Overview of Ongoing Solar Sail Projects Worldwide

ESTEC/DLR Gossamer Workshop
14 February 2011
Noordwijk, NL

W. Keith Belvin …
NASA Langley Research Center
Hampton, VA USA

… with contributions from many others

Solar Sail Overview

- **Second International Symposium on Solar Sailing (July 2010)**
  - **Review of Mission Applications**

- **Recent/Ongoing Solar Sail Projects**
  - USA
  - Canada
  - UK
  - ESTEC and DLR
  - Japan

- **Future Directions**

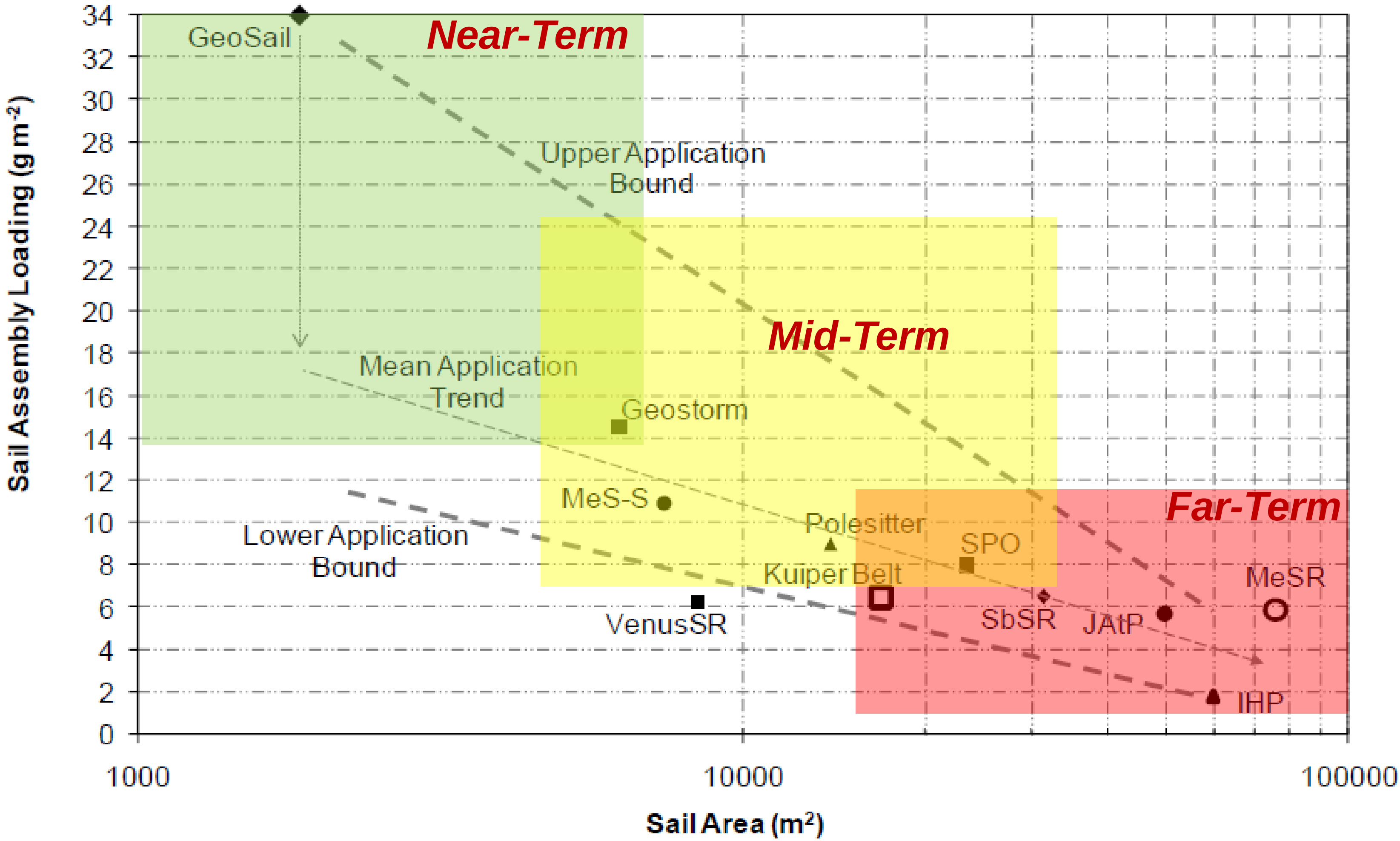
Solar Sail Benefits

Enabled or Significantly Enhance	Marginal benefit	No benefit
Non-Inertial Orbits, such as GeoSail or a Mercury Sun-Synchronous Orbiter	Venus escape at end of sample return mission	Planetary escape at start of mission
Highly Non-Keplerian Orbits such as Geostorm and Polesitter	Mercury and high-energy small body Sample Return missions	Mars missions
Kuiper-Belt fly-through	Outer solar system planet fly-by	Outer solar system rendezvous and centred trajectories
Solar Polar Orbiter	Oort Cloud	Loiter at the Gravitational Lens
Interstellar Heliopause Probe		

***SOLAR SAIL MISSION APPLICATIONS AND FUTURE ADVANCEMENT*, Malcolm Macdonald, Colin McInnes,**
Proceedings of the Second International Symposium on Solar Sailing July 20 - 22, 2010 New York, USA.
http://www.citytech.cuny.edu/isss2010

Positive Characteristic	Negative Characteristic
Very High Energy transfer trajectory	Mars and Venus rendezvous
Inner Solar System	Outer Solar System rendezvous
Highly Non-Keplerian and Non-Inertial orbits	Short orbit period with rapid slew manoeuvres
Final stage in a multi-stage system	High radiation environment
Fly-by beyond the orbit of Neptune	High pointing stability required
	Required to rendezvous with a passive body
	Fly-by beyond solar gravitational lens

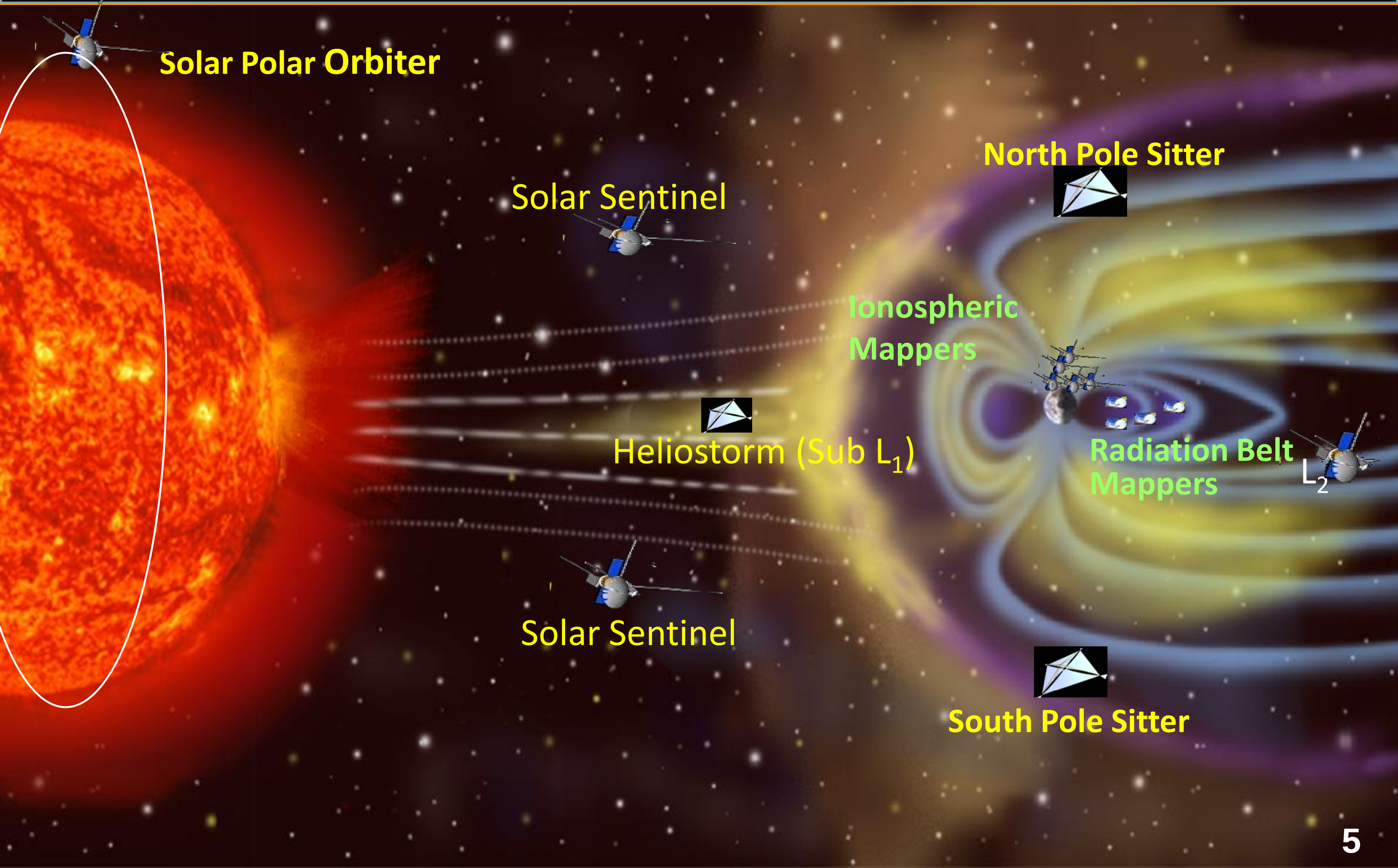
Solar Sail Performance Requirements



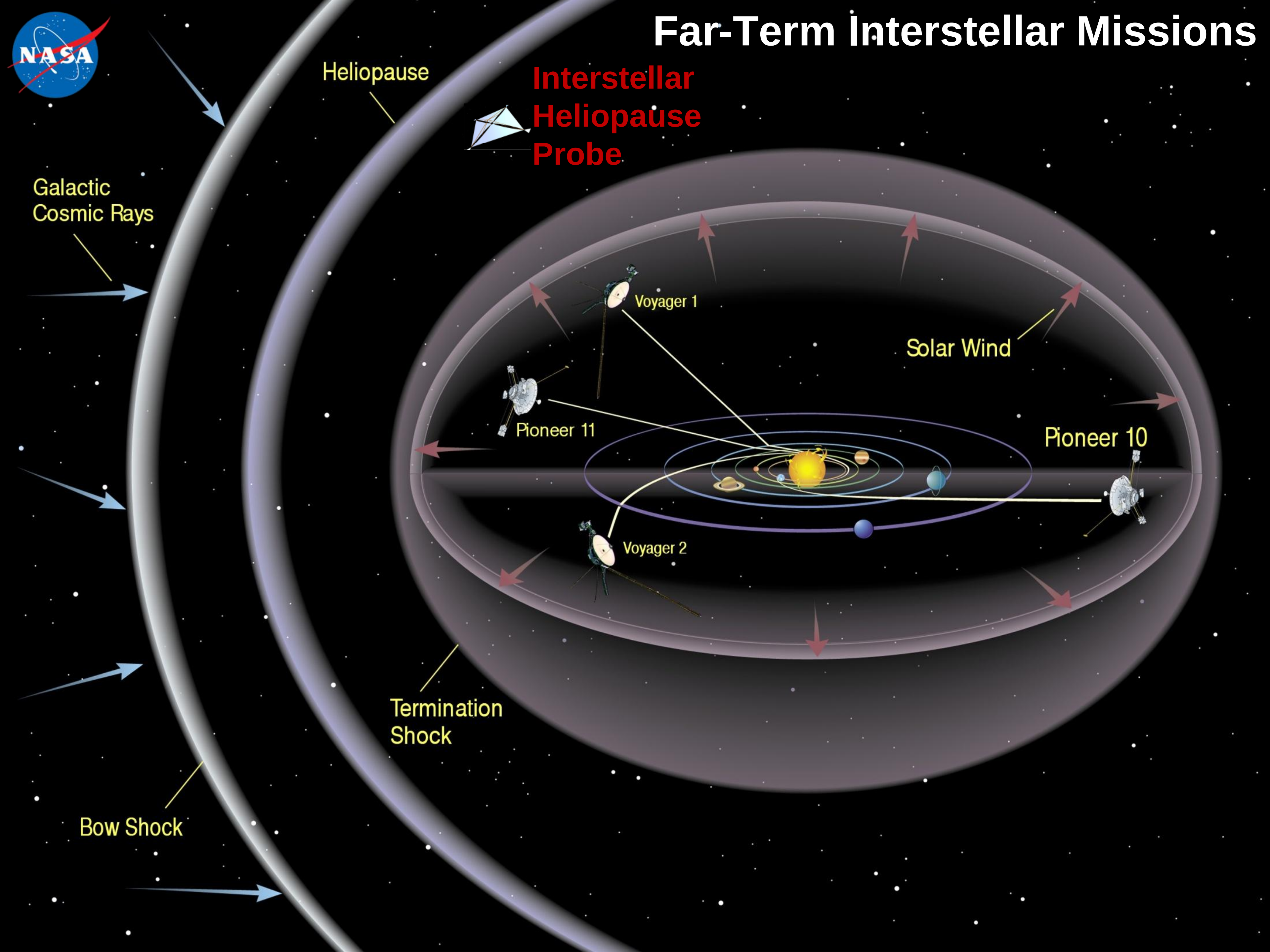
Solar sail mission catalogue application technology requirements. *IHP ≡ Interstellar Heliopause Probe; JAtP ≡ Jupiter Fly-by with Atmospheric Probe release; MeSR ≡ Mercury Sample Return; MeS-S ≡ Mercury Sun-Synchronous; SbSR ≡ High-Energy Small-Body Sample Return; SPO ≡ Solar Polar Orbiter; VenusSR ≡ Venus Sample Return.*

