Solar Sailing

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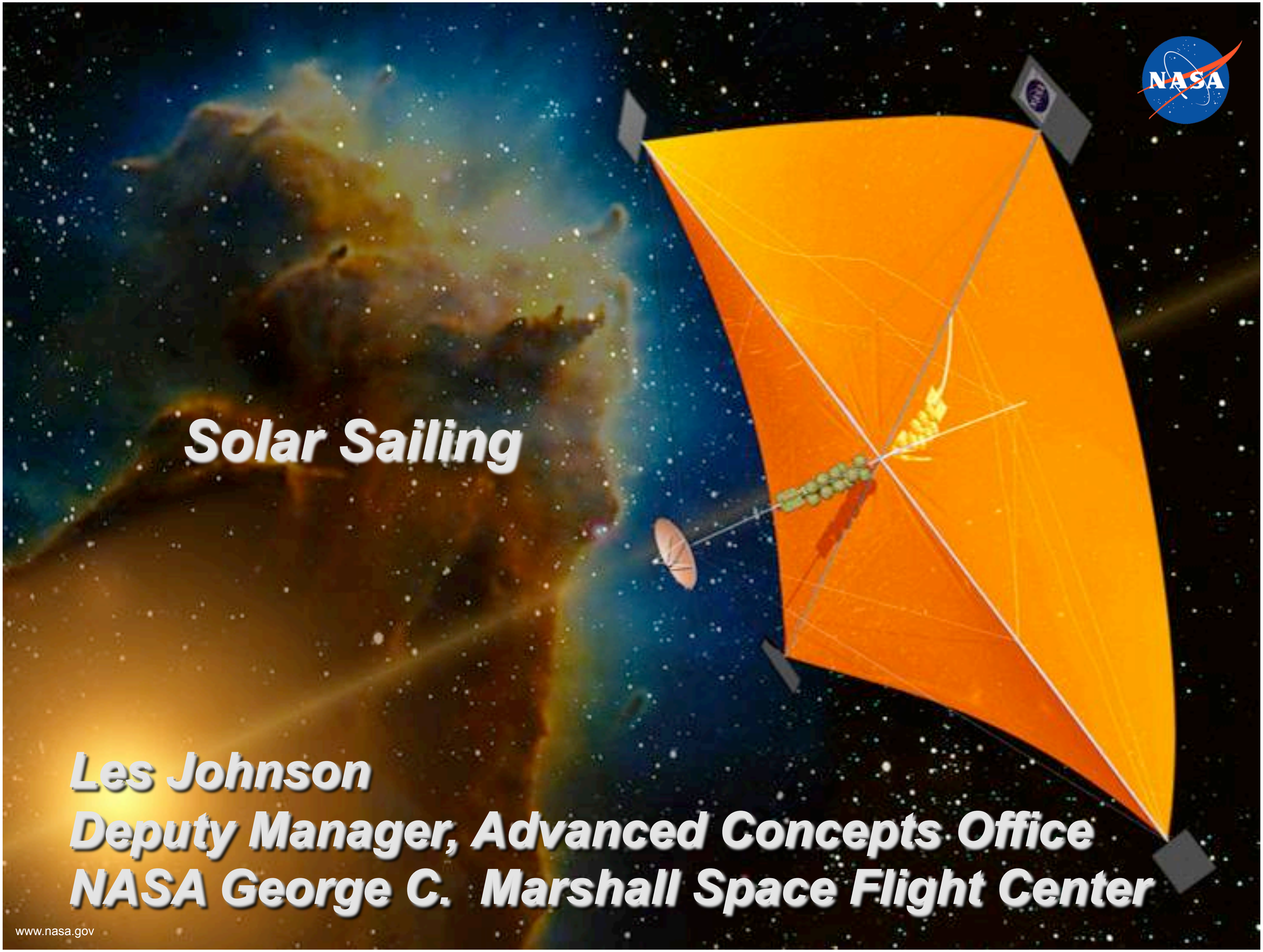
Solar sailing is a topic of growing technical and popular interest. Solar sail propulsion will make space exploration more affordable and offer access to destinations within (and beyond) the solar system that are currently beyond our technical reach. The lecture will describe solar sails, how they work, and what they will be used for in the exploration of space. It will include a discussion of current plans for solar sails and how advanced technology, such as nanotechnology, might enhance their performance. Much has been accomplished recently to make solar sail technology very close to becoming an engineering reality and it will soon be used by the world's space agencies in the exploration of the solar system and beyond.

The first part of the lecture will summarize state-of-the-art space propulsion systems and technologies. Though these other technologies are the key to any deep space exploration by humans, robots, or both, solar-sail propulsion will make space exploration more affordable and offer access to distant and difficult destinations.

The second part of the lecture will describe the fundamentals of space solar sail propulsion and will describe the near-, mid- and far-term missions that might use solar sails as a propulsion system.

The third part of the lecture will describe solar sail technology and the construction of current and future sailcraft, including the work of both government and private space organizations.



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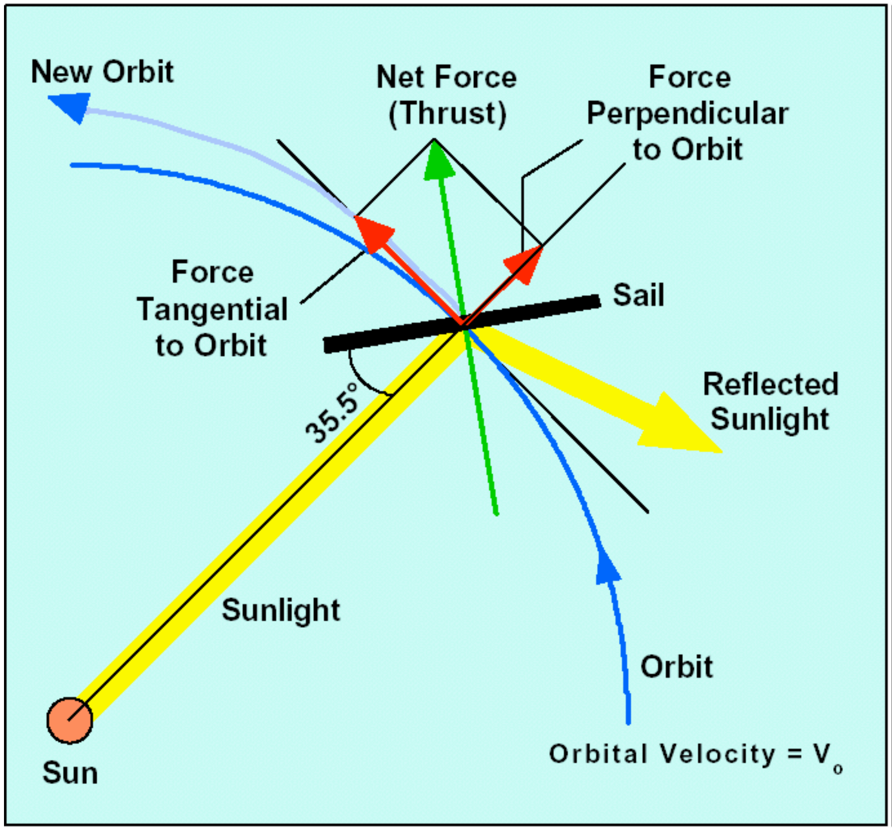
Acknowledgement

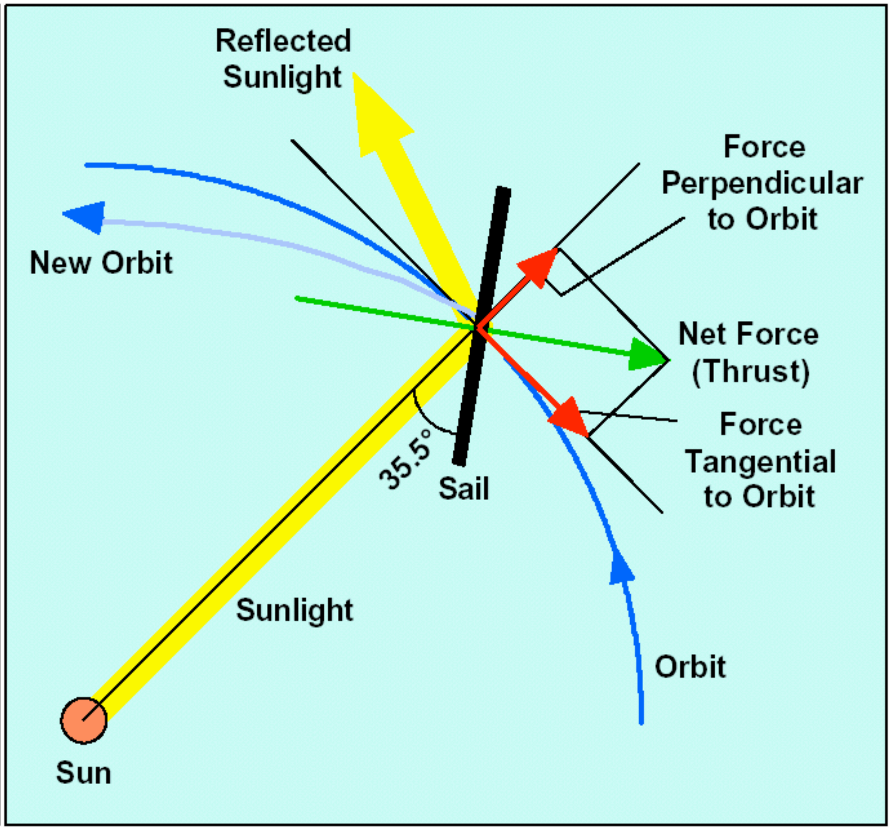
This work was funded in whole or in part by the In-Space Propulsion Technology Program, which is managed by NASA's Science Mission Directorate in Washington, D.C.

The program objective is to develop in-space propulsion technologies that can enable or benefit near and mid-term NASA space science missions by significantly reducing cost, mass, or travel times.

SOLAR SAIL Propulsion Fundamentals

- Solar sails use photon "pressure" of force on thin, lightweight reflective sheet to produce thrust; ideal reflection of sunlight from surface produces 9 Newtons/km^2 at 1 AU
- Net force on solar sail perpendicular to surface
- One component of force always directed radially outward
- Other component of force tangential to orbit (add/subtract V_o) [<0.2 oz per football field]



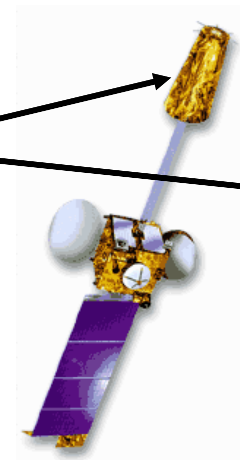


Solar Sail Technology History

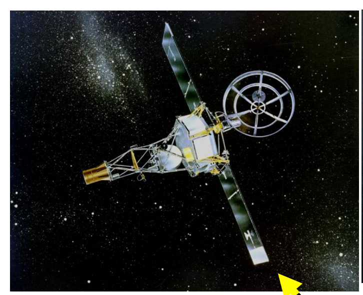
Used Since 1962

- 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
- Japanese
  - developing 50 meter sail to combine with an ion thruster for outer planet missions
  - Have flown sounding rocket, balloon, and LEO Polar orbit development experiments
- 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.

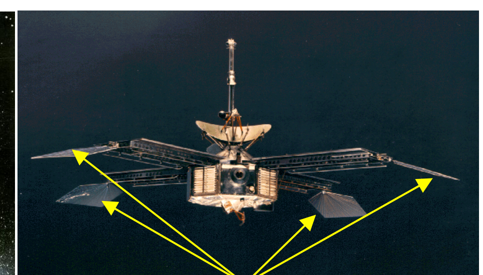
Mariner 10: "the solar sailing technique for conservation of attitude control gas was improvised successfully and thereby qualified as a technique for use in future missions." – Bruce Murray, Flight to Mercury, Columbia University Press 1977, page 142.



