M09-0138-Abstract

Title of Presentation: Solar Sails

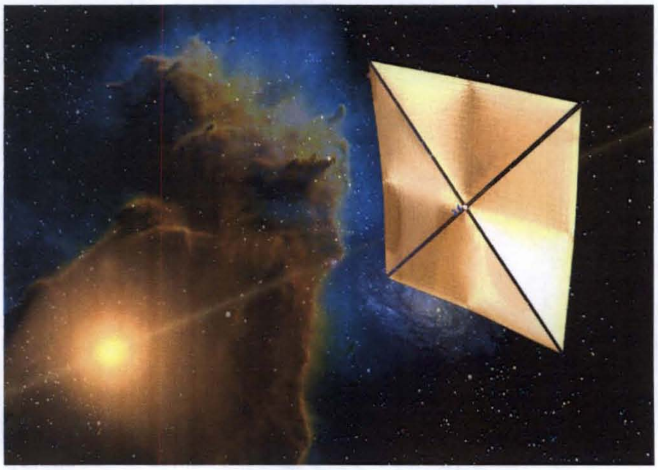
Primary Author: Roy Young

Organization of Primary Author: NASA/Marshall Space Flight Center

Phone: 256-544-3485

Email: Roy.Young@nasa.gov

Abstract: The Solar Sail Propulsion investment area has been one of the three highest priorities within the In-Space Propulsion Technology (ISPT) Project. In the fall of 2003, the NASA Headquarters' Science Mission Directorate provided funding and direction to mature the technology as far as possible through ground research and development from TRL 3 to 6 in three years. A group of experts from government, industry, and academia convened in Huntsville, Alabama to define technology gaps between what was needed for science missions to the inner solar system and the current state of the art in ultralightweight materials and gossamer structure design. This activity set the roadmap for development. The centerpiece of the development would be the ground demonstration of scalable solar sail systems



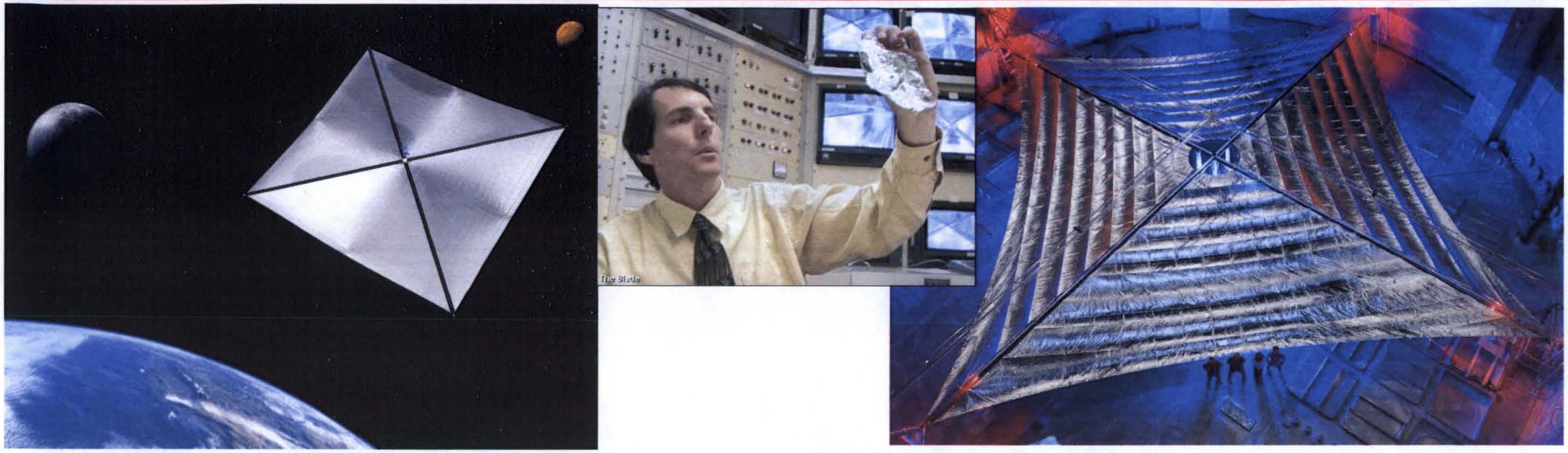
including masts, sails, deployment mechanisms, and attitude control hardware and software. In addition, new materials would be subjected to anticipated space environments to quantify effects and assure mission life. Also, because solar sails are huge structures, and it is not feasible to validate the technology by ground test at full scale, a multi-discipline effort was established to develop highly reliable analytical models to serve as mission assurance evidence in future flight program decision-making.

Two separate contractor teams were chosen to develop the SSP System Ground Demonstrator (SGD). After a three month conceptual mission/system design phase, the teams developed a ten meter diameter pathfinder set of hardware and subjected it to thermal vacuum tests to compare analytically predicted structural behavior with measured characteristics. This process developed manufacturing and handling techniques and refined the basic design. In 2005, both contractor teams delivered 20 meter, four quadrant sail systems to the largest thermal vacuum chamber in the world in Plum Brook, Ohio, and repeated the tests. Also demonstrated was the deployment and articulation of attitude control mechanisms. In conjunction with these tests, the stowed sails were subjected to launch vibration and ascent vent tests. Other investments studied radiation effects on the solar sail materials, investigated spacecraft charging issues, developed shape measuring techniques and instruments, produced advanced trajectory modeling capabilities, and identified and resolved gossamer structure dynamics issues.

Technology validation flight and application to a Heliophysics science mission is on the horizon.

Solar Sails

Roy Young, NASA/Marshall Space Flight Center



General Description:

Utilizes solar photon pressure (<9 Newtons/km^2) to obtain continuous thrust. Sail thin film (< 3 microns) is compactly stowed for launch and deployed / supported by ultralight weight trusses.

Technology Benefits:

- No propellants.
- Low system complexity (no high loads, voltages, temperatures, toxic matl's)
- Low environmental impact on payload
- Enables access to previously infeasible orbits (e. g., hovering versus orbiting, inclination change, extrasolar trajectories))

Technology Area Status:

- **Two US teams designed, fabricated, and tested competing ultralightweight sail concepts for system level ground demonstration:**
    - 10 m system ground demonstrators were developed and tested in FY04.
    - 20 m system ground demonstrators tests completed July 2005. Final Review September 2005.
- **Developed and tested high-fidelity computational models, tools, and diagnostics.**
- **Multiple R&D efforts for materials evaluation, optical properties, long-term environmental effects, charging issues, and smart adaptive structures.**

M09-0138-Presentation

National Aeronautics and Space Administration

NASA

Solar Sails

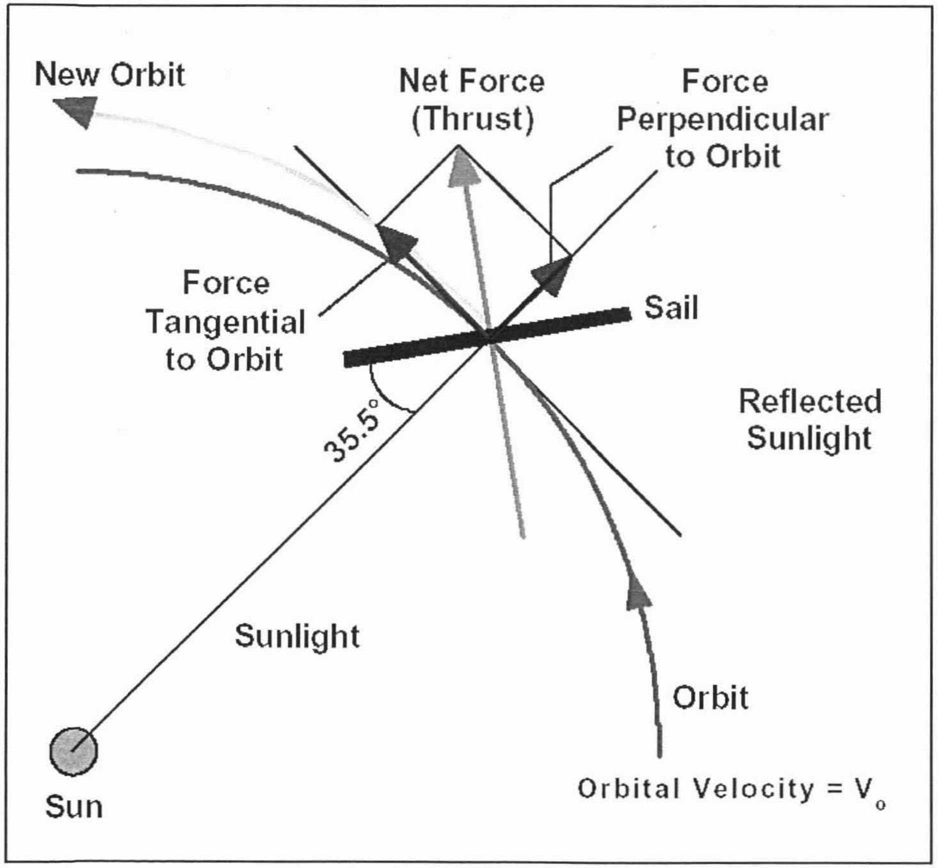
In Space Propulsion Technology Project
NASA Marshall Space Flight Center
Roy [illegible]g
Ear[illegible]ence Technology Conference 2006
June 27-29, 2006