SOLAR SAIL MISSION APPLICATIONS AND FUTURE ADVANCEMENT, Malcolm Macdonald, Colin McInnes, **Proceedings of the Second International Symposium on Solar Sailing July 20 - 22, 2010 New York, USA.**
http://www.citytech.cuny.edu/isss2010

Near- and Mid-Term "Space Weather" Missions

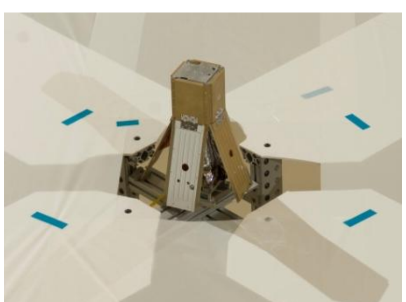


Far-Term Interstellar Missions



NASA NanoSail-D:
A Solar Sail Demonstration Mission

- NASA's Marshall Space Flight Center and Ames Research Center
- Use of existing hardware, simple demonstration of deployment
- Cube-Sat class satellite, 10 m^2 deployed sail area
- Demonstrate orbital debris mitigation (Deorbit System for Spacecraft)



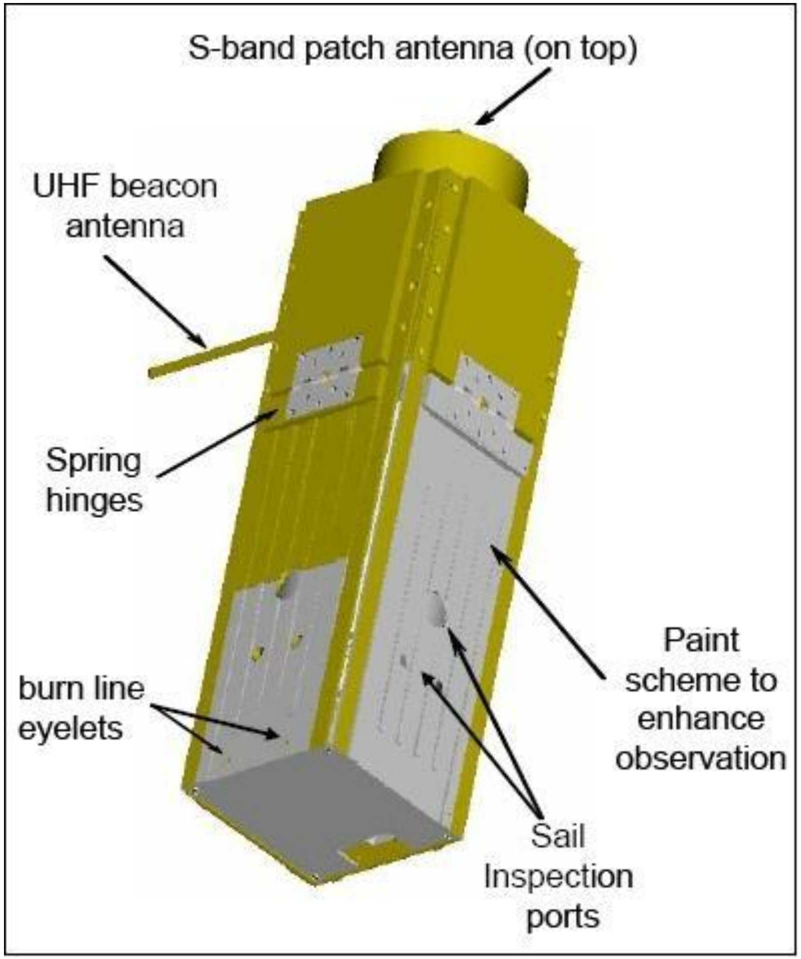
NanoSail-D 2 Summary

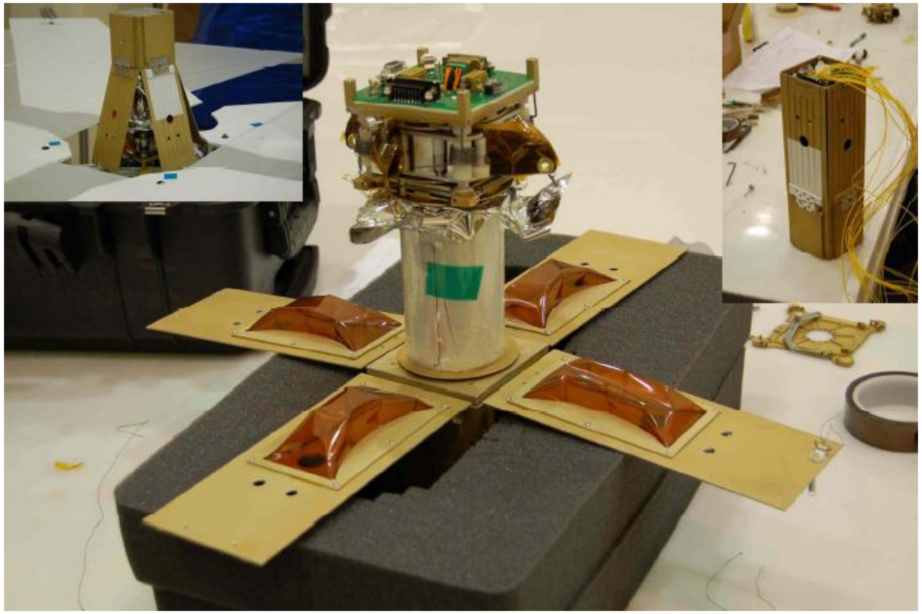
- Launched on 20 November 2010, FASTSAT was deployed into a circular orbit at 650 km altitude).
- The Nanosail was expected to be ejected from the P-POD on 6 December but, although the bay door opened, ejection did not occur.
- On 17 January, the CubeSat separated on its own from the P-POD and deployed its sail on 20 January.
- The beacon signal began transmitting at 437.270 MHz on 19 January and stopped transmitting on 21 January when the battery power was exhausted.
- The time from deployment to re-entry will be 70-120 days, depending on atmospheric conditions.

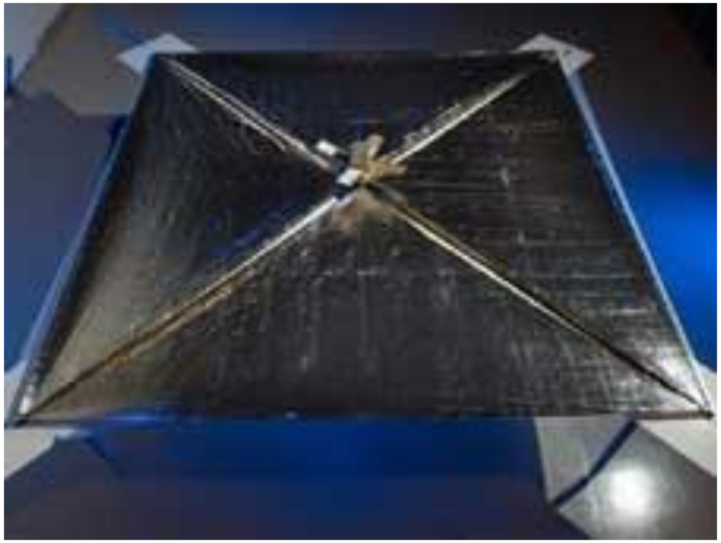
- NanoSail-D2 has a mass of 4.2 kg.
- Square shape and is composed of four triangular segments with a total area of 10 m^2. The sail material is 7.5 μm thick aluminium coated CP1 (Clear Polyimide).
- NanoSail-D2 uses four light-weight 2.25 m long TRAC (Triangular Rollable And Collapsible) booms which were developed by the Air Force Research Laboratory (AFRL) at Kirtland Air Force Base in New Mexico.
- The TRAC booms consist of two stainless steel metal strips formed into a c-shaped curve and laser welded together back-to-back forming an inverted v-shape.

http://nanosaild.engr.scu.edu/dashboard.htm

NanoSail-D Hardware







- Sail in Cubesat 2U Volume
- Integrated with Cubesat 1U Volume Bus

NanoSail-D “Trac” Booms

Elgiloy “Trac” Booms

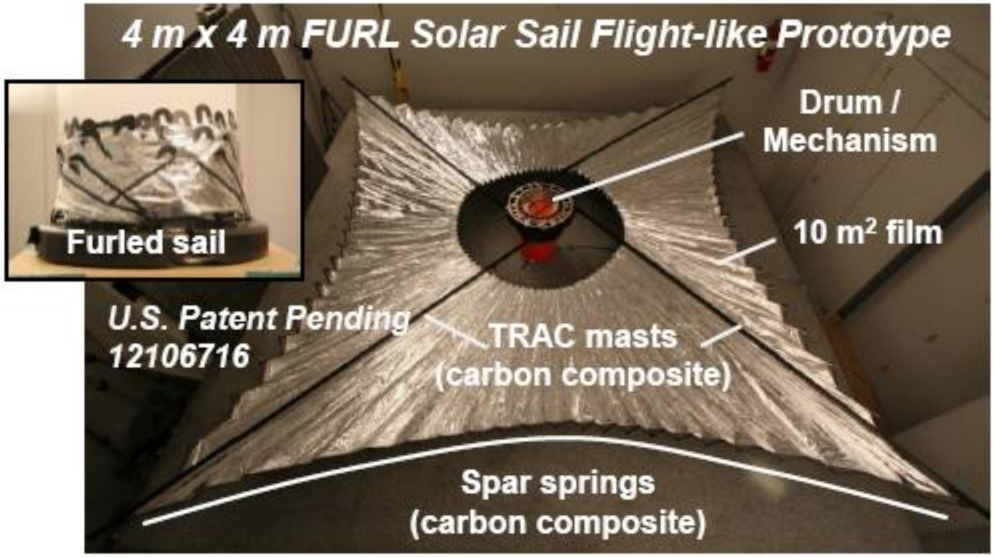
Boom Housing

Triangular Rollable And Collapsible (TRAC)

Elgiloy “Trac” Booms provided by AFRL – Pats Pending

AFRL Sail – October 2009

Retractable Solar Sail Payload for Micro-Satellites



- Open cross-section pinches and roll-stows
- Stored strain energy enforces deployment

Technical Approach

- Masts and film synchronously deploy from 38 cm drum
- Retraction kinematics enforced by a single actuator and elastic deformations of spar springs
- Designed for 100 deploy / retract cycles on-orbit, 5 min
- Demonstrated 100+ deploy / retract cycles on proof-of-concept demonstration unit without failure or binding
- Preparing for t-vac testing to demo structure at TRL 6

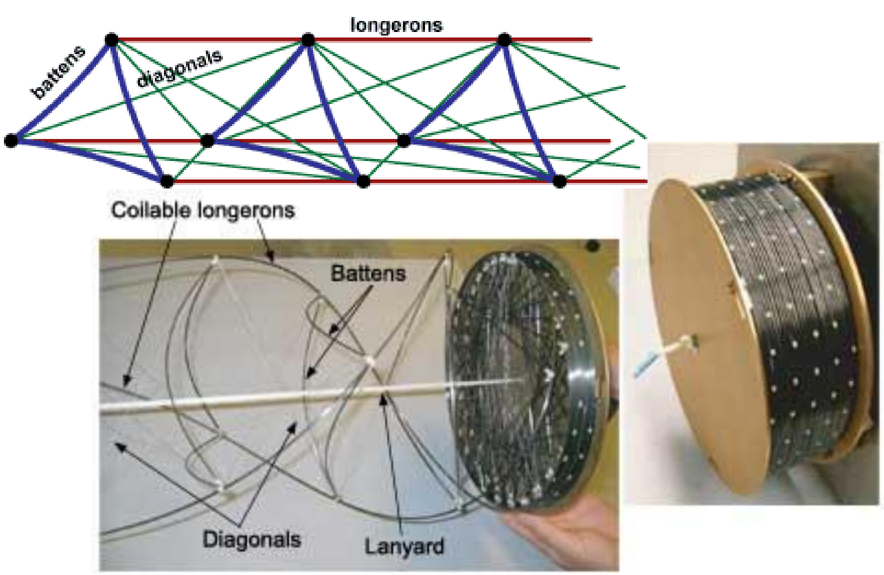
Mission Payoff

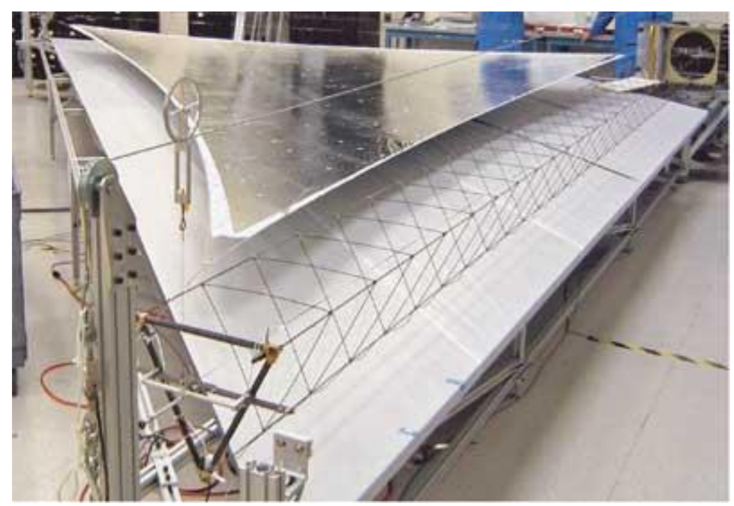
- Enables always changing orbits by providing continuous, propellant-free acceleration
- Reflects/scatters a range of the EM spectrum
- 0.16 mN max thrust from 6 kg system
- Extends missions with added delta V

