L·GARDE

SMART SPACE TECHNOLOGY

SUNJAMMER

Sunjammer

A Solar Sail Demonstration

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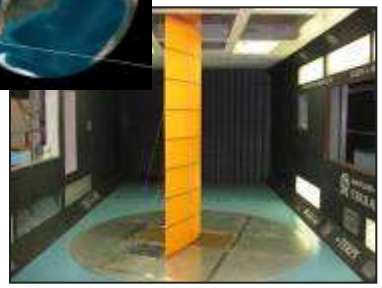
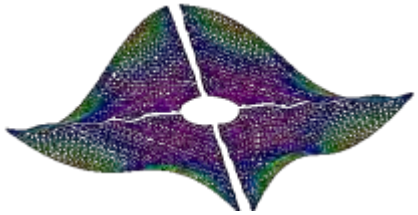
L'Garde



L	Bill Larkin
G	Galye Bilyeu
A	Alan Hirasuna
R	Rich Walstrom
D	Don Davis
E	et al.

World Class Design and Analysis Capabilities

- Founded in 1971 in Orange County, CA,
- Historic provider to DoD of Inflatable RV Decoys
- World Leader in Deployable Space Structures



1971 1973 1978 1987 1990 1996 1997 1998 2001 2002 2003 2006 2007 2009 2010 2011 2012 2014

L'Garde is a world leader in the development of inflatable and deployable structures for terrestrial and space applications. L'Garde is focused on providing agile and responsive research and development services to its customers.