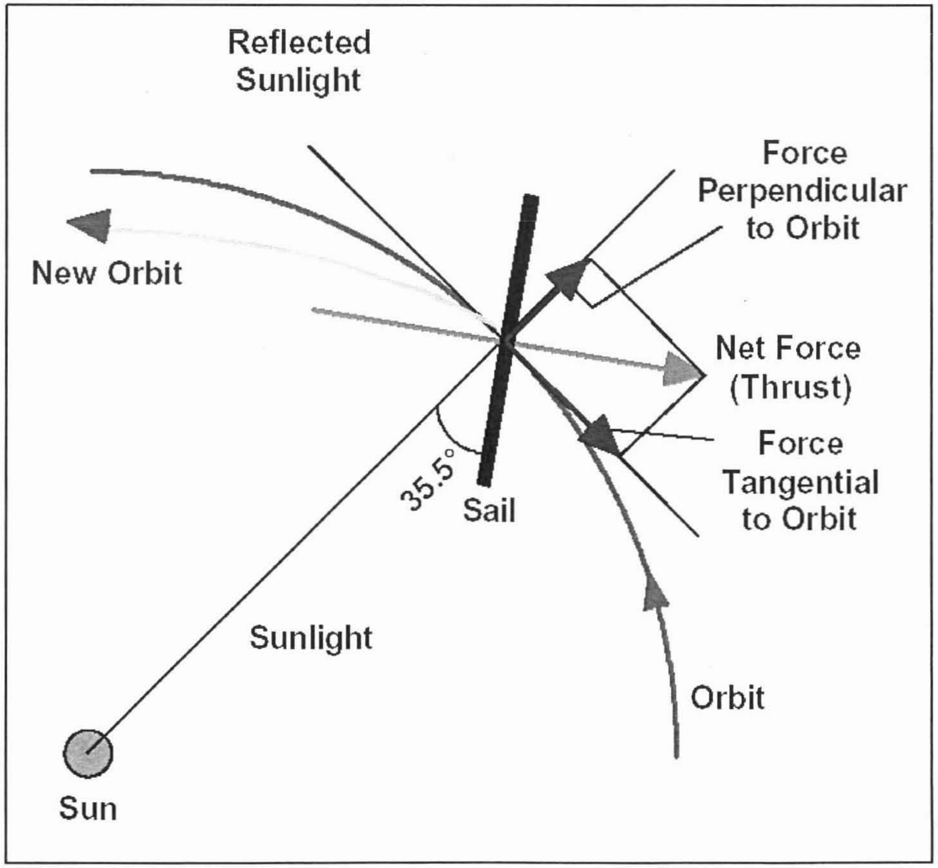
www.nasa.gov


Technology Overview

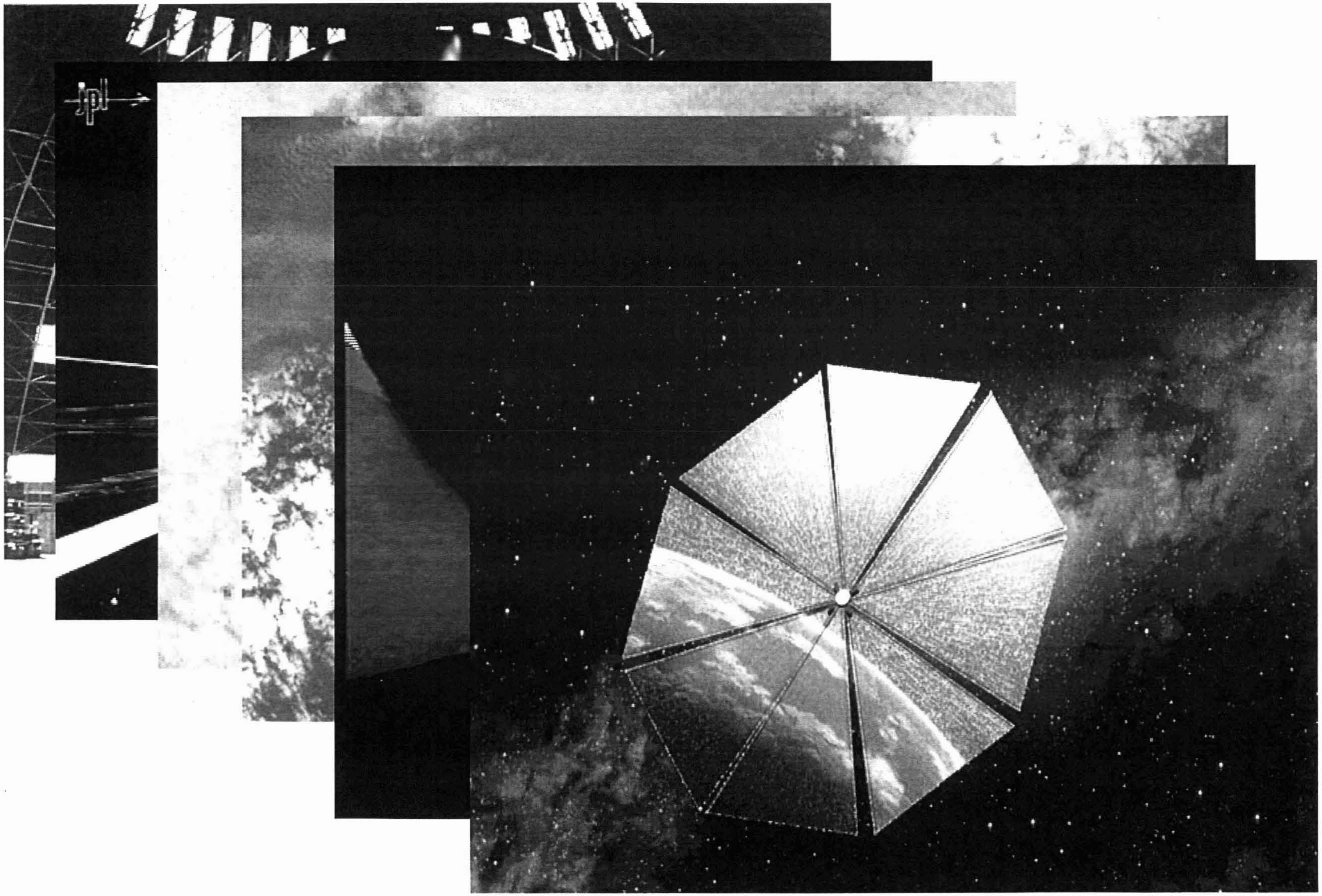
Solar Sail Propulsion Fundamentals

- Solar sails use photon "pressure" 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)





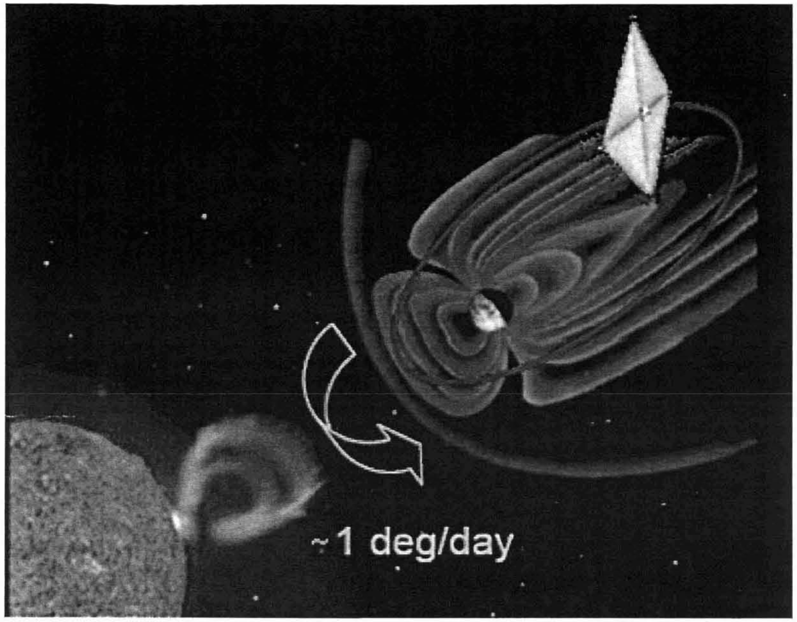
Solar Sail Heritage
(Big Shiny Things in Space)

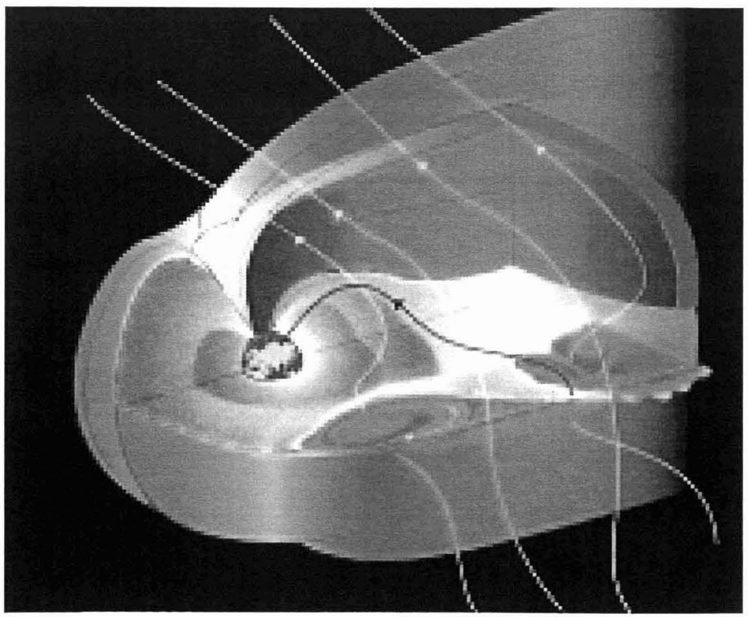


COSMOS - 2005


Missions Supported

GeoSail





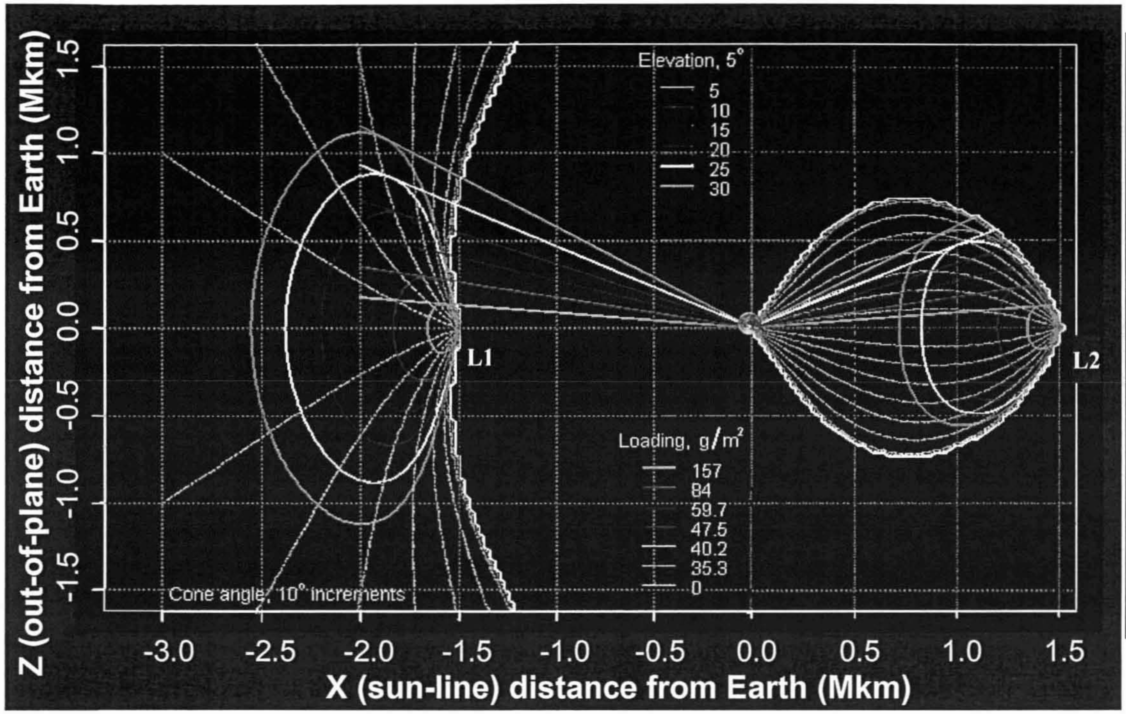
Science Objectives

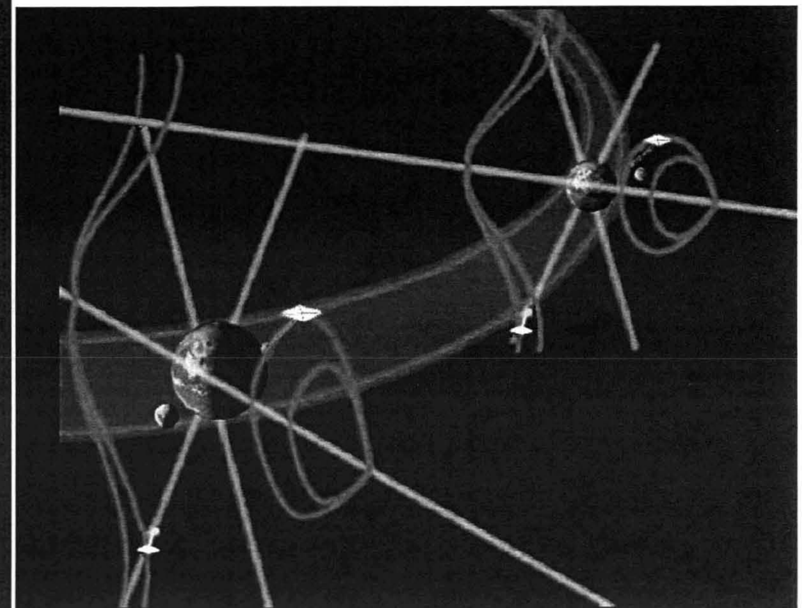
- Understand how spontaneous magnetic reconnection occurs in a magnetic current sheet
- Understand the mechanism behind reconnection mode destabilization and saturation in the magnetotail
- Analyze the plasma structure at the sub-second resolution
- Understand reconnection and particle dynamics at the day/dawn side low-latitude boundary layer along the earth's magnetopause

Mission Description

- Precess orbit apsis line to stay permanently in Geomagnetic tail
- Launch direct to operational orbit (10 x 30 $_{ER}$), minimal mission if sail fails to deploy
- 40 m square sail @ 55 g/m^2 with characteristic acceleration ~ 0.1 mms^2
- Demonstrate new science capability on technology demo mission
- Payload: magnetometers (2), electrostatic analyzer, solid state telescope (5 kg / 5 W or enhance 11 kg / 8.5 W)