[Stowed Sail] (1991



Mariner 2 Dacron Solar Sail (1962)



solar sails on Mariner IV (1964)

Solar Sail Technology Classes

Mission Class	Timeline	SOA	Technology Challenges	Potential NASA Mission Applications
GEO/GTO Short Life	Past/Now	Encounter(?), Cosmos, ST-7, Znamya, Inflatable Antenna Exp	AO, radiation belts effects, high GG torques	None
1 Au	**Near Term**	**ISP Ground Demo, ST-5 Geostorm**	**Validation in a space environment, Infusion into mission applications**	**L1 Diamond** **Solar Polar Imager (SPI)** **Heliostorm**
<0.25 Au	Mid-Term	Conceptual	Materials environments, Thrust vector range, Lightweight system, 100s m system scale size	Particle Acceleration Solar Observatory (PASO) Titan Explorer Saturn Ring Observer
Extra Solar	Far-Term	Conceptual	Ultra-lightweight system Integrated system architecture Sub to kilometer system scale size	Interstellar Probe (ISP) Geospace System Response Imagers (GSRI) Outer Heliosphere Radio Imager (OHRI)

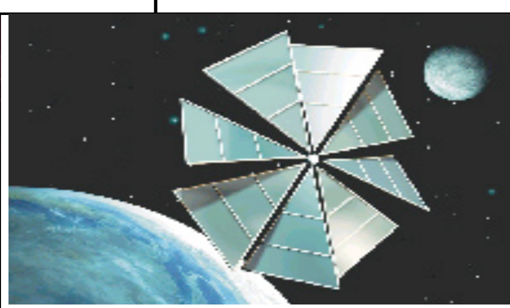
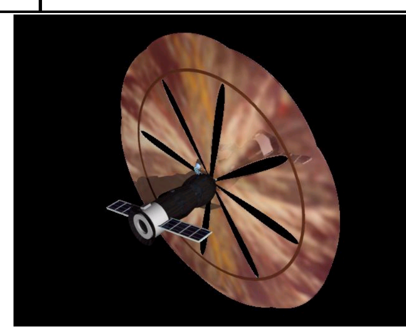
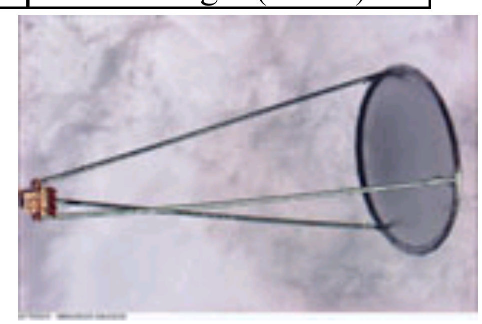
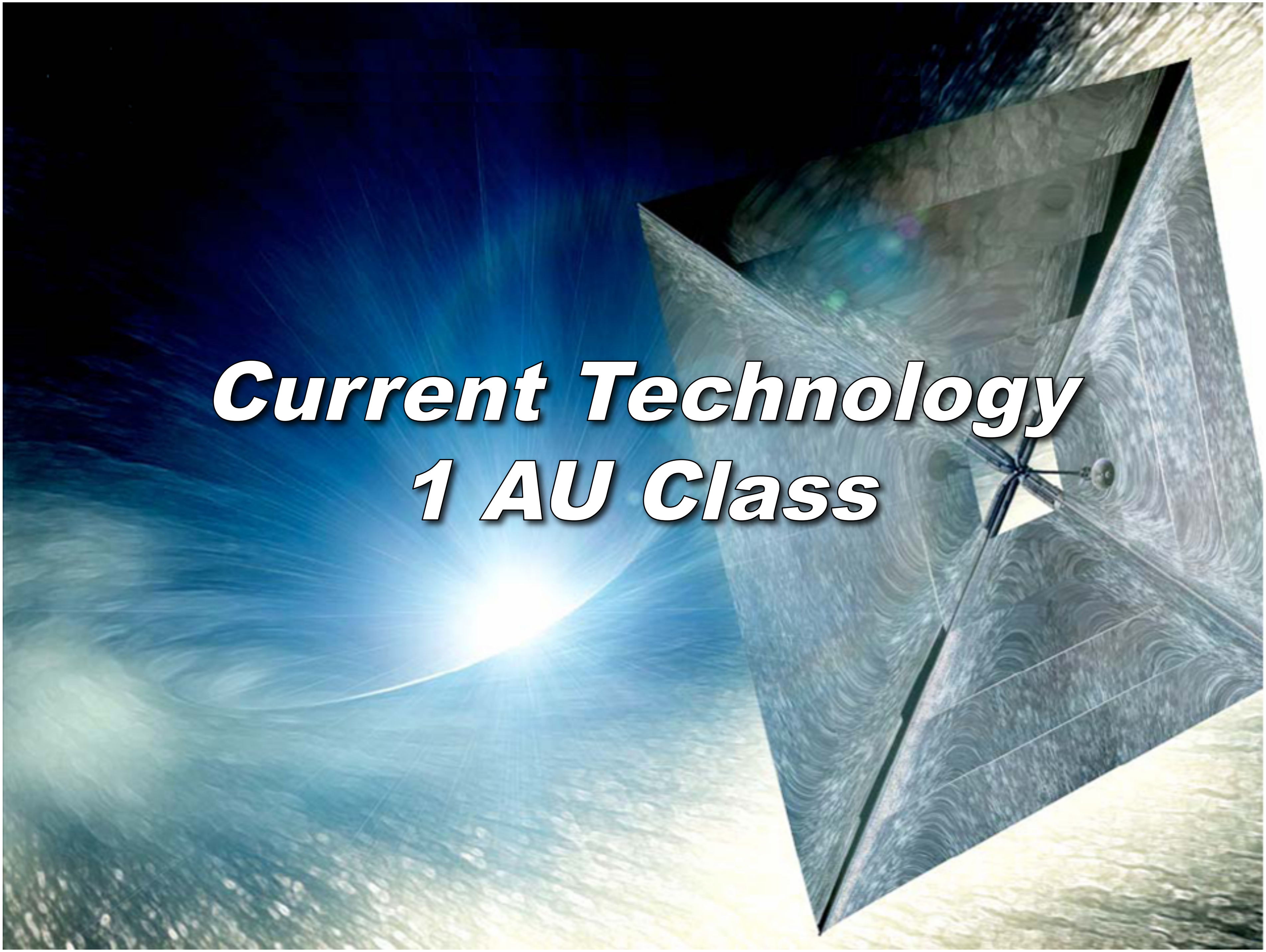
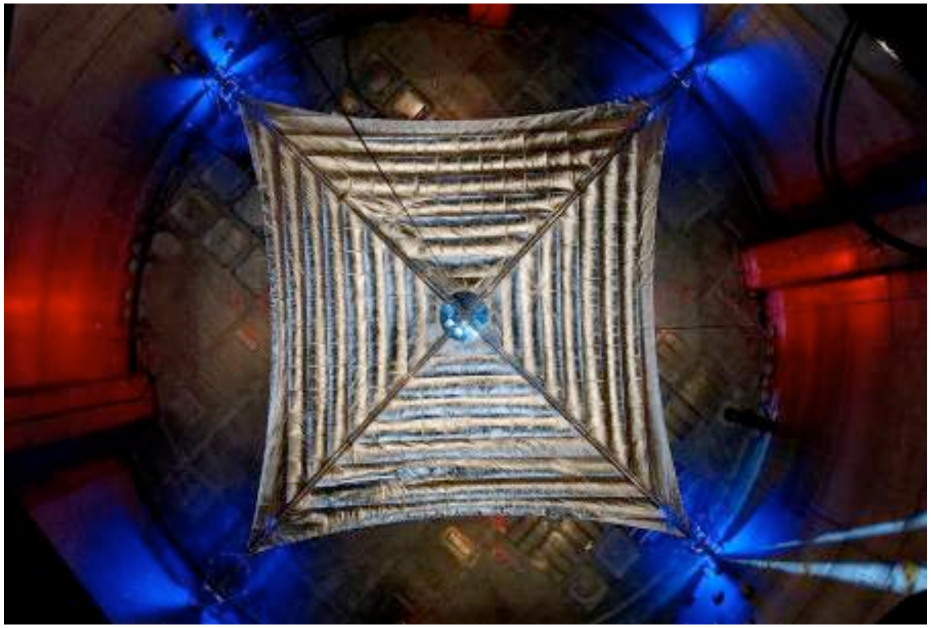
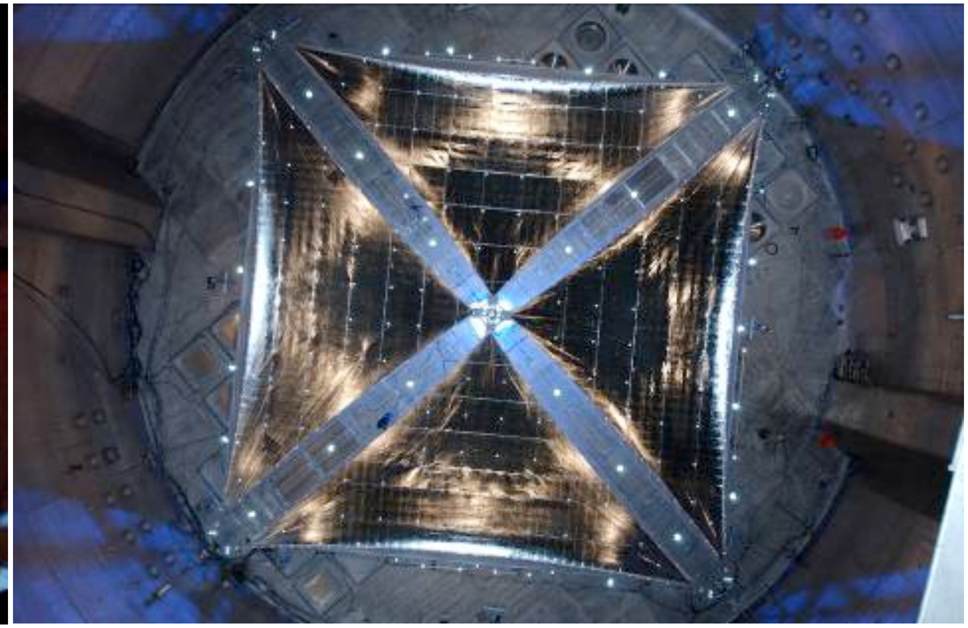


Photo courtesy of The Planetary Society




Current Technology
1 AU Class

Solar Sail Propulsion Technology Status





- **Technology Area Status:**
  - **Two competing teams designed, fabricated, and tested solar sails and performed system level ground demonstrations:**
    - **10 m system ground demonstrators were developed and tested in 2004.**
    - **20 m system ground demonstrators designed, fabricated, and tested under thermal vacuum conditions in 2005.**
  - **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.**

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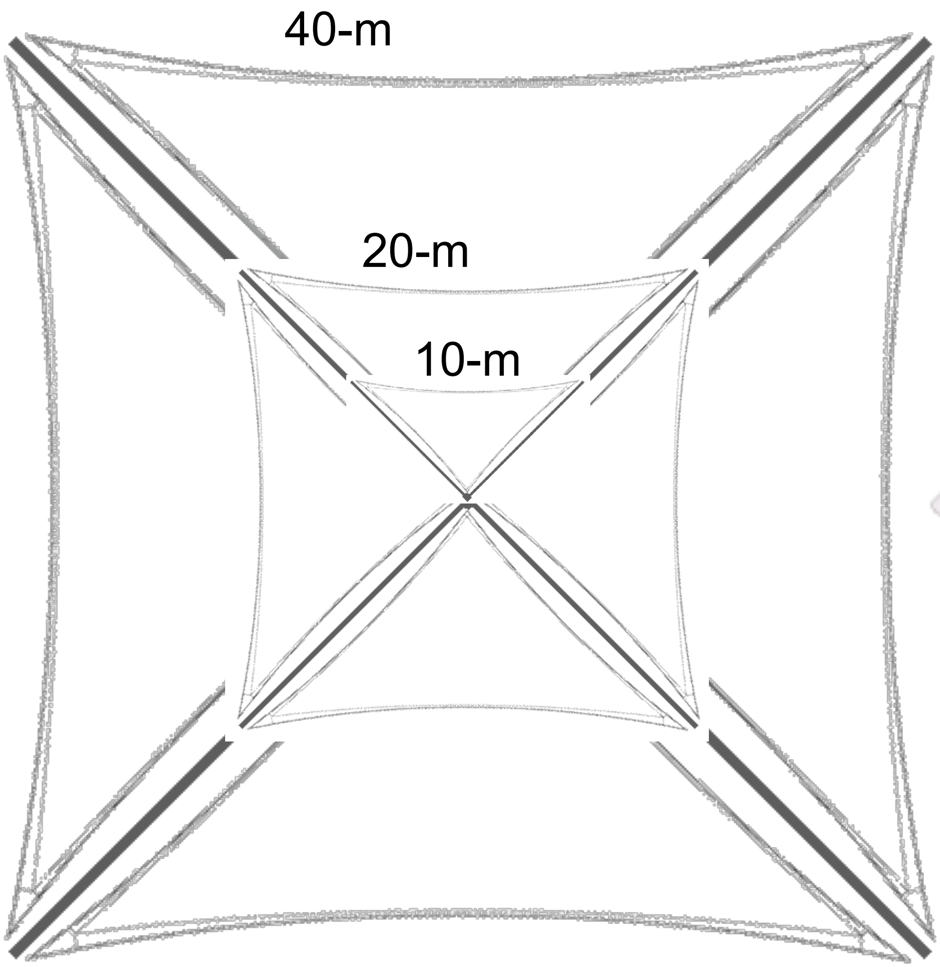
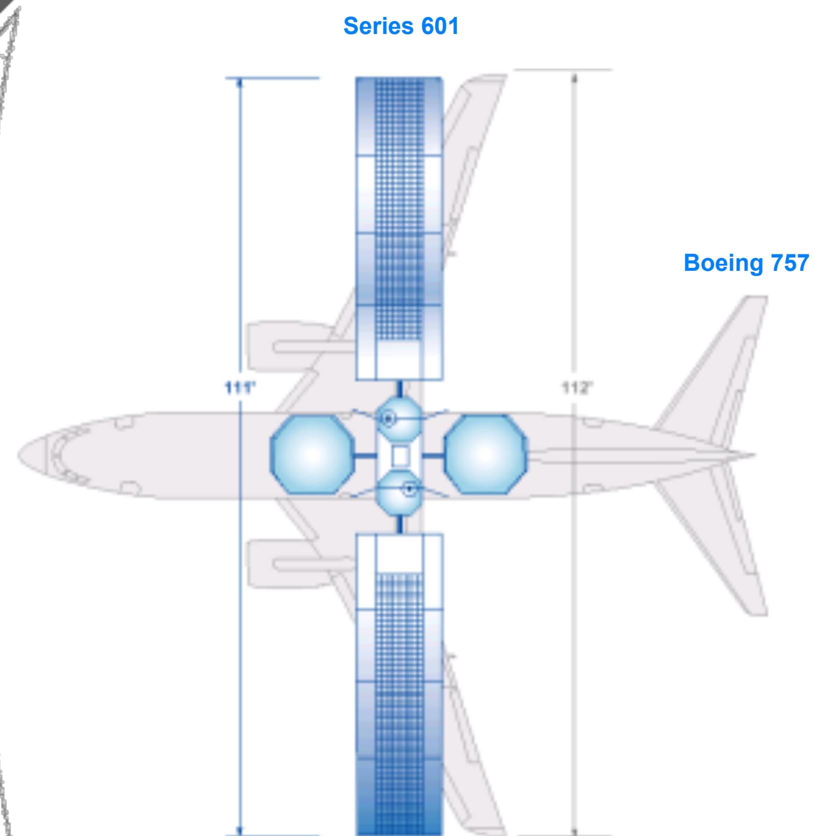
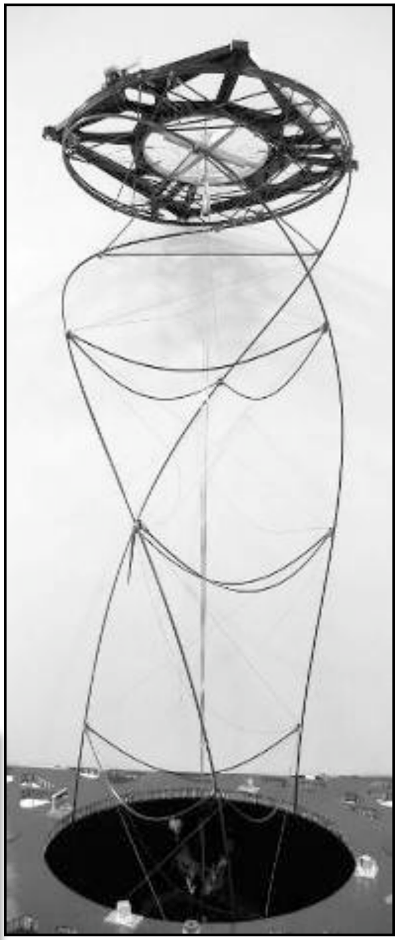
10, 20, and 40-m Solar Sail Systems