NASA Sponsored Solar Sail Boom Development

- **SAILMAST** - Ultra-Light Coilable Boom (Developed by ATK Space Systems)
- Replaced conventional fiber glass longerons in coilable boom with high stiffness graphite.
- Validated Strength and Stiffness through extensive ground testing and analysis
    - 40-meter boom in an ambient laboratory environment
    - Overhead and air-bearing supports used to offset the effects of gravity during deployment and characterization tests
    - Static load tests and dynamic tests conducted in a horizontal plane to obviate the effects of gravity

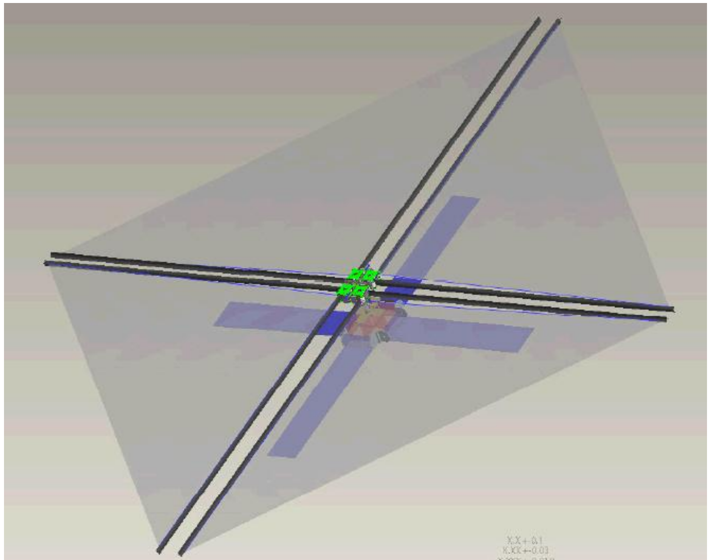
McEachen, M. ,The Validation of SAILMAST Technology and Modeling by Ground Testing of a Full- Scale Flight Article, 48th AIAA Aerospace Sciences Meeting, 4- 7 Jan 2010 Orlando, Florida, AIAA-2010-1491 .

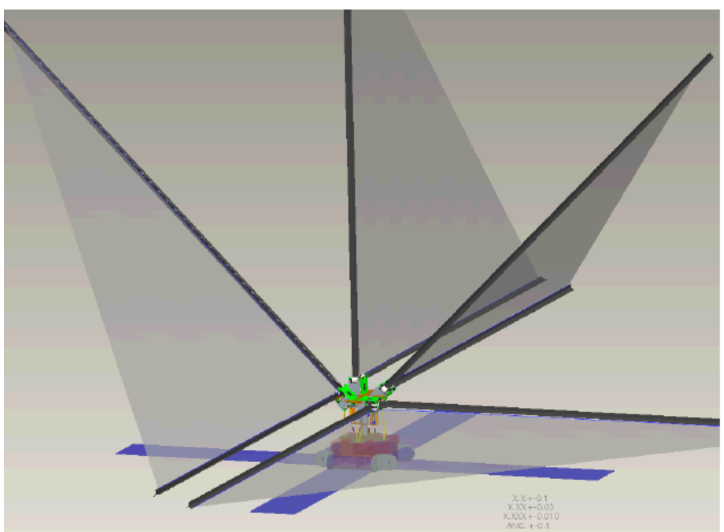




FeatherSail

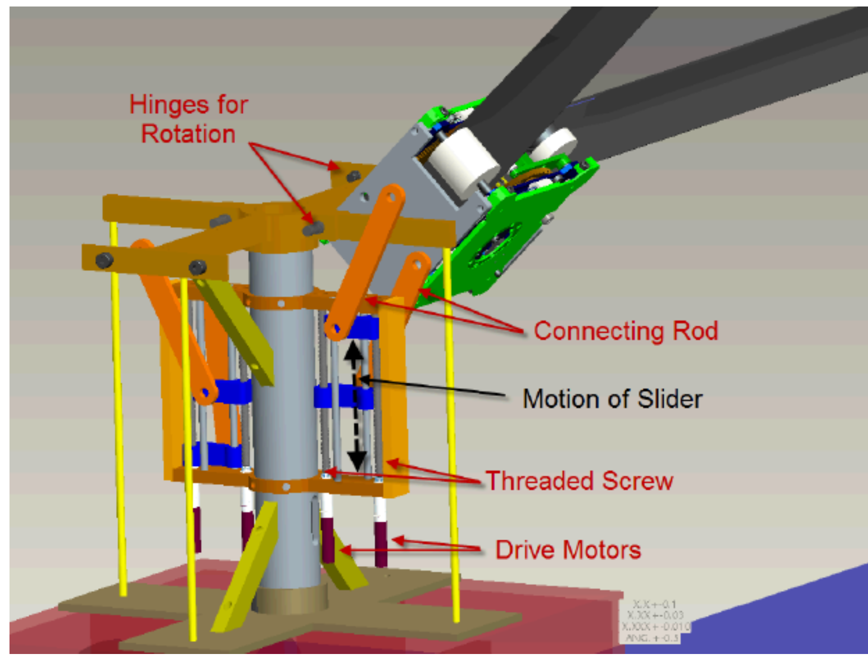
Marshall Space Flight Center





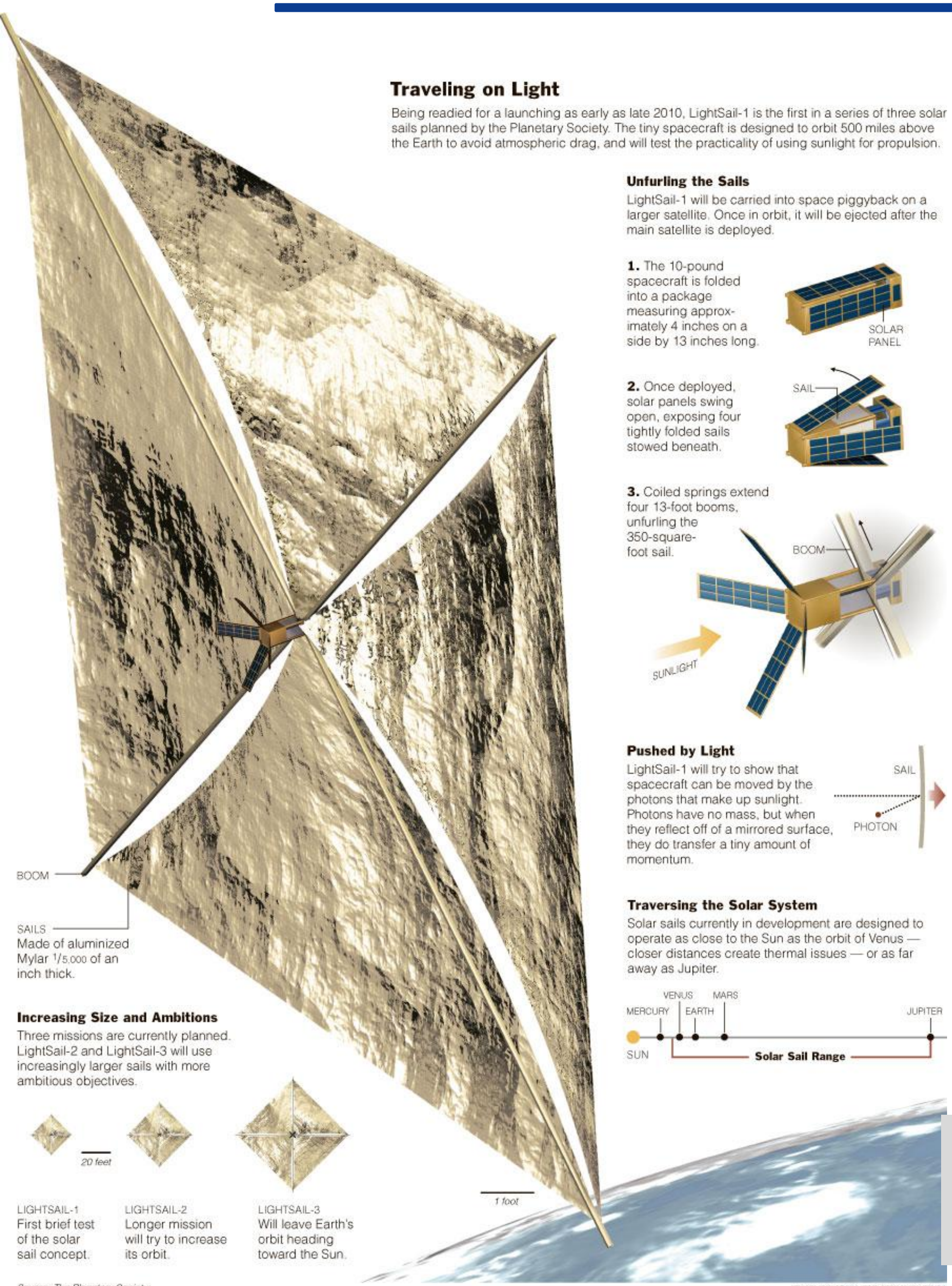
•The goal of the FeatherSail design concept is to demonstrate recent technological innovations:

- •Dependable sail deployment systems;
- •Steerable solar sails;
- •Deployable thin film solar arrays;
- • Low temperature, radiation tolerant Silicon-Germanium (SiGe) electronics.



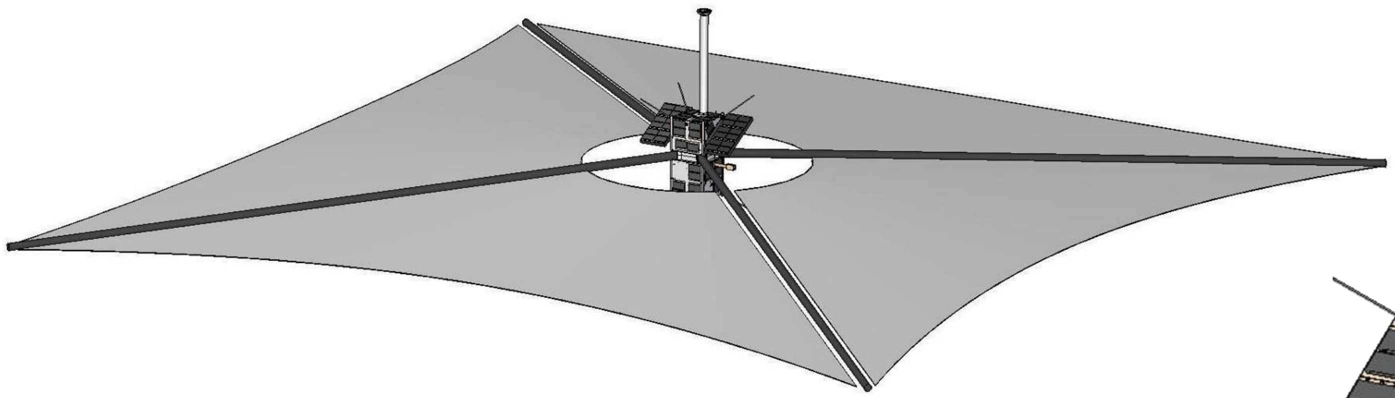
FEATHERSAIL – THE NEXT GENERATION NANO-CLASS SAIL VEHICLE, Dean Alhorn, **Proceedings of the Second International Symposium on Solar Sailing July 20 - 22, 2010 New York, USA.**
http://www.citytech.cuny.edu/isss2010