PoleSitter



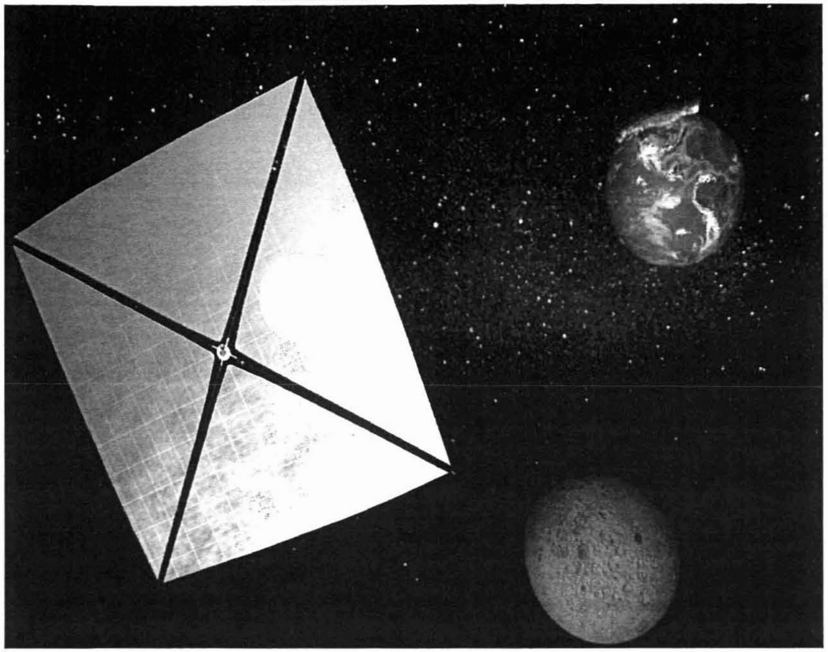


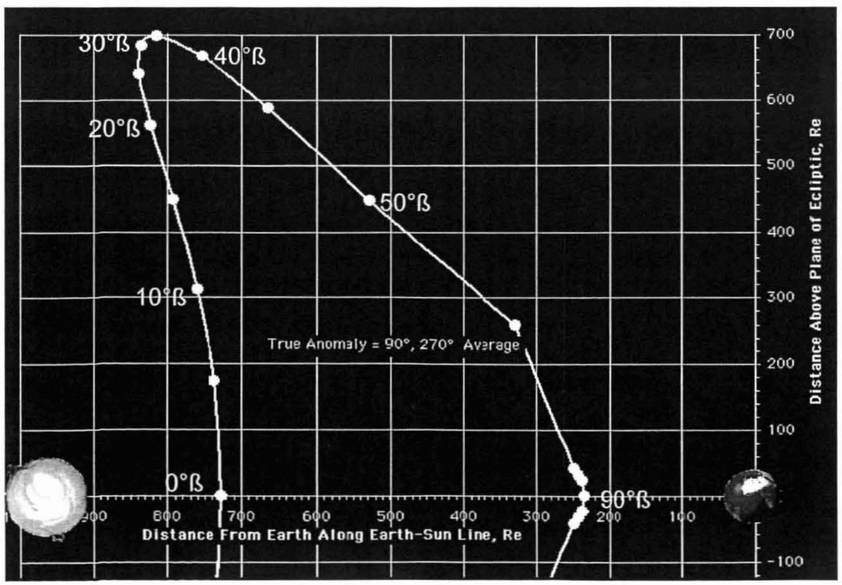
Polesitter Provides:

- **Near real-time imaging of Antarctic weather (Artic as well with sail at North L2 point)**
- **Data relay for the NPOESS satellite system**
- **Continuous communications/high speed data channel for Antarctic bases**
- **Solar sail areal density of 30 – 40 g/m^2, 0.23-0.3 mm^2 characteristic acceleration**

Polesitter Support of ESMD:

- **Slightly sunward of L1 for small increased leadtime for Coronal Mass Ejections (CMEs) warnings for Lunar astronauts.**
- **Continuous hemispheric visibility including Lunar south pole region for comm/high speed data.**





HelioStorm

Science Objectives

- **Understand the Sun-to-Earth evolution of CMEs, shocks and particle radiation from solar eruptions**
- **Remote- and local sense Earth-impacting solar disturbances**
- **Determine the structure of the solar wind on spatial and temporal scales that are relevant for driving magnetospheric processes**
- **Provide warning time to protect lunar and Earth-orbiting and ground assets**
- **Provide a demonstration platform for Exploration and a pathfinder for the Solar Polar Imager science mission**

Mission Description

- **Delta II Launch Vehicle**
- **Trajectory: ballistic transfer from Earth to L1 Halo (~90 days), solar sail transition from L1; 80m square sail @ 14.3 g/m2**
- **Continuous Solar Viewing: 2 years In Final Orbit**
- **Flight System Concept**
- **Solar-array powered S/C with solar sail**
- **Payload: Fields and Particles+ Imaging (33 kg/24 W)**

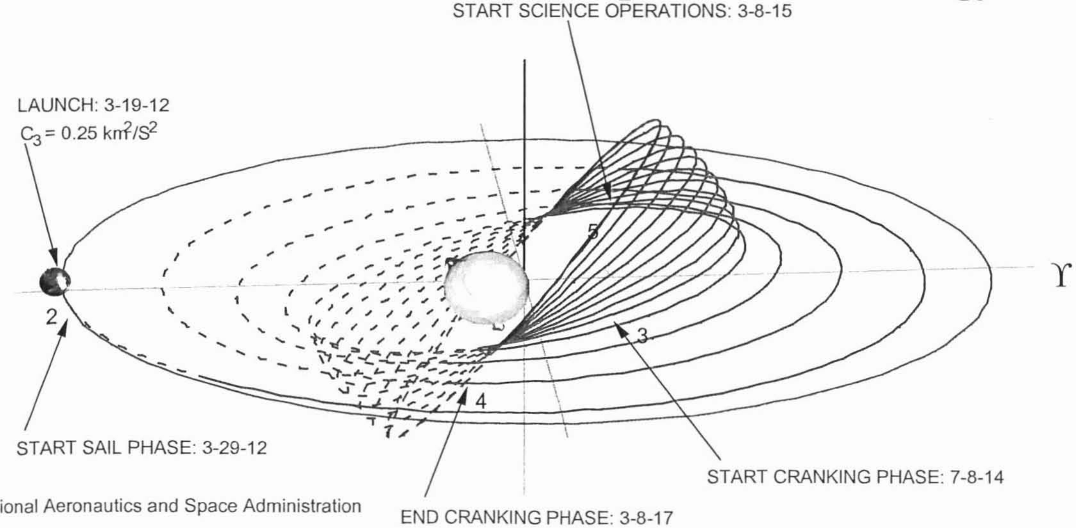
Solar Polar Imager (SPI)

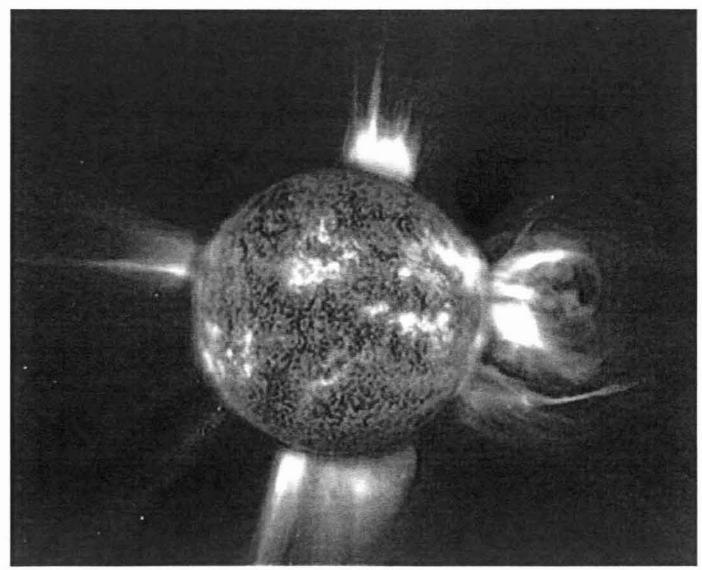
Science Objectives

- What is the relationship between the magnetism and dynamics of the Sun's polar regions and the solar dynamo?
- What advantages does the polar perspective provide for space weather prediction?
- What is the azimuthal structure and dynamics of the corona and CMEs?
- How are variations in the solar wind linked to the Sun at all latitudes?
- How are solar energetic particles accelerated and transported in radius and latitude?
- How does the solar irradiance vary with latitude?

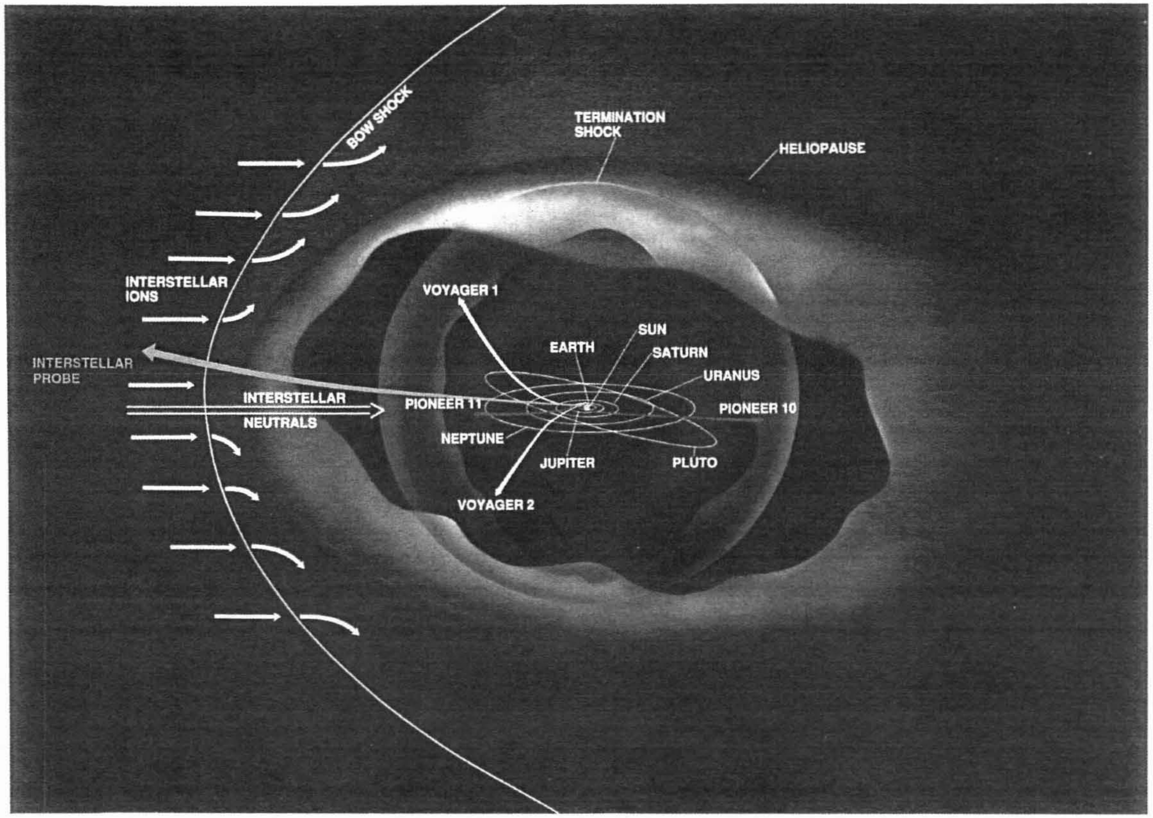
Mission Description

- SC in highly inclined ~75° 3:1 resonant heliocentric 0.48 AU orbit
- Payload: Fields and Particles+ Imaging (44 kg/50 W, 34 kg/24.5 W)
- Uses solar sail to reach high inclination in 5-7 years; 150 m square sail @ 13 g/m2
- Collect *in situ* data during cruise
- Average data rate > 60 kbps; store and dump, 2 passes/week
- Gimbaled antenna for uninterrupted helioseismology data