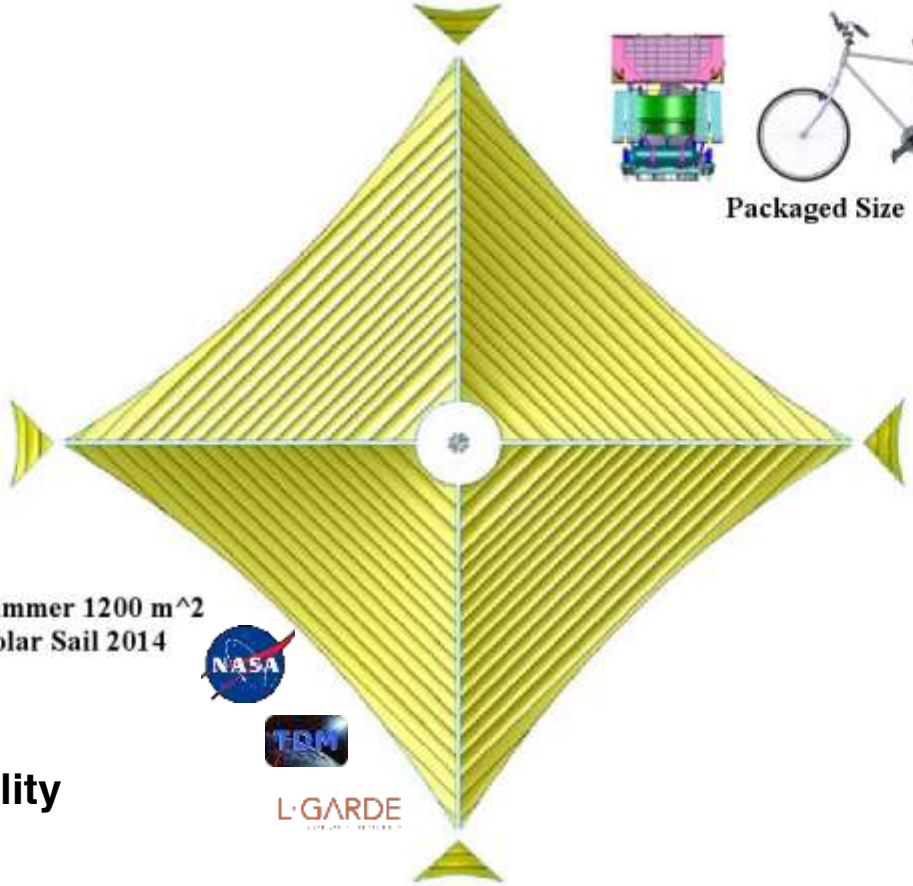
L'Garde Solar Sails

83 m^2 ISP
L'Garde Solar
Sail 2004

X ~4 =>

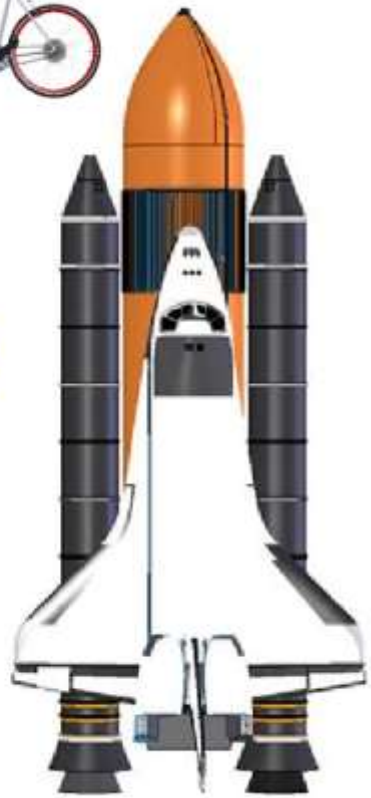
318 m^2 ISP
L'Garde Solar
Sail 2005

X ~4 =>



Sunjammer 1200 m^2
Solar Sail 2014

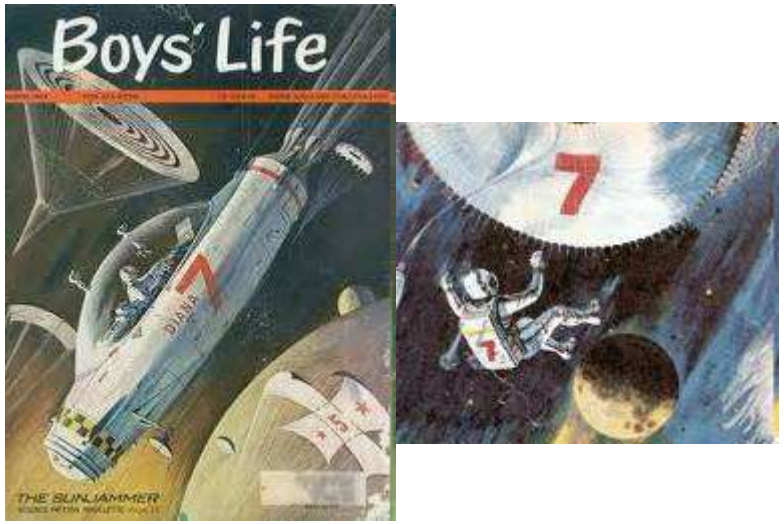
Packaged Size



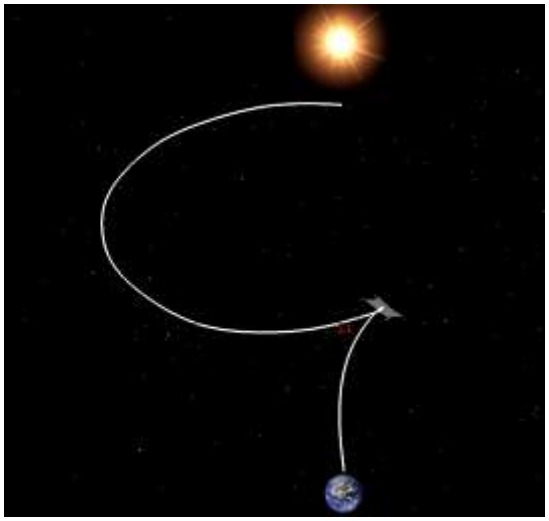
Design Features

- High Density Packagability
- Controlled Deployment
- Structural Scalability
- Propellantless Operation

What is Sunjammer?



Named After Clarke Short Story
(With Permission)



- Sunjammer is an exciting project supported by NASA Space Technology Mission Directorate (STMD) as part of the Technology Demonstration Missions Program.
- Sunjammer will demonstrate the propellantless propulsion potential of solar sails through deployment and navigation of 1200 m^2 sail after launch as secondary payload.
- Sunjammer is the final solar sail demonstration before infusion.