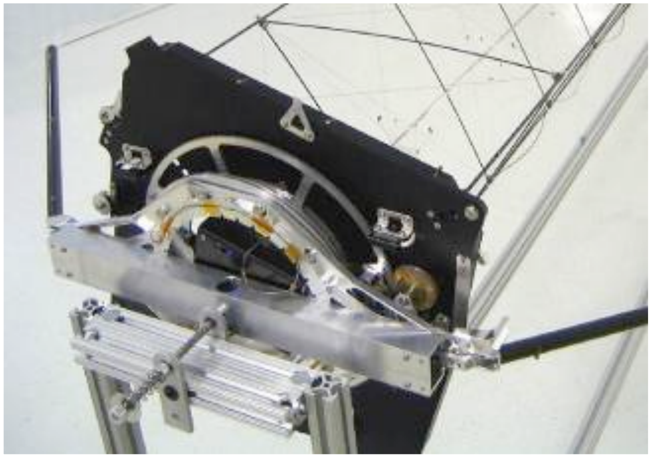




ATK Solar Sail Development

- PI: David Murphy, ATK Space Systems
- Technical Team:
  - ATK (Goleta, CA) systems engineering & coilable booms
  - SRS Technologies (Huntsville, AL): Sail manufacture & assembly
  - LaRC (Hampton, VA) Sail Modeling & Testing
  - MSFC (Huntsville, AL) Materials Testing
- Overall Strategy
  - Leveraged ST 7 Phase A Design
    - Improve performance with Ultra-Light Graphite Coilable booms
      - Synergy with SailMast Testbed selected to fly on ST8
    - 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





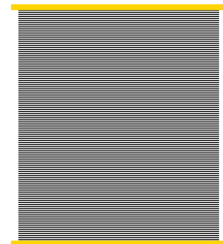
ATK Solar Sail Development, Continued

- 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 acceleration
  - 0.76 mm/s^2
  - 0.34 mm/s^2 with 130 kg SC

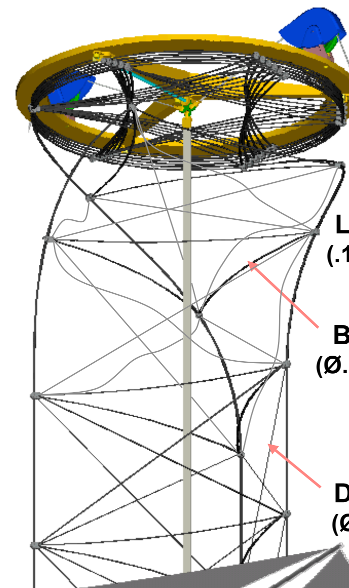
Stowed CoilABLE

Ø20-in. (50.5 cm)

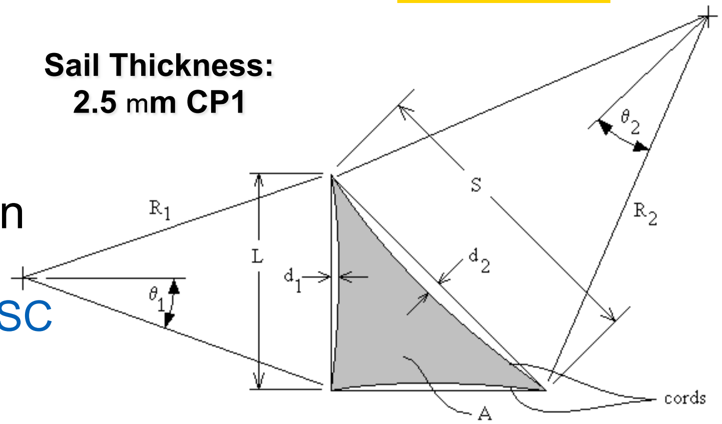
18.7-in.-tall (<0.55% of length)

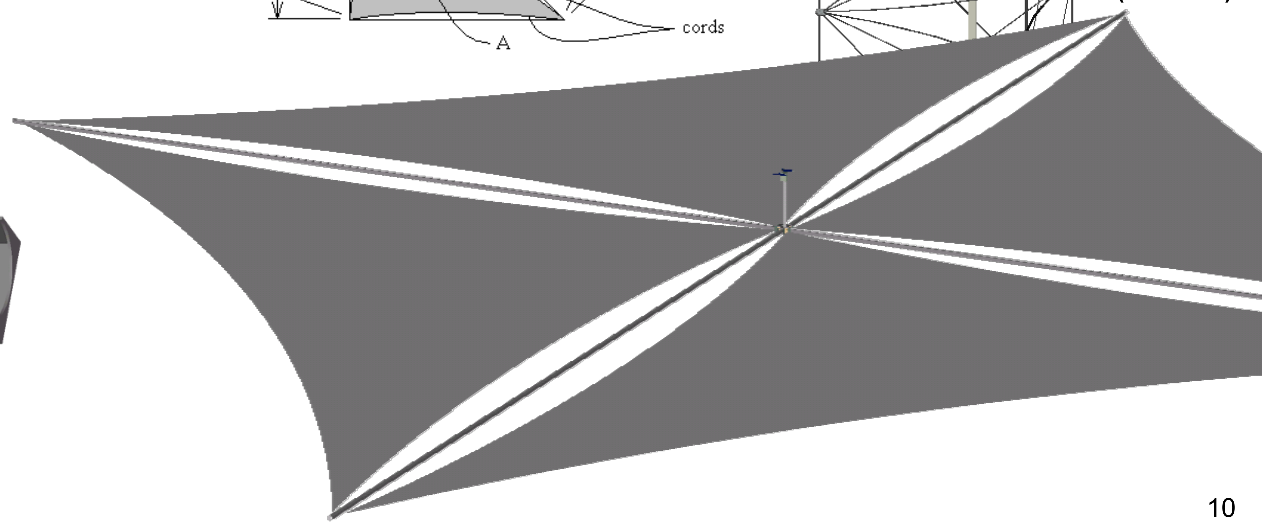


CoilABLE Mast Linear Mass: ~ 70 g/m

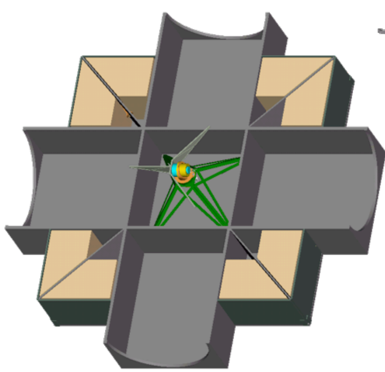


Sail Thickness: 2.5 mm CP1



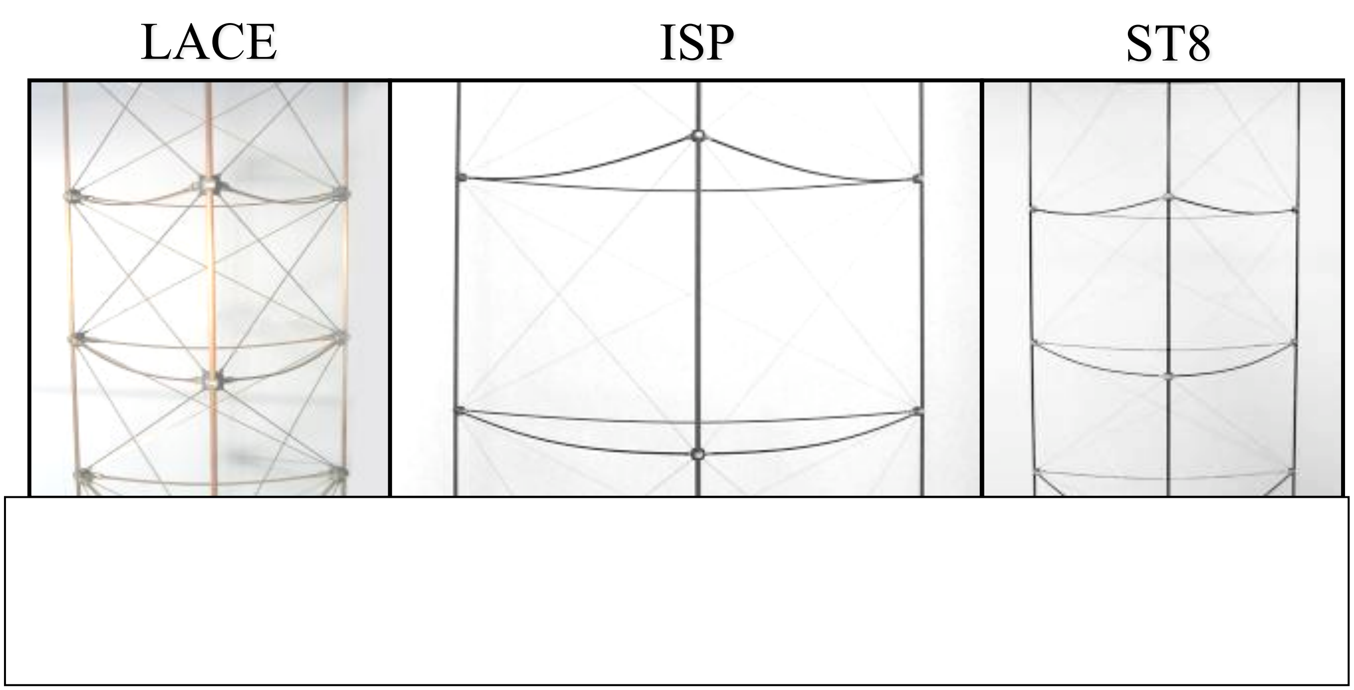


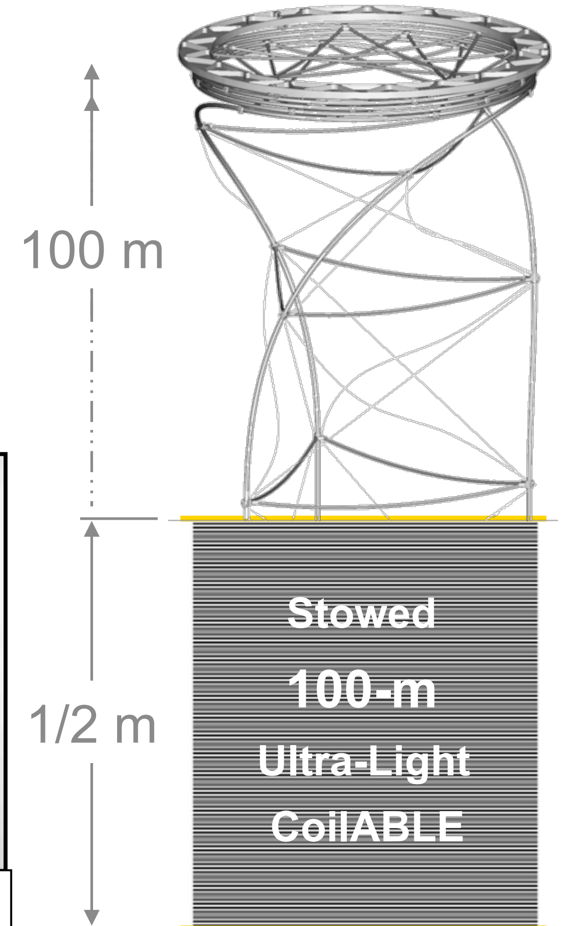
Cut-Away of Stowed Package



CoilAble Mast Heritage

- **Able Engineering Company Established in 1975 (now ATK Space Systems)**
  - 30 CoilAble systems have 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**