Interstellar Probe

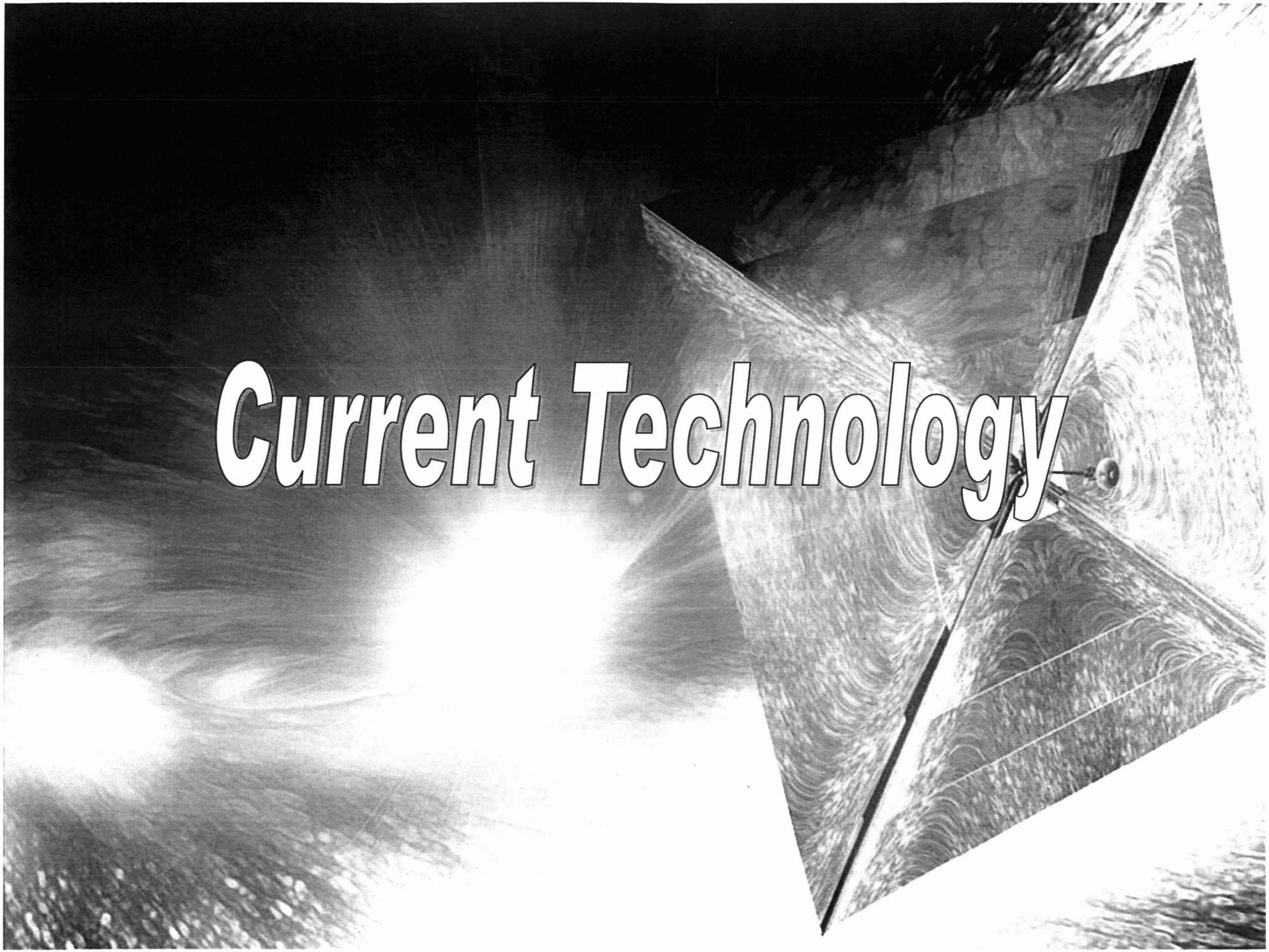


Mission Description

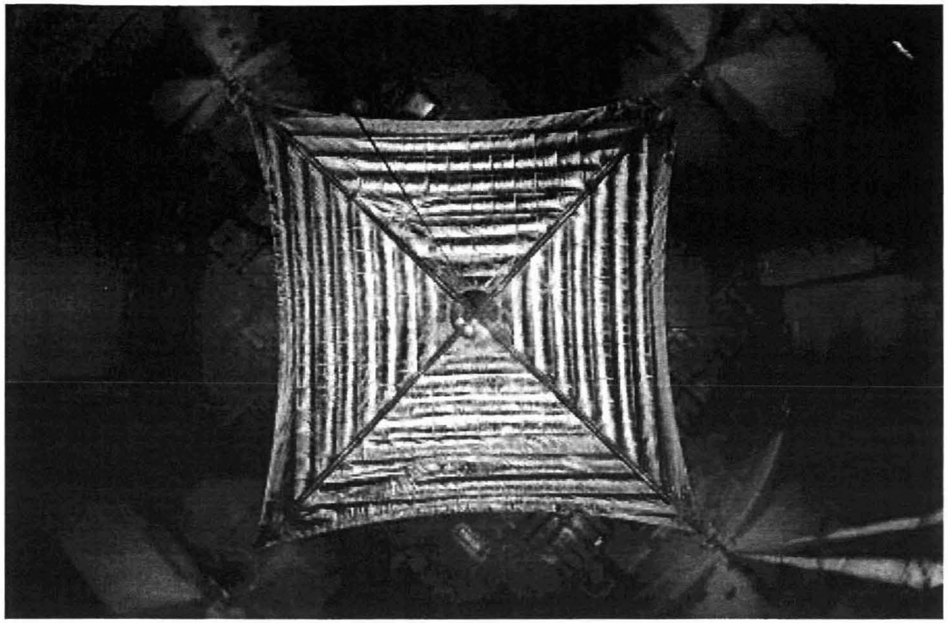
- Example mission design
  - Delta II 7425 launch (719 kg cap. to C3=0)
  - Flight system launch mass: 564 kg
  - Solar sail trajectory targeted for nose of heliosphere
  - 0.25 AU solar pass, 200 AU in 15 yrs.
- Flight system concept
  - Solar sail: < 1 g/m^2 , 200 m radius
  - "Flying Antenna" design implementation (191 kg)
  - Sized for 30 year operations
  - Payload: fields & particles + Imaging

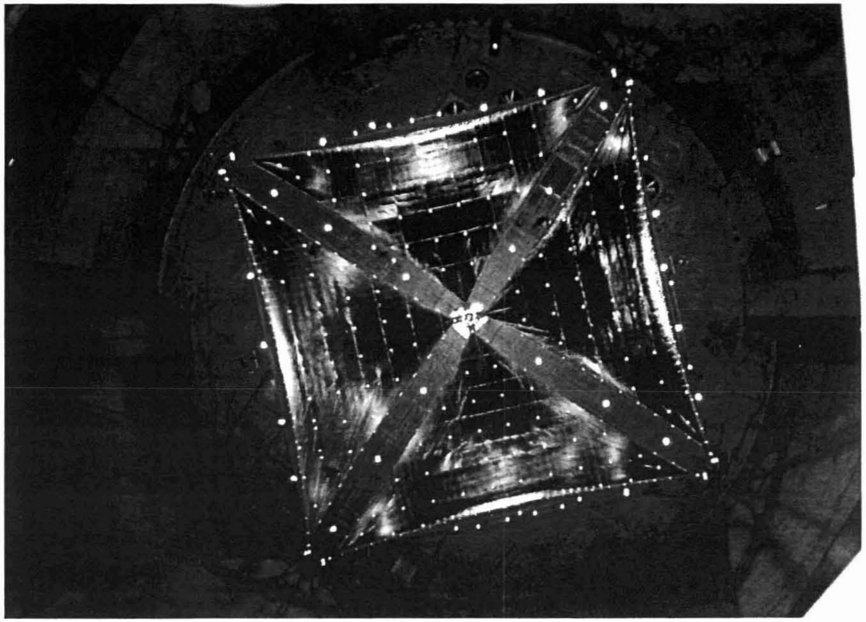
Science Objectives

- Explore interstellar medium and determine directly the properties of the interstellar gas, the interstellar magnetic field, low-energy cosmic rays, and interstellar dust
- Determine structure & dynamics of heliosphere as example of interaction of a star with its environment
- Study, in situ, structure of solar wind termination shock, & acceleration of pickup ions & other species
- Investigate origin and distribution of solar-system matter beyond the orbit of Neptune


Current Technology

Solar Sails Technology Status

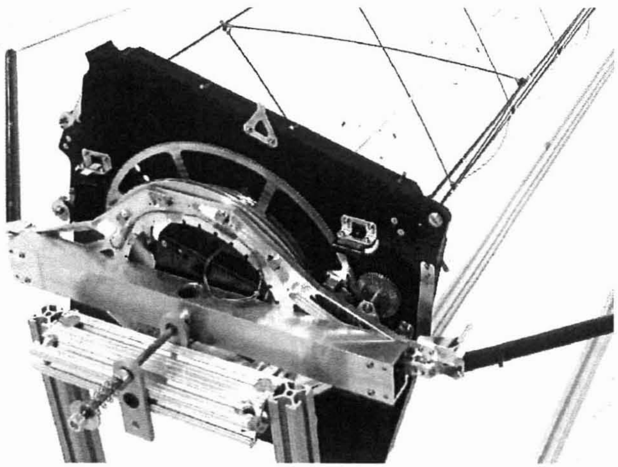


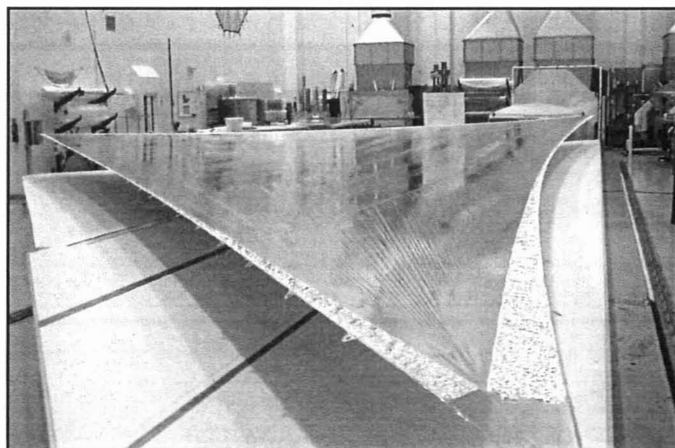


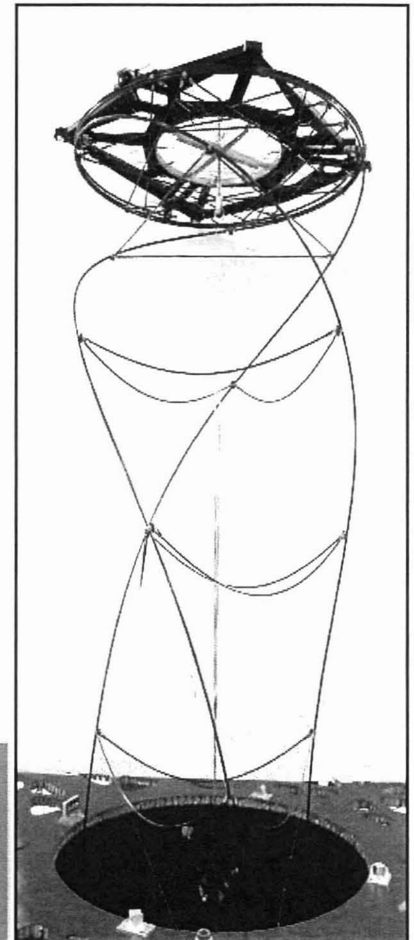
- **General Description:**
  - Propellantless propulsion utilizes solar photon pressure (<9 Newtons/km2) to obtain thrust. Sail film is compactly stowed for launch and deployed / supported by ultra-light weight trusses.
- **Technology Benefits:**
  - No propellants required
  - Low system complexity (challenge is scaling to large area with ultra-low density)
  - Low environmental impact on payload
  - Enables access to previously inaccessible orbits (e. g., non-Keplerian, fixed reference, and high inclination orbit changes)
- **Technology Area Status:**
  - Two parallel awards to design, fabricate, and test competing sail concepts for system level ground demonstration:
    - 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.
  - Multiple awards to develop and test high-fidelity computational models, tools, and diagnostics.
  - Multiple awards for materials evaluation, optical properties, long-term environmental effects, charging issues, smart adaptive structures.

