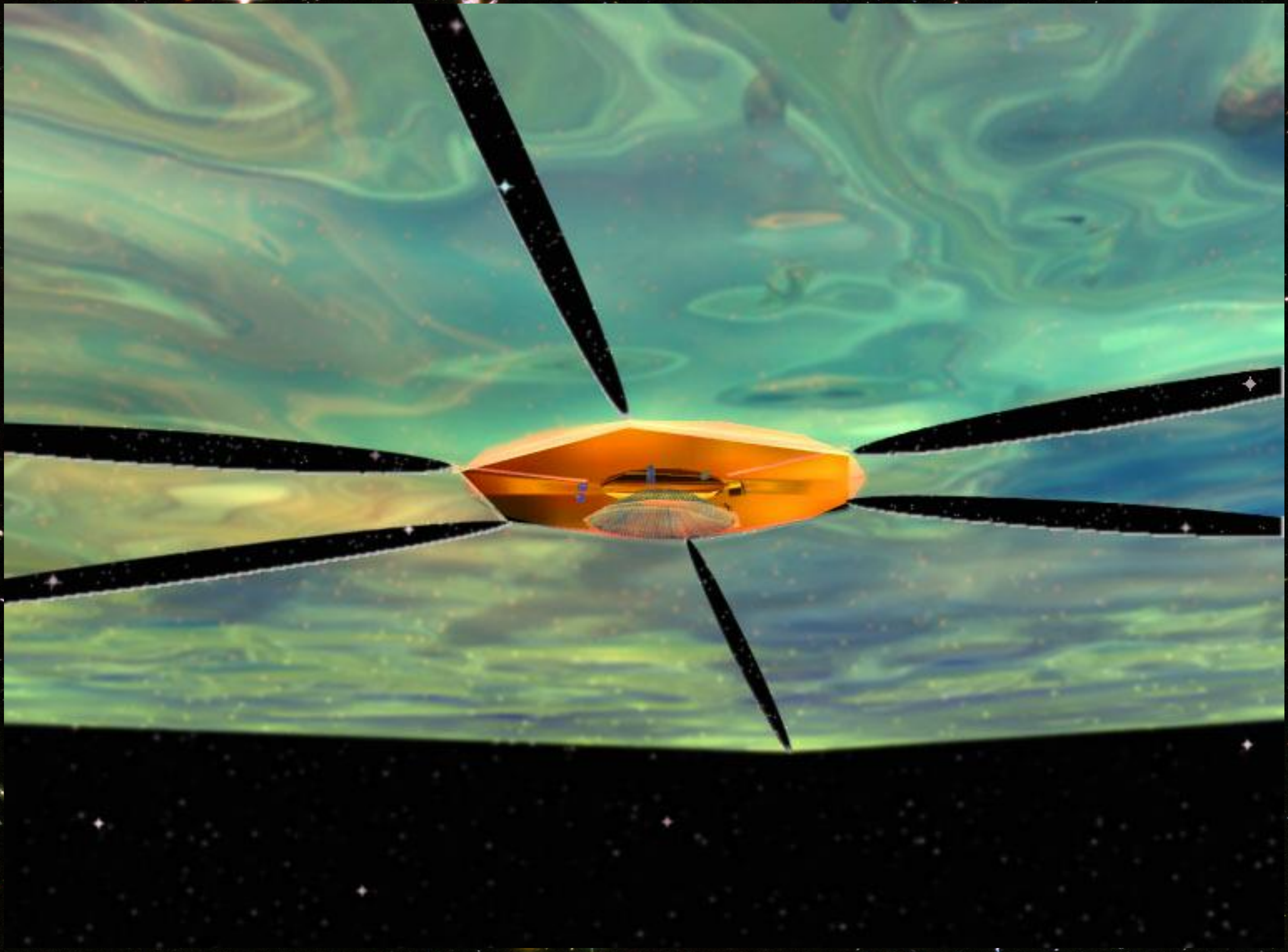
- **Sail Requirements**
  - 500 - 800 meters diameter
  - 1 g/m^2 density
  - Survivable to T=3000K for close solar approach
- **Science Objectives**
  - Explore the nature of the interstellar medium and its implications for the origin and evolution of matter in our Galaxy and the Universe.
  - Explore the influence of the interstellar medium on the solar system, its dynamics and its evolution
  - Explore the impact of the solar system on the interstellar medium as an example of the interaction of a stellar system with its environment
  - Explore the outer Solar System in search of clues to its origin, and to the nature of other planetary systems.

- The first mission to beyond the Heliopause
  - 250 AU minimum
  - Reach 250 AU within 20 years from launch
  - 15-20 AU/year target velocity
- Two propulsion concepts considered
  - BASELINE: Solar Sails (via close solar approach)
  - OPTION: Nuclear Electric (fission reactor)
  - REJECTED: All Chemical with Gravity Assists

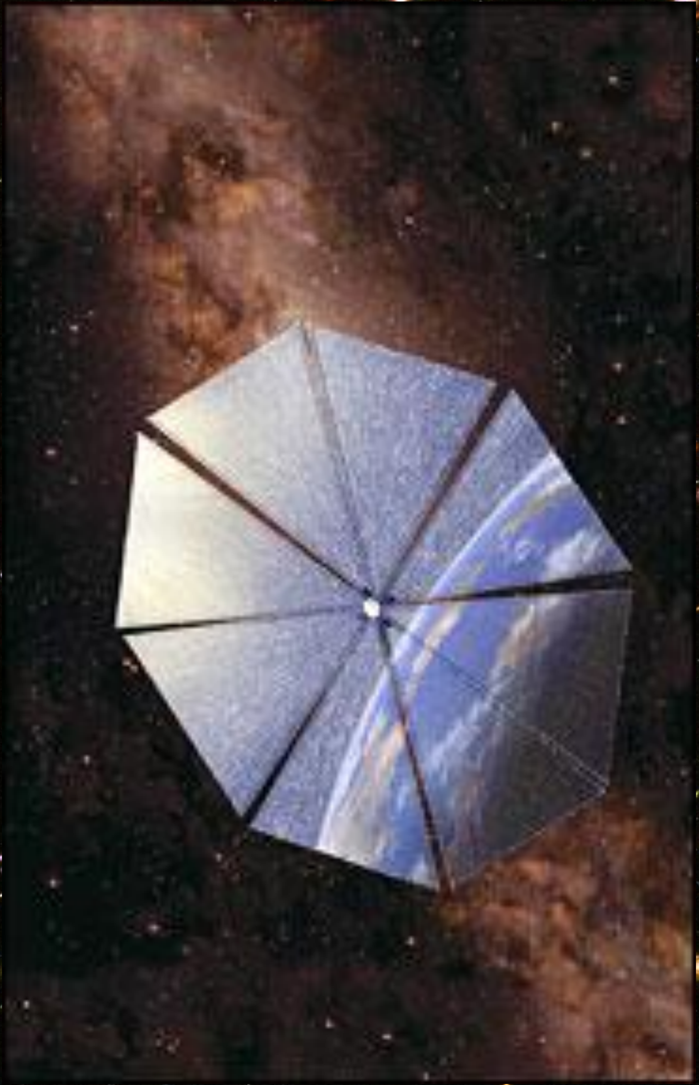


Carbon fiber μ-truss fabric (1 gm/m^2, 2 mm thick)

Interstellar Probe Flight Configuration
Fully Deployed Sail



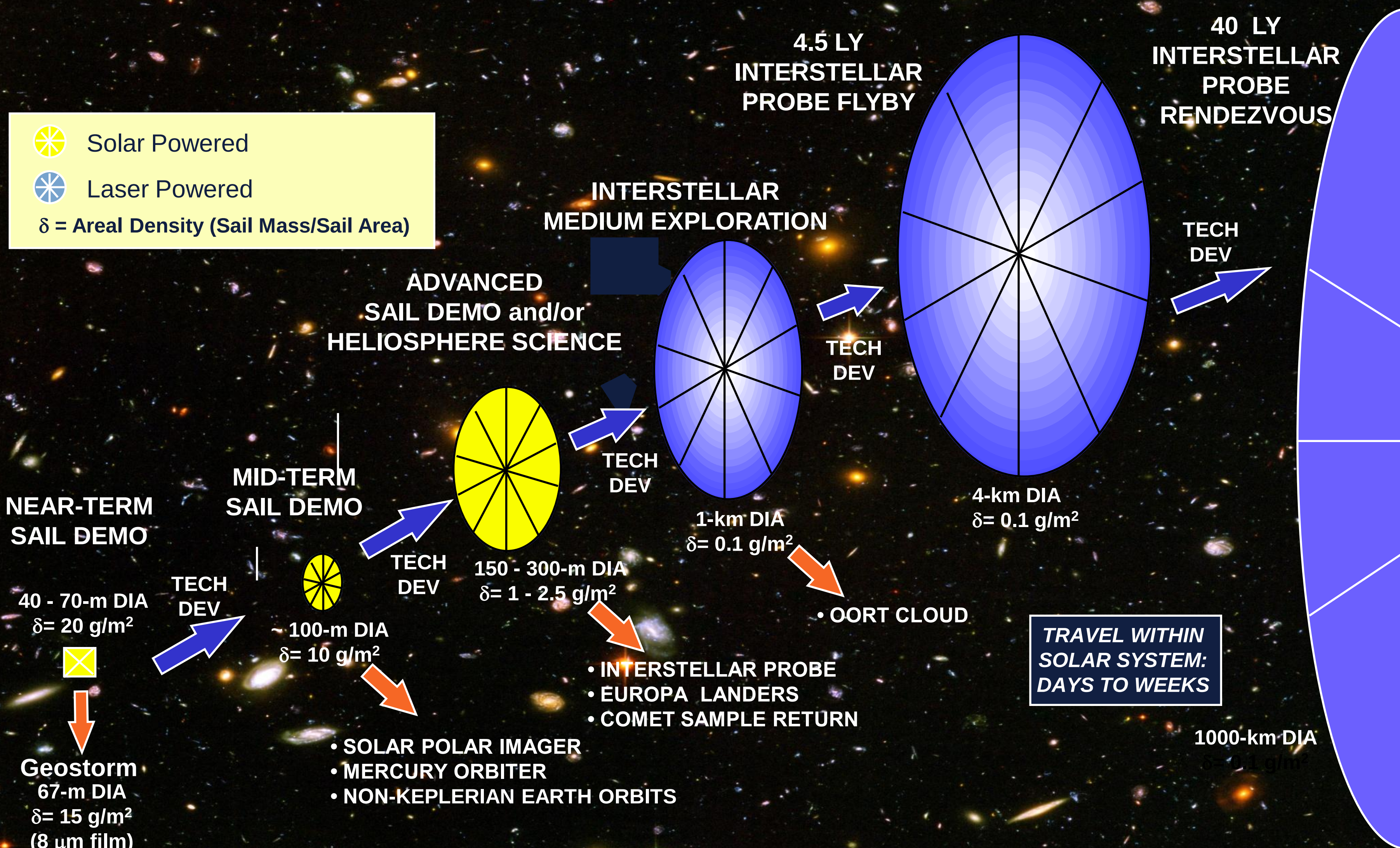
Very Large Solar Sails With A Very Close Solar Approach May Enable Interstellar Travel



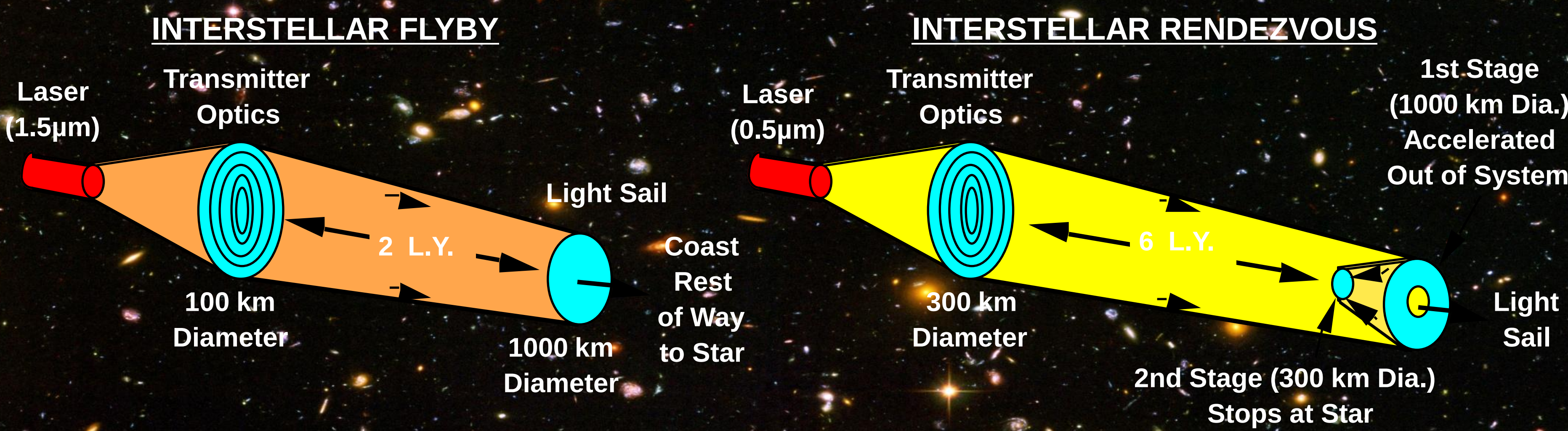
- **100-km class sail unfurled at less than 0.2 AU may enable a trip to the nearest star in under 1000 years.**

- **1000 years ago…**
  - China was the world's most populous empire. By the late 11th century, the Song Dynasty had a total population of some 101 million people, an average annual iron output of 125,000 tons/year
  - The Islamic world was experiencing a Golden Age and continued to flourish under the Arab Empire
  - Leif Ericson landed in North America
  - Olso Norway was founded and lots of wars were fought in Europe
- **We have recorded history going back 1000 years and will likely know to turn on the radio to listen for the probe "calling home."**