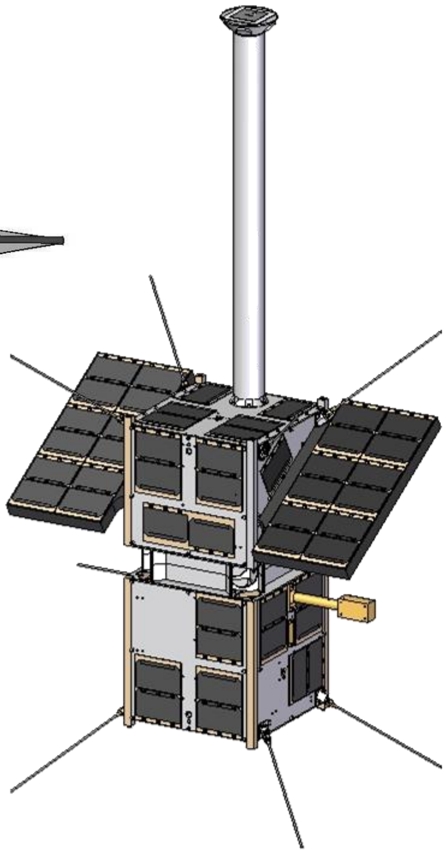
Planetary Society – LightSail-1



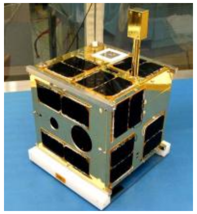
[Lightsail 1 - Flying on Light for Less](http://www.citytech.cuny.edu/isss2010), Jim Cantrell and Louis Friedman, Proceedings of the Second International Symposium on Solar Sailing July 20 - 22, 2010 New York, USA.
http://www.citytech.cuny.edu/isss2010

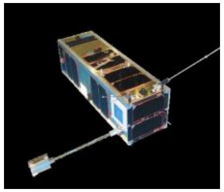
CanX-9 With Sail and Bus

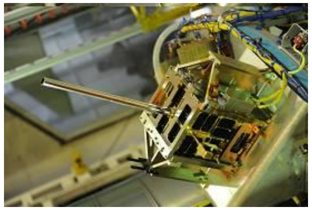




- Canadian Advanced Nanospace eXperiment program
- Developing/flying significantly capable nanosats (1-10+ kg)
- Providing nanosat launch services via XPOD launcher



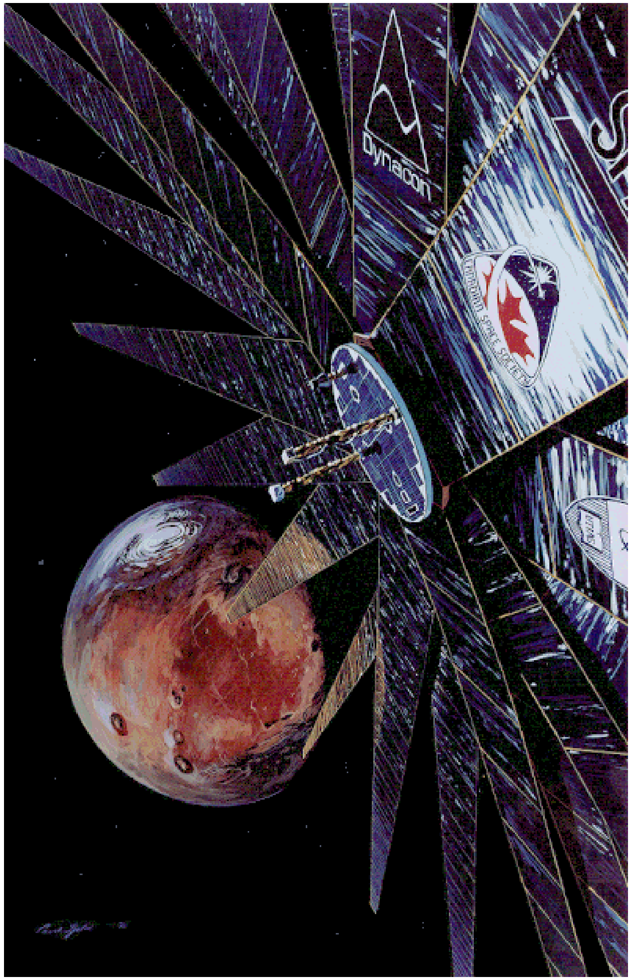




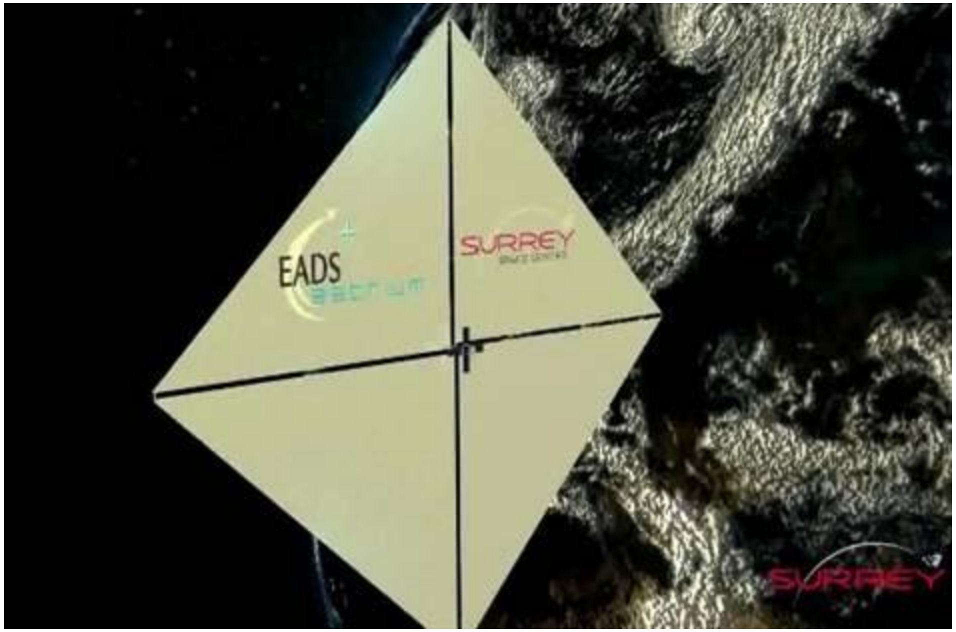
A Nanosatellite Mission to Assess Solar Sail Performance in LEO Kieran A. Carroll
Proceedings of the Second International Symposium on Solar Sailing July 20 - 22, 2010 New York, USA.
http://www.citytech.cuny.edu/isss2010

Canada Solar Sail Project (CSSP) Eventual Preliminary Design

- **Novel spinner**
- **“Pinwheel” configuration**
- **30 vanes, each 30 x 0.5 m, stowed and deployed roller-blind fashion**
- **3 of the vanes with adjustable angle of attack for spin-rate control**
- **Precess spin vector (and hence sail pointing) direction via shifting mass center**
- **25 kg, 500 m^2**
- **Microsat-class**
- **Scout or Pegasus launch to escape**



CubeSail



Dr Vaios Lappas
Space Vehicle Control Group
Senior Lecturer
Email: v.lappas@surrey.ac.uk

- **Use sail as a 'propellantless' deorbiting system.**

- **The CubeSail would simply unfurl a 16-square-foot (5-square-meter) sail. Launch of the 6.6-pound (3-kg) sail is set for late 2011.**

- **Note: An update on this work is to be given by Dr. Lappas at the Third Gossamer Workshop (ESTEC)**

GeoSail

•GEOSAIL is a low cost, innovative mission whose main purpose is to demonstrate solar sails as a feasible propulsion concept

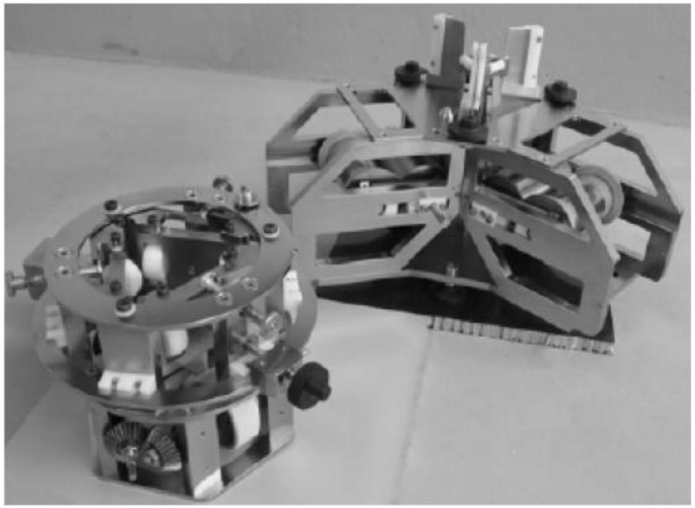
• It was devised by McInnes/Macdonald in 2000 and then refined in other work

• Within this mission, a solar sail is used to precess the apse line of an elliptical orbit whose major axis lies along the Earth's geomagnetic tail.

•The precession rate is chosen such that the orbit apogee remains continuously in the geomagnetic tail, thus allowing for long duration magnetospheric plasma research

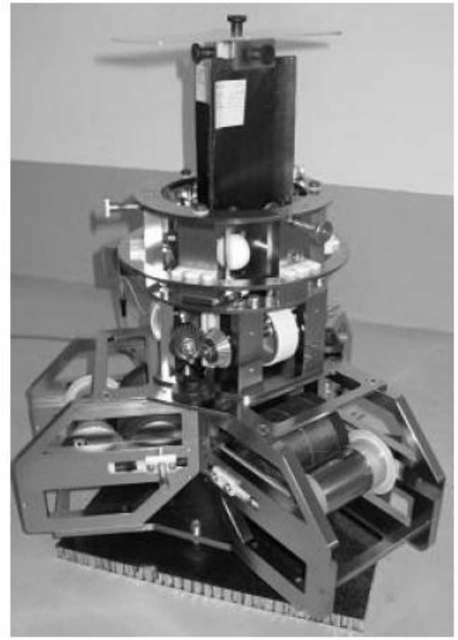
Practical Systems Design for an Earth Magnetotail Monitoring Solar Sail Mission , Vaios Lappas, Proceedings of the Second International Symposium on Solar Sailing July 20 - 22, 2010 New York, USA.
http://www.citytech.cuny.edu/isss2010

GeoSail Mechanism/Booms



(a)

(b)



(c)

IOB Breadboard Deployment Module (a) separated in fixed and ejectable parts (b) launch mode (c) deployed

- **In Orbit Bonding (IOB) technology shifts the assembling process into orbit.**
- **The storage of two semi-finished half sections allows compact storage**
- **Optimises the structure with respect to the mass requirements**
- **The IOB sail design allows jettisoning of this mass fraction after reaching its desired size, thus substantially reducing the sail mass**

ESA/DLR Gossamer Solar Sail Program

11/06/2009: DLR-ESA Gossamer Roadmap

Gossamer -1: **2014** **2013,**

demonstration of safe deployment of a 5m x 5m solar sail, 320km

- *Apr 2014 Shipment of CubeSat flight models to the launch site*
- *Second half Jun 2014 Launch*

Gossamer -2: **? 2014,**

deployment of a 20m x 20m solar sail, demonstration of limited orbit and full attitude control, 500km

- Verification of deployment and sail attitudes changes by 4 on board wide field cameras and free flying „Inspector“

Gossamer -3: **? 2015,**

deployment of a 50m x 50m solar sail, demonstration of full orbit and attitude control, > 10.000km

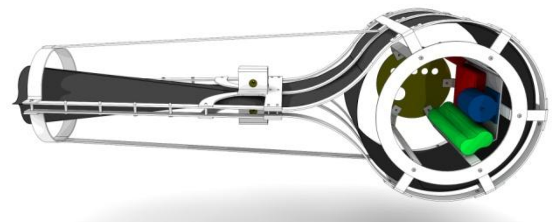
- Real Solar Sailing

[*The Three-Step DLR-ESA Gossamer Road Map to Solar Sailing*](http://www.citytech.cuny.edu/isss2010), Franz Lura, Bernd Biering, Ulrich R.M.E. Geppert and R. Reinhard, Proceedings of the Second International Symposium on Solar Sailing July 20 - 22, 2010 New York, USA. http://www.citytech.cuny.edu/isss2010