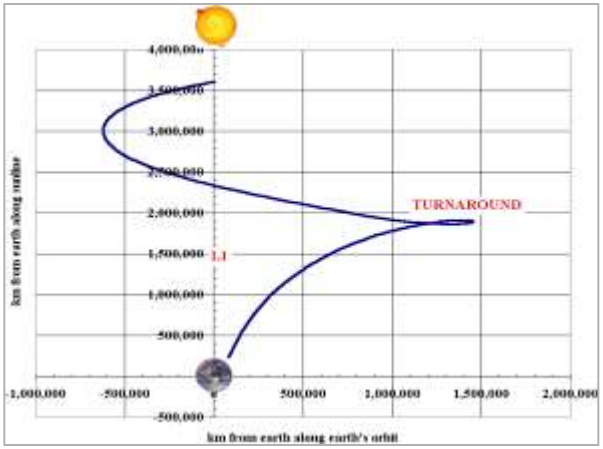
Mission Overview

Demonstration Objectives

1. **Demonstrate segmented deployment of a solar sail**
2. **Demonstrate attitude control plus passive stability and trim using beam-tip vanes.**
3. **Execute a navigation sequence with mission-capable accuracy.**
4. **Fly to and Possibly Maintain Position at sub-L1 and/or Pole Sitter Positions**

Access to Space:
Manifested as Secondary on DSCOVR Launch to L1
(F9 1.1 in Q4 2014)

DSCOVR Spacecraft



Notional Trajectory After Earth Escape Burn

Mission Operations Trajectory Simulation

Sail Deployment Simulation

Infusion Partners

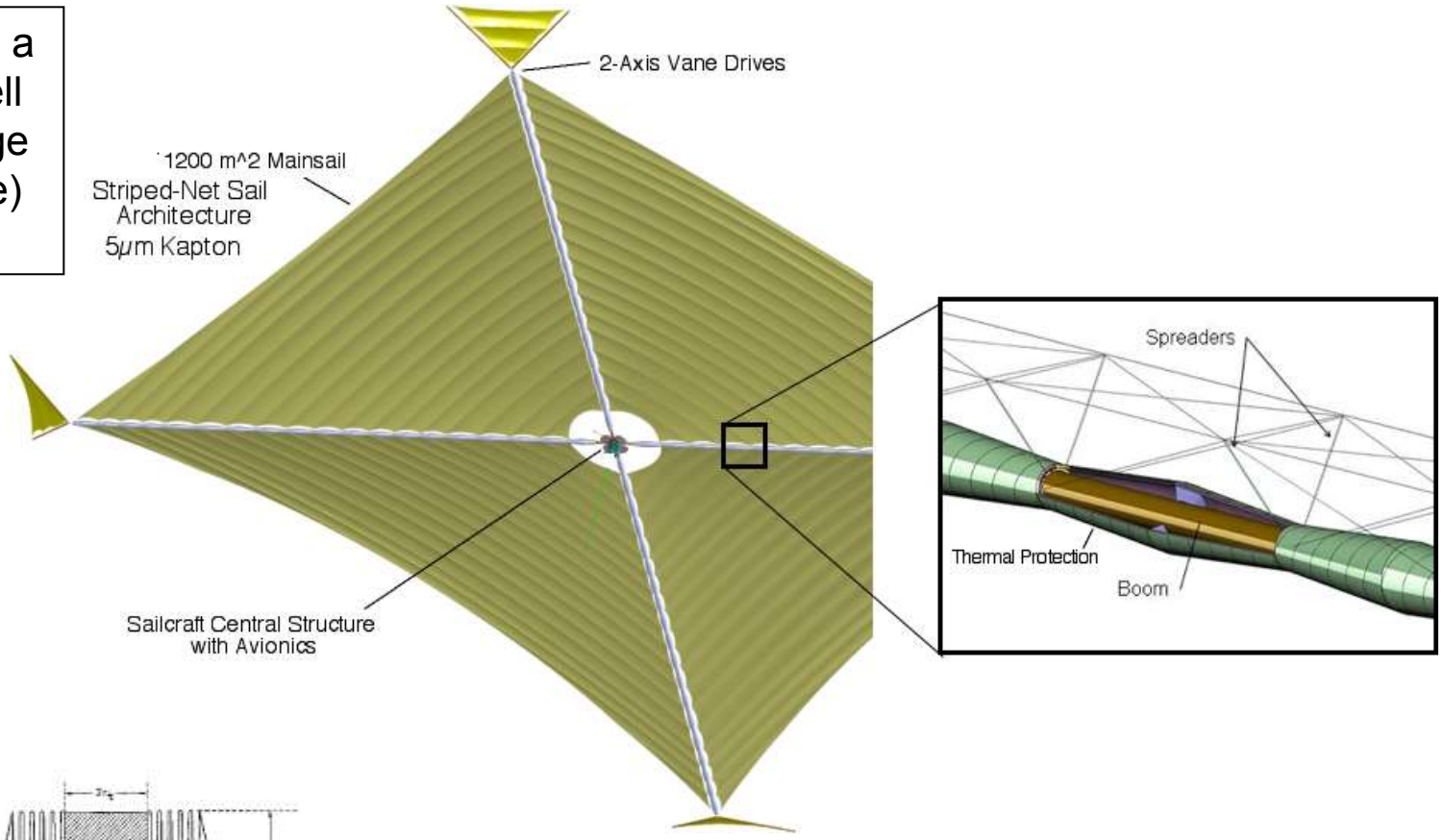
Demonstration is Not Enough – TDM Programs Need Infusion