Near-Term Solar Sail Applications Lead to Interstellar Capability with Laser Sails

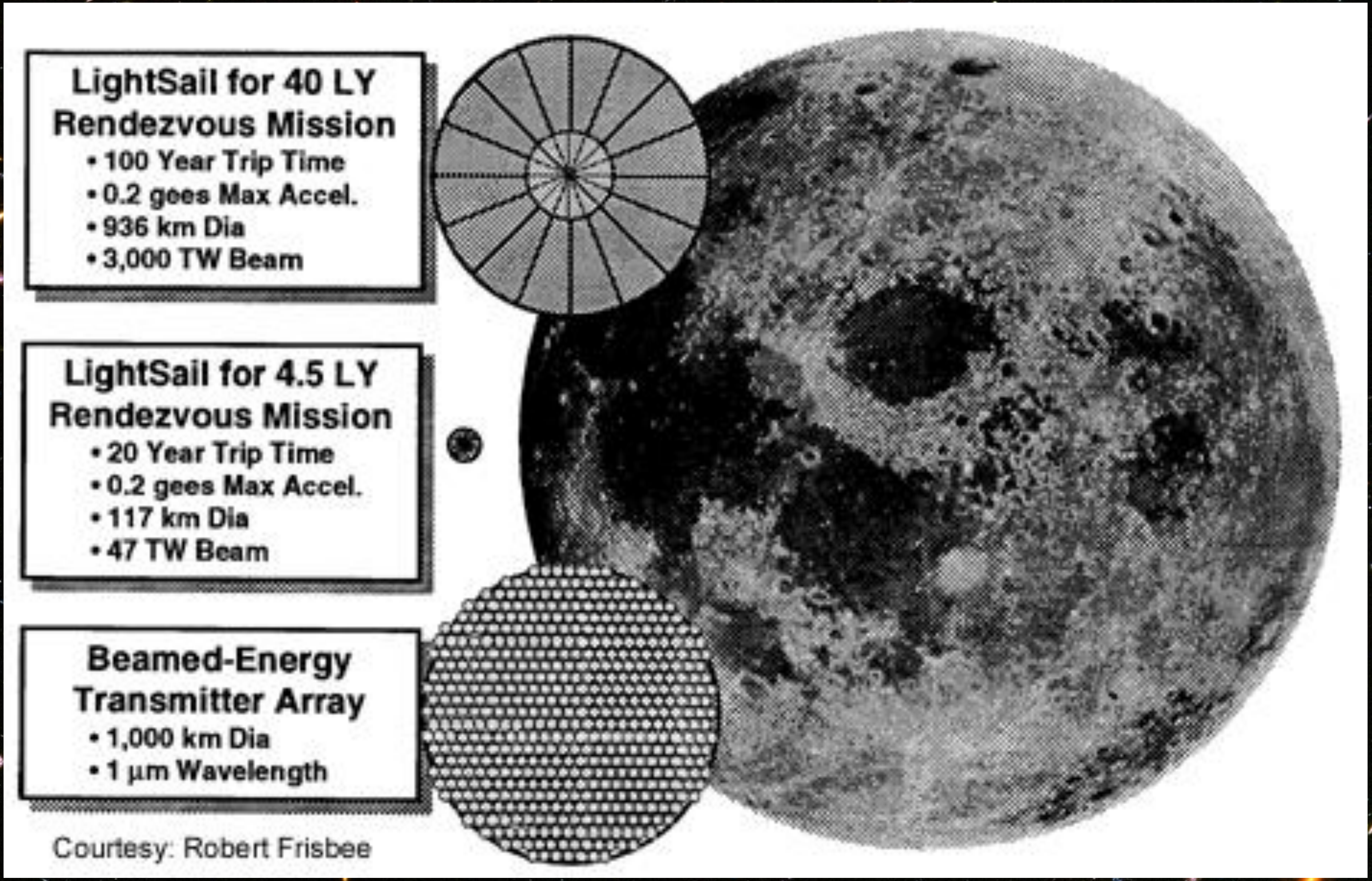


Interstellar Light Sail Concept

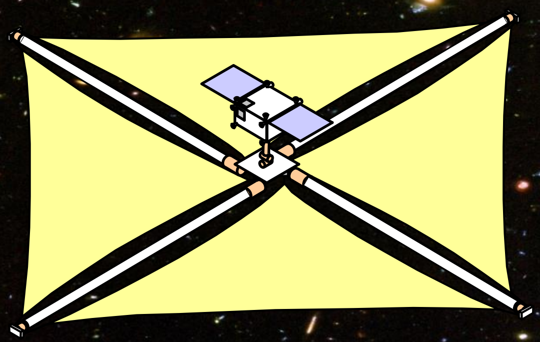


- Advantages
  - Perform interstellar missions in < 50 years
  - Only competitor is antimatter
  - Use as a solar sail once in orbit about target
  - Use solar power satellite as driver for robotic flybys
- Disadvantages
  - Very high laser / microwave powers (0.1-1,000 TW)
  - Very large optics (100-1,000 km)
- Far-term concept, but one of the few ways to do "fast" interstellar missions