DLR Deployable Boom Project

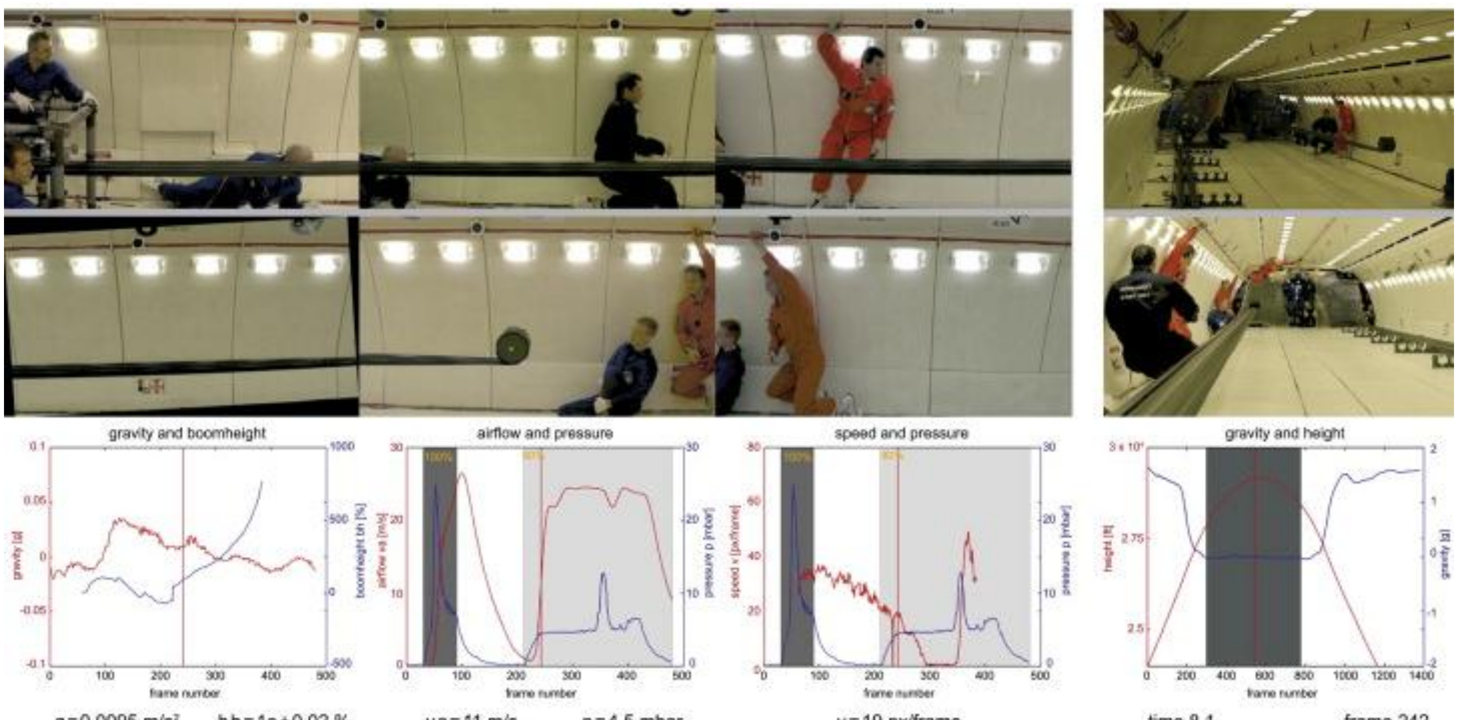
Deutsches Zentrum für Luft- und Raumfahrt e.V. in der Helmholtz-Gemeinschaft

Deployable CFRP Boom with Control System – DLR



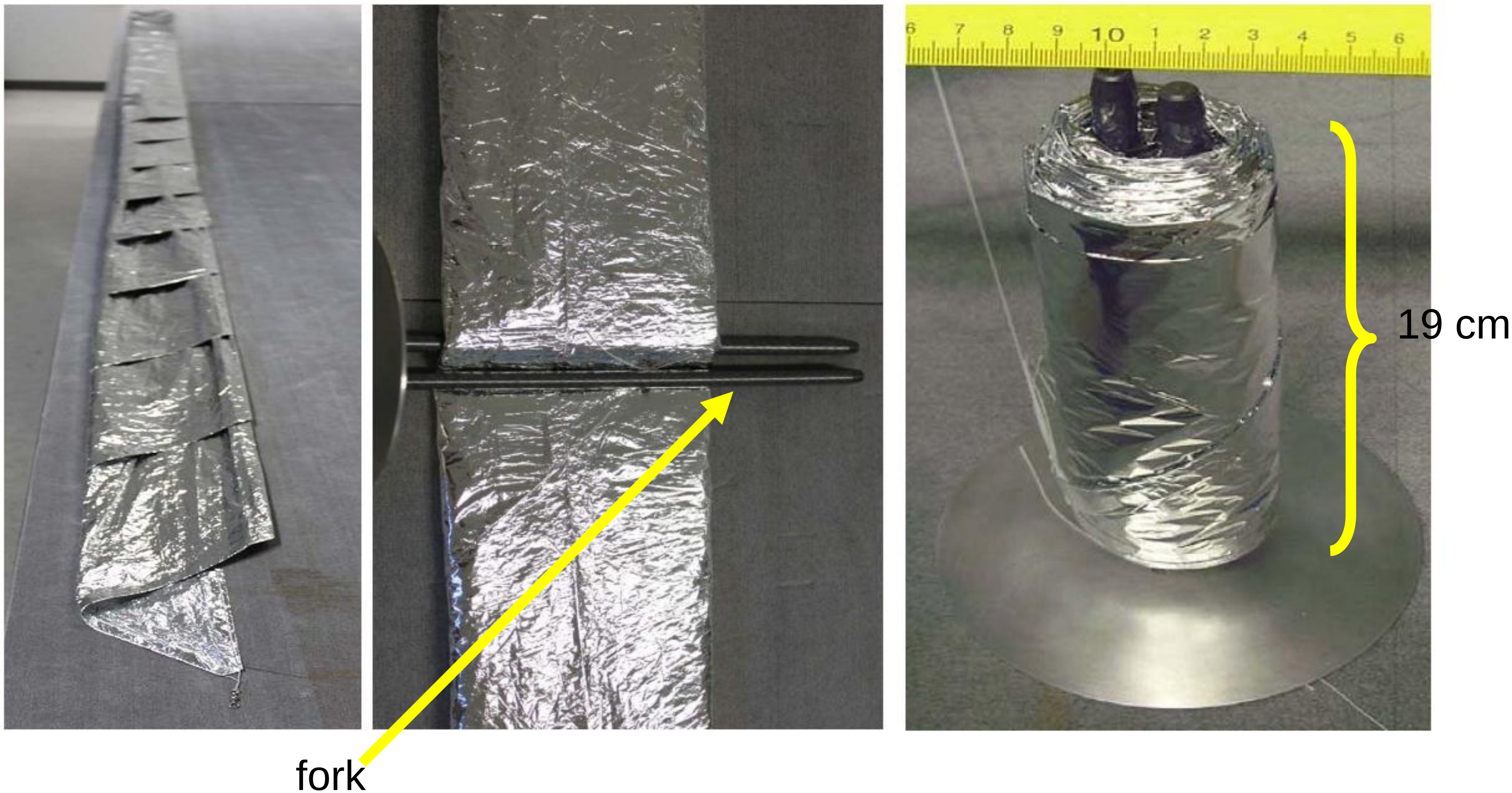
Deployment Mechanism – DLR

Ultralight deployable booms for solar sails and other large gossamer structures in space ,Joachim Block, Marco Straubel and Martin Wiedemann· DLR – German Aerospace Center – Braunschweig, Germany. [Acta Astronautica](), [Volume 68, Issues 7-8](), April-May 2011.



Gossamer-1: Folded and Furled 5m x 5m Sail

roll folding along · roll folding cross · coil



The Three-Step DLR-ESA Gossamer Road Map to Solar Sailing, **Franz Lura, Bernd Biering, Ulrich R.M.E. Geppert and R. Reinhard, Proceedings of the Second International Symposium on Solar Sailing July 20 - 22, 2010 New York, USA.** http://www.citytech.cuny.edu/isss2010

Gossamer-1: Distribution of Responsibilities

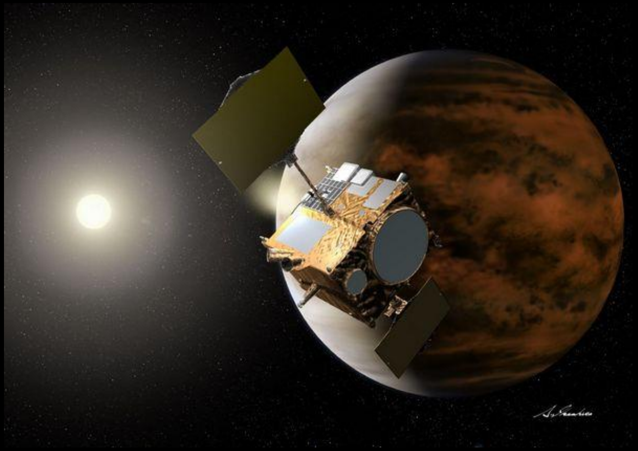
• ***Boom technology:*** **DLR Institute of Composite Structures and Adaptive Systems (J. Block)**

•***Service module:*** **Kayser-Threde (M. Leipold)**

•***Launch coordination with QB50:*** **ESA (R. Reinhard)**

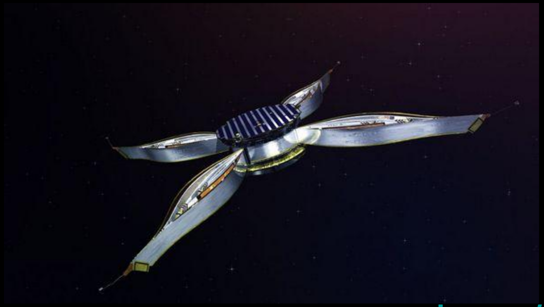
•***Sail and deplyoment technology:*** **DLR Institute for SpaceSystems (F. Lura)**

***The Three-Step DLR-ESA Gossamer Road Map to Solar Sailing*, Franz Lura, Bernd Biering, Ulrich R.M.E. Geppert and R. Reinhard, Proceedings of the Second International Symposium on Solar Sailing July 20 - 22, 2010 New York, USA. http://www.citytech.cuny.edu/isss2010**



Japanese Aerospace Exploration Agency and Mitsubishi HeavyIndustries, Ltd. succeeded in launching Venus probe “Akatsuki” which created a “first” in Japan’s space technology development, by an H-IIA rocket launched from the Tanegashima spaceport. Akatsuki's H-IIA rocket carried aloft a group of smaller satellites.

A lot of interest has centered on a solar sail project called Ikaros (Interplanetary Kite-craft Accelerated by Radiation Of the Sun).

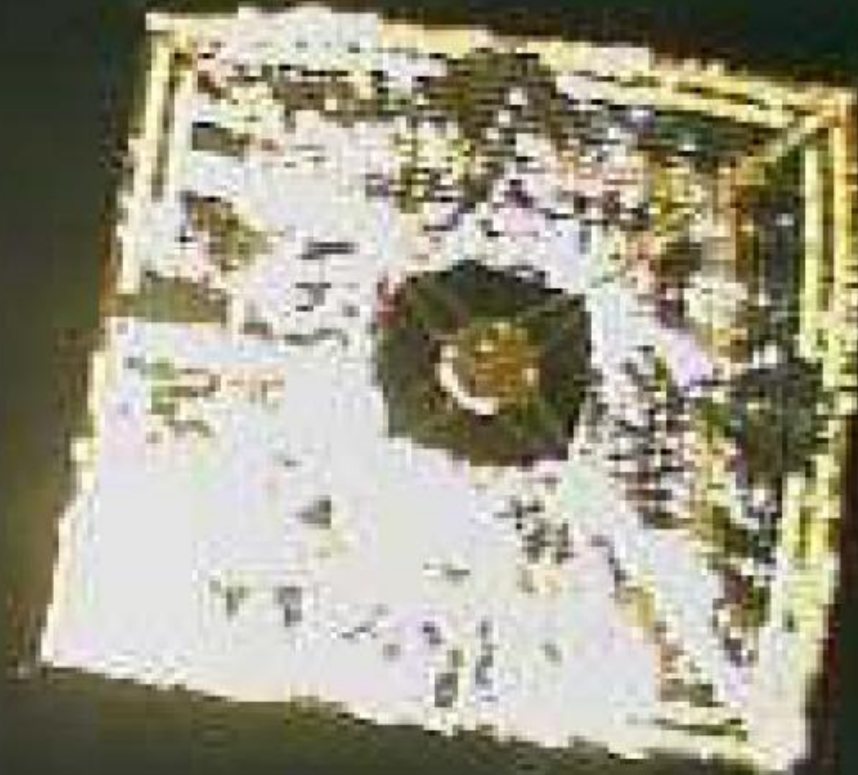


http://www.jspec.jaxa.jp/e/activity/ikaros.html

IKAROS

Interplanetary Kite-craft Accelerated by Radiation Of the Sun

The Deep Space Solar Power Sail Demonstrator



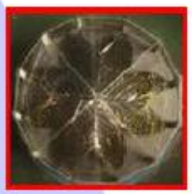
Sail Size: 14m x 14m
S/C Weight: 307kg
Orbit: Venus Transfer

Launch: May 21, 2010
Sail Deployment: June 9, 2010

Sail Development in JAXA

2002
Vacuum Chamber Test (D=2m)

2003
Balloon Drop Test (D=4m)

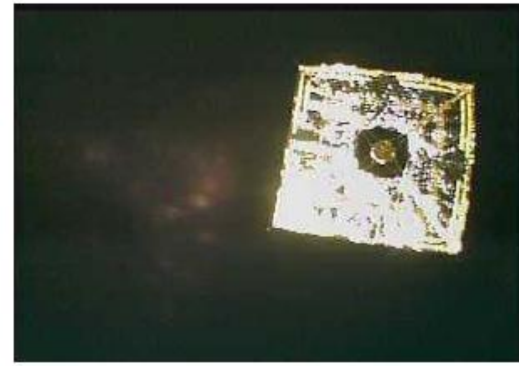


2003-2004
Spin Table Test (D=2.5m)