ATK Task Summary

- PI: David Murphy, ATK Space Systems
- Proposal 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
  - Leverages 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 2-4 μm CP1, compliant border, 3 point attach
    - Thrust Vector Control uses sliding masses along boom with spreader bars and micro-PPT at mast tip



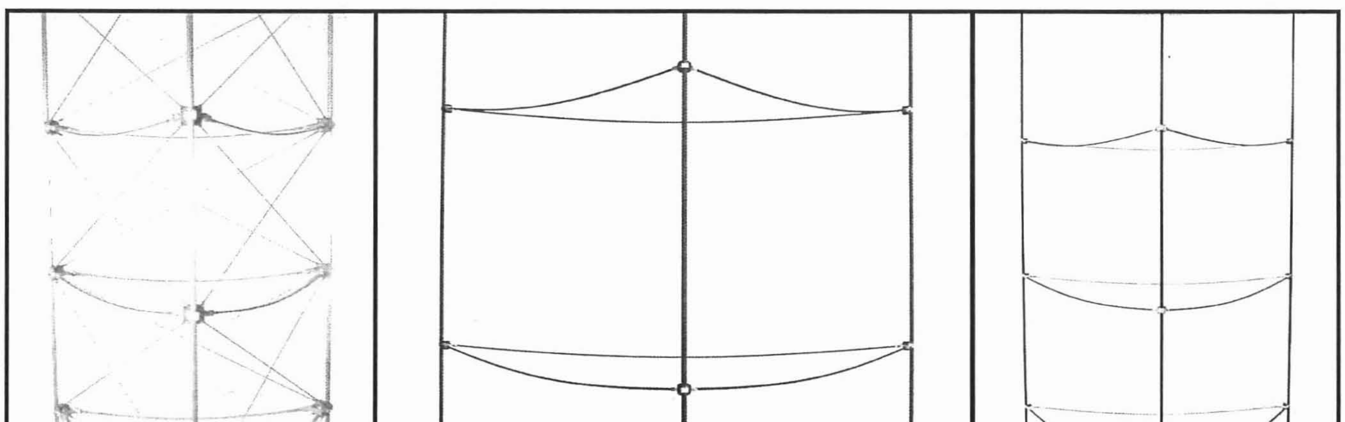




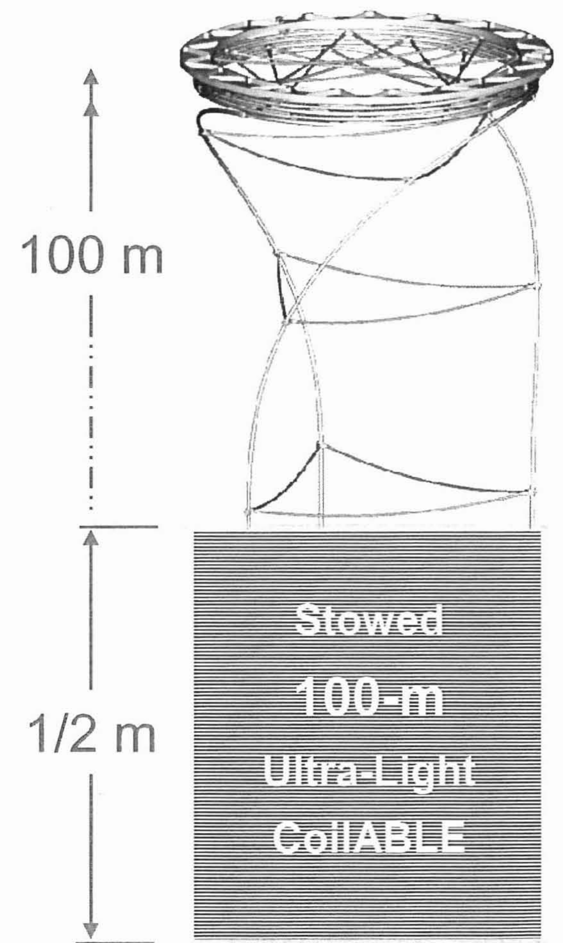
CoilAble Mast Heritage

- 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

LACE | ISP | ST8



LACE	ISP	ST8
$\varnothing_M = 25.5$ cm	$\varnothing_M = 39.5$ cm	$\varnothing_M = 24.0$ cm
$L_S/L_D = 2.0\%$	$L_S/L_D = 0.85\%$	$L_S/L_D = 0.88\%$
$\rho_L = 240$ g/m	$\rho_L = 70$ g/m	$\rho_L = 34$ g/m



SRS Solar Sail Membrane Features

Membrane Design:

4-quadrant planar sail - 3-point sail attach with scalloped edges

- Designed determinant features, Biaxial membrane Design
- Compliant Border interface between edge cable and membrane
  - Shear insensitive, Cord/Material CTE mismatch insensitive
  - Thermal Gradient insensitive

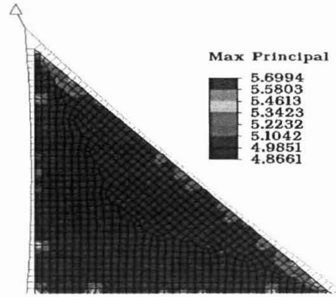
Sail Material: *CP1 Polyimide*

- High Operating Temperature (>200 oC)
- UV Stable
- Essentially Inert
- Soluble (Wet Process), modifiable with variety additives - improve conductivity and thermal properties
- ***~2 micron polyimide***
- ***Flight Proven --- flying on Numerous GEOCOM satellites***

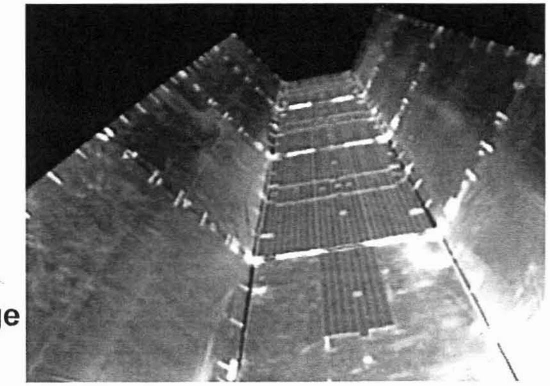
Sail Construction Methods:

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

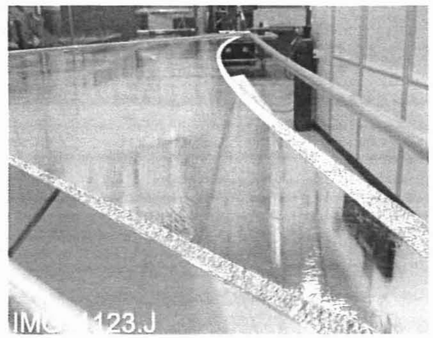
- Scalable Construction Methods --- current system >20m
- Adhesive less Bonding Methods --- eliminates sticking and contamination risks.



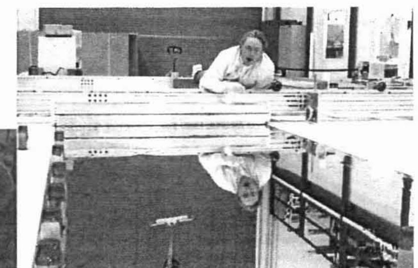
FEM of Parobolic Edge



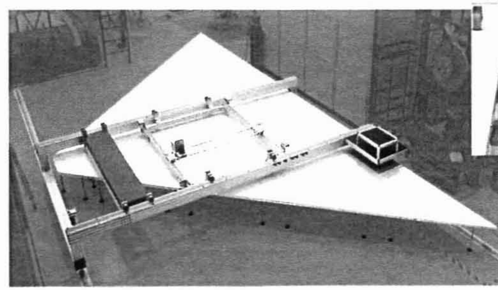
160 m^2 of film per satellite. Film Is 1 mil material supported by 5 mil edge designs