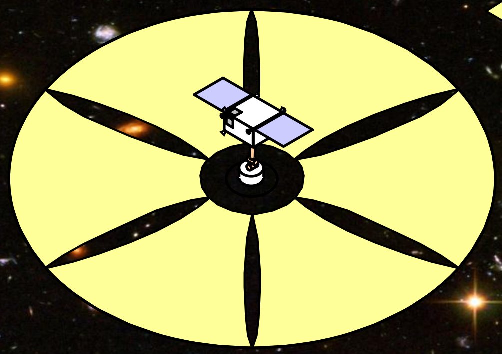
Laser Sails Are BIG



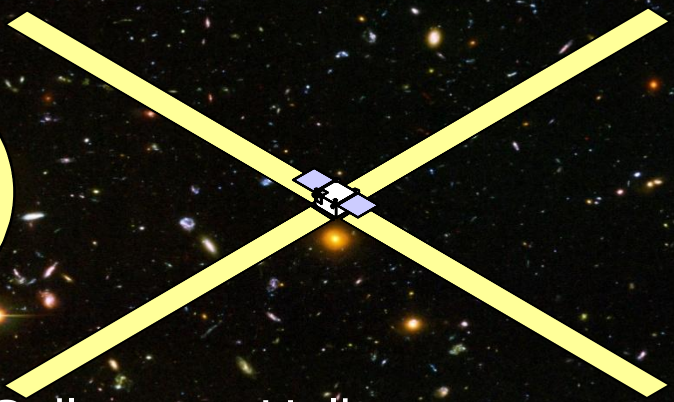
Types of Sail Designs



Square Sail

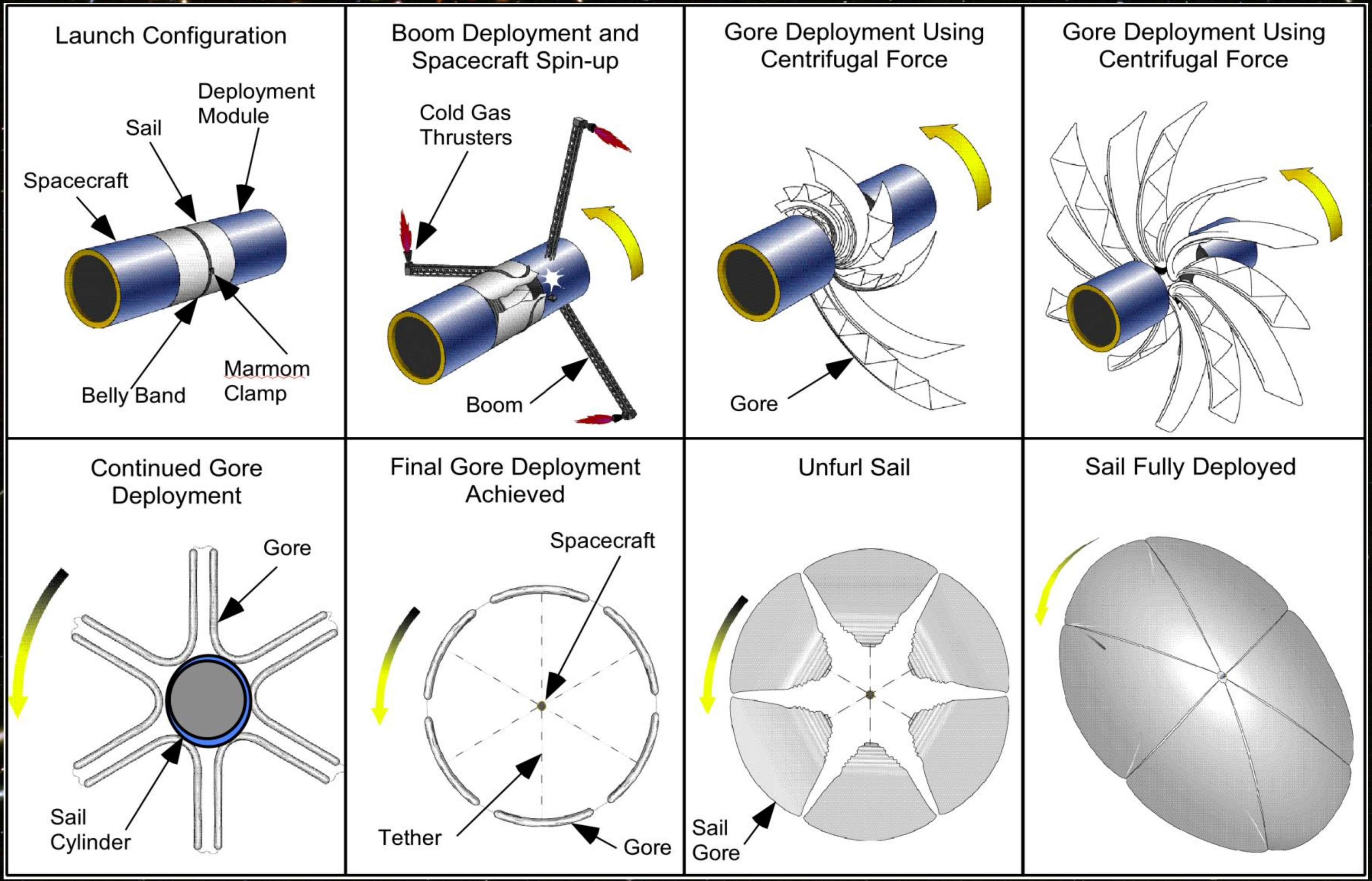


Spinning Disk Sail

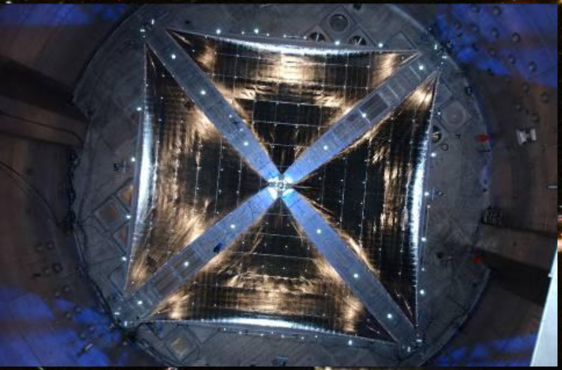


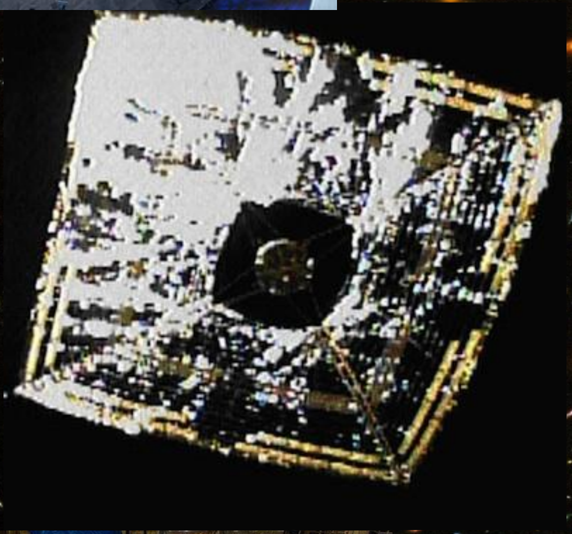
Heliogyro

Spinning Solar Sail
Deployment Sequence



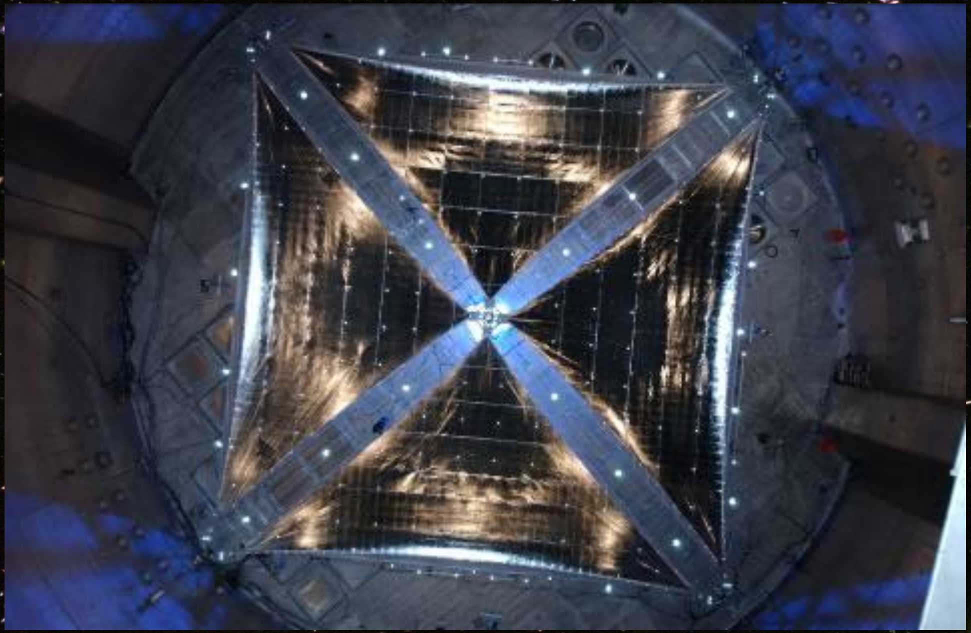
Solar Sail Technology – Many Players





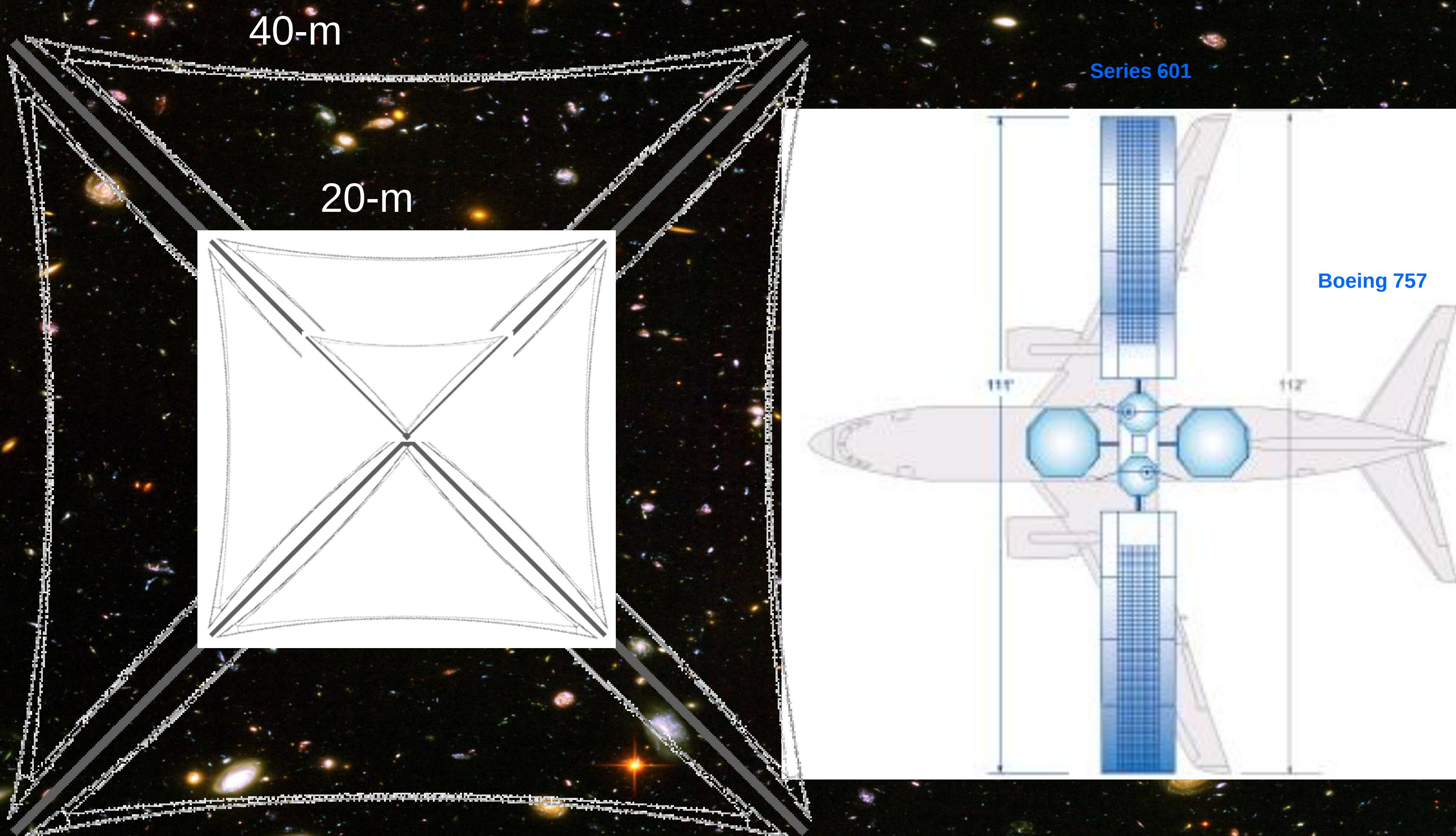
- **NASA developed 80m class solar sail propulsion systems to ~TRL-5/6 in the mid-2000's**
  - Tested inner 20m sail core under thermal vacuum conditions in 2005
- ***JAXA is flying a 14m solar sail to Venus (launched in 2010)***
- **NASA is flying NanoSail-D subscale solar sail prototype**
- **The Planetary Society's *Cosmos-1* twice suffered launch vehicle failure; *LightSail-1* is their new project**

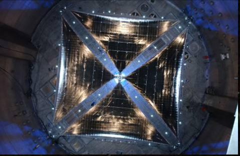
NASA Solar Sail Propulsion Technology Status



♦ Technology Area Status:
- **Two solar sail technologies were designed, fabricated, and tested under thermal vacuum conditions in 2005:**
  - **10 m system ground demonstrators were 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.**

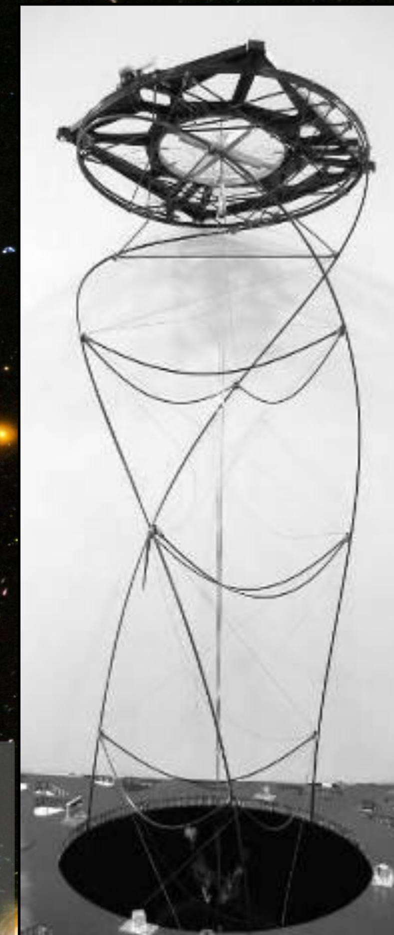
10, 20, and 40-m Solar Sail Systems

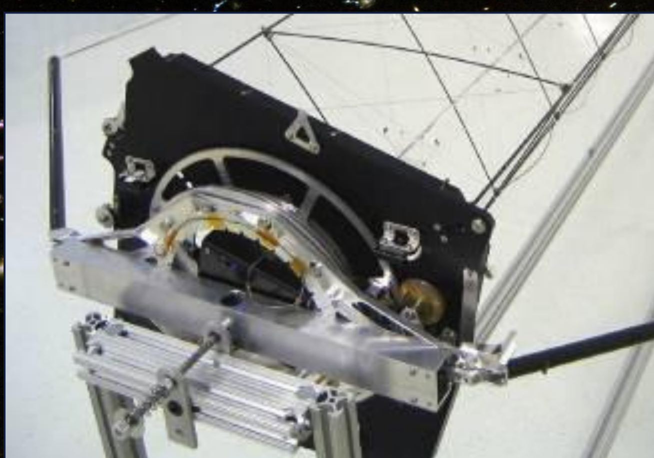


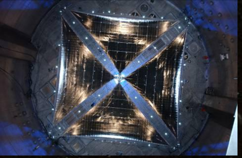


ATK Solar Sail Development

- Technical Team:
  - ATK (Goleta, CA) systems engineering & coilable booms
  - Nexsolve (Huntsville, AL): Sail manufacture & assembly
  - LaRC (Hampton, VA) Sail Modeling & Testing
  - MSFC (Huntsville, AL) Materials Testing
- Overall Strategy
  - Leveraged New Millennium Program ST 7 Phase A Design Concept
    - – Improve performance with Ultra-Light Graphite Coilable booms
      - –Sail membrane, AL coated 2.5 µm CP1, compliant border, 3 point attach
    - – Thrust Vector Control uses sliding masses along boom with spreader bars and micro-PPT at mast tip







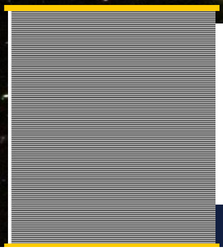
ATK Solar Sail Development, Continued

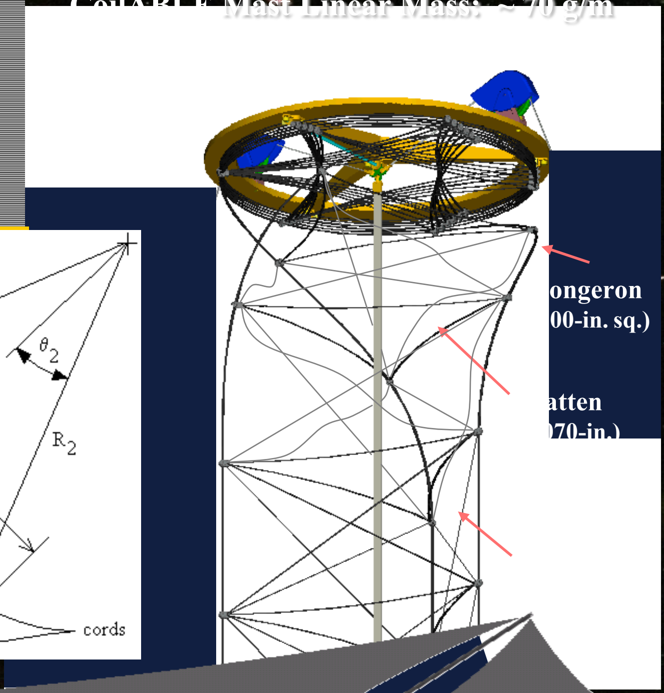
- Operating Temperature
  - 16°C at .98 au
- First Natural Frequency
  - 0.02 Hz
- Stowed Package
  - 1.5 m dia. by 0.53 m
- System Mass:
  - 108 kg (w/ contingency)
- Characteristic acceler
  - 0.76 mm/s²
  - 0.34 mm/s² with 130 kg SC

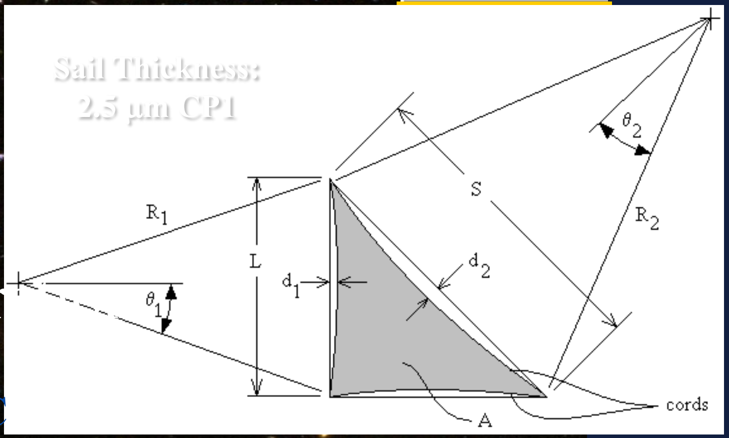
Stowed CoilABLE

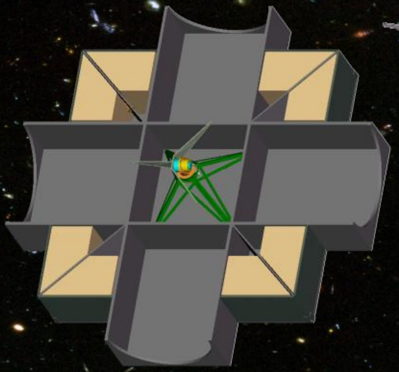
Ø20-in. (50.5 cm)

18.7-in.-tall (<0.55% of length)