SRS 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

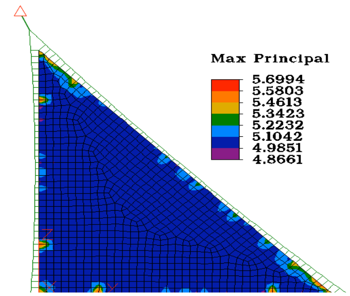
Sail Material: *CP1 Polyimide*

- 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***

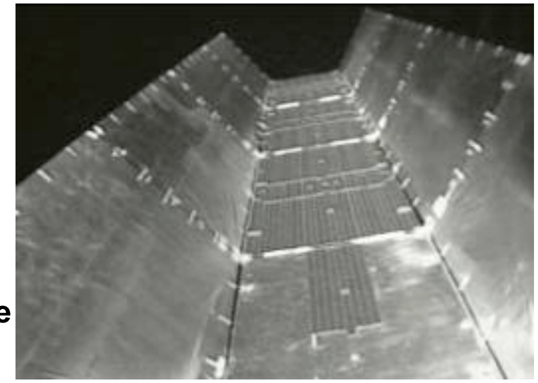
Sail Construction Methods:

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

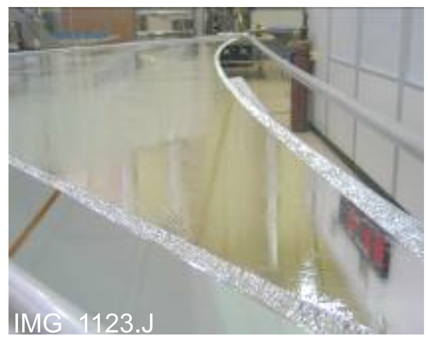
- Scalable Construction Methods --- current system >20m
- Adhesive less Bonding Methods --- eliminates sticking and contamination risks.



FEM of Parobolic Edge

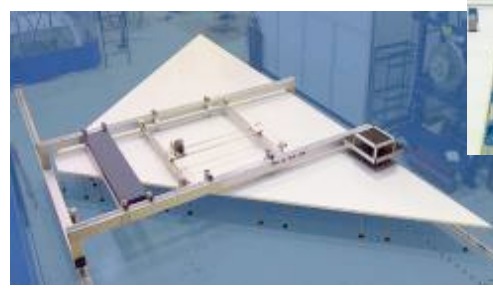


160 m^2 of film per satellite. Film Is 1 mil material supported by 5 mil edge designs



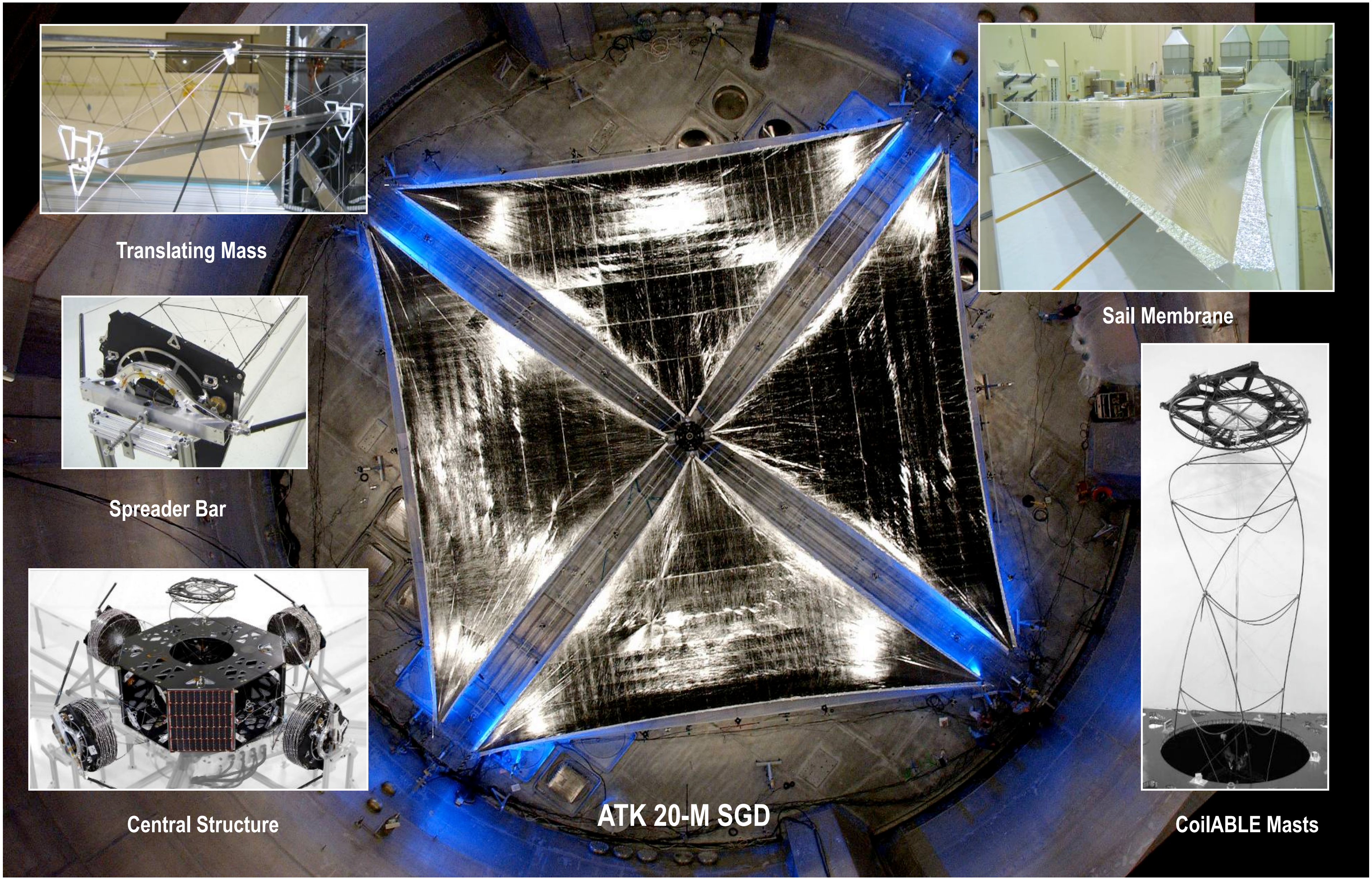
Sail with Compliant Border

Sail Production



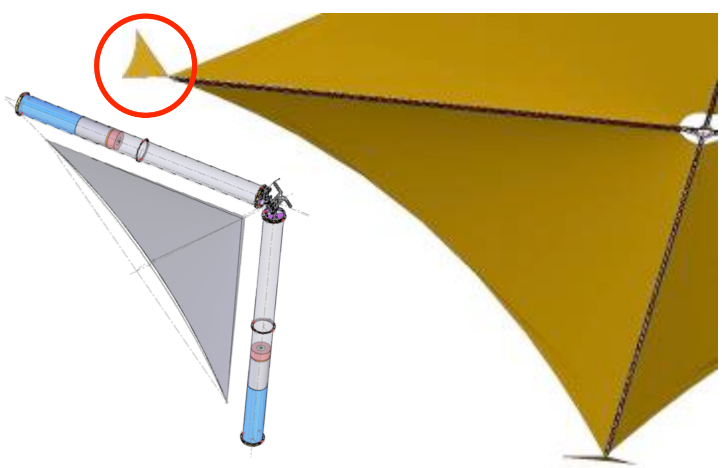
SRS CNC Seaming System

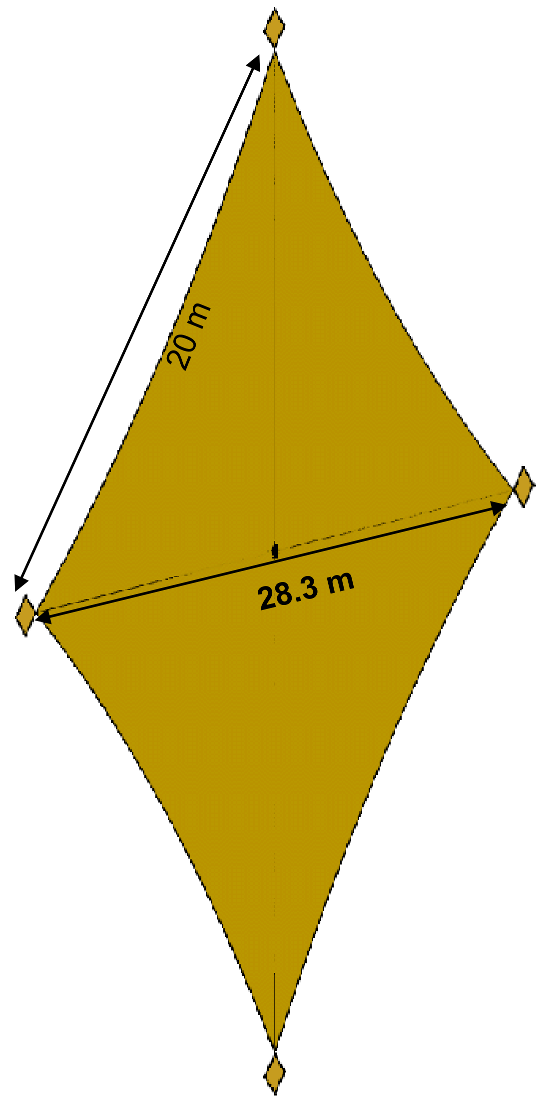
ATK 20-m System Ground Demonstrator



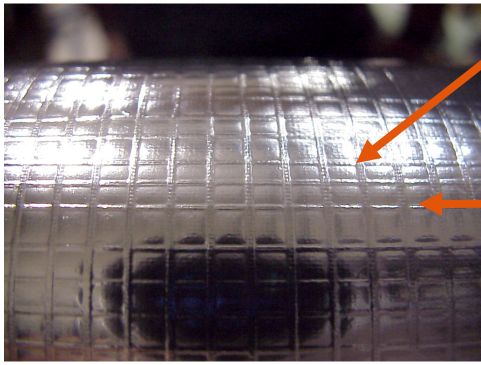
L'Garde Solar Sail Development

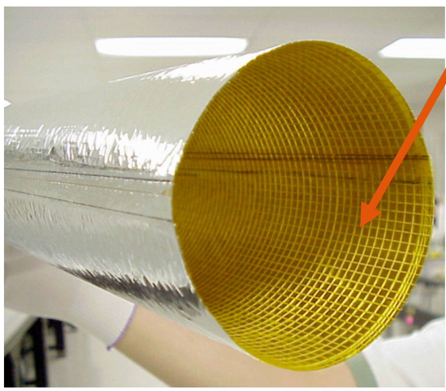
- PI: David (Leo) Lichodziejewski, L'Garde, Inc.
- Technical Team:
  - L'Garde, Inc. (Tustin, CA) systems engineering and inflatable truss
  - Ball Aerospace & Tech Corp. (Boulder, CO) mission eng. & bus design
  - LaRC (Hampton, VA) sail modeling & testing
  - JPL (Pasadena, CA) mission planning & space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





Beam Characteristics



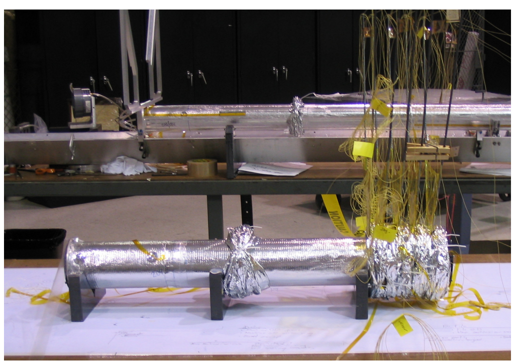


Load bearing longitudinal uni-directional fibers
- Fibers impregnated with resin (rigid below -20^{o} C)
- 0.48 AU design requires greater fiber density to withstand loads from the increased solar flux