2004
Ballistic Flight Test (D=10m)
(Sounding Rocket)

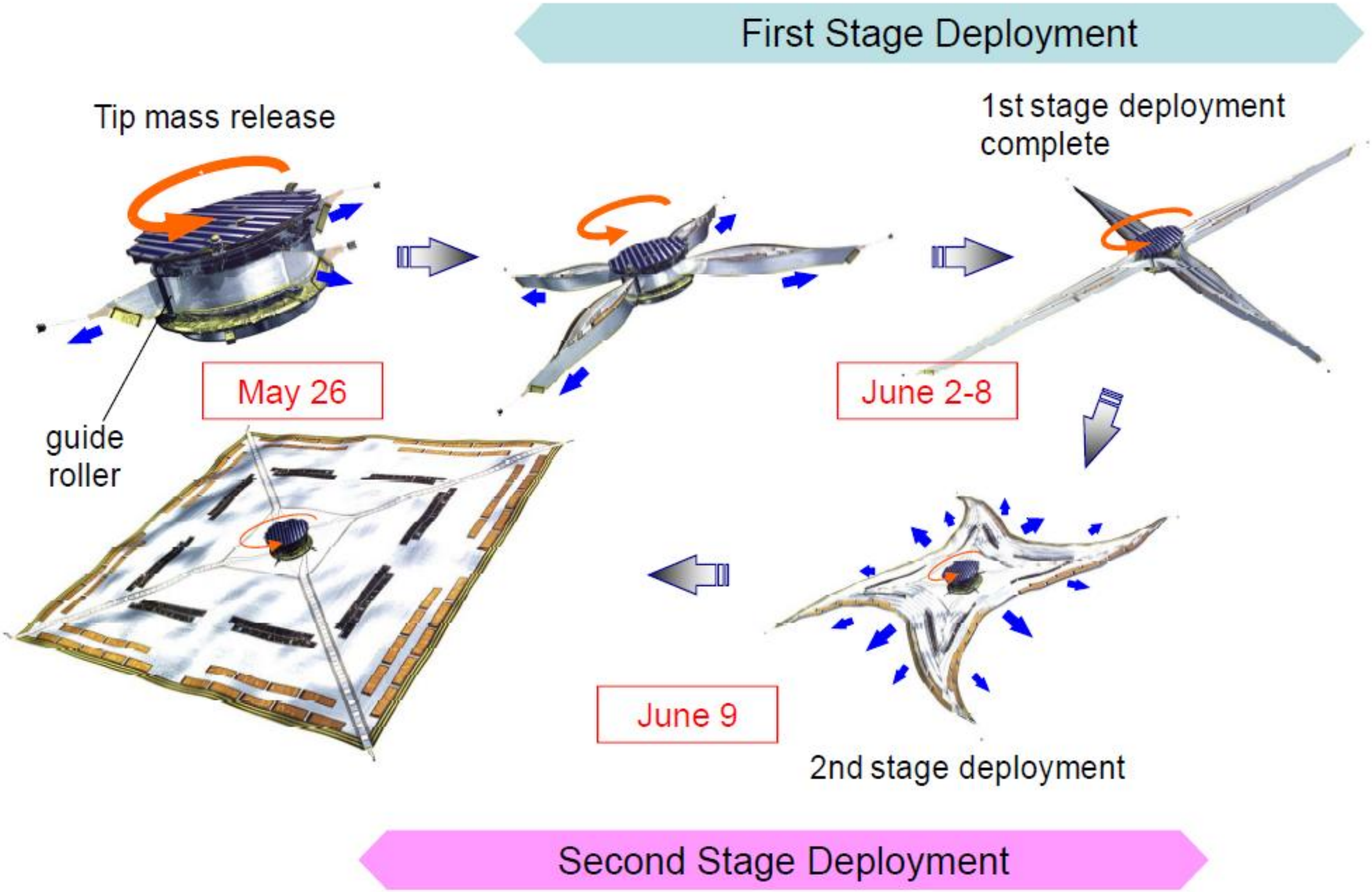
2006
LEO Demonstration (D=2.7m)
(M-V#7 SSSAT)

2006
Balloon Test (D=20m)

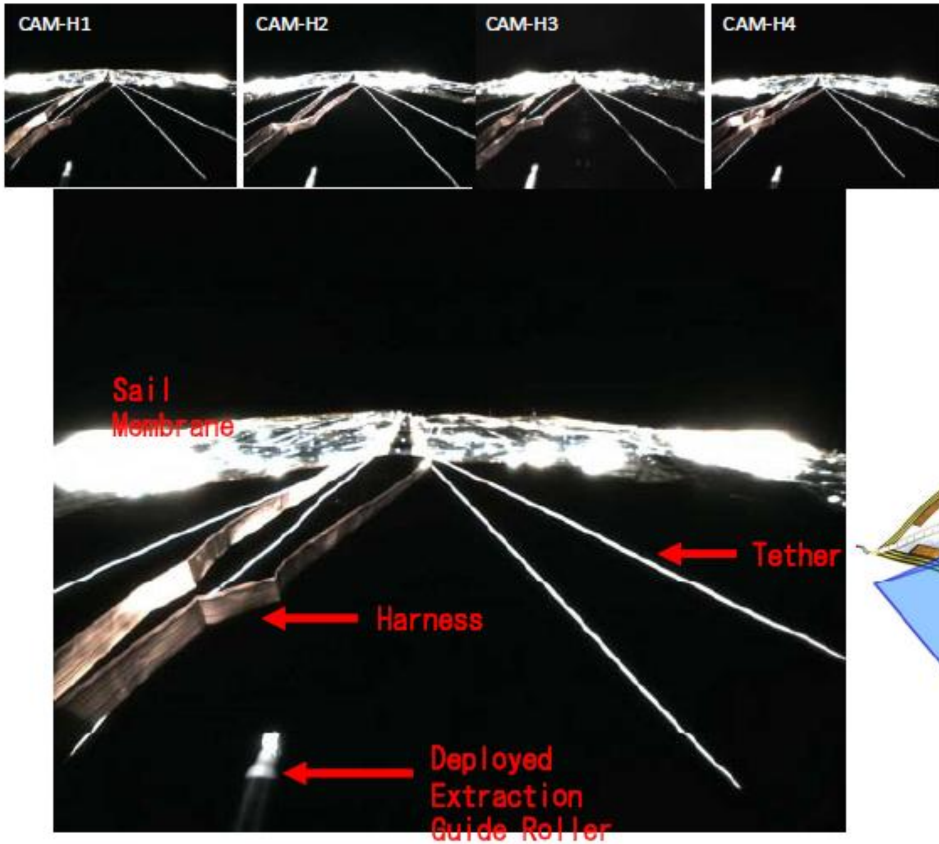


2010
Interplanetary Demonstration!
(D=20m)

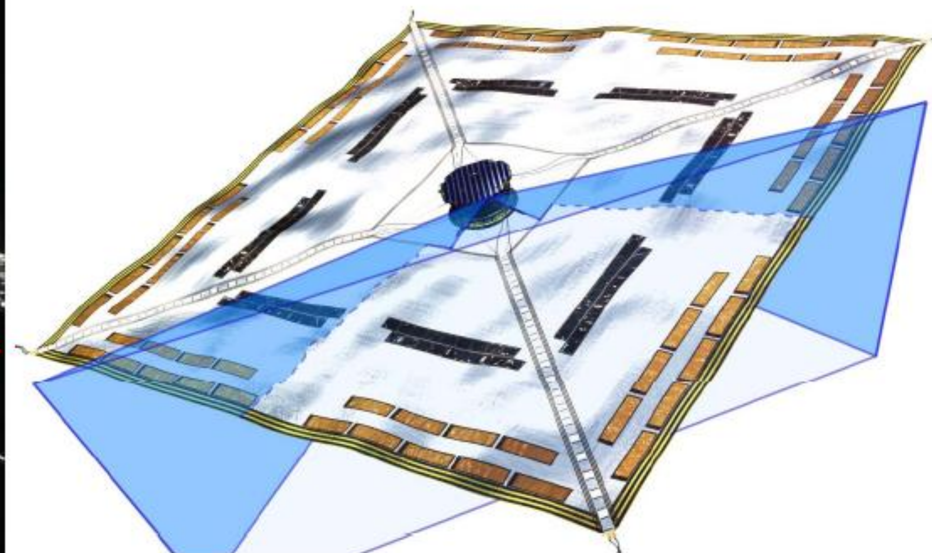
Sail Deployment Sequence



Deployment Confirmed by Onboard Cameras!