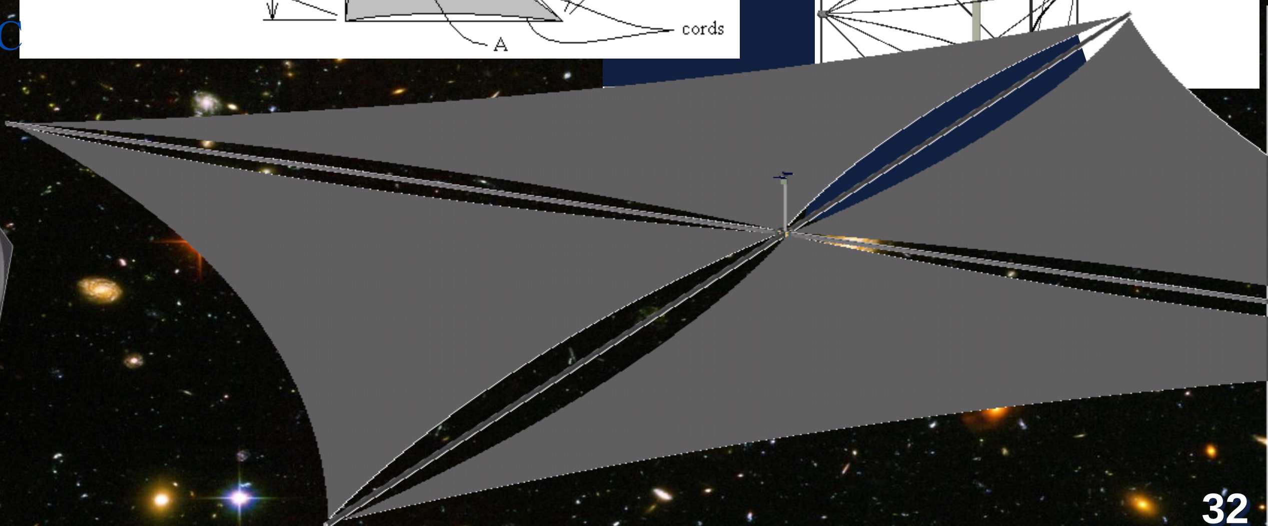


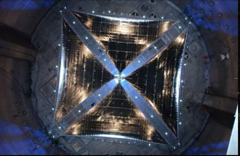






Cut-Away of Stowed Package

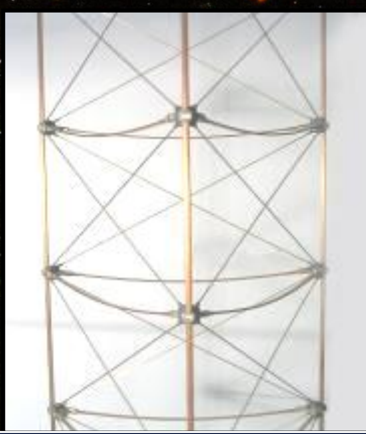




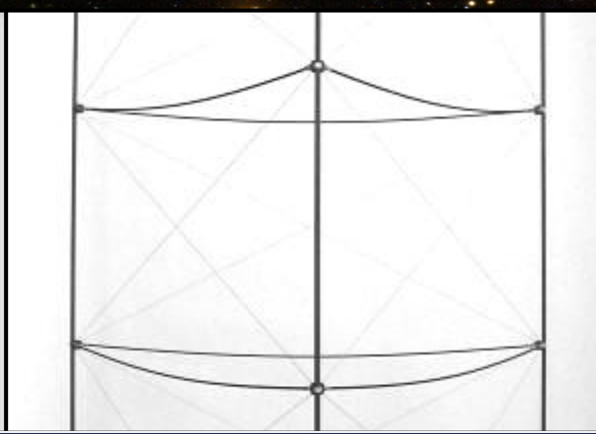
CoilAble Mast Heritage

- Able Engineering Company Established in 1975 (called ATK Space Systems at the time of the demo)
  - 30 CoilAble systems had been flown to date
  - A phenomenal Stiffness to Weight ratio, High Dimensional Stability, Robust deployment, and Compact Stowage
- Recent flight mast designs
  - Mars Pathfinder (1999) 1-meter boom: 130 g/m
  - IMAGE spacecraft (2000) 10-meter booms: 93 g/m
- 100% Product Success Rate With No On-Orbit Failures

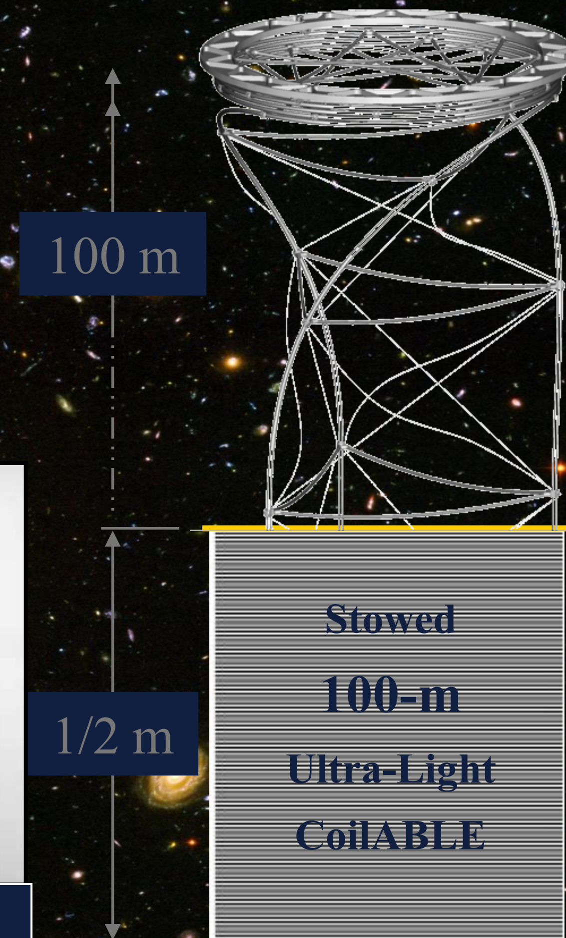
LACE

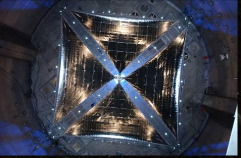


ISP



ST8





Nexsolve Solar Sail Membrane Features

Membrane Design:

4-quadrant planar sail

- Compliant Border interface between edge cable and membrane
  - Shear insensitive, Cord/Material CTE mismatch insensitive
  - Thermal Gradient insensitive

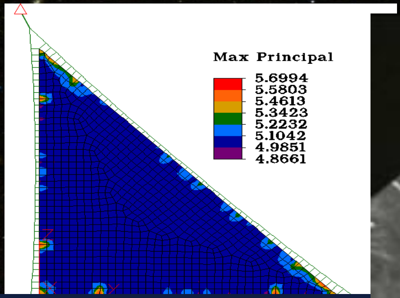
Sail Material: ***CP1 Polyimide***

- High Operating Temperature (>200° C)
- UV Stable
- Essentially Inert
- Soluble (Wet Process), modifiable with variety additives - improve conductivity and thermal properties
- ***2.5 micron polyimide***
- ***Flight Proven --- flying on Numerous GEOCOM satellites***

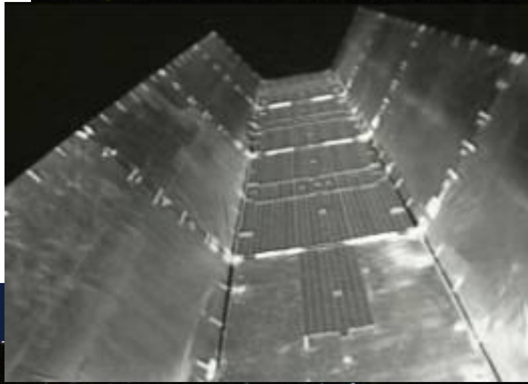
Sail Construction Methods:

A gossamer film construction similar to gusseted, reflective blankets flying on numerous GEOCOM satellites

- Scalable Construction Methods --- current system >20m
- Adhesive less Bonding Methods --- eliminates sticking and contamination risks.



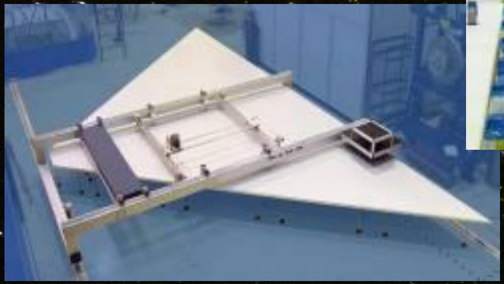
FEM of Parobolic Edge



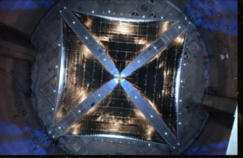
160 m^2 of film per satellite.
Film Is 1 mil material supported by 5 mil edge designs