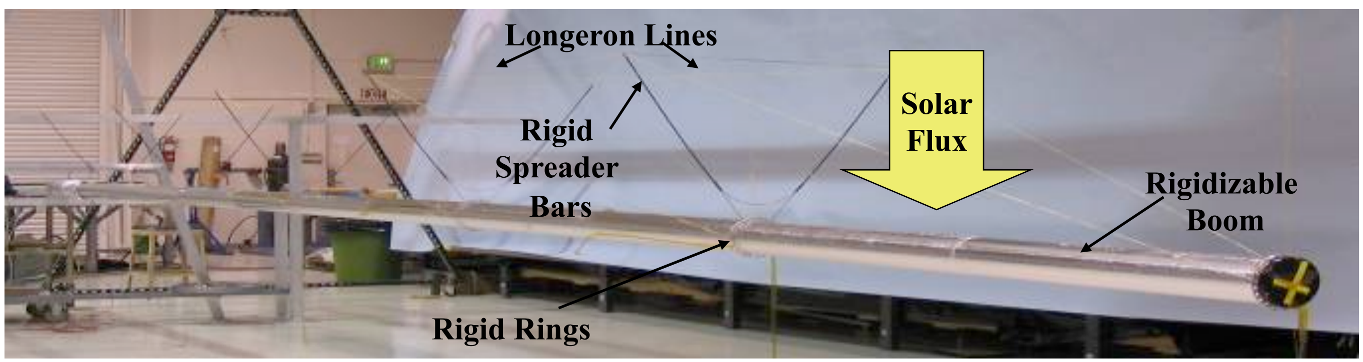
Spiral wrap
- Stabilizes longitudinal fibers
- Allows over-pressurization for deployment anomalies

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

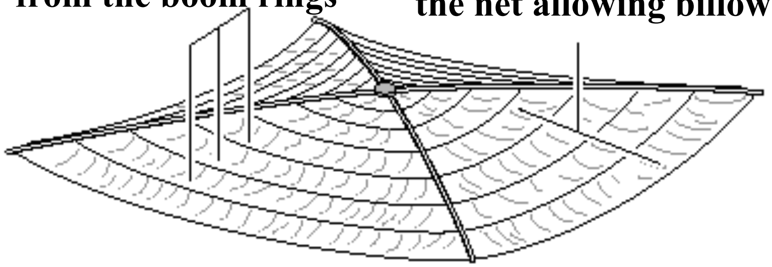


Stowed 7 m boom (~.5 m)



Deployed 7 m boom

Net/Membrane Sail



Net/Membrane Sail Schematic

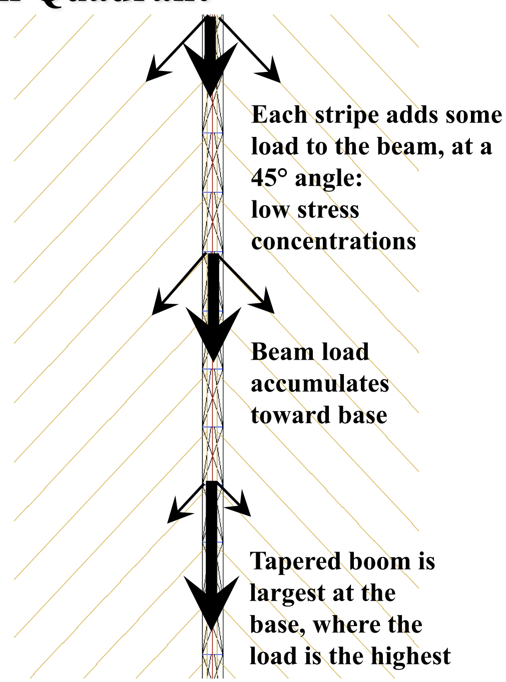
20m Sail Quadrant

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

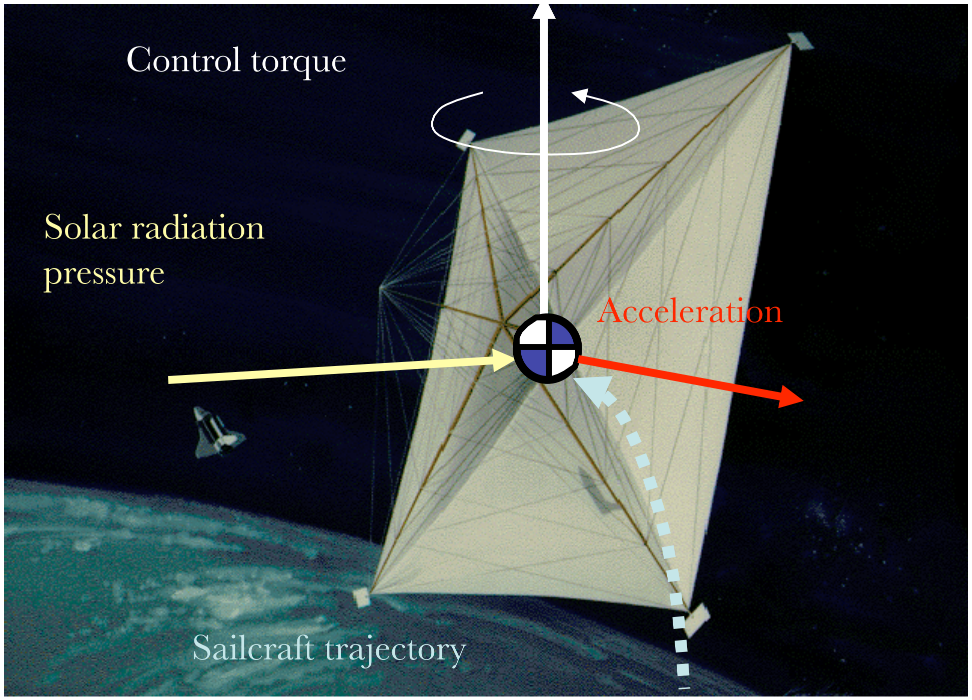
Advantages

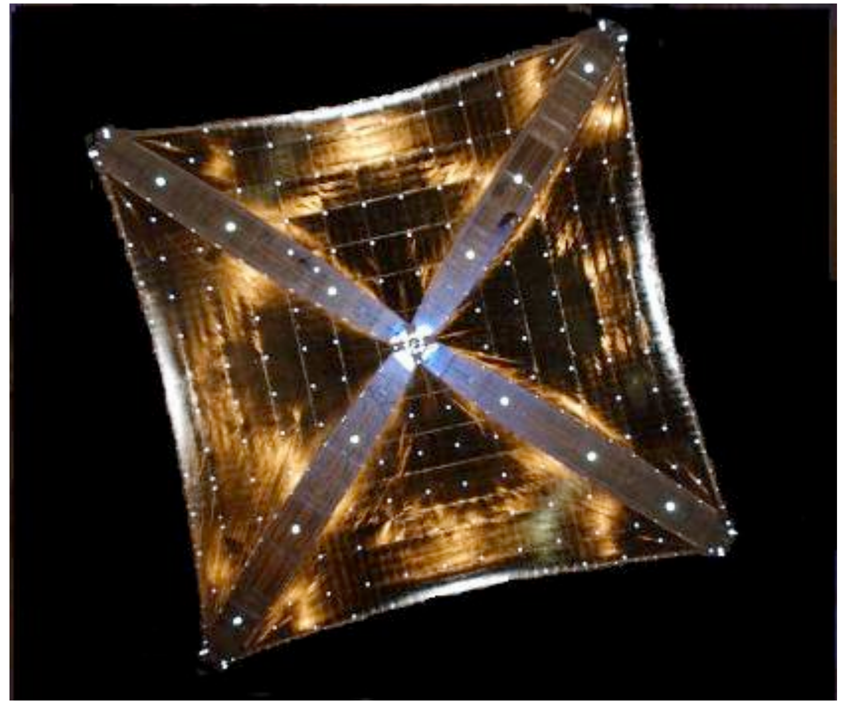
- Net defines the overall sail shape, not the membrane
- Stability and geometry of the sail is effectively decoupled from membrane properties
- Sail shape, and hence thrust vector, sailcraft stability and performance, are predictable and stable
- No high local stress concentrations in the sail, loads 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 (SGD)

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)

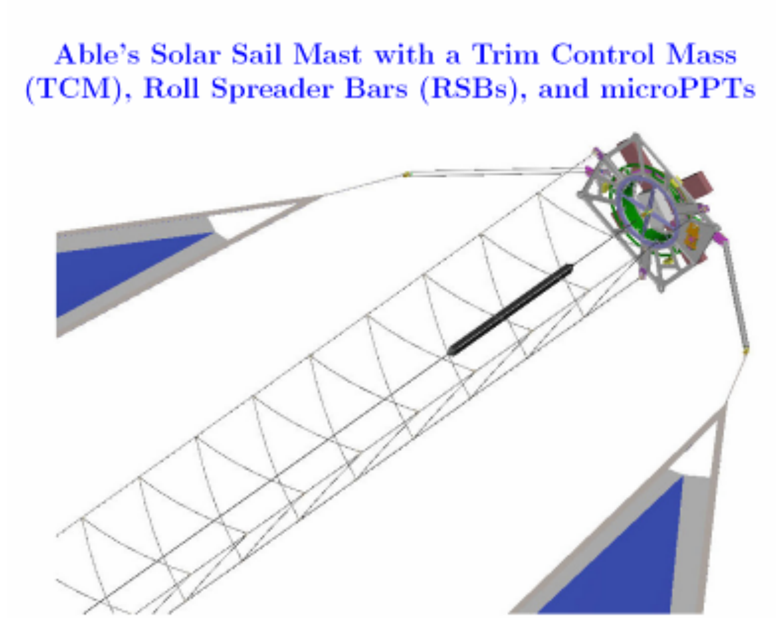
Developed a lightweight integrated instrumentation package to allow measurement of sail shape, tension and temperature; boom & sail vibration modes and stress; and deployment monitoring.

Solar Sail Subsystem Development– cont.

Samples prior to UV exposure

Material Testing

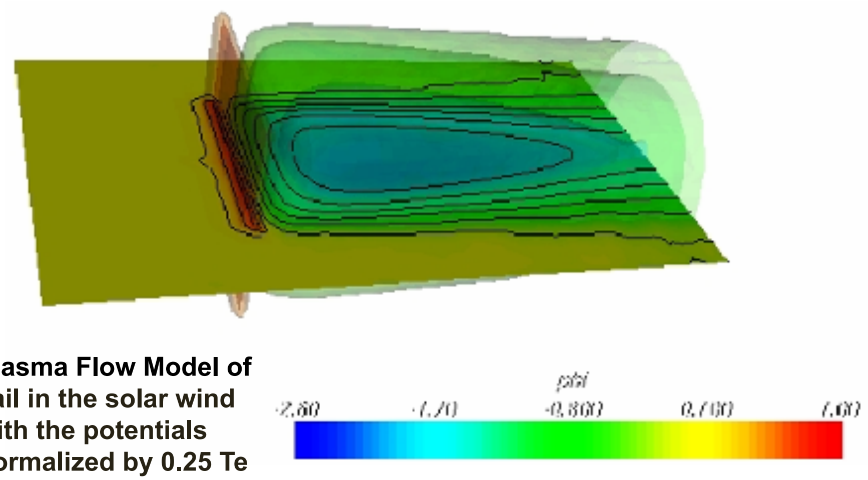
Characterized engineering performance of candidate SS materials at .5 and 1 AU, gauging material property tolerances after exposure to simulated mission-specific charged-particle and micrometeoroid environments.



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.



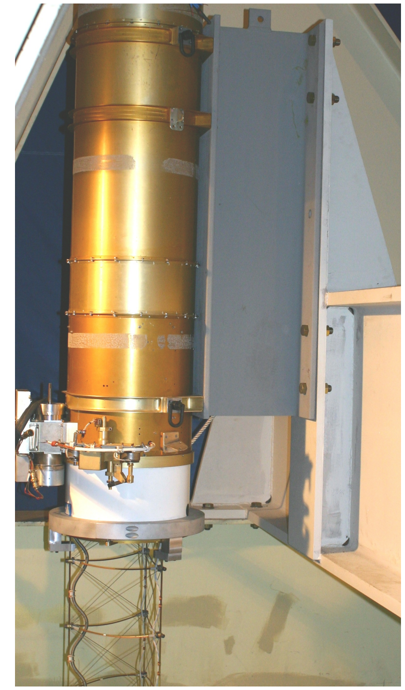
Plasma Flow Model of sail in the solar wind with the potentials normalized by 0.25 Te

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

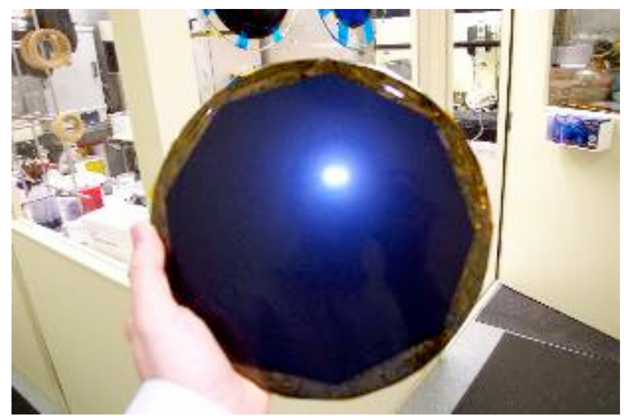
Identified nonlinear mechanism for existing 40 meter coilable boom. Assess potential for control structures interactions.