Sail with Compliant Border

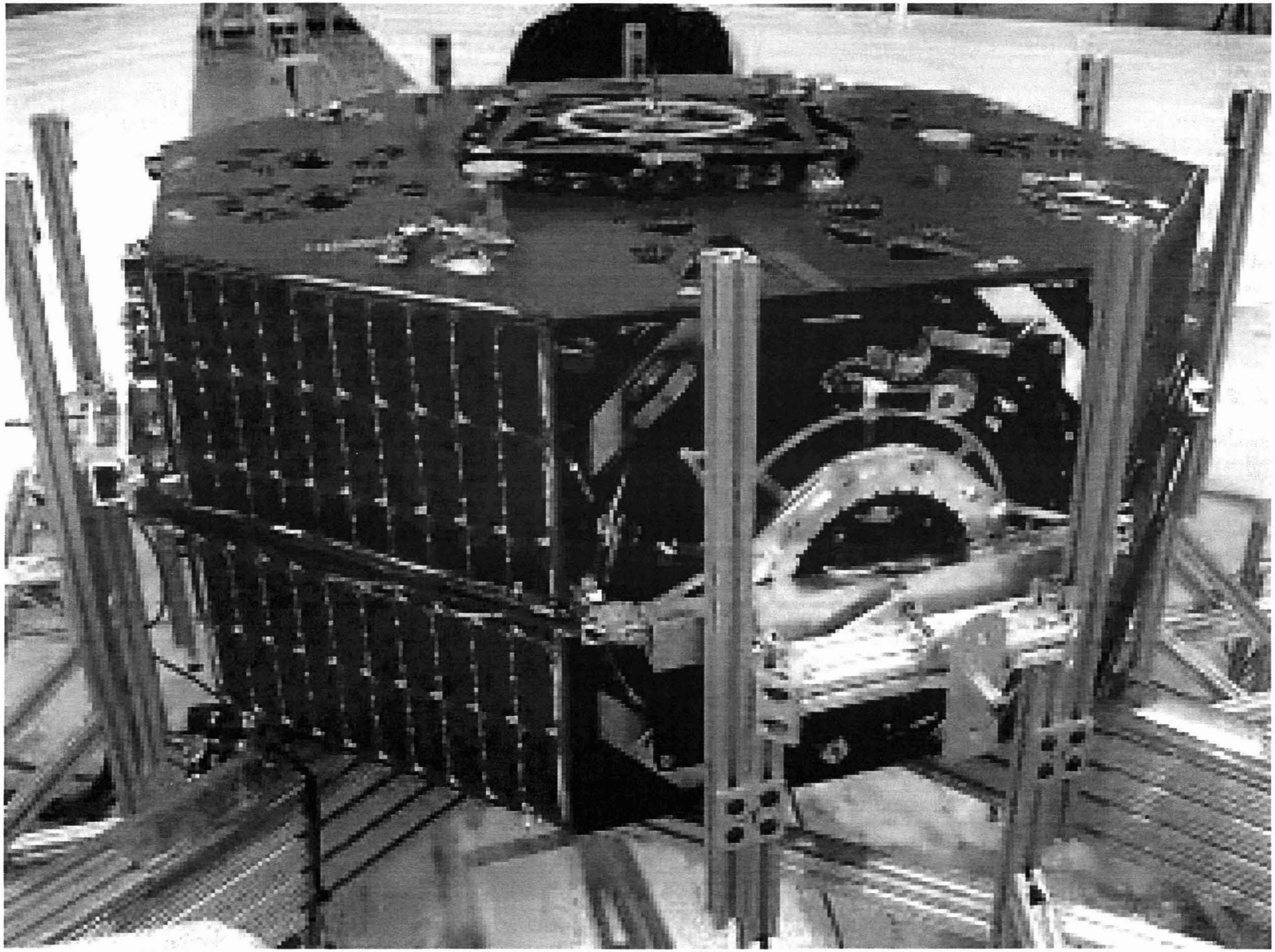


Sail Production



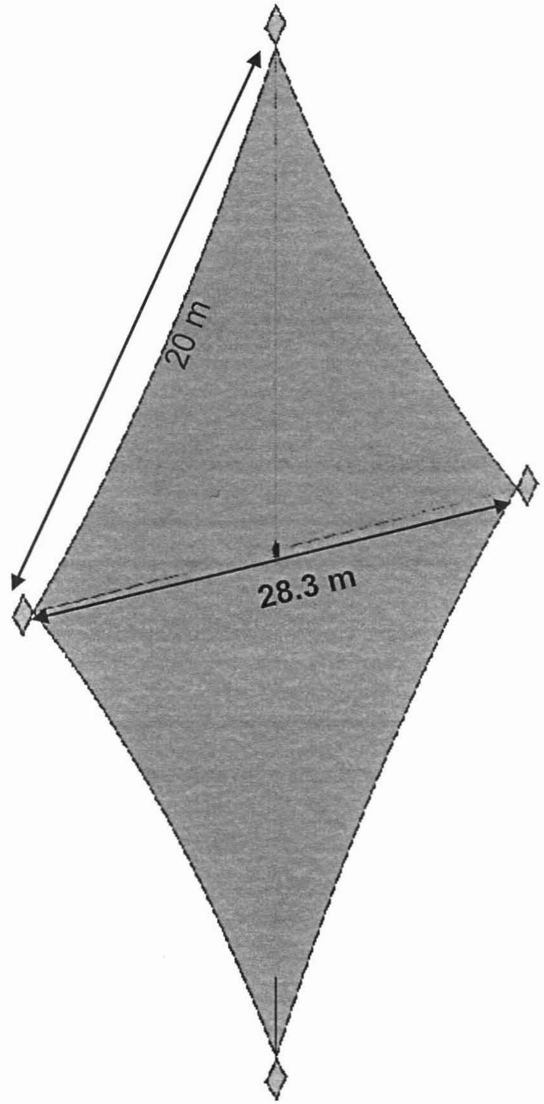
SRS CNC Seaming System

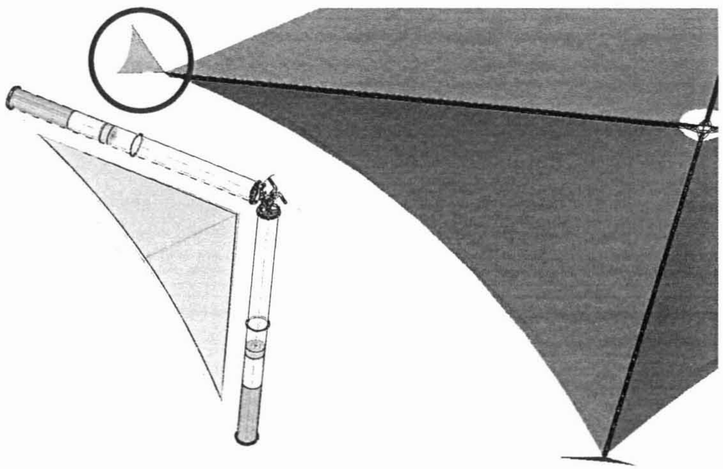
ATK Ambient Deployment at Plum Brook



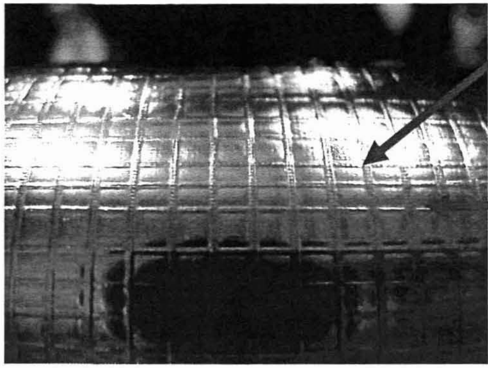
L'Garde Task Summary

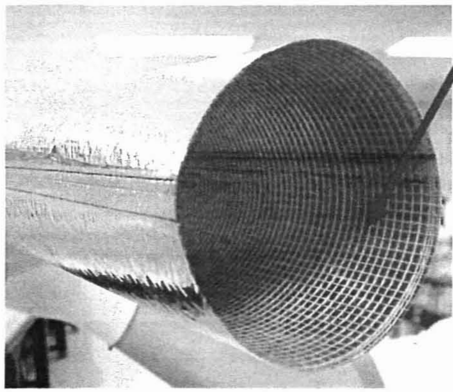
- ♦ PI: David (Leo) Lichodziejewski, L'GARDE, Inc.
- ♦ Proposal Team:
  - L'GARDE, Inc. (Tustin, CA) systems engineering and inflatable truss
  - Ball Aerospace & Tech Corp. (Boulder, CO) mission eng. & bus design
  - LaRC (Hampton, VA) sail modeling & testing
  - JPL (Pasadena, CA) mission planning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





Beam Design



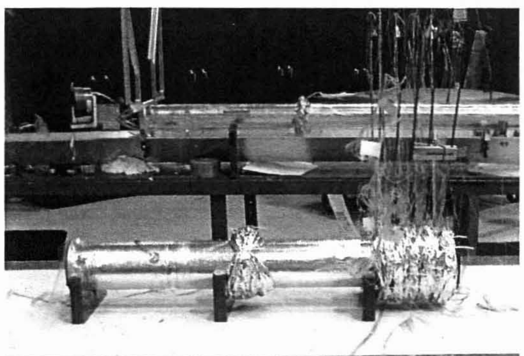


Load bearing longitudinal uni-directional fibers
- Fibers impregnated with sub-Tg resin (rigid below -20° C)
- 0.48 AU design requires greater fiber density to withstand loads from the increased solar flux

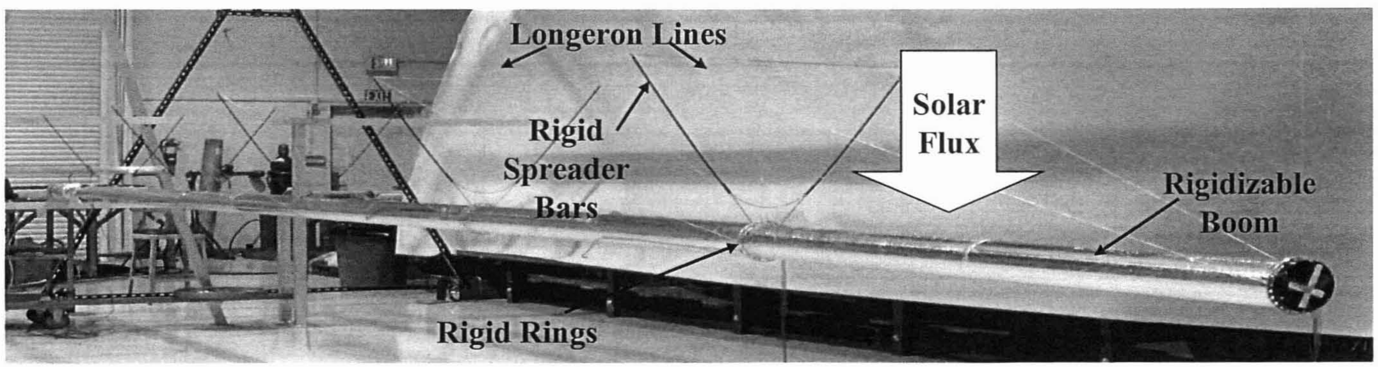
Spiral wrap
- Stabilizes longitudinal fibers
- Allows over-pressurization for deployment anomalies

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

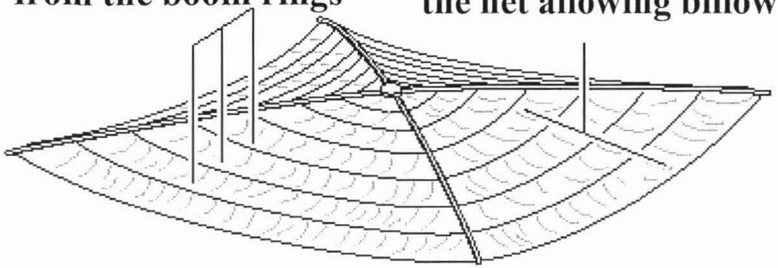


Stowed 7 m boom (~.5 m)

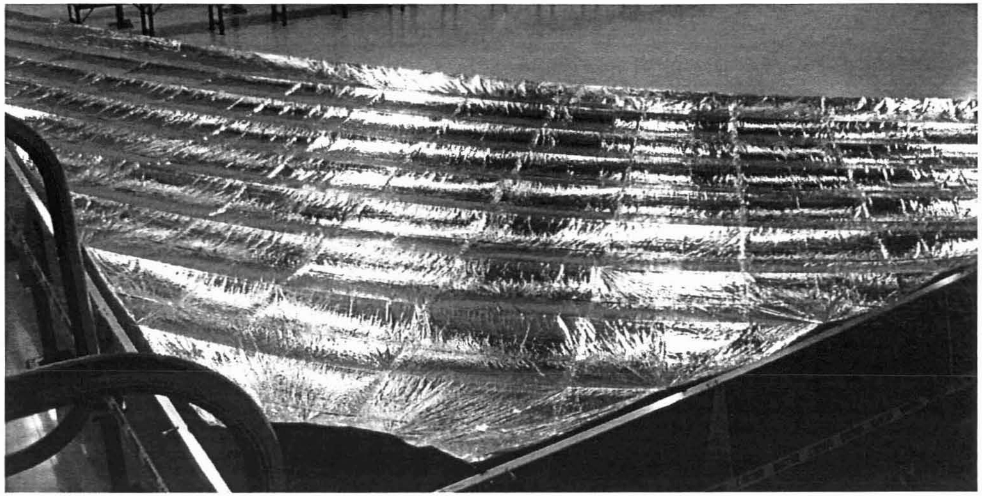


Deployed 7 m boom

Net/Membrane Sail Design



Net/Membrane Sail Schematic



20m Sail Quadrant

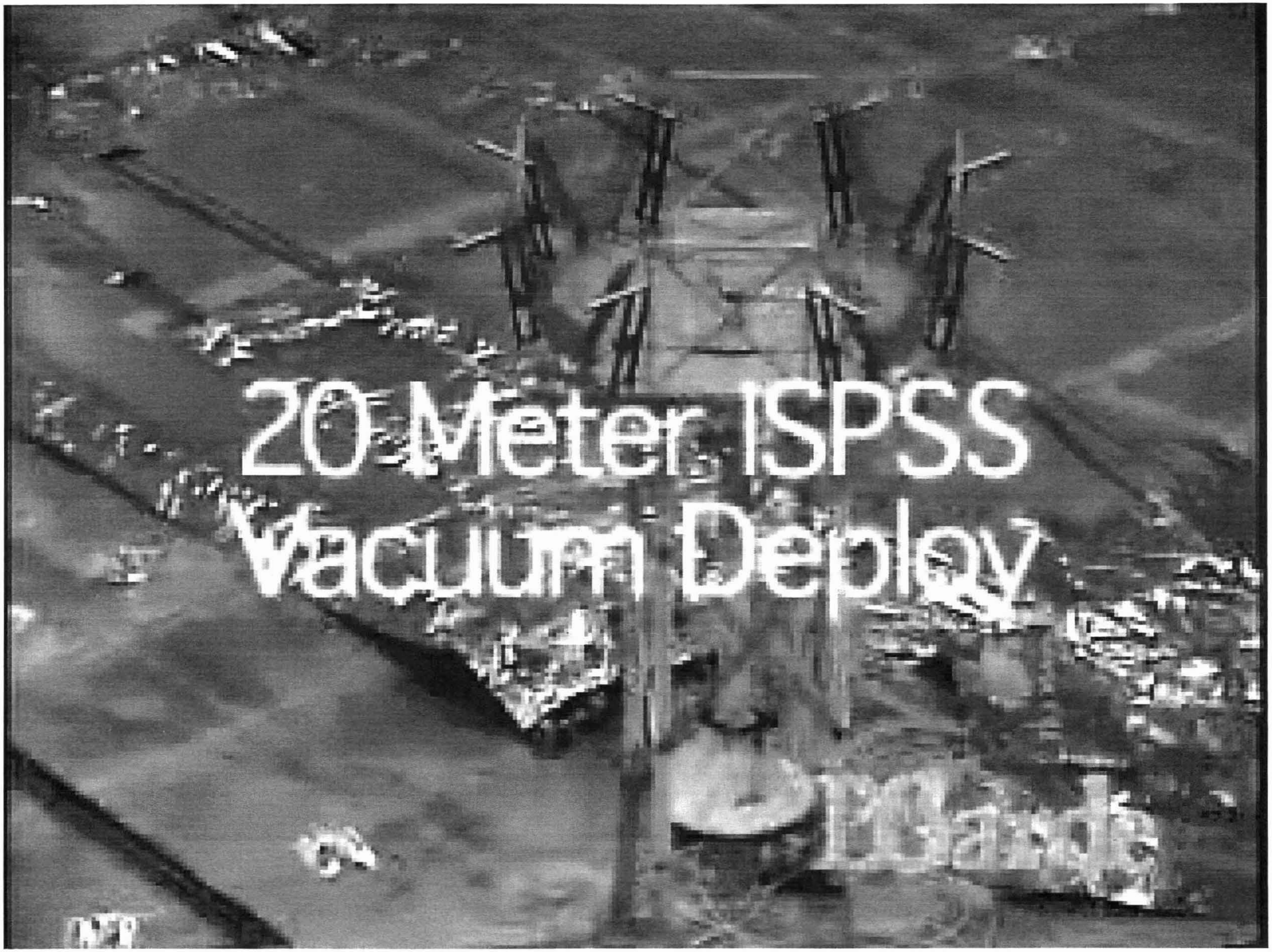
Net Membrane

- Sail is supported by a high modulus, low CTE net, additional membrane material allows thermal compliance
- Sail properties effect local billow between net members only, global sail shape is stable