Sail with Compliant Border

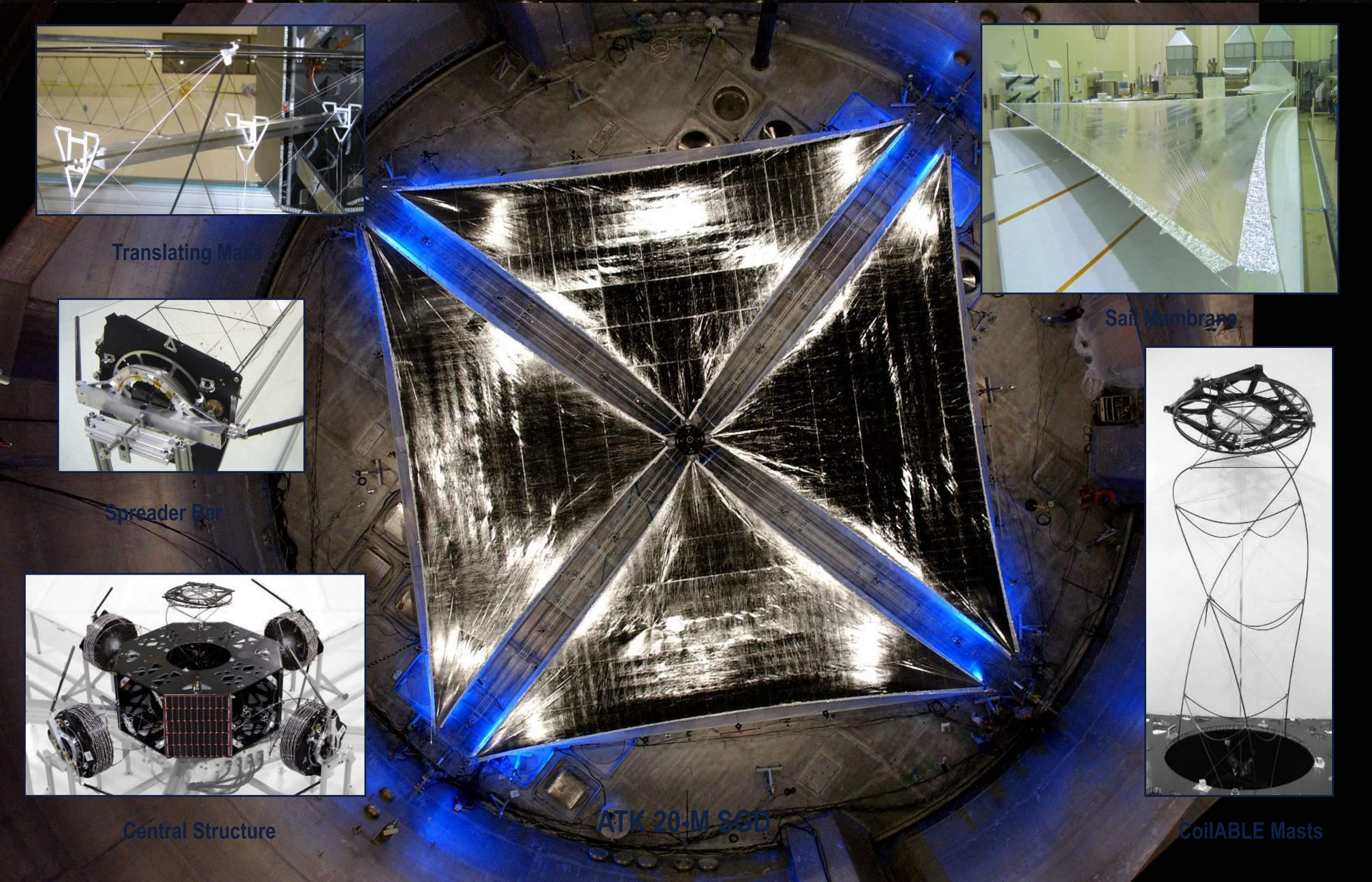
Sail Production



SRS CNC Seaming System



ATK 20-m System Ground Demonstrator



Translating Mass

Spreader Bar

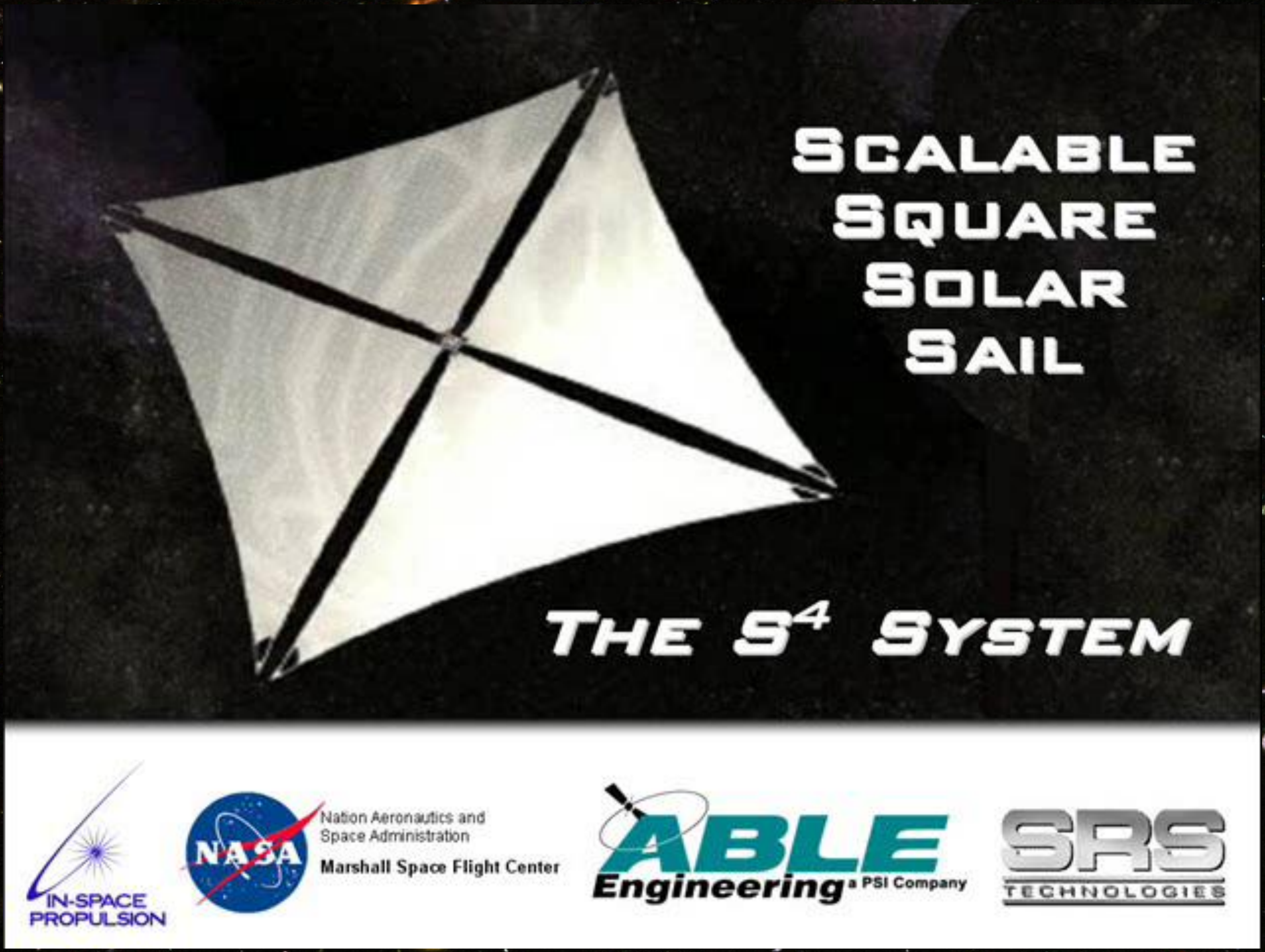
Central Structure

Sail Membrane

CoilABLE Masts

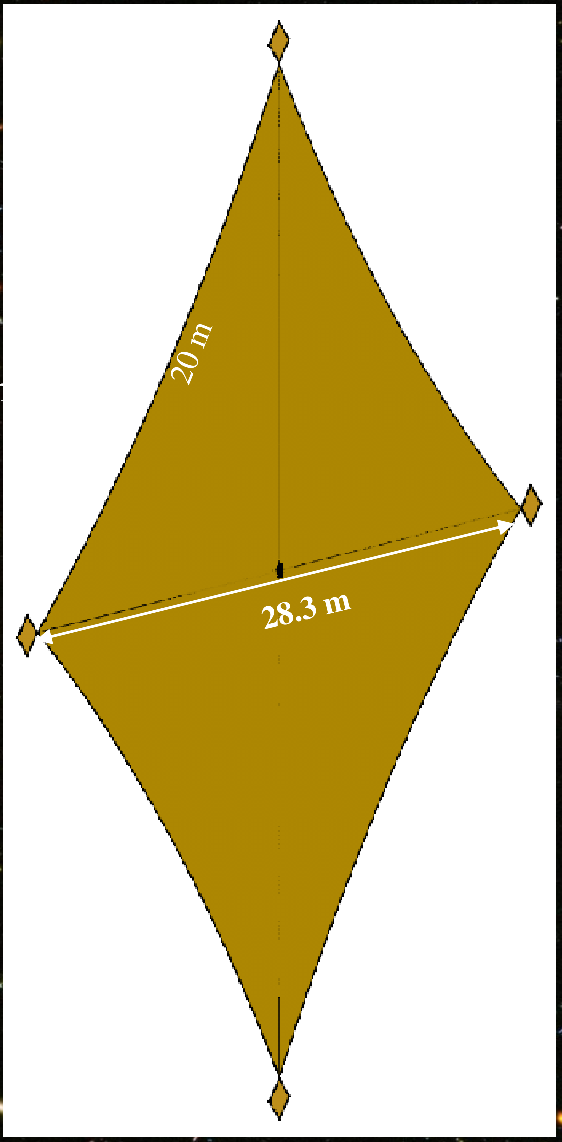
ATK 20-M SGD

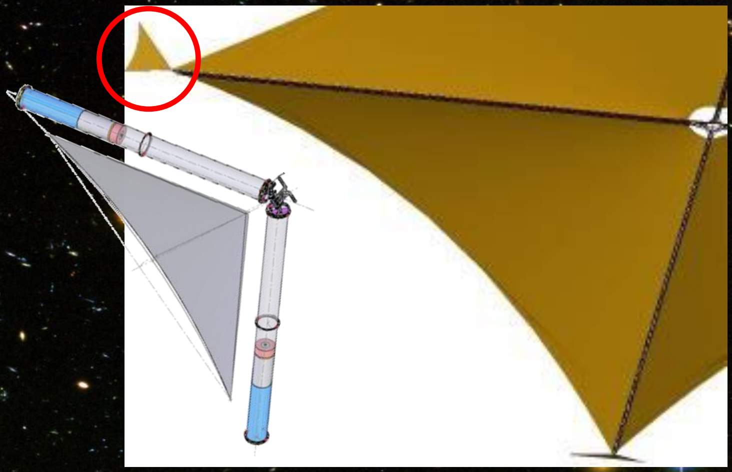
ATK Sail Deployment



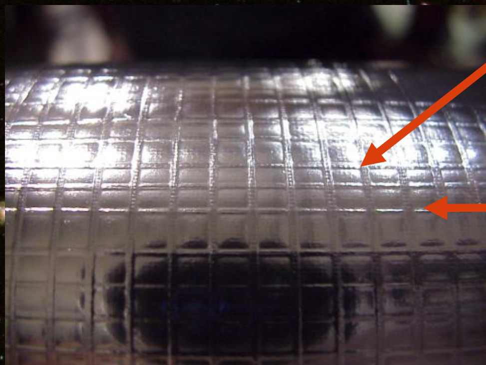
L’Garde Solar Sail Development

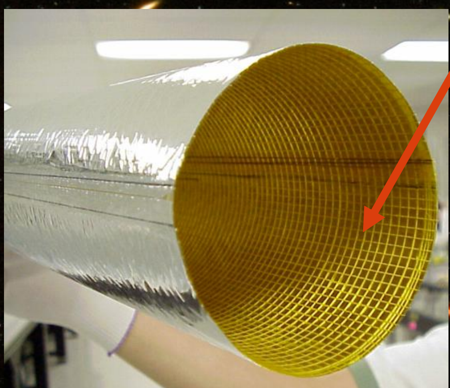
- Technical Team:
  - L’Garde, Inc. (Tustin, CA) systems engineering and inflatable truss
  - Ball Aerospace & Tech Corp. (Boulder, CO) mission eng. & bus design
  - LaRC (Hampton, VA) sail modeling & testing
  - JPL (Pasadena, CA) mission planning & space hazards
- Overall Strategy
  - Concept Leveraged ST-5 Phase A design concept and Team Encounter experien
    - Sail membrane, AL coated 2 μm Mylar attached with stripped net
    - Lightweight Boom With Sub-Tg Rigidization
    - 4 Vane Thrust Vector Control





Beam Characteristics



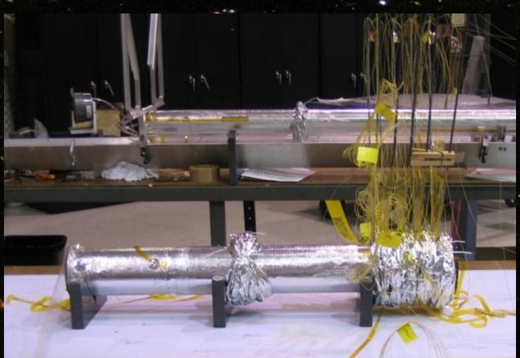


Load bearing longitudinal uni-directional fibers
- Fibers impregnated with resin (rigid below -20^{o} C)
- 0.48 AU design requires greater fiber density to withstand loads from the increased solar flux

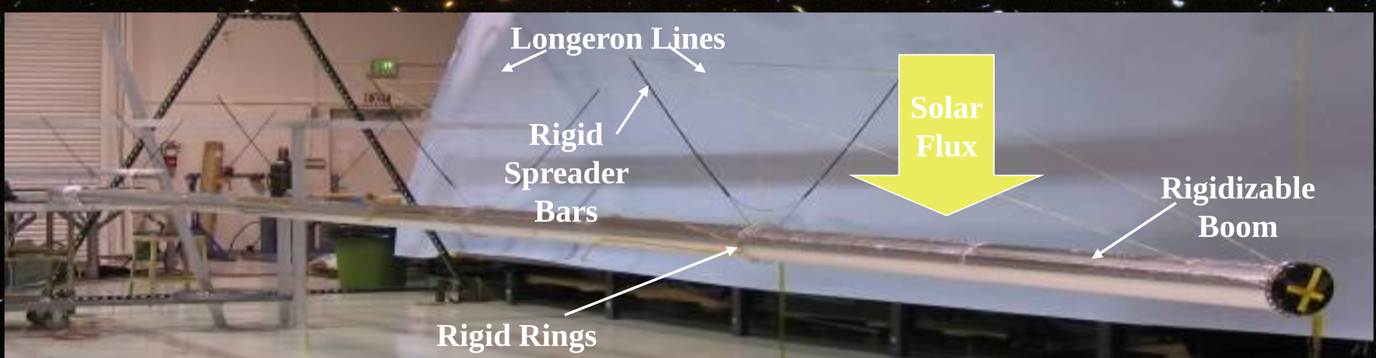
Spiral wrap
- Stabilizes longitudinal fibers
- Allows over-pressurization for deployment anomalies

Bonded Kapton bladder and Mylar
- Encapsulation "skin" carries shear
- Aircraft fuselage like structure

Beam Structure
- Sail structure is stressed for solar loading in one direction for mass efficiency
- Truss system comprised of mostly tension elements, minimal rigid components
- Highly mass efficient, ~36g/m linear density

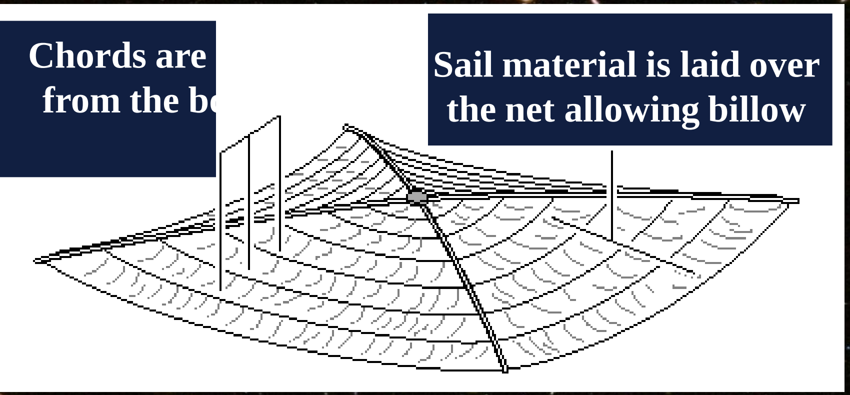


Stowed 7 m boom (~.5 m)



Deployed 7 m boom

Net/Membrane Sail



Net/Membrane Sail Schematic

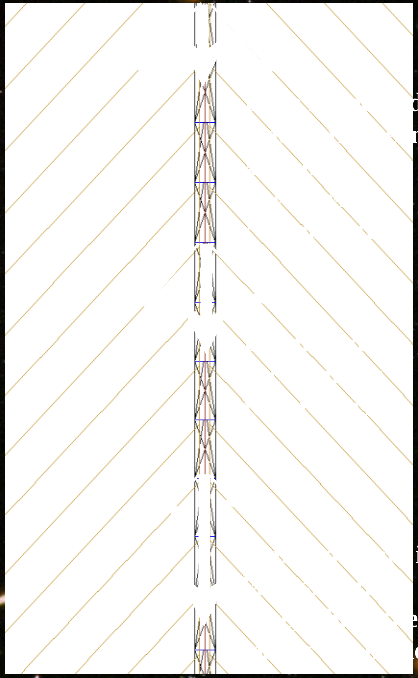

20m Sail Quadrant

Net Membrane

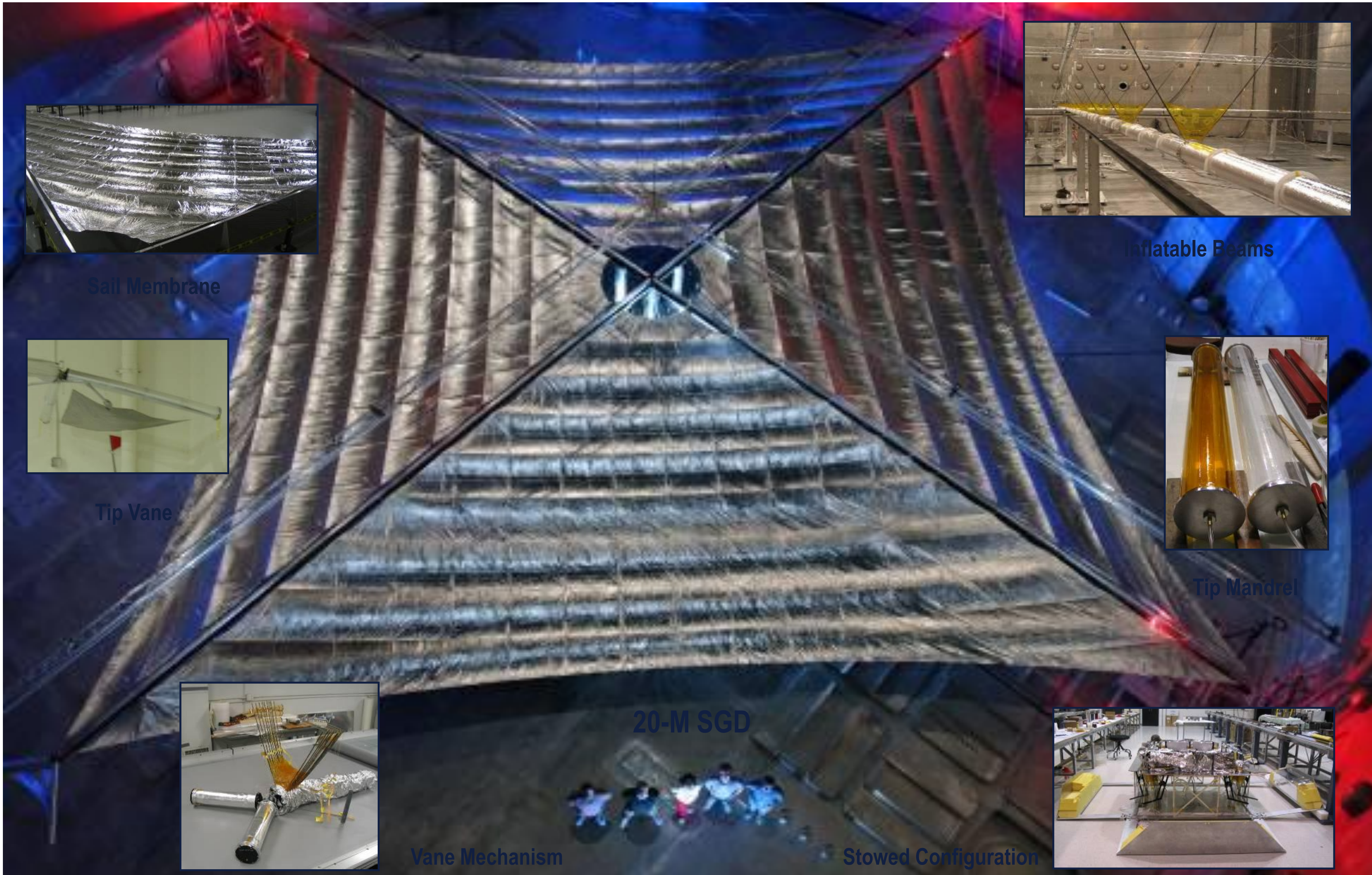
- Sail is supported by a low CTE net with additional membrane material added to allow for thermal compliance
- Sail properties effect local billow between net members only, global sail shape is stable