Mounted SAFE Mast Canister System

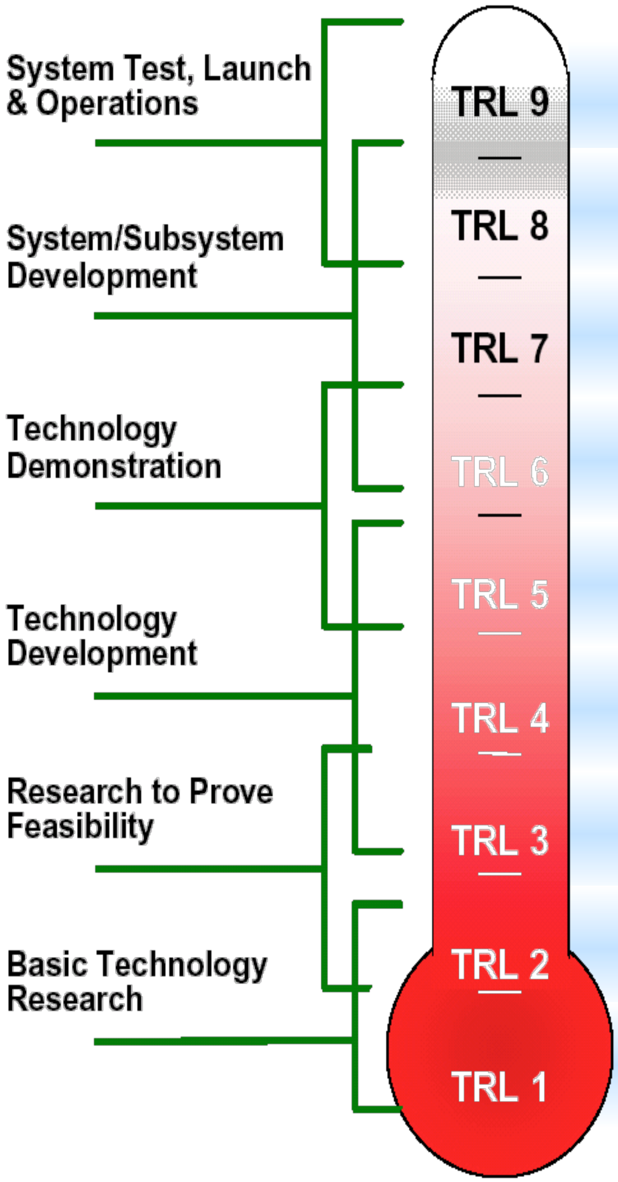
Advanced Manufacturing Technologies

Developed and refine the technology of sail assembly for manufacturing large monolithic sails, improving membrane coating processes and technologies



Sail sample with carbon black nanotubes

Technology Readiness Level (TRL)



Actual system "flight proven" through successful mission operations

Actual system completed and "flight qualified" through test and demonstration (Ground or Flight)

System prototype demonstration in a space environment

System/subsystem model or prototype demonstration in a relevant environment (Ground or Space)

Component and/or breadboard validation in relevant environment

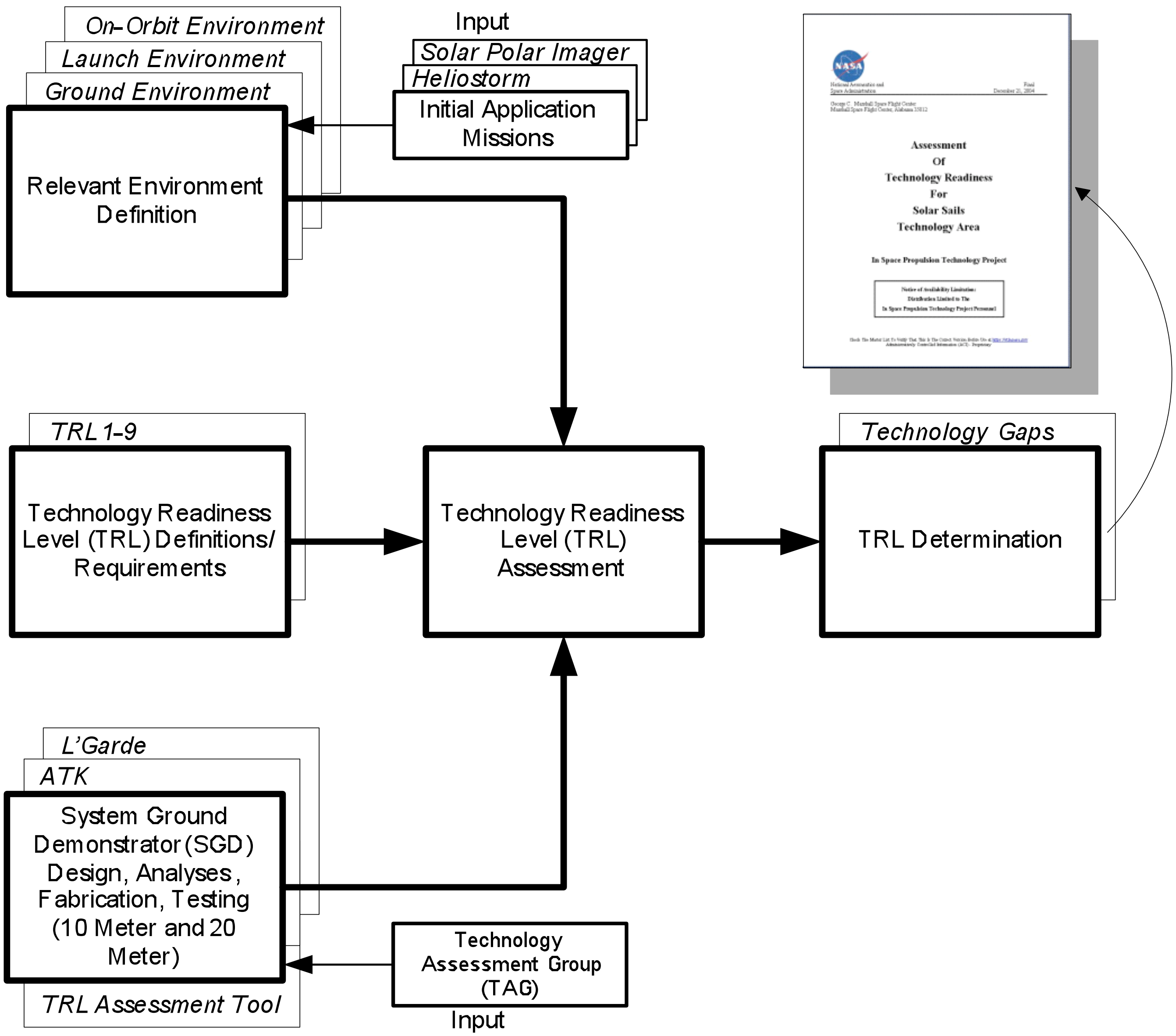
Component and/or breadboard validation in laboratory environment

Analytical and experimental critical function and/or characteristic proof-of-concept

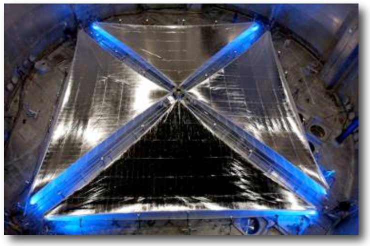
Technology concept and/or application formulated

Basic principles observed and reported

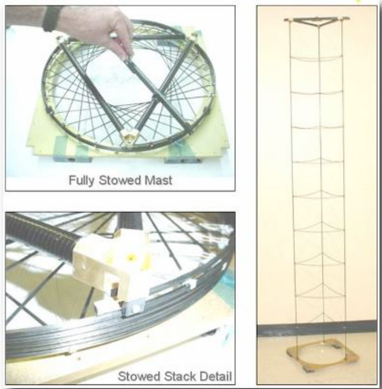
TRL Assessment Process Flowchart



TRL Assessment Methodology

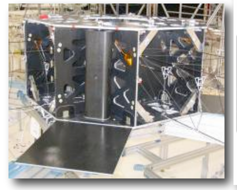


ATK 20M System

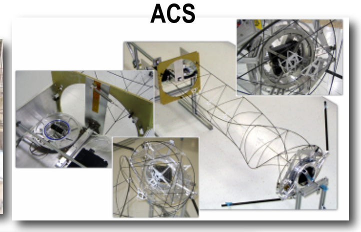


Masts

Central Structure



ACS



Sails

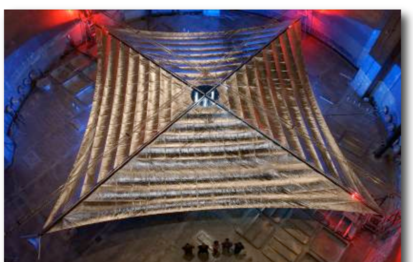
System	Subsystems	Components
ATK 20M Quadrant	Sails	Materials & Coating
		Deployment Sequencers
		Grounding Straps
		Compliant Border
	Masts	Battens
		Longerons
		Diagonals
		Corner Group
		Halyards
		Lanyards
		Deployment Motors
	ACS	Translating Masses
		Motors/ Control Mechansms
		Spreader Bars
		Mast 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

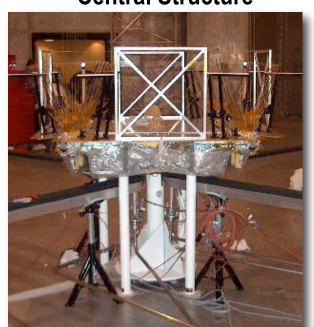
→ Identify Subsystem Components → Assess Component/ Subsystem TRL (3-5) → Assess System TRL (6)



L'Garde 20M System

Beams

Central Structure



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

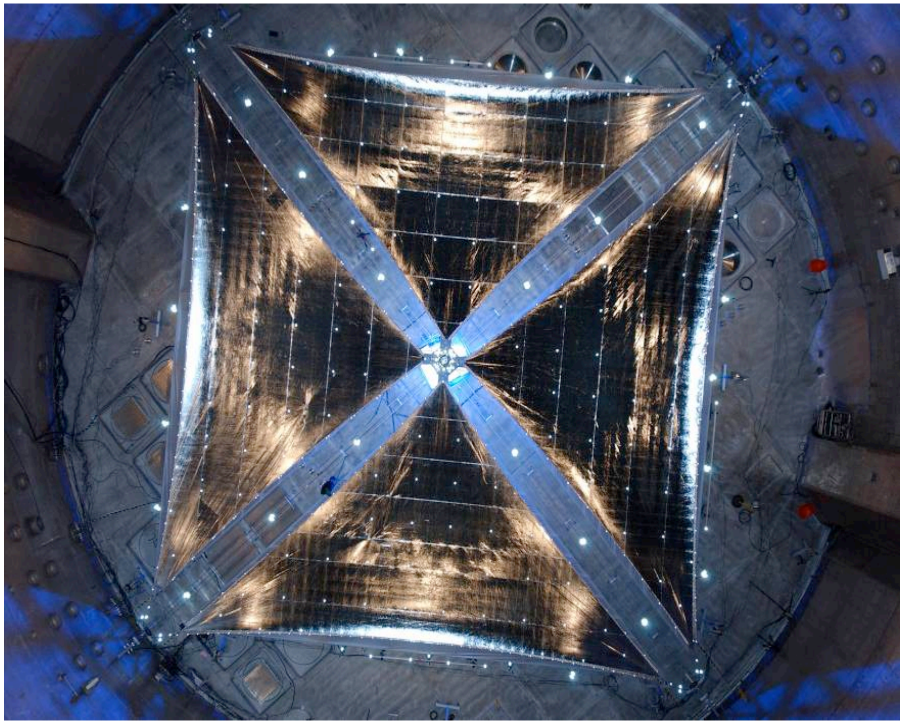
TRL 3-5 Assessment Worksheet (Example)