Advantages

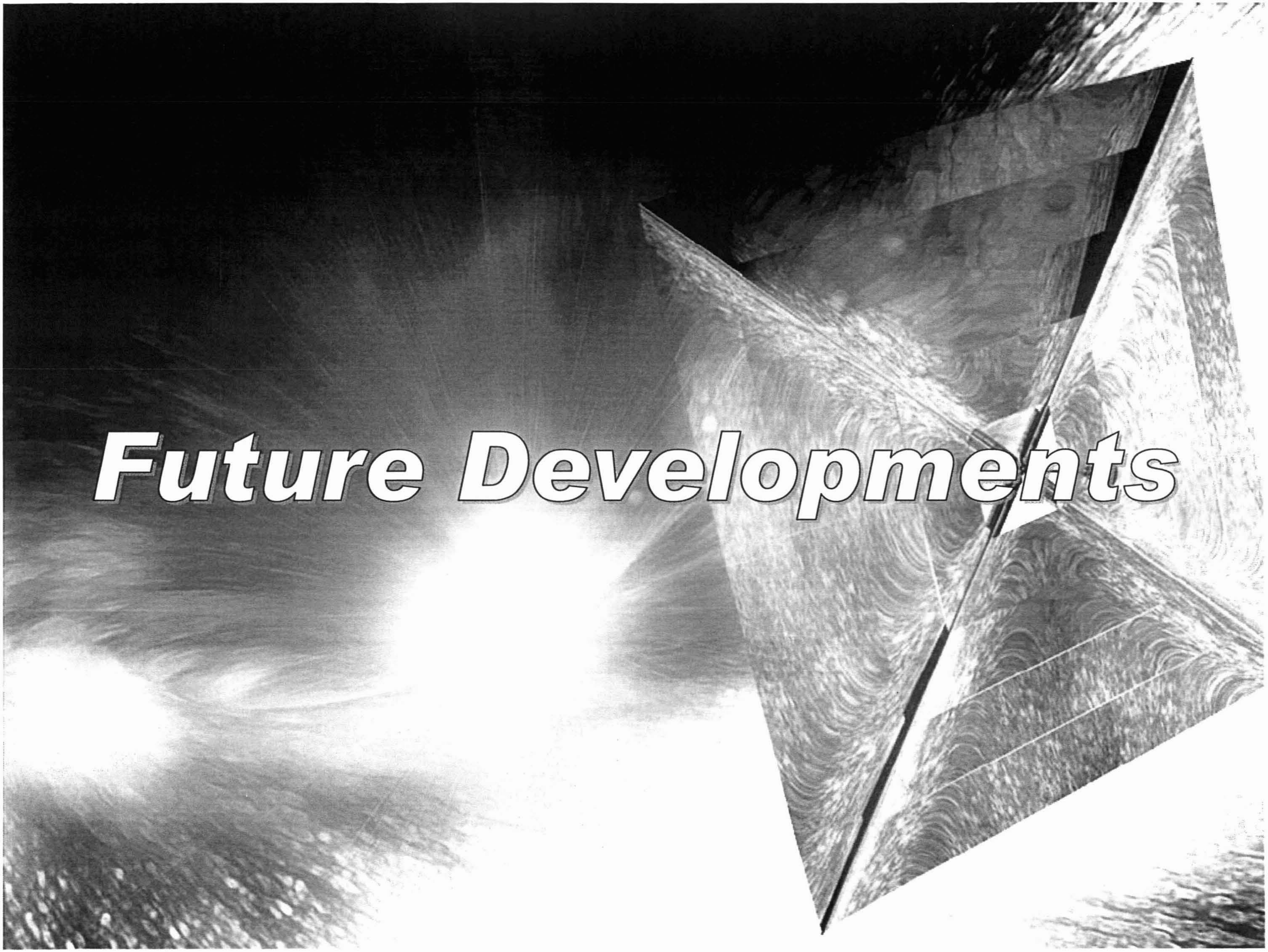
- Net defines the overall sail shape, not the membrane
- Stability and geometry of the sail is effectively decoupled from membrane properties
- Sail shape, and hence thrust vector, sailcraft stability and performance, are predictable and stable
- No high local stress concentrations in the sail, loads 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 20m GSD Vacuum Deploy

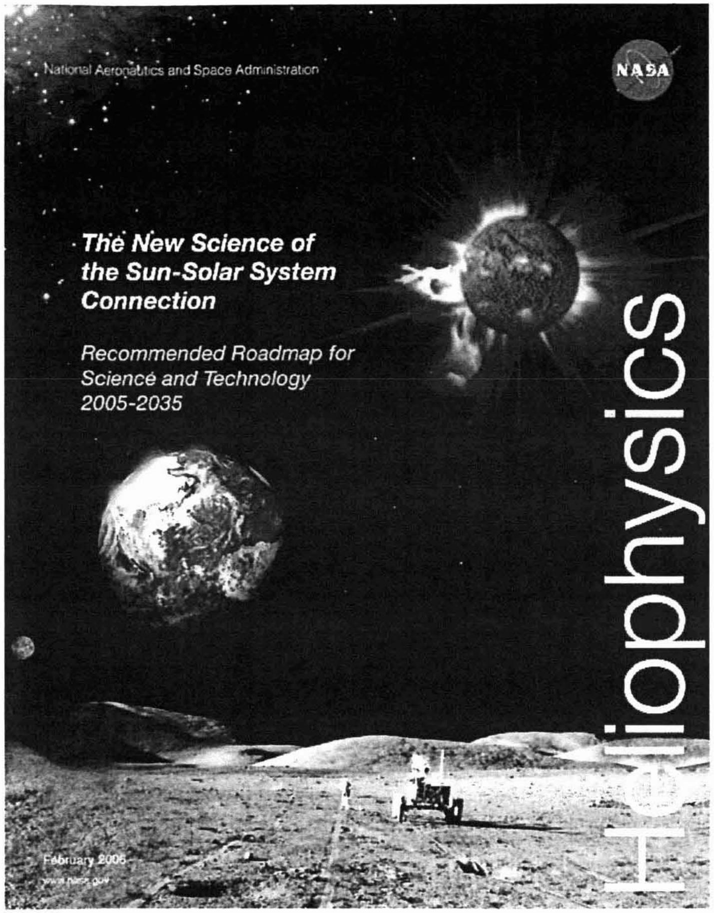


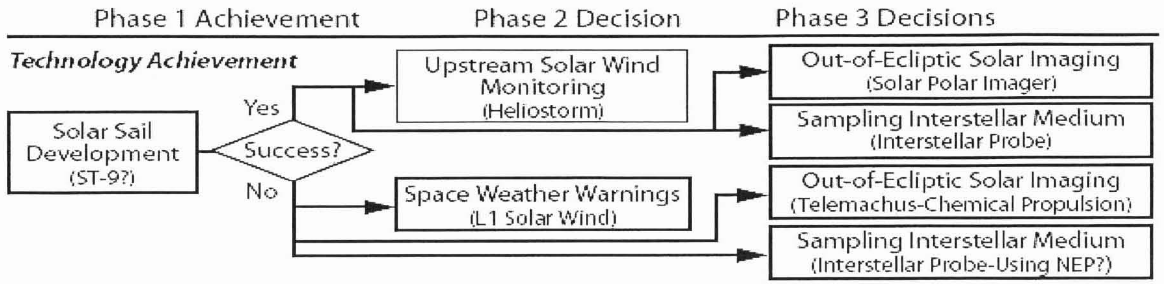
Solar Sails Notables

- Designed, built, delivered, and safely tested in a ground environment two 20m solar sail systems using different technologies
- Subjected materials to high doses of radiation verifying on-orbit life time characteristics
- Developed a flight mechanics simulation capable of modeling non-Keplerian orbits
- Conducted static and dynamic response tests and multiple deployments of two 400 square meter sails from a one square meter box at a high vacuum in the largest diameter space test chamber in the world (Plum Brook). 500 Gb of data generated.
- Subjected stowed systems to launch loads and ascent vent tests prior to deployment.
- Modal Test Frequencies measured matched predicted values to within ten percent.
- Developed repair techniques for membranes and booms.
- Developed and used in test the largest high resolution photogrammetric shape measurement system in the world.
- Developed a mission concept to extend warning times to Earth for damaging solar events from 30 minutes to 90 minutes.
- Successfully applied conventional finite element modeling techniques to large area gossamer space structures.
- Determined the extent to which gossamer structures can be verified by test on the ground.
- Identified a tendency for torsional dynamic modes in the booms to migrate to bending modes.
- Discovered that wrinkles and other small defects have small impact on propulsion performance.
- Discovered significant robustness against spacecraft charging.


Future Developments

Heliophysics Draft Roadmap – 5/2006





Solar Sail Demo (SSD) **page 62**

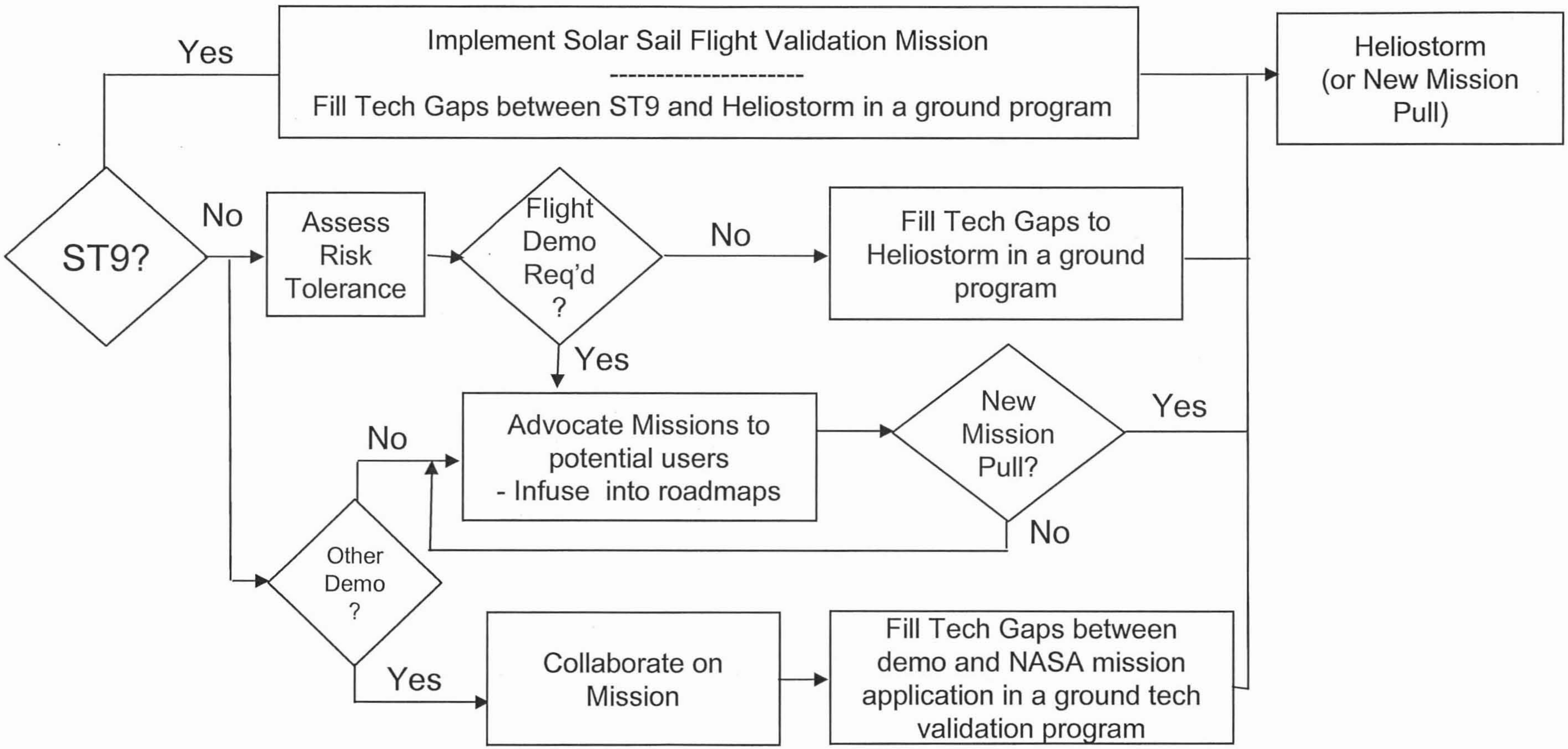
Because of the impossibility of fully validating Solar Sail technology on the ground, the application of solar sails to a strategic science mission **absolutely** requires a prior successful flight validation. **- page 93**

Heliostorm, in the LWS line, uses solar sails to hover twice as far up-stream as an L1 mission. **This is the preferred option.** The Helio-physics mission cost would be similar to an Explorer if NOAA and DoD partner with NASA. - **page 60**