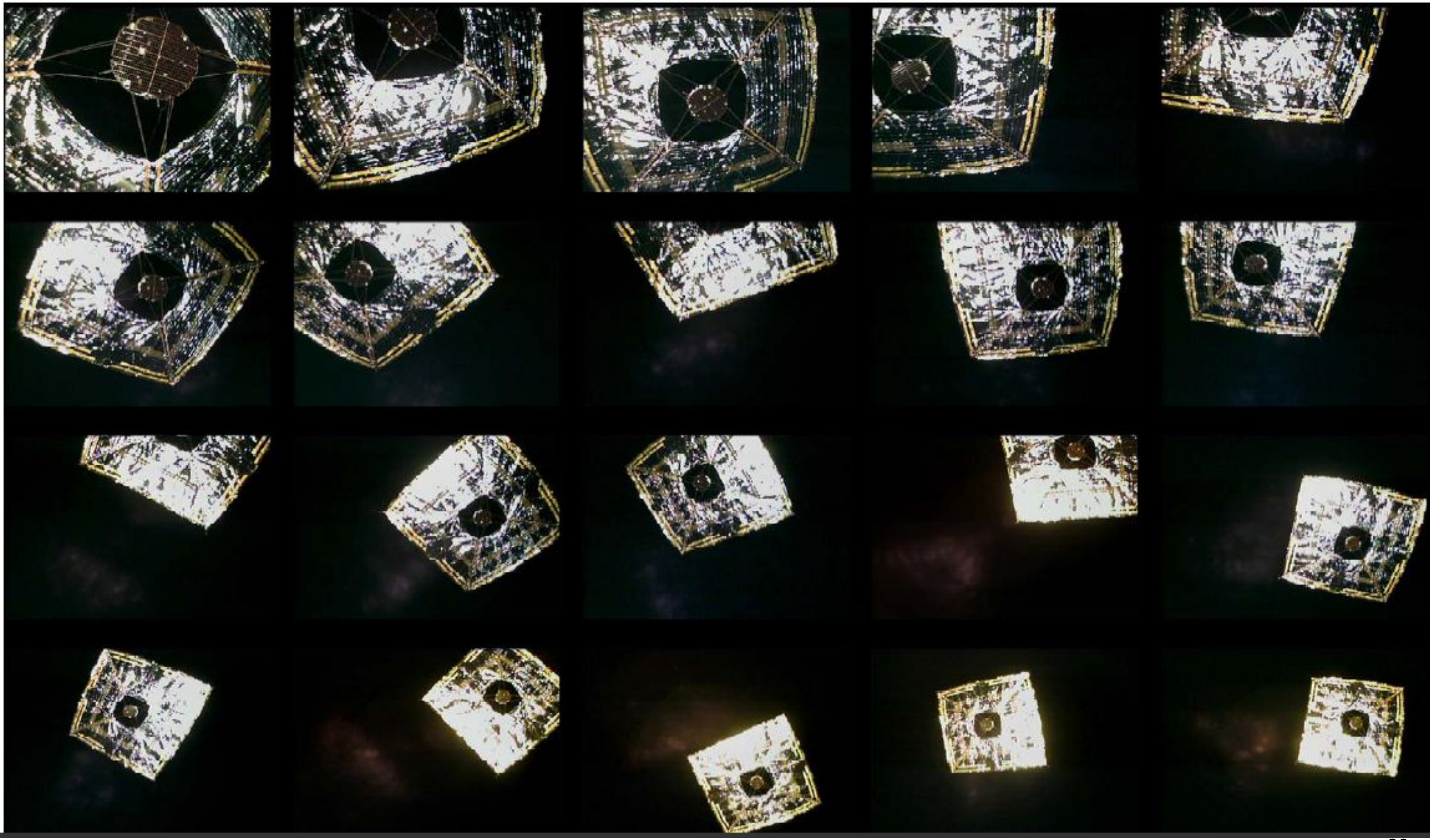
Captured by onboard camera



FOV of onboard camera

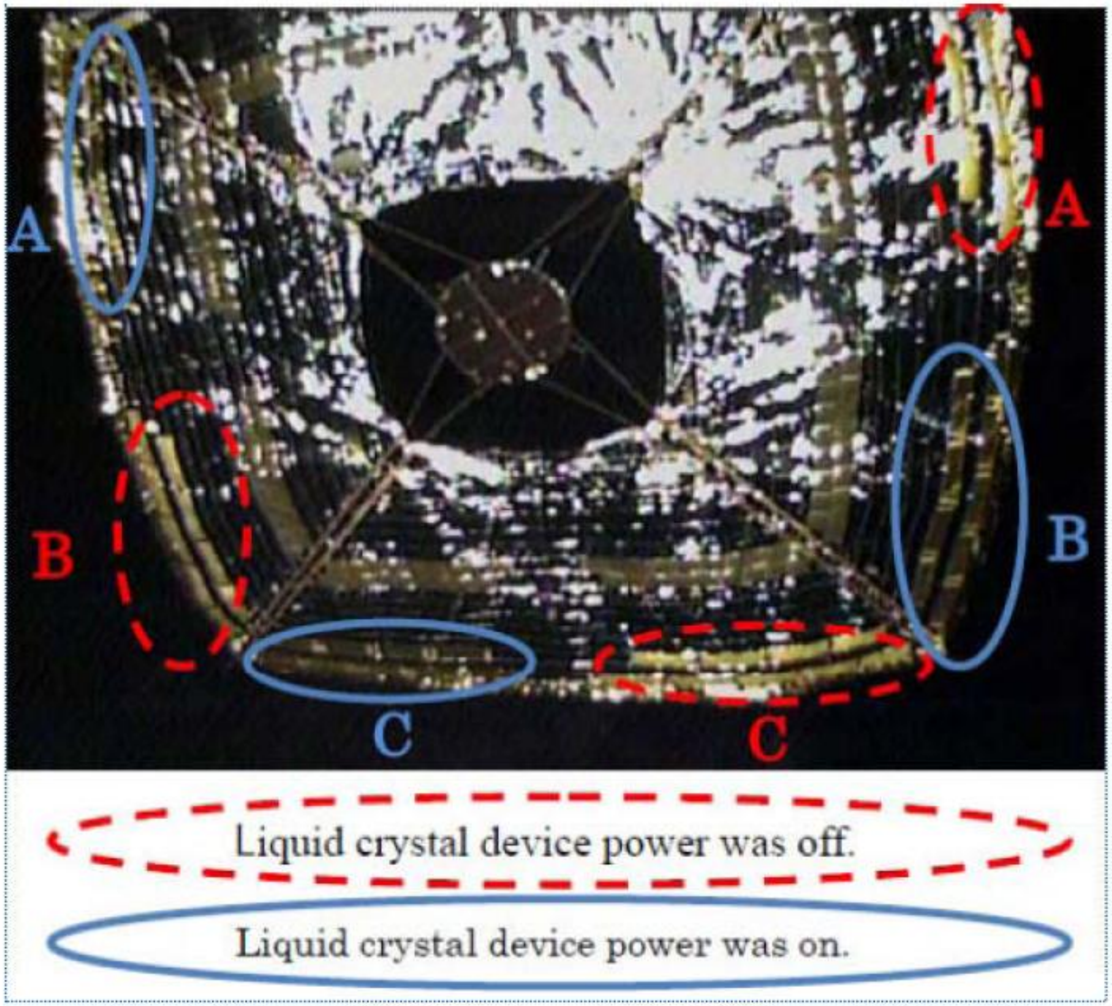
Shots by DCAM

On June 14, 2010



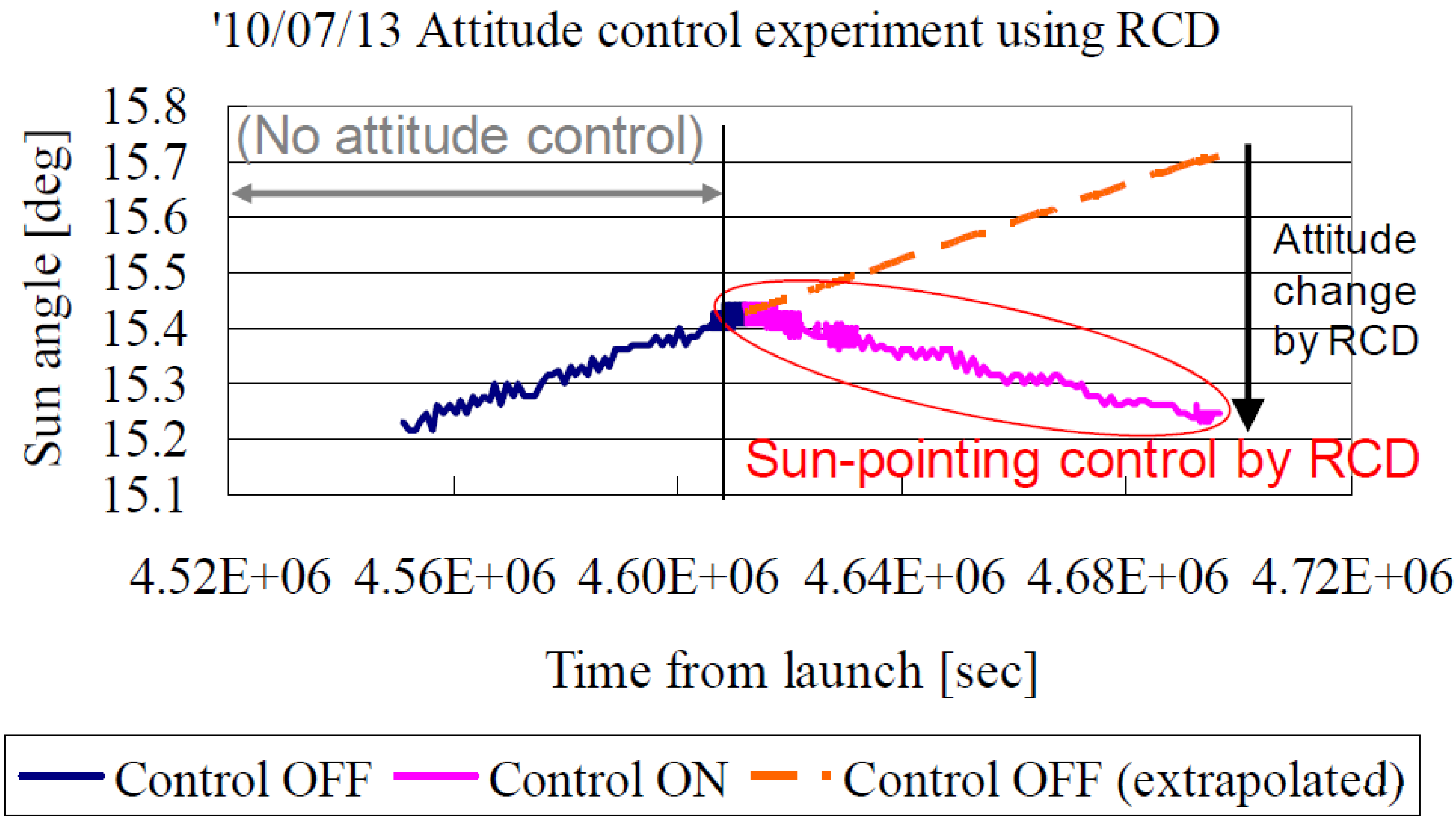
SRP even for attitude control! : Reflectivity Control Device

On June 19, 2010



72 liquid crystal elements are loaded along the edge of the sail.
Optical reflectivity can be controlled electrically.
By synchronizing spin phase with the reflectivity changing, the attitude control purely by SRP is realized.

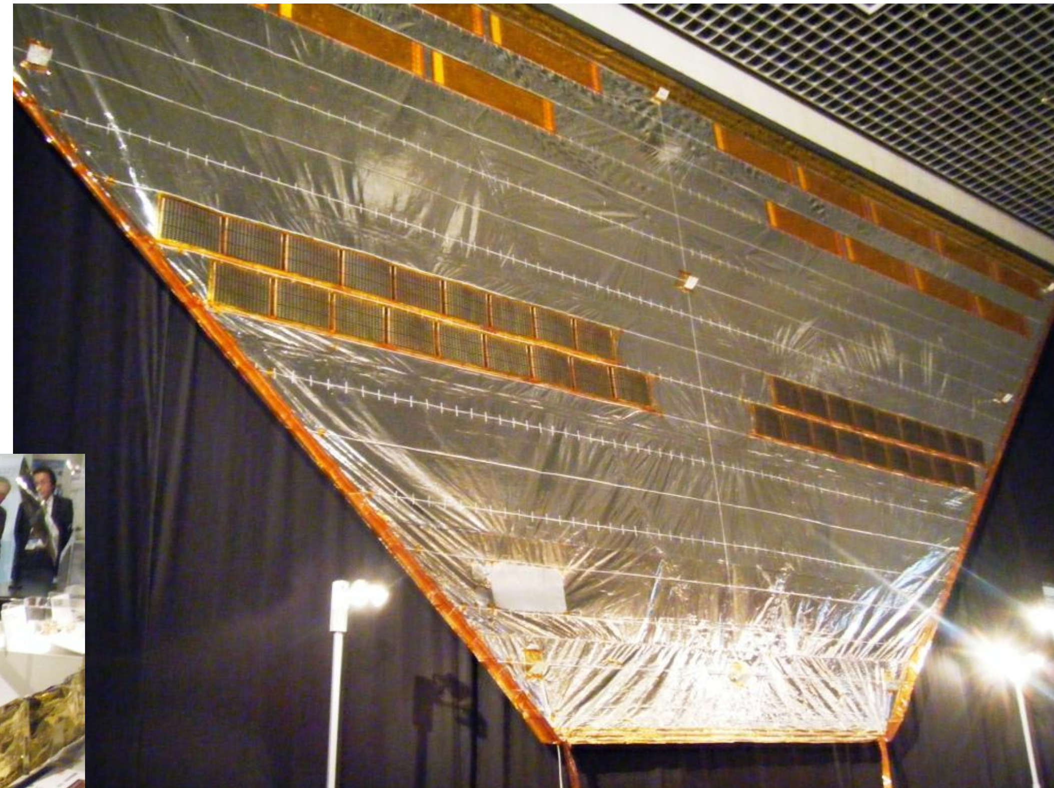
Attitude Control by RCD



Ikaros measurements suggest about 1.12 milli Newtons of force.