L'GARDE **10m MAST** TRL ASSESSMENT

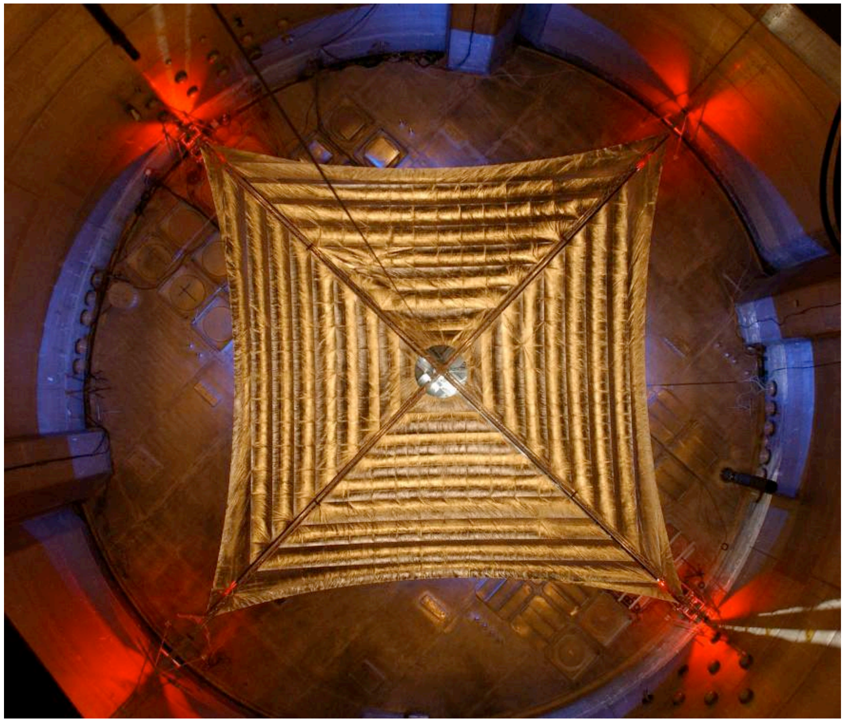
TRL LEVEL	COMMENTS	CONDITIONS	BOOM & RIGIDIZATION SYSTEM	INFLATION SUBSYSTEM	HEATER WIRES	INSULATION	END CAPS	SPREADER SYSTEM & RINGS	CATS CRADLE	TOTAL % Complete	NOTES
TRL 3: Analytical and experimental critical function and/or characteristic proof of concept achieved in a laboratory environment	At this step in the maturation process, active research and development (R&D) is initiated. This includes both analytical studies to set the technology into an appropriate context and laboratory-based studies to validate empirically that the analytical predictions are correct. These studies and experiments validate the benefits offered by the technology advancement to the applications/concepts formulated at TRL 2.	Laboratory tests have demonstrated that the technology advance as predicted by the analytical model and has the potential to evolve to a practical device.	100	100	100	100	100	100	100	100	The detailed relevant environment was not defined by the government to the contractors in the NRA, only a generic Design Reference Mission. The NASA TRL Assessment Document fully defines the relevant environment for solar sail technology at the .5 to 1 AU utilizing a Delta II launch vehicle. This definition was done at the start of Phase III of their contracts and therefore the contractors were given credit for relevant environment definition at TRL 3.
		Analytical models both replicate the current performance of the technology advance and predict its performance when operating in a breadboard environment.	100	100	100	100	100	100	100	100	
		A determination of the "relevant environment" for the technology advance has been made. (See Note)	100	100	100	100	100	100	100	100	
TRL 4: Component and/or breadboard validated in a laboratory environment	Following successful "proof-of-concept" work, basic technological elements must be integrated to establish that the "pieces" will work together to achieve concept-enabling levels of performance for a component and/or breadboard. This validation must be devised to support the concept that was formulated earlier, and should also be consistent with the requirements of potential system applications. The validation is relatively "lowfidelity" compared to the eventual system; it could be composed of ad hoc discrete components in a laboratory.	A "component" or "breadboard" version of the technology advance will have been implemented and tested in a laboratory environment.	100	100	100	100	100	100	100	100	Models used to predict propulsion performance in a relevant environment. Propulsion qualification tests cannot be conducted on the ground for a solar sail. Analytical models not developed for other relevant natural or induced environments
		Analytical models of the technology advance fully replicate the TRL 4 test data.	100	100	100	100	100	100	100	100	
		Analytical models of the performance of the component or breadboard configuration of the technology advance predict its performance when operated in its "relevant environment" and the environments to which the technology advance would be exposed during qualification testing for an operational mission. See NOTE	100	100	100	100	100	100	100	100	
TRL 5: Component and/or breadboard validated in a relevant environment	At this TRL, the fidelity of the environment in which the component and/or breadboard has been tested has increased significantly. The basic technological elements must be integrated with reasonably realistic supporting elements so that the total applications (component-level, sub-system level, or system-level) can be tested in a "relevant environment".	The "relevant environment" is fully defined. See NOTE	100	100	100	100	100	100	100	100	The detailed relevant environment was not defined by the government to the contractors in the NRA, only a generic Design Reference Mission. The NASA TRL Assessment Document fully defines the relevant environment for solar sail technology at the .5 to 1 AU utilizing a Delta II launch vehicle. This definition was done at the start of Phase III of their contracts and therefore the contractors did not test components at a fully defined relevanet environment. Natural Environment - inflation system leaks - new material needed; no UV, e, p on boom material or spreader system (kapton pockets, kevlar lines), no e, p on insulation Ground environment - lines showed signs of chaffing - possible ground shipping issue. Assembly process and procedure is not repeatable and no method available to verify correct assembly. Limited test life (limited number of deployments without damage) Models - no deployment dynamics model, no charging model
			AVERAGE OF NATURAL, LAUNCH & GROUND ENVIRONMENTS								
		The technology advance has been tested in its "relevant environment" throughout a range of operating points that represents the full range of operating points similar to those to which the technology advance would be exposed during qualification testing for an operational mission. See NOTE	62.5	62.5	100	75	100	62.5	62.5	75	
		Component or breadboard has been tested in the relevant natural environment	50	50	100	50	100	50	50		
		Component or breadboard has been tested in the relevant launch environment	NA	NA	NA	NA	NA	NA	NA		
		Component or breadboard has been tested in the relevant ground environment	75	75	100	100	100	75	75		
		Analytical models of the technology advance replicate the performance of the technology advance operating in the "relevant environment"	75	75	75	75	75	75	75	75	
		Analytical predictions of the performance of the technology advance in a prototype or flight-like configuration have been made.	100	100	100	100	100	100	100	100	

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

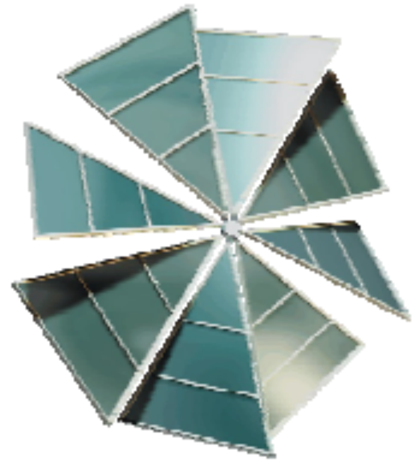


L'Garde

Technology Gaps

Solar Sail Technology Gaps	Post 10M System Impacts	20M System Gap Update
No modeling of deployment and deployment dynamics has been done.	Deployment dynamics could impact the design and operation of a solar sail system, which could cause significant design changes. Significant design changes could invalidate previous model validation efforts.	• ATK had accelerometers on their tips for deployment and L'Garde used photogrammetry and video to view boom tips. • L'Garde experienced asymmetric deployment issues during vacuum testing. Maintaining attitude control and stability during deployment is critical and L'Garde has conducted an initial deployment simulation tool. Based on the 20-m system
Materials environmental testing is incomplete or in some cases has not been done at all. No testing has been done on seams, bonds, adhesives, ground straps, ripstop, sequencers, targets, inflatable booms or graphite epoxy components.	Results of materials testing could necessitate materials changes and impact design.	• Ground System Demonstrator (GSD) material testing has been done in support of L1 Diamond (.95 AU) and Solar Polar Imager (.5 AU), considered to be the Initial Application Missions (IAM). • Additional testing that was done on the L'Garde sail material indicates an issue with coated Mylar in a VUV environment. Material loses strength in 3 years and disintegrates in a 6 years. Final analyses of the test results are underway. • No testing has been done to date on seams, booms, beams, targets, repairs or elements.
Meteoroid/orbital debris (M/OD) testing has been very limited. M/OD testing should be done with the integrated ripstop.	The functionality of ripstop has not been tested or proven Tear resistance is imperative to a good flight design.	• Limited ATK ripstop testing done by SRS. • L'Garde ripstop demonstrated during deployment testing. • L'Garde boom insulation needs investigation. MOD impact on boom rigidity could be an issue.
Scalability between the 10m and 20m designs is in question due to the design changes occurring after the 10m system testing was complete.	Significant design changes, as well as the inclusion of the attitude control system in the 20m design, impacts the ability to assess the scalability between the 10m and 20m designs. The process for evaluating model scaling has not been established. Scalability between ground demos needs to be established so that models can validate and then used to support much larger flight designs.	• Data on model scalability between the 10 and 20 M systems is TBD. • The sensitivity of the sail models to design changes has not been determined.
Scalability to a science mission needs to be studied in detail. Facilities do not exist to manufacture, assemble or test a large-scale sail system. Current manufacturing and assembly processes for the most part are manual and labor intensive.	Feasibility of manufacturing a 10-20m design has been proven but the processes and facilities to manufacture a much larger flight system have not been proven. Current facilities and techniques appear to be inadequate to handle a larger sail system and fabrication scalability has not been proven. New techniques, processes, and facilities need to be developed for a larger sail system. A rigorous study should be conducted to look at all of the factors involved in fabricating, assembling and testing a larger sail.	• Limited additional information between the 10M and 20M ground demonstrator systems. • An assessment of facilities for ambient deployment was conducted by ISPT with several sites identified. • ATK has developed a beam/longeron splice technique. • L'Garde has manufactured booms up to 50 m in length for another program

Kosmos-3M



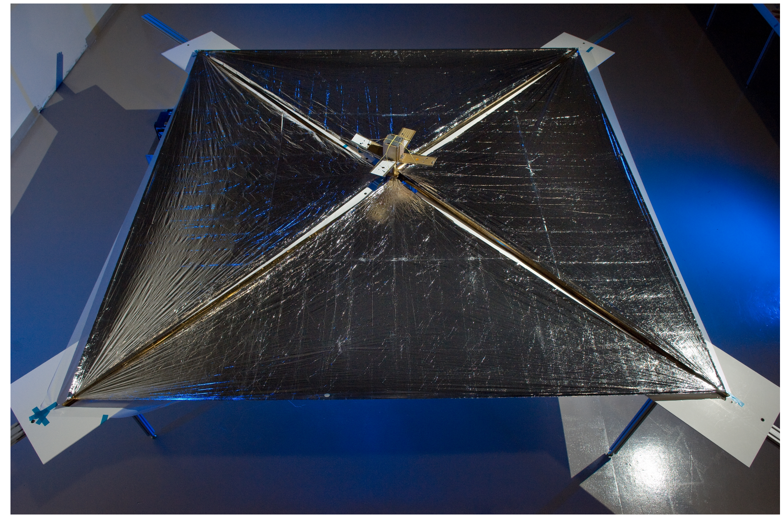
December 2 , 2005

"The Planetary Society solar sail team is working to try again to fly the world's first solar sail spacecraft. With a tested spacecraft design, almost all flight components available, and at least two attractive launch vehicle possibilities, we are well positioned to reach our goal…But we will need much more to reach orbit. The total funding required for our project is $4 million, and we will need a major corporate or individual sponsor."

Soyuz-Fregat

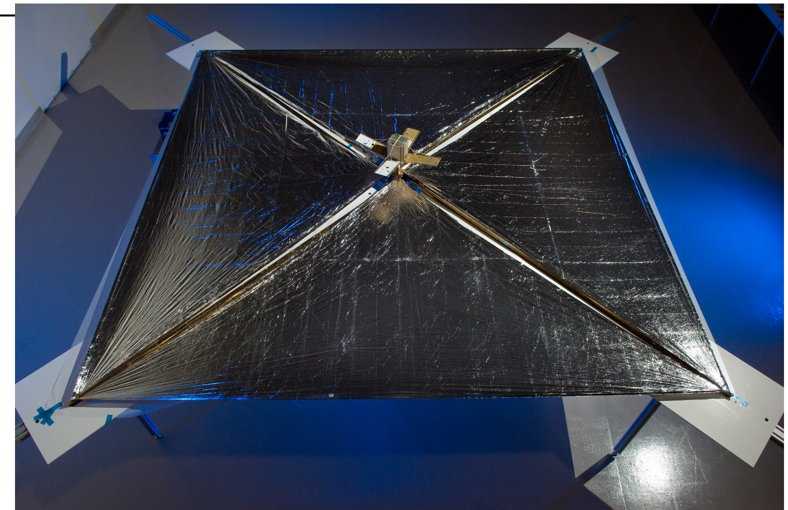
NASA NanoSail-D Demonstration Solar Sail