Advantages

- Net defines the overall sail shape, not the membrane
- Stability and geometry of the sail is effectively decoupled from membrane properties
- Sail shape, and hence thrust vector, sailcraft stability and performance, are predictable and stable
- No high local stress concentrations in the sail, loads are transferred though the net, not the membrane
- Very scalable, larger net/membrane sails simply add additional net elements to control overall shape

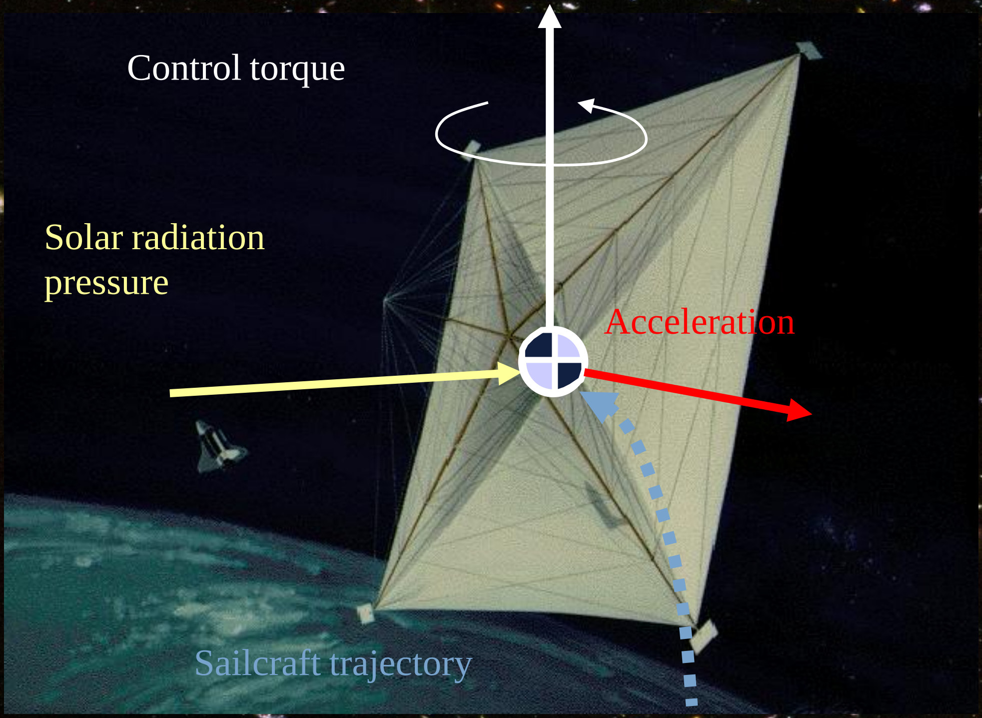


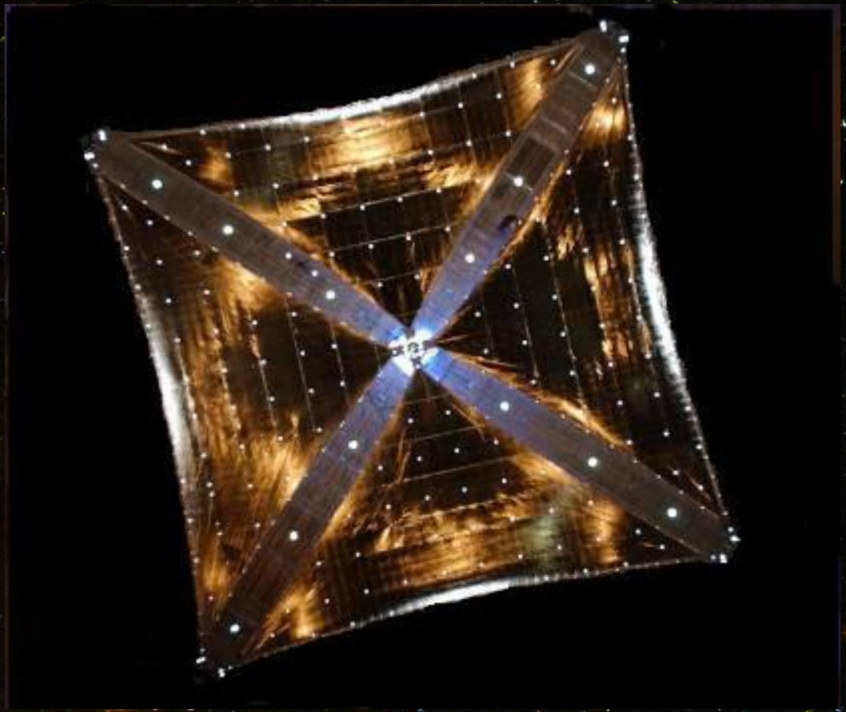
L'Garde 20-m System Ground Demonstrator



L'Garde Inflatable Sail Deployment

Solar Sail Subsystem Development





Solar Sail Spaceflight Simulation Software (S5)

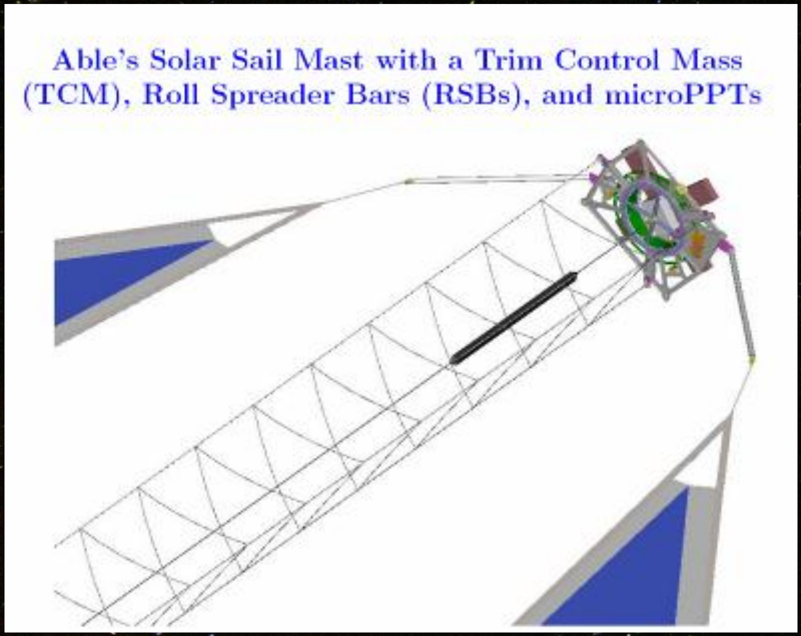
Developed an integrated simulation and analysis software tool for optimal design of solar sail trajectories and for evaluation of guidance navigation and control strategies.

Optical Diagnostic System (ODS)

Developed a ground integrated instrumentation package to allow measurement of sail shape, tension and temperature; boom & sail vibration modes and stress; and deployment monitoring.

Solar Sail Subsystem Development– cont.

Samples prior to UV exposure



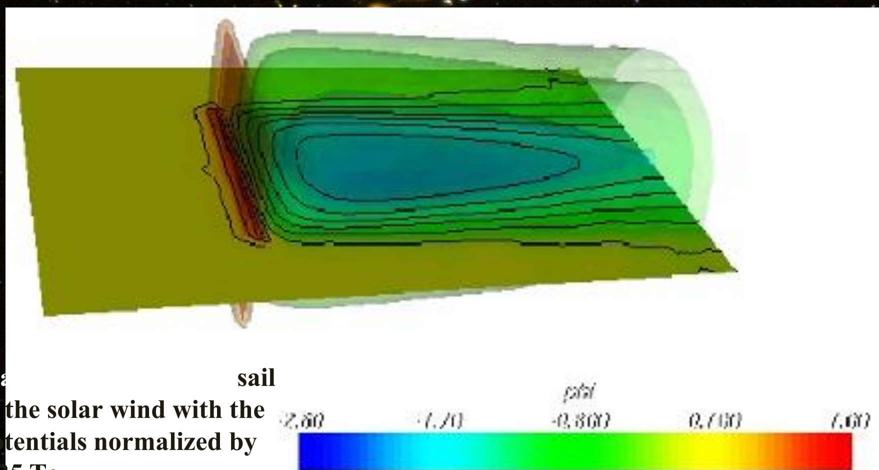
Material Testing

Characterized engineering performance of candidate SS materials at .5 and 1 AU, gauging material property tolerances after exposure to simulated mission-specific charged-particle and micrometeoroid environments.

Development of a Lightweight Robust SACS and a Software Toolkit for Solar Sails

Developed of a highly integrated, low cost, low mass, low volume, and low power attitude determination and control system and develop a high-fidelity multi-body modeling and simulation software toolkit.

Solar Sail Subsystem Development– cont.



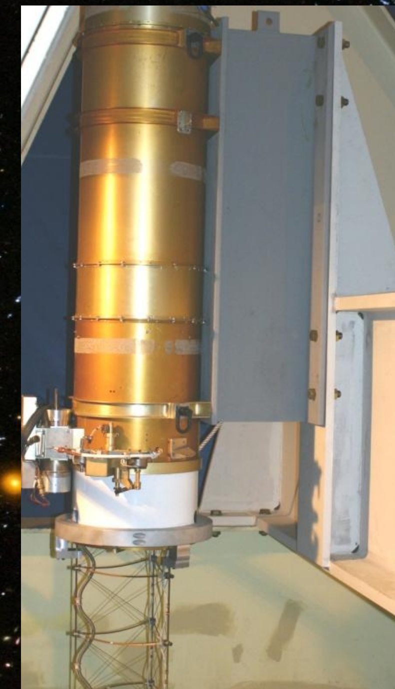
Pla sail in the solar wind with the potentials normalized by 0.25 Te

Sail Charging Analysis

Developed environmental and sail configuration models and design guideline criteria for solar sails. Conduct laboratory assessment of potential for destructive charging fields and arcing events within the sail and surrounding environment.

Smart Adaptive Structures

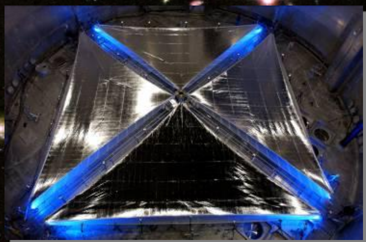
Identified nonlinear mechanism for existing 40 meter coilable boom. Assess potential for control structures interactions.