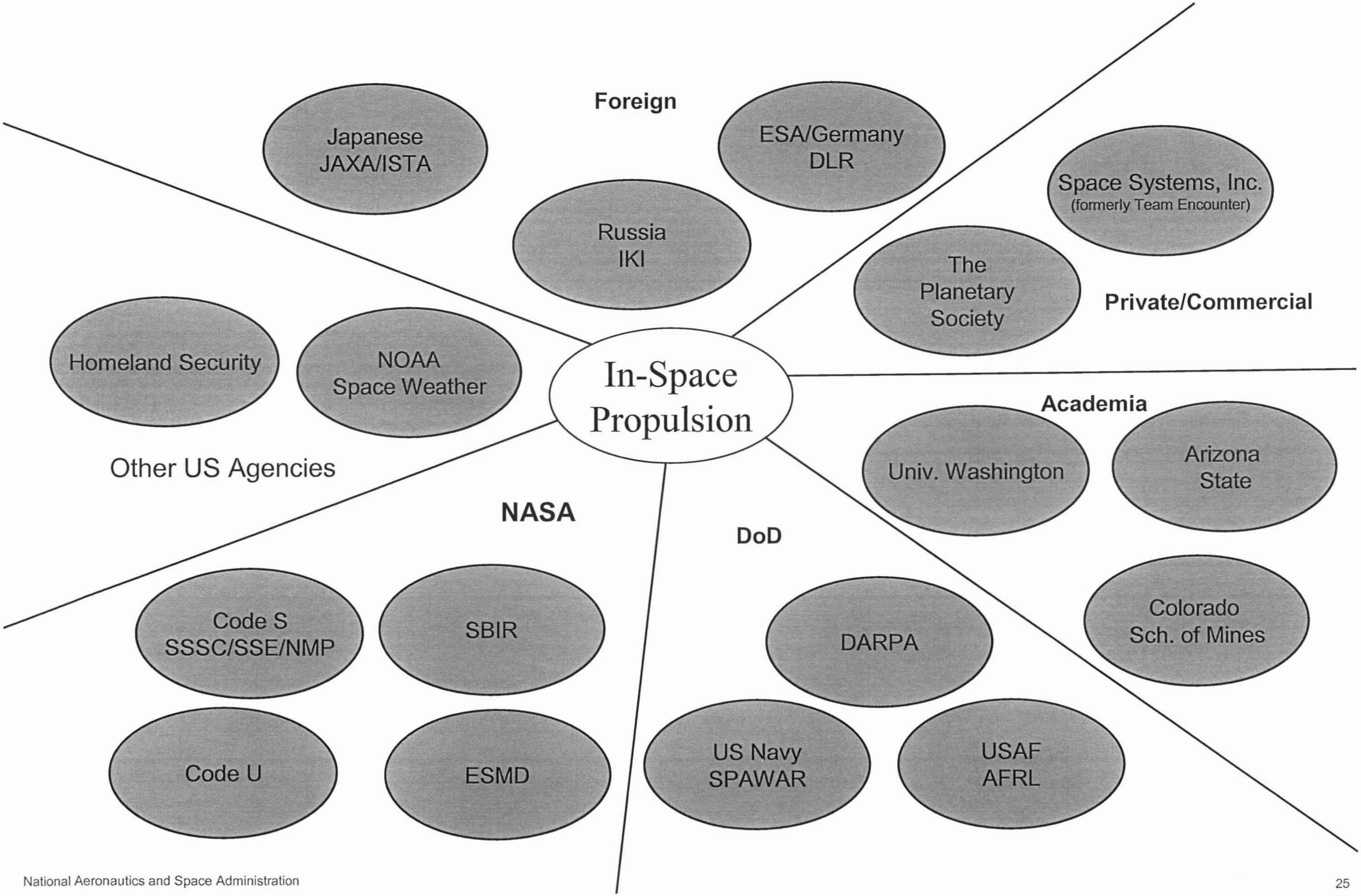
We encourage continued development of this technology *(solar sails)* and support the idea of a flight demonstration during Phase 1 of this Roadmap (CY 2005 – 2015). **- page 118**

Progress in key areas of Heliophysics science requires access to unique vantage points and in some cases, non-Keplerian orbits. For example, imaging of the Sun's polar regions requires a high-inclination, heliocentric orbit. Conventional technology would require either 5 years of solar electric propulsion and multiple Venus flybys just to reach a 38° inclination in the inner heliosphere (as for ESA's Solar Orbiter) or a Jovian gravity assist and conventional propulsion to provide an eccentric 0.25 x 2.5 AU polar orbit (as for our future Telemachus mission). **Neither means is as efficient or cost effective as solar sail technology. – page 97**

TRL Completion Logic



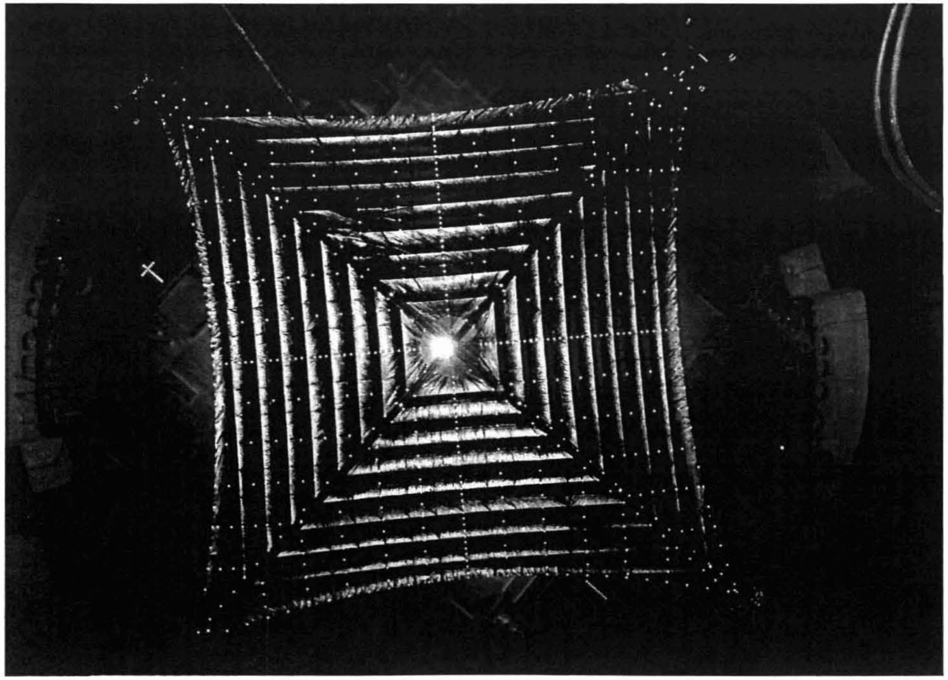
Growing Number of Solar Sail Activities

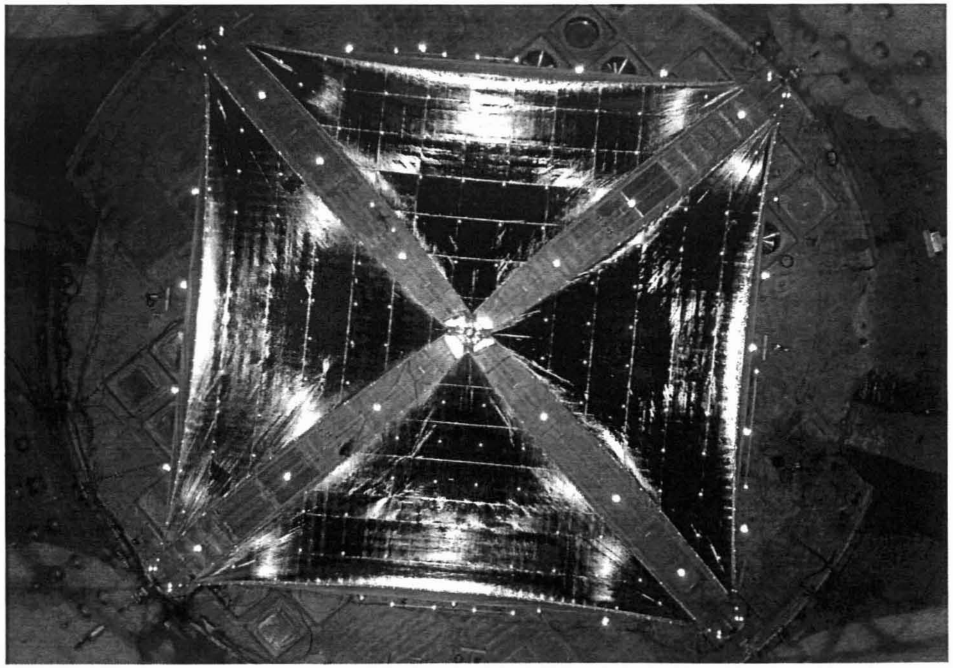


Technology Advantages

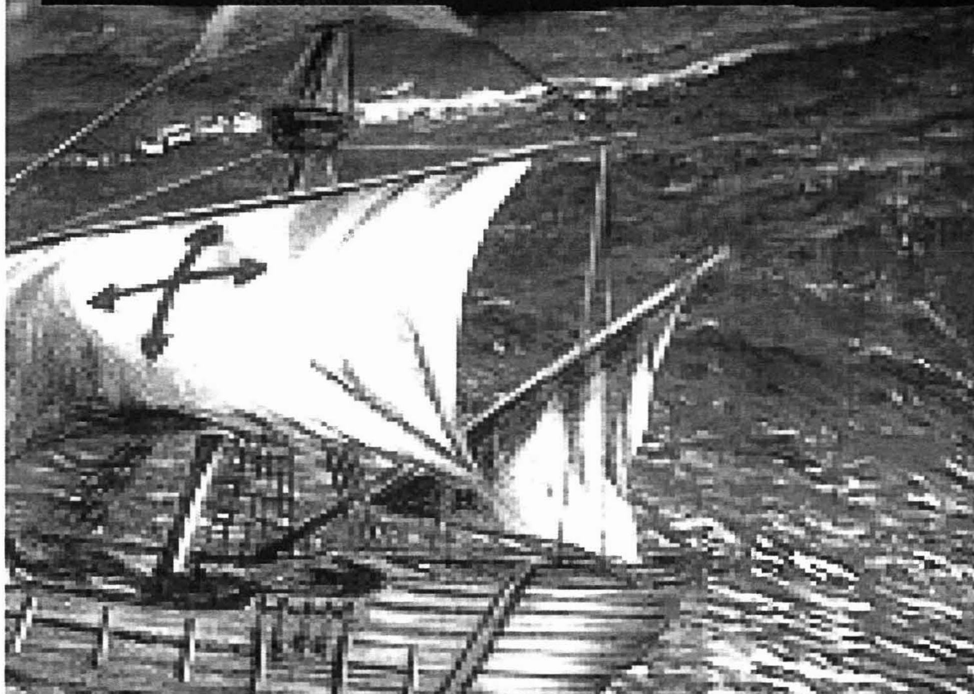
Low Cost to Develop & Operate

- ♦ Simple
  - Few moving mechanical parts
  - Low complexity
  - Quasi-Steady State
  - Small in size – payloads and stowed system
  - Autonomous, robotic
- ♦ Safe
  - No High temperatures
  - No High pressures
  - No High Power
  - No Toxic fuels
  - Loads are vanishingly small
- ♦ Technology Benefits
  - No propellants required
  - Low system complexity (challenge is scaling to large area with ultra-low density)
  - Low environmental impact on payload
  - Enables access to previously inaccessible orbits (e. g., non-Keplerian, fixed reference, and high inclination orbit changes)





For additional information on the Solar Sails Propulsion task areas within the In-Space Propulsion Technology Program, please contact:



Solar Sails – Catch the wave Of the future!!!

Edward E. (Sandy) Montgomery IV
Technology Area Manager, Solar Sail Propulsion
Mail Stop VP51
MSFC, AL 35812

Phone: 256-544-3485
Email: Sandy.montgomery@nasa.gov

Roy Young
Lead System Engineer
Mail Stop EI61
MSFC, AL 35812

phone: 256-544-0283
Email: roy.young@nasa.gov

Charles L. Adams, P.E.
Systems Engineer
Gray Research
MSFC, AL 35812

Phone: 256-544-3501
Email: charles.l.adams@msfc.nasa.gov

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