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



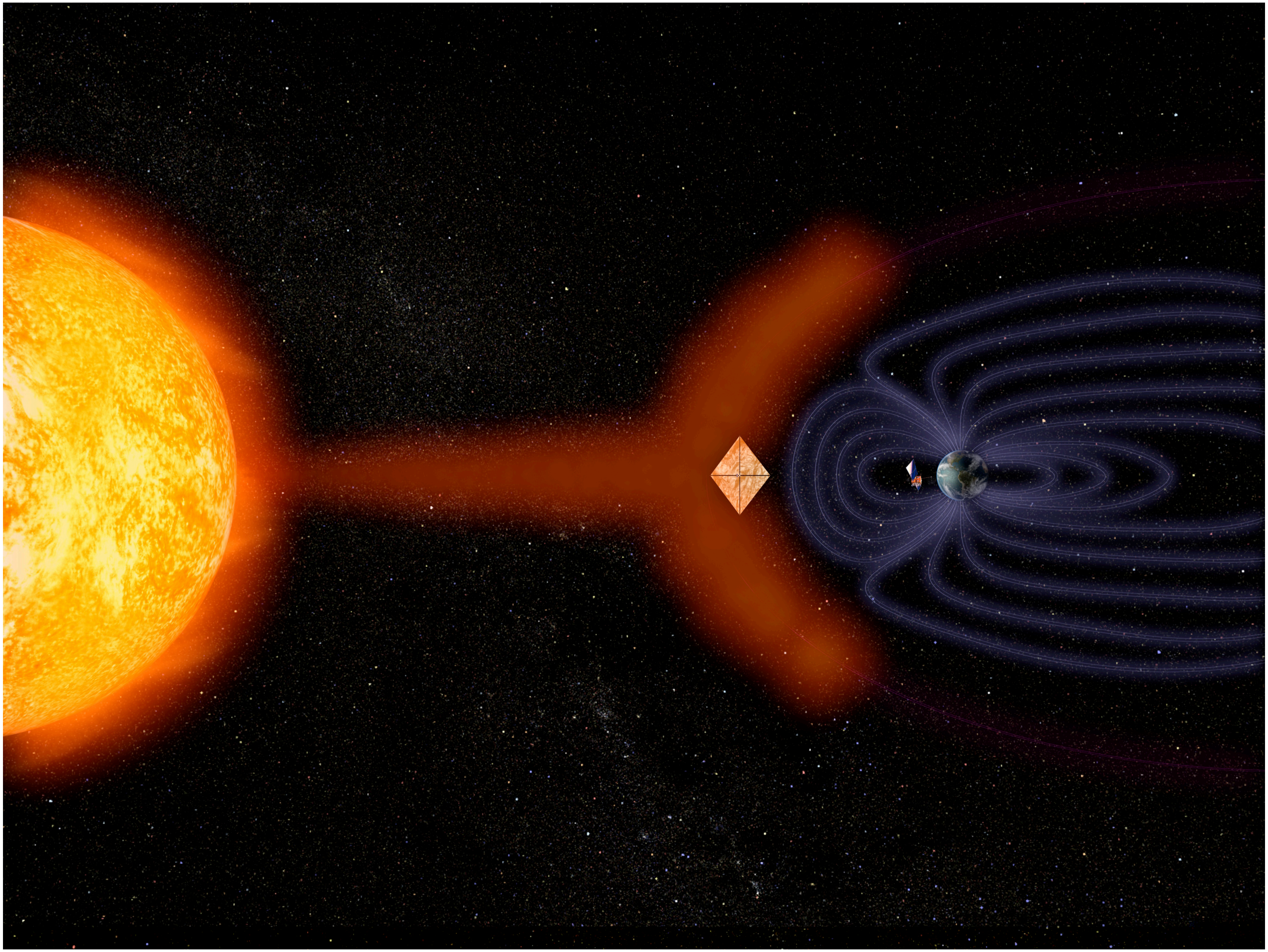
NanoSail-D Flight Launch Attempted July 2008

- Launch
  - Falcon-1, flight 3
  - Kwajalein, Missile Range
  - Primary payload: AFRL PnPSat
  - Secondary P-POD payloads (2)
    - PharmaSAT-1
    - DeOrbitSail (DOS)
- Mission Description
  - Primary deployed in 685 X 340 km orbit
  - 685 km circular orbit, 9 degree inclination
  - Deployed after circularized at 685 km
  - Acquisition/detumble < 2 days
  - 10 m^2 sail ~ 77 days to deorbit

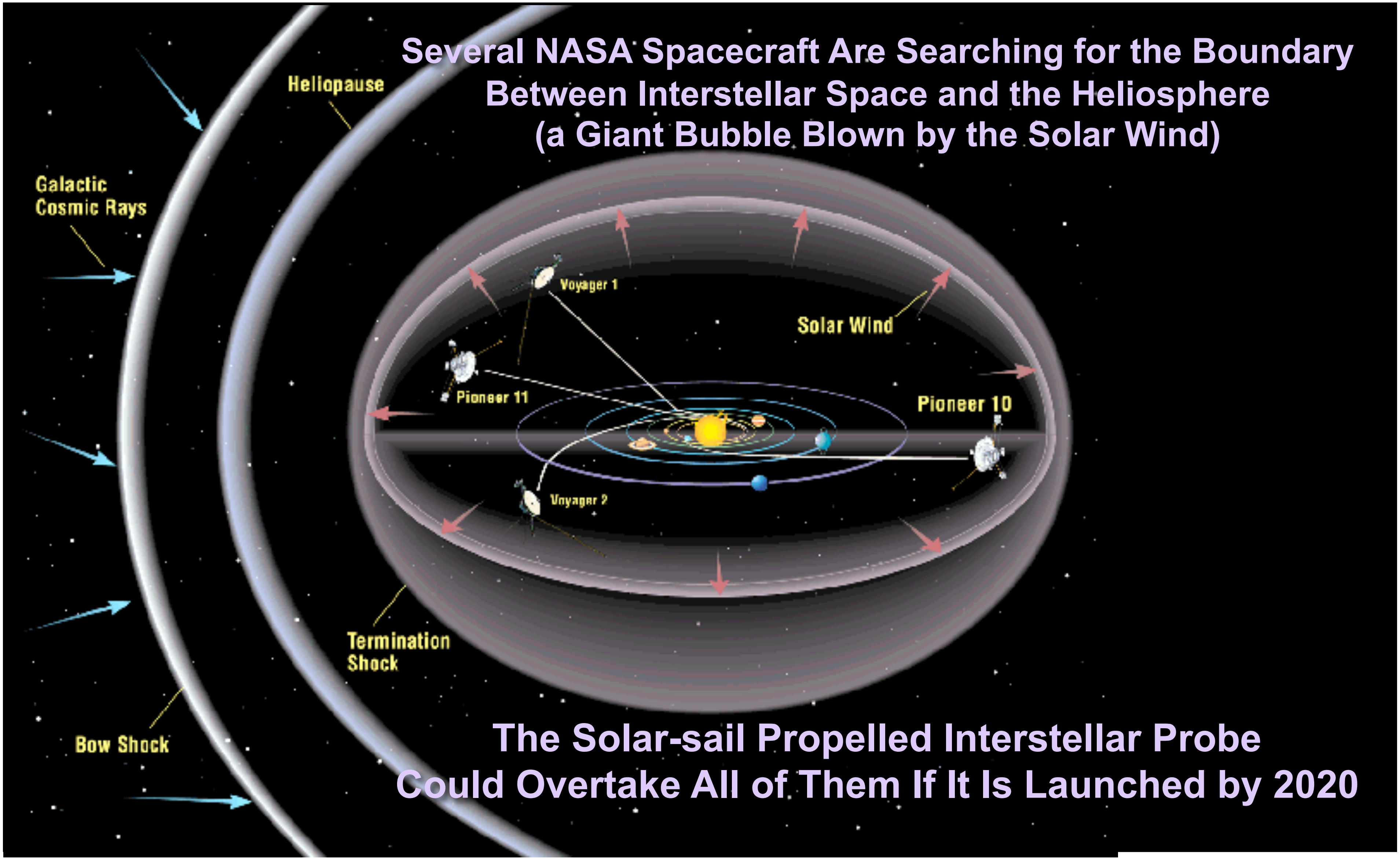



The Future

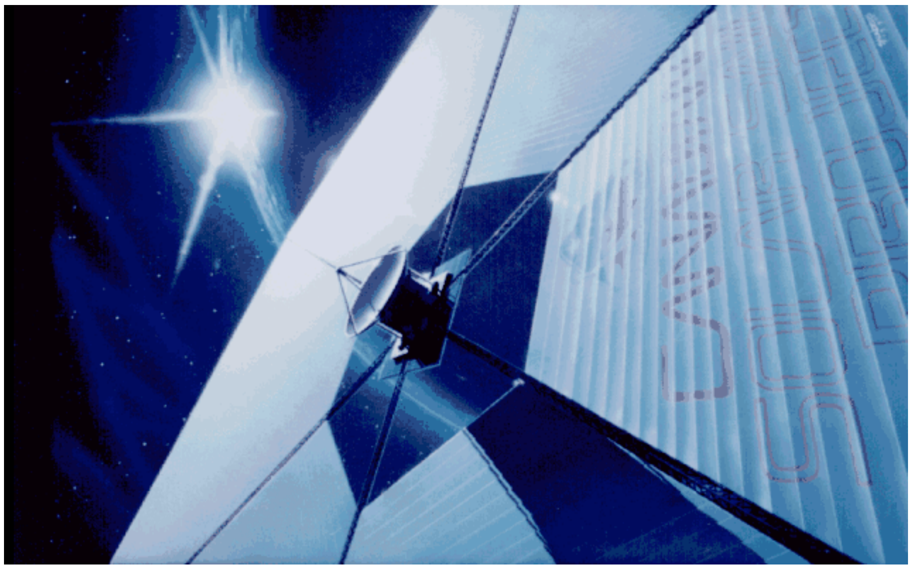
Heliostorm: Advanced Warning Of Solar Flares



Solar Sails: The Race to the Heliopause



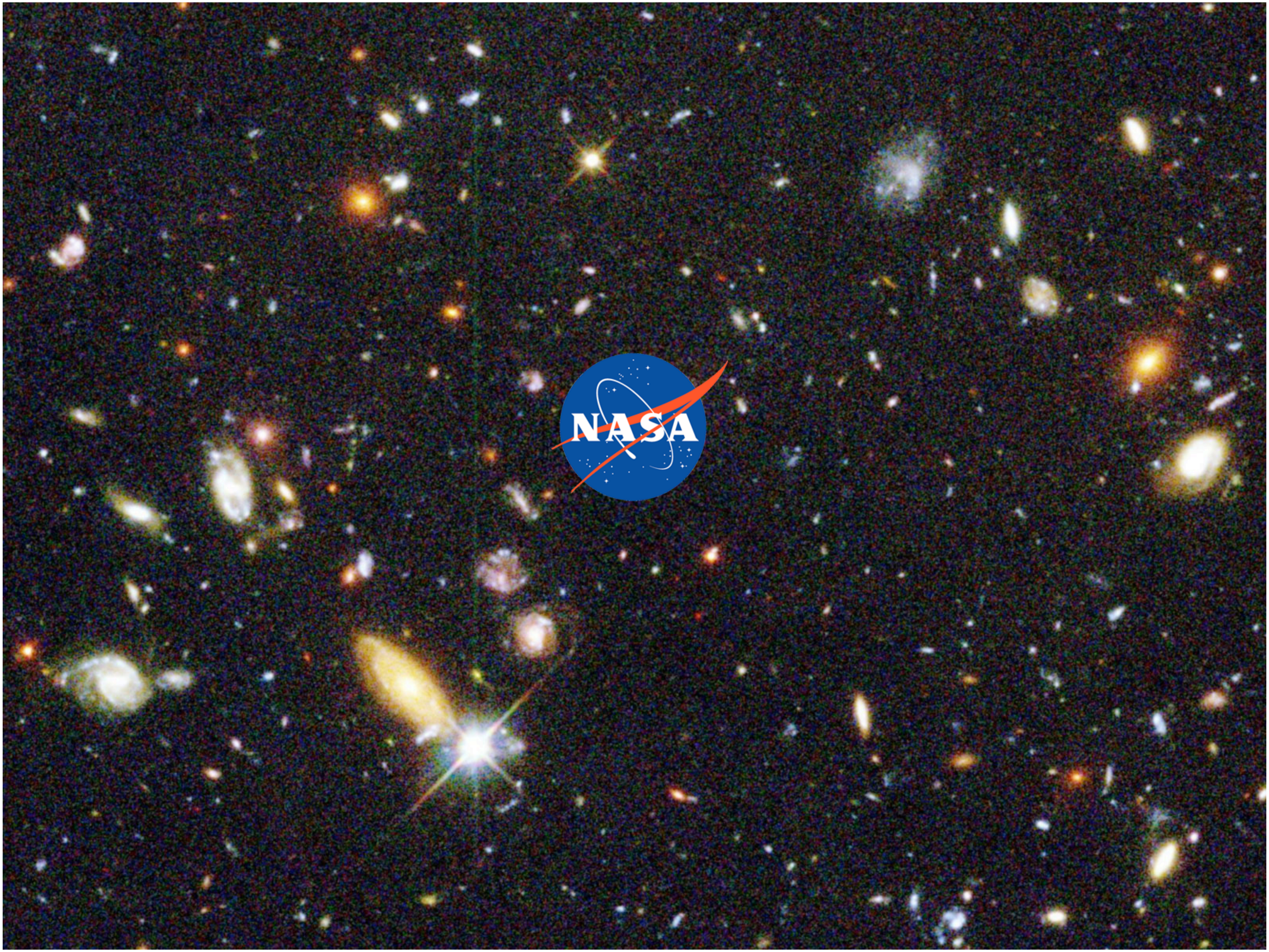
Solar Sails:
Ultimate Goal- 200 AU with < 15 year trip time



Systems Requirements
- Travel Distance - 200 AU
- Travel Time < 15 years
- $\Delta V > 60$ km/s

Material Challenges
- High Temperature Tolerance 70 - 2000K (@ 200 - 0.25 AU)
- High Emissivity 0.4 - 0.9
- High Tensile Strength
- Good Gamma and UV Radiation Tolerance
- Low Coefficient of Thermal Expansion 3 x 10-6 (per ^{0}C)
- Sail Fabric Areal Density 0.5 g/m^2
- Fabric Thickness < 0.35 μm (polyimide ρ = 1.4 gm/m^3)
- Sail Structure Areal Density 0.5 g/m^2

Garner; Layman; Gavit; Knowles "A Solar Sail Design for a Mission to the Near-Interstellar Medium"; STAIF January, 2000, Albuquerque, NM. : American Institute of Physics Press. AIP Conference Proceedings, Vol. 504, 2000, p.947


NASA