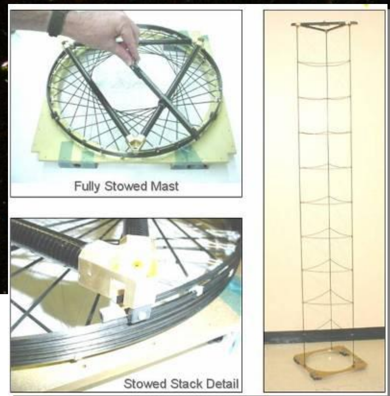
Mounted SAFE Mast Canister System

TRL Assessment Process Flowchart

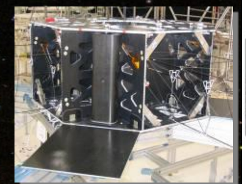
TRL Assessment Methodology



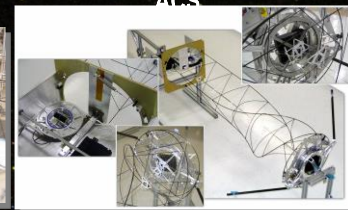
ATK 20M System



Central Structure



ACS



System	Subsystems	Components
ATK 20M Quadrant	Sails	Materials & Coating
		Deployment Sequencers
		Grounding Straps
		Compliant Border
	Masts	Battens
		Longerons
		Diagonals
		Corner Group
		Halyards
		Lanyards
		Deployment Motors
	ACS	Translating Masses
		Motors/ Control Mechansms
		Spreader Bars
		Mast Tip Mechanism
		Control Wiring
		Software
	Central Structure	Carrier Assembly
		Doors & Actuators
		S/C Interface
		Sail Drum

ACS

Central Structure

Sails

Masts/Beams

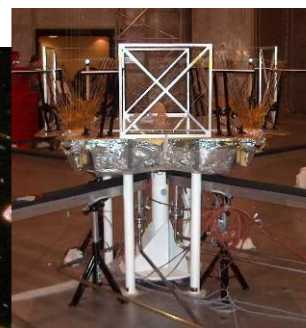
Identify Solar Sail Major Subsystems

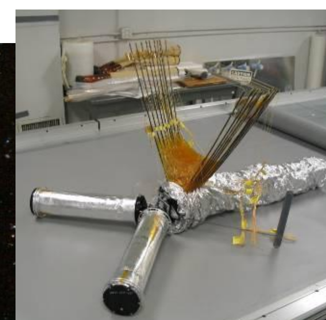
ATK

L'Garde

→ Identify Subsystem Components → Assess Component/ Subsystem TRL (3-5) → Assess System TRL (6)

L'Garde 20M System





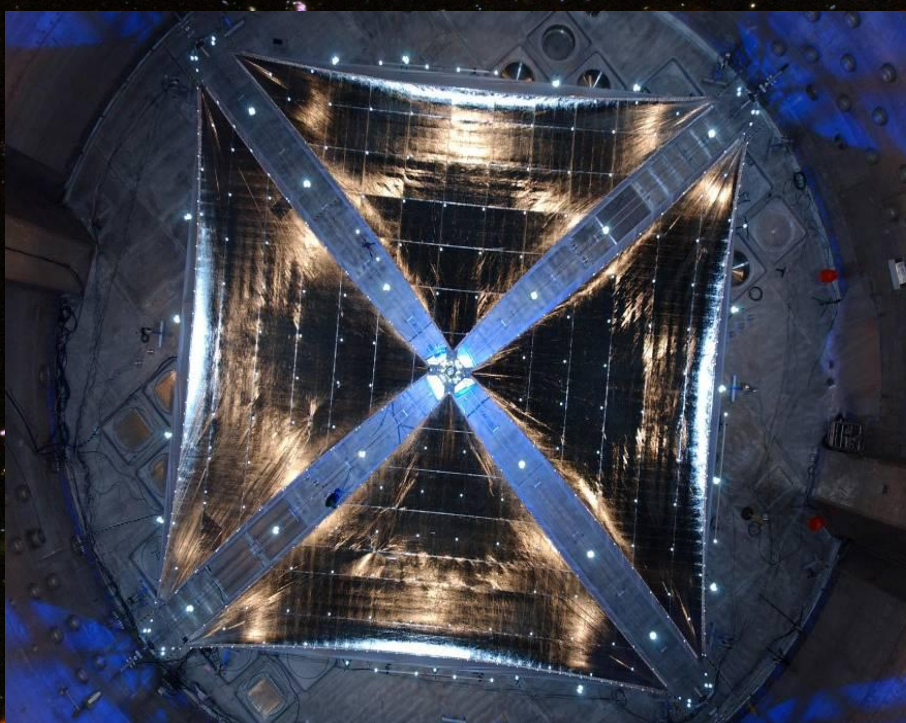
ACS

Sails

System	Subsystems	Components
L'Garde 20M System	Sails	Materials & Coatings
		Integrated Ripstop
		Grounding Straps
		Stripped Net
	Beams	Boom & Rigidization System
		Inflation Subsystem
		Heater Wires
		Insulation
		End Caps
		Spreader System & Rings
		Cat's Cradle
	ACS	Tip Vanes
		Vane Cant Mechanism
		Vane Rotation Mechanism
		Control Wiring
		Software
	Central Structure	Carrier Assembly
		Doors & Actuators
		S/C Interface

TRL Assessment Results Comparison

Vendor	Post 10M TRL 5 Completion Average	Post 20M TRL 5 Completion Average	Post 10M TRL 6 Completion Average	Post 20M TRL 6 Completion Average
ATK	76%	89%	60%	86%
L'Garde	75%	84%	68%	78%

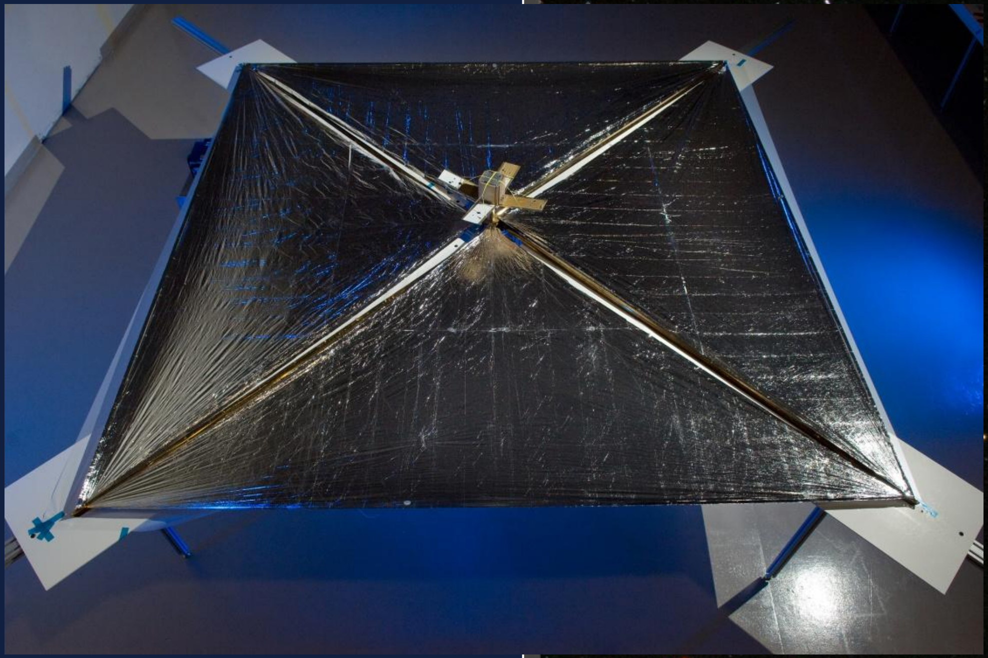


ATK

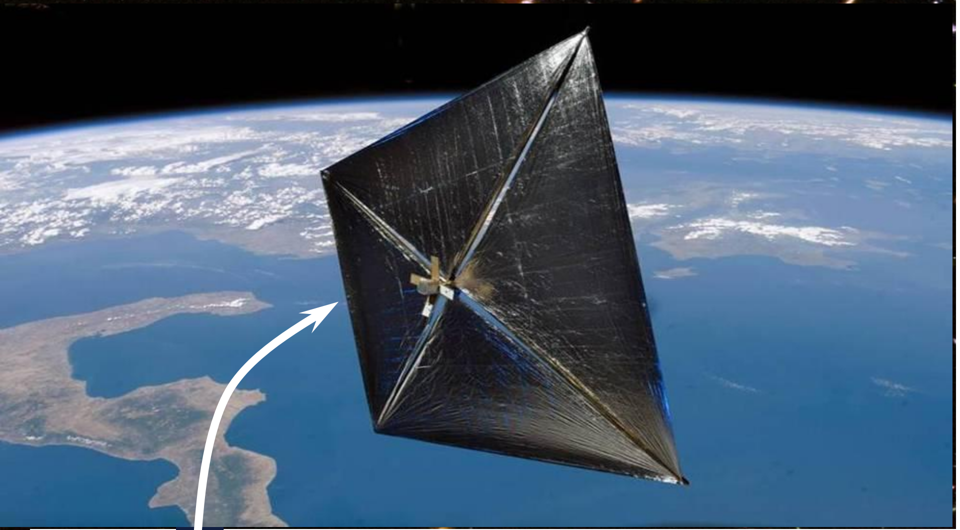
L'Garde

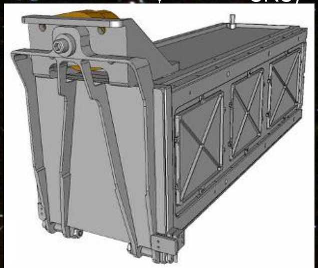
NanoSail-D Demonstration Solar Sail

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

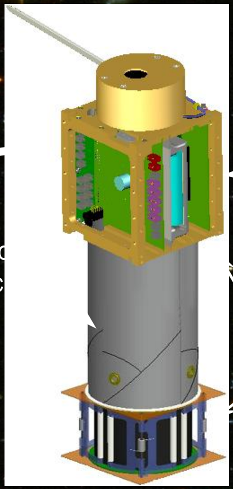


NanoSail-D Mission Configuration





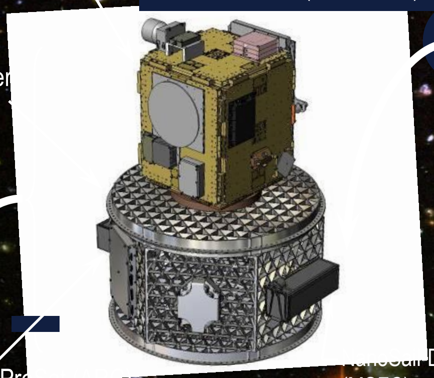
PPOD Deployer
(Cal-Poly)



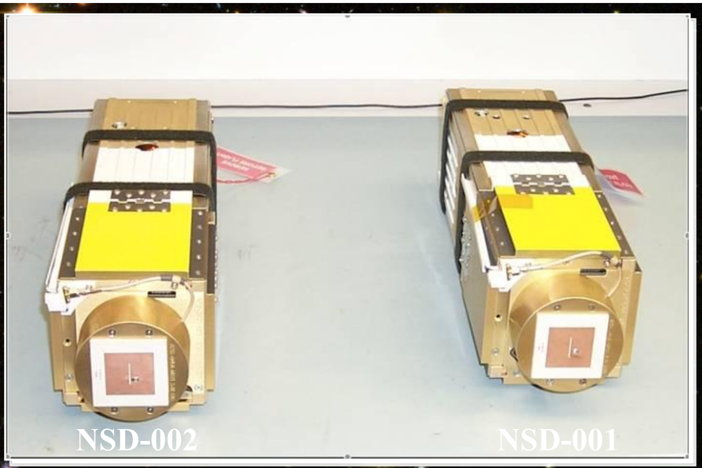
NanoSail-D
(Aluminum Closeout Panels Not Shown)

Stowed Configuration

SpaceX Falcon-1

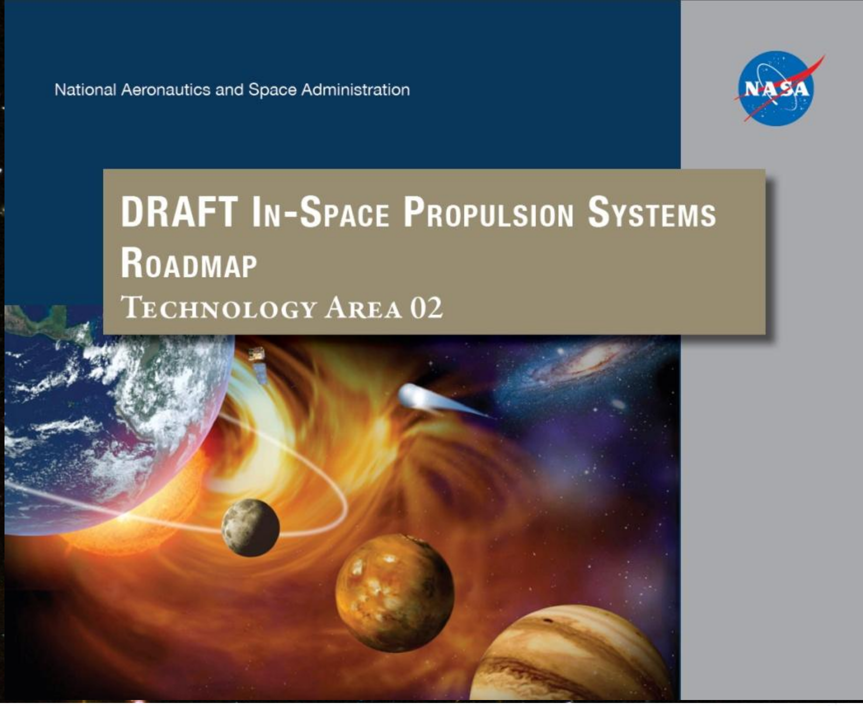


Ride Share Adapter
(Space Access Technology)



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

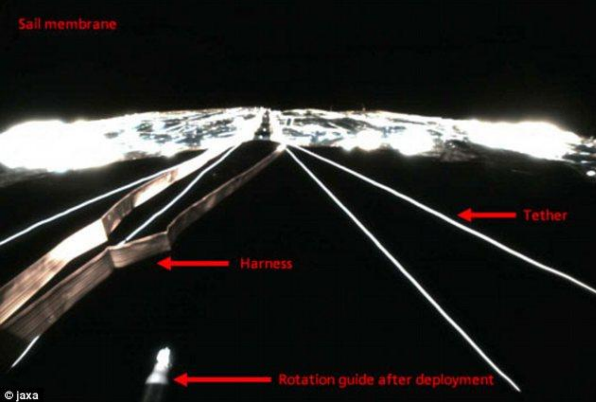
Solar Sail Propulsion is a Near-Term Priority NASA Technology



Rank	Description	
1	Power Processing Units (PPUs) for ion, Hall, and other electric propulsion systems	N
2	Long-term in-space cryogenic propellant storage and transfer	M
3	High power (e.g. 50–300 kW) class Solar Electric Propulsion scalable to MW class Nuclear Electric Propulsion	M
4	Advanced in-space cryogenic engines and supporting components	M
5	Developing and demonstrating MEMS-fabricated electrospray thrusters	N
6	Demonstrating large (over 1000 m^2) solar sail equipped vehicle in space	N
7	Nuclear Thermal Propulsion (NTP) components and systems	F
8	Advanced space storable propellants	M
9	Long-life (>1 year) electrodynamic tether propulsion system in LEO	N
10	Advanced In-Space Propulsion Technologies (TRL <3) to enable a robust technology portfolio for future missions.	F