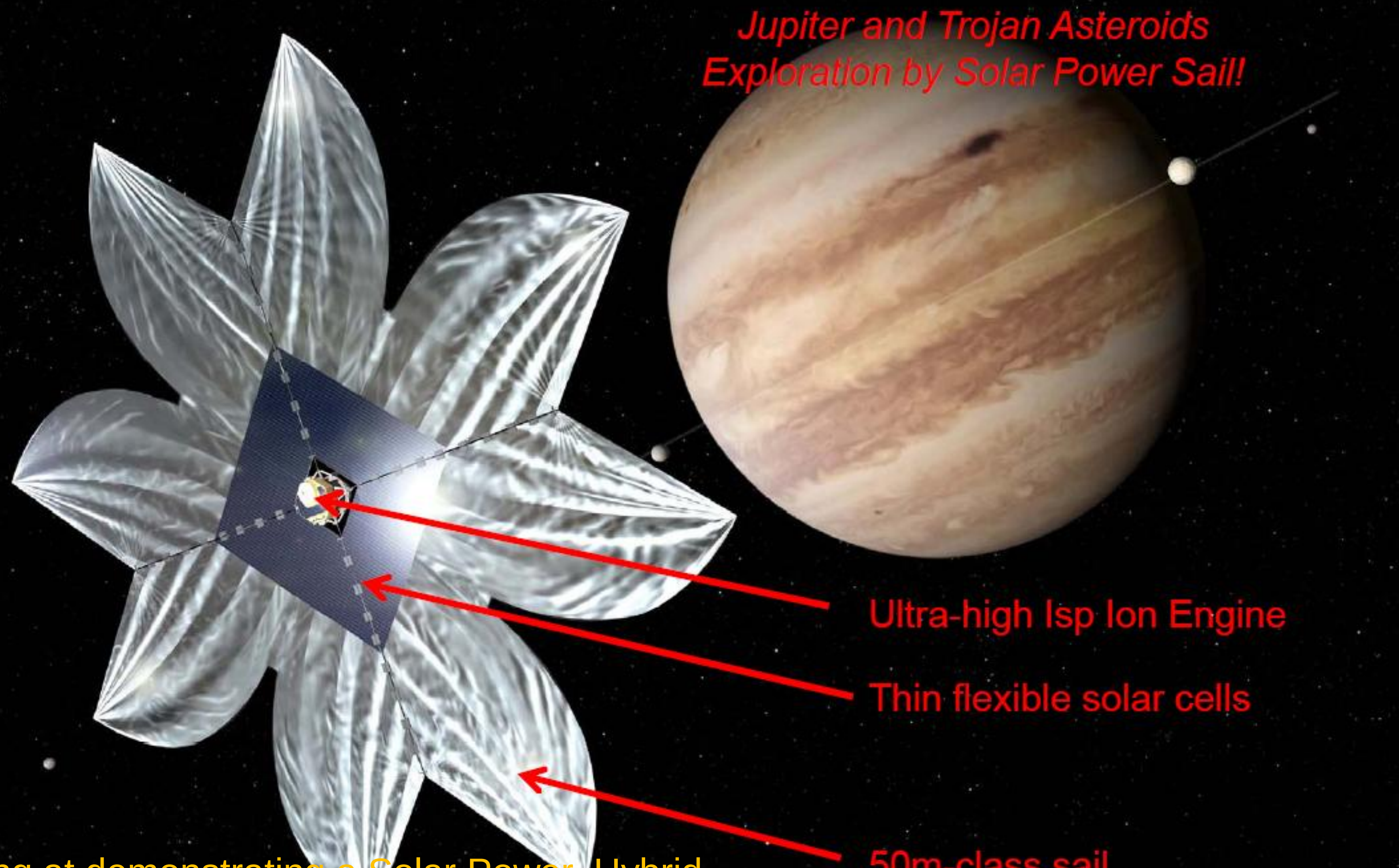
Ikaros Hardware in Museum

Hub with Stowed Sail



Sail Quadrant

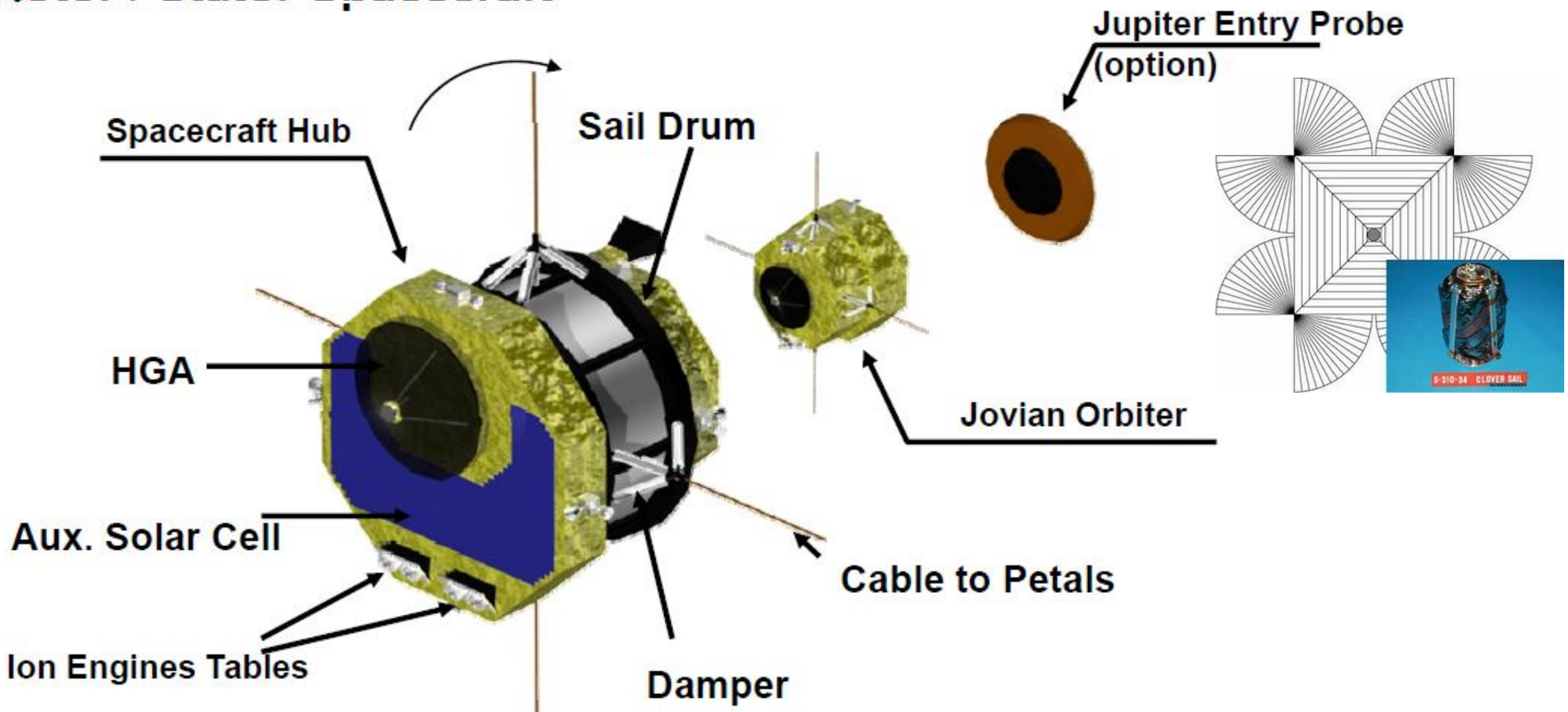
Solar Power Sail to Jupiter and Beyond



Aiming at demonstrating a Solar Power, Hybrid propulsion spacecraft and science in outer solar system, Jovian system and Trojan asteroids flybys/rendezvous.

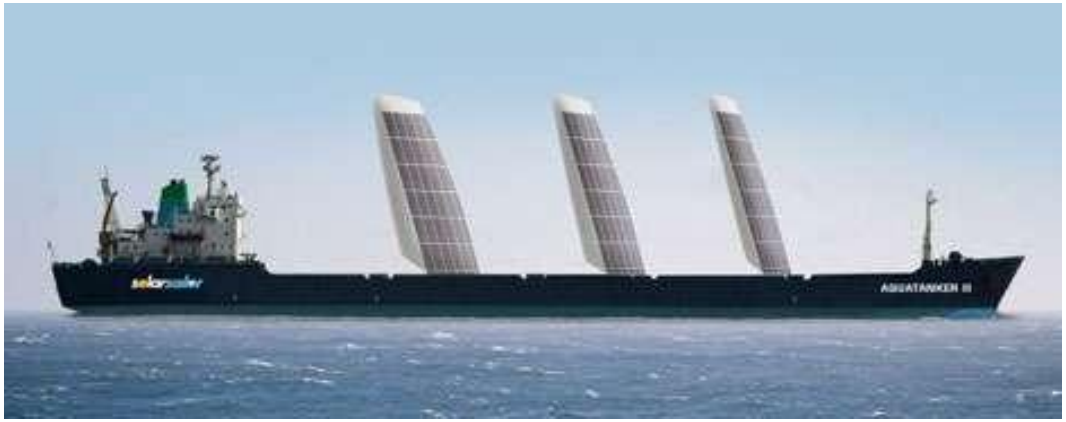
Solar Power Sail (COSPAR04-A-01655, Paris, 2004)

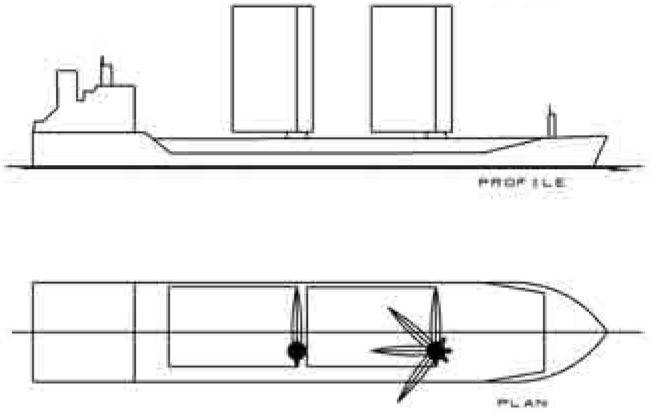
- **Hybrid Propulsion combining Electric Propulsion with Photon Propulsion**
- **Deploying Large Membrane including Thin Film Solar Cell, spanned by Centrifugal Forece**
- **Rotor / Stator Spacecraft**



JAXA envisions Ikaros as the first step toward a future solar sail mission to Jupiter and asteroids that could fly in 2019 or 2020, said Junichiro Kawaguchi, JAXA program manager.

Hybrid Propulsion – A Look at the Future?



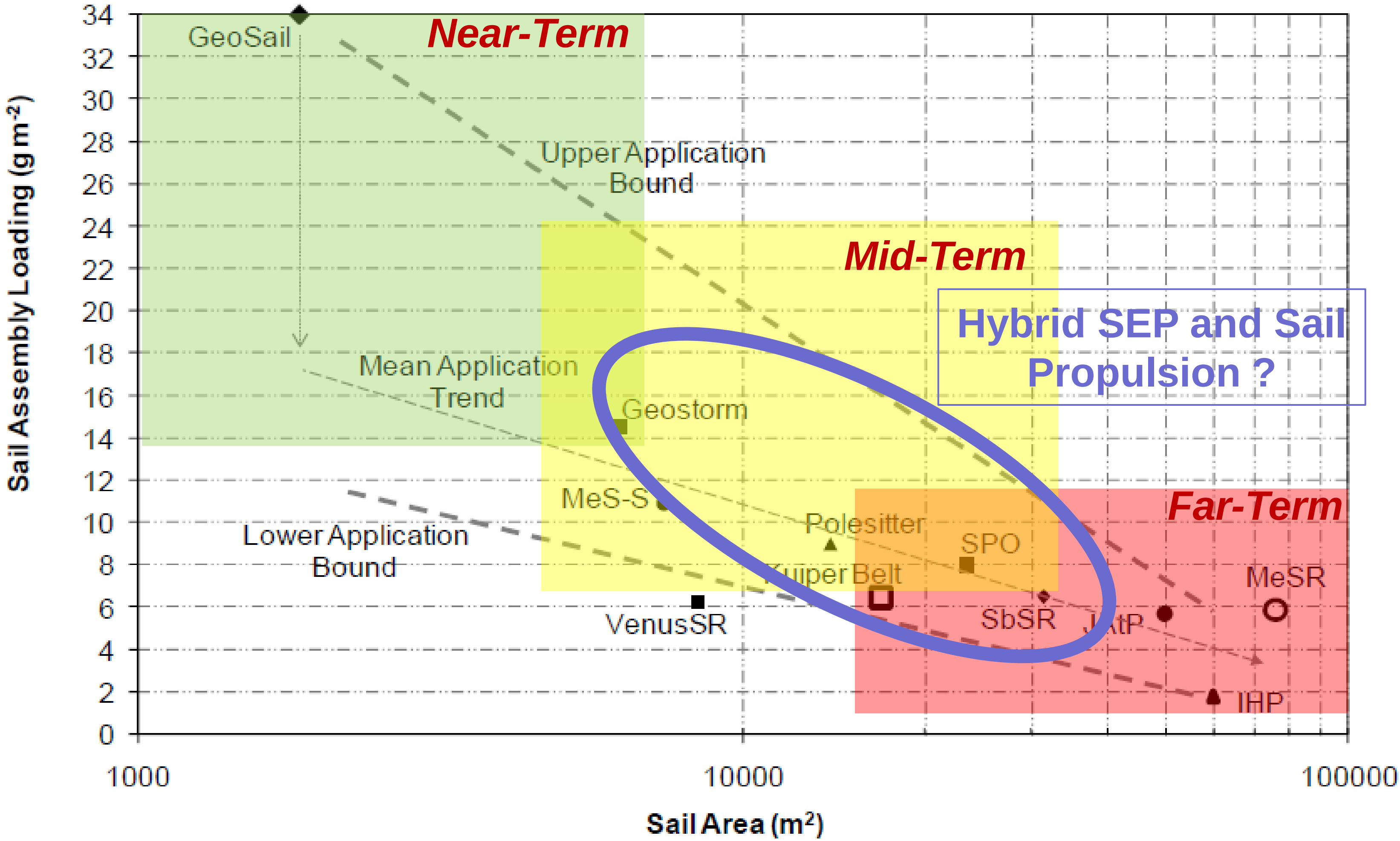


•Australian Solar Sailor company announced they'd signed a deal with China's biggest shipping line, COSCO, to fit some of their jumbo jet sized solar-powered sails to a tanker and bulk carrier.

•The 30 meter long sails, festooned in photovoltaic panels are expected to catch enough wind to reduce fuel costs by between 20% and 40%, and the PV cells provide the ships with 5% of their electricity.

•A computer automatically angles the sails for maximum wind and solar efficiency, and if all goes to plan the sails will have recovered their initial cost within four years.

Future Hybrid Sail Performance



Solar sail mission catalogue application technology requirements. *IHP ≡ Interstellar Heliopause Probe; JAtP ≡ Jupiter Fly-by with Atmospheric Probe release; MeSR ≡ Mercury Sample Return; MeS-S ≡ Mercury Sun-Synchronous; SbSR ≡ High-Energy Small-Body Sample Return; SPO ≡ Solar Polar Orbiter; VenusSR ≡ Venus Sample Return.*

***SOLAR SAIL MISSION APPLICATIONS AND FUTURE ADVANCEMENT, Malcolm Macdonald, Colin McInnes,* Proceedings of the Second International Symposium on Solar Sailing July 20 - 22, 2010 New York, USA.**
http://www.citytech.cuny.edu/isss2010

Summary

- *Numerous activities related to Cubesat class Solar Sails*
  - *NanoSail-D2 deployed, LightSail, Feathersail … (USA)*
  - *Cubesat sail work in Canada, UK, ESA/DLR*
  - *Primary focus is for deployment demonstration and use as deorbit systems*

- *Ikaros (JAXA) is the largest sail to have flown and to acquire quantitative flight performance data.*

- *Currently, only Japan and DLR/ESA have firm plans to deploy large sail systems (~50 m class).*
  - *NASA continues to evaluate mission applications with strong technology pull for solar sails.*

- *Future space missions may benefit by hybrid propulsion to expand the capability of in-space propulsion.*
  - *For Example: Solar Electric Propulsion on Solar Sails.*


Questions?