Sunjammer is Being Planned, Designed, and Executed with an Eye Always on Infusion

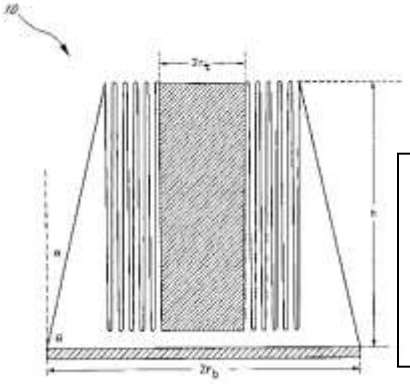
Partner	Contribution	Stakeholder Expectations
NOAA	• Ground Stations Website EPO • Mag. Analysis	• NOAA expects to receive magnetometer data from the sensor suite. • NOAA has interest in continuing work after demo is complete.
Celestis	Project Funds	• L'Garde will accommodate a total of 4kg Celestis memorial payload on board the carrier and sailcraft portions of the spacecraft. MOA is in place.
SSHI	Sponsorship Revenues	• L'Garde will grant certain commercial rights to SSHI who will sell sponsorship of the mission to commercial entities. A portion of L'Garde revenues will be directed to risk reduction cost offsetting efforts.
Imperial College London	Magnetometer	• Imperial College London will develop and provide flight/science quality magnetometers for Sunjammer. This work is funded by UK Space Agency. Data will shared with Imperial College. Flight qualification will be provided as well.
University College London	Plasma Sensor	• University College London will develop and provide a flight/science quality plasma detector for Sunjammer. This work is funded by UK Space Agency. Data will shared with University College. Flight qualification will be provided.
NASA STMD	Ride Share!! & Interest	• Committee on a Decadal Strategy for Solar and Space Physics (Heliophysics) urged development of a program **very** similar to Sunjammer

L'Garde Solar Sail 101

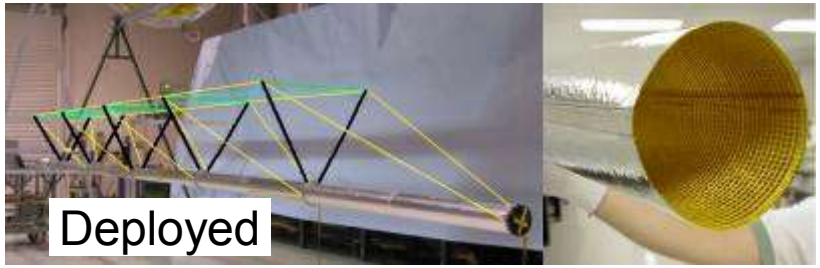
The L'Garde Sail Is a Unique Design Well Suited to Very Large (High Performance) Solar Sails



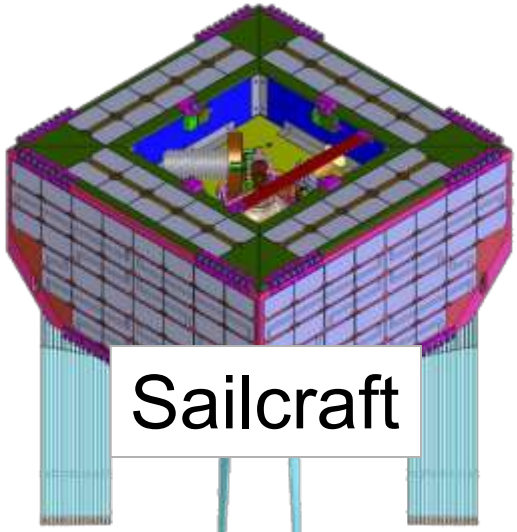

Stowed



Telescopically packaged, Sub-Tg rigidized, inflatably deployed booms