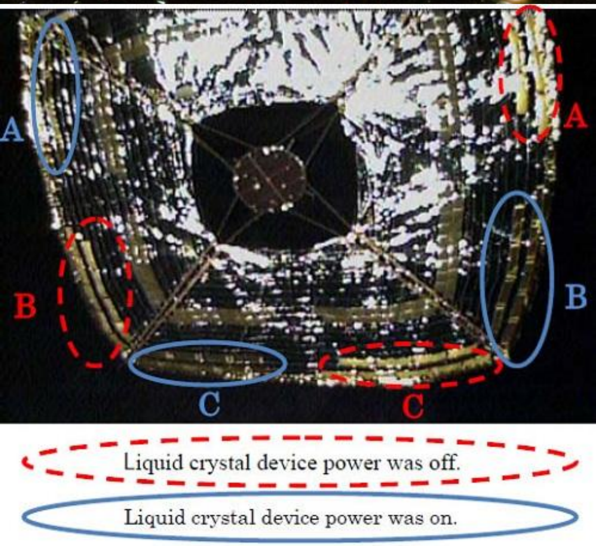
* From NASA Office of Chief Technologist Draft In-Space Propulsion Systems Roadmap Technology Area 02

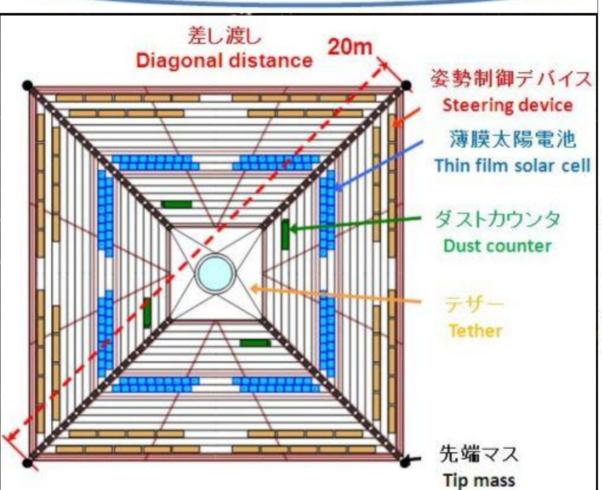
Interplanetary Kite-craft Accelerated by Radiation Of the Sun (IKAROS)

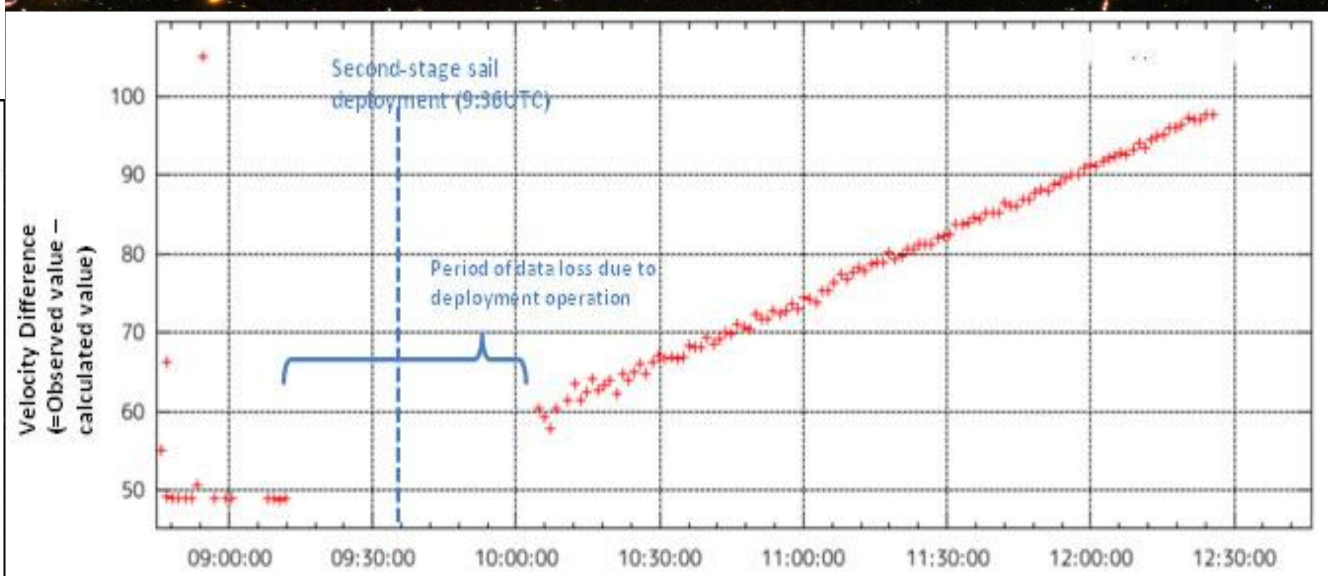


- IKAROS was launched on May 21, 2010
- The Japan Aerospace Exploration Agency (JAXA) began to deploy the solar sail on June 3.
- IKAROS has demonstrated deployment of a solar sailcraft, acceleration by photon pressure and attitude control
    - Deployment was by centrifugal force
    - Sail membrane is 7.5 mm thick

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



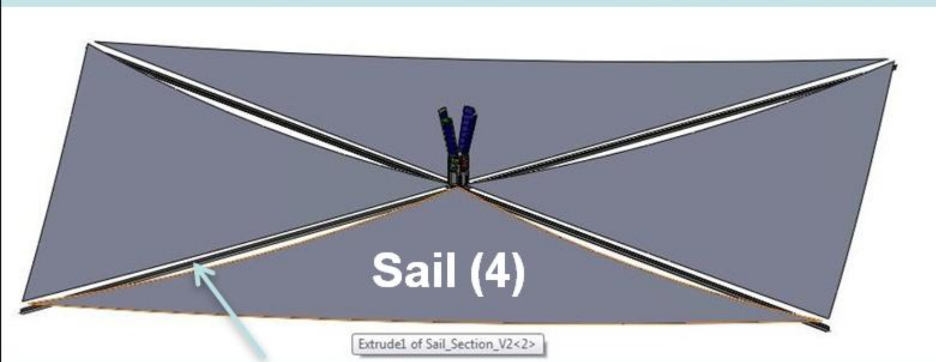




LightSail-1 (The Planetary Society) Status

- **Cubesat design**
  - 4.5 kg
  - Two 2-megapixel cameras
  - Four sun sensors
  - Six accelerometers for measuring solar acceleration
- **Sail Material: aluminized 4.5 micron Mylar film**
- **32 square meters solar sail area fully deployed**
- **2011 planned launch**

The LightSail-1 Spacecraft



Trac Booms (4)

Sun Sensor (4)

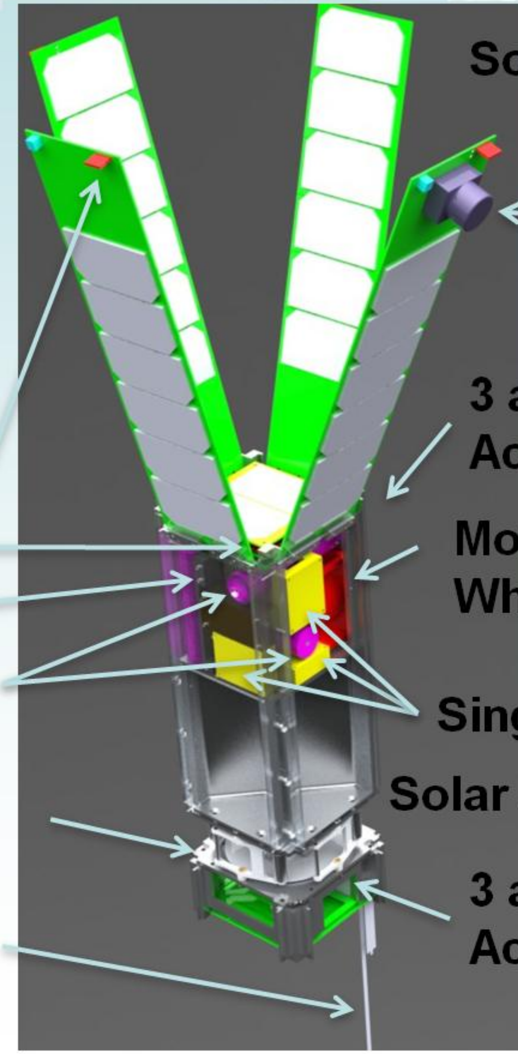
Avionics Package
- C&DH Board
- Power Regulation
- Transceiver
- Payload interface Board

Battery

Torque Rod (3)

Sail Deployment Mechanism

Whip Antenna



Solar Panels (10)

Cameras (2)

3 axis Accelerometer (2)

Momentum Wheel

Single Axis Gyro (3)

Solar Sail Storage (4)

3 axis Accelerometer (2)

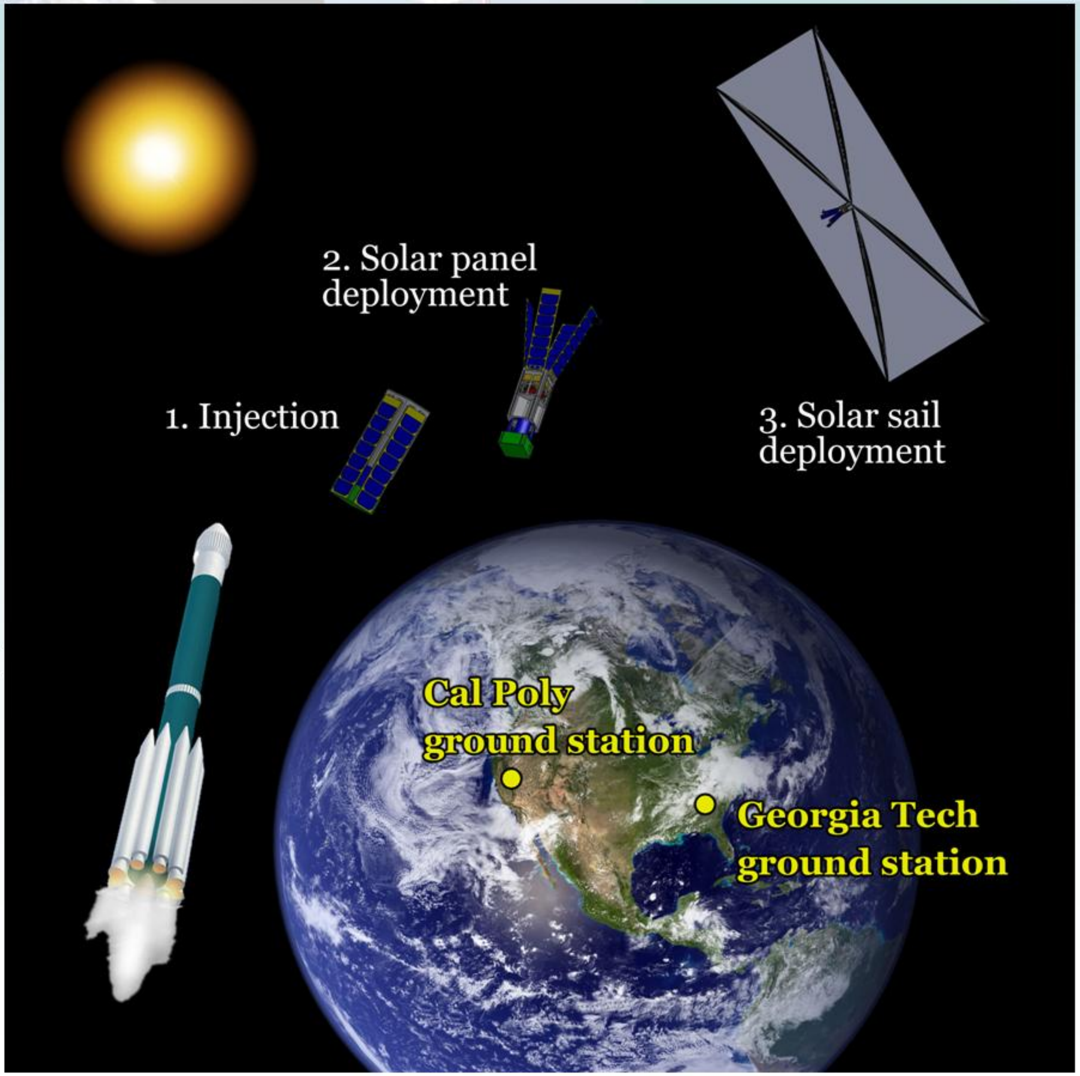
LightSail-1
Concept of Operations

Drift away from primary vehicle, eject from PPOD, deploy whip antenna, 3 axis stabilization. Solar panel deployment followed by Solar Sail (Sail deployment video stored for downlink)

Sun Synchronous Orbit 824 km, inclined 98°

Delta 7920-10

Secondary launch with NPP (June 2011) Vandenberg AFB



Sail uses sun energy to gain orbit energy (up to 4.29×10^{-5} m/s^2 when "on"). 3 - 4 week mission life.

9.6 Kbps 437 MHz downlink FSK. Acceleration data and 2 camera images/day

Command and Control from Cal Poly and Ga. Tech and other ground stations as appropriate

Amateur Optical trackers to provide position data

Solar Sail Technology Status

- **JAXA has taken solar sail propulsion to TRL-7**
- **NASA's large first generation solar sails are a mature technology ready for flight validation and subsequent mission implementation**
  - Unless space validation is initiated soon, the TRL will begin to slip
  - Based on 2006 ST-9 studies, a validation mission can be flown for under $200M
- **Cubesat scale sails are a mature technology for selected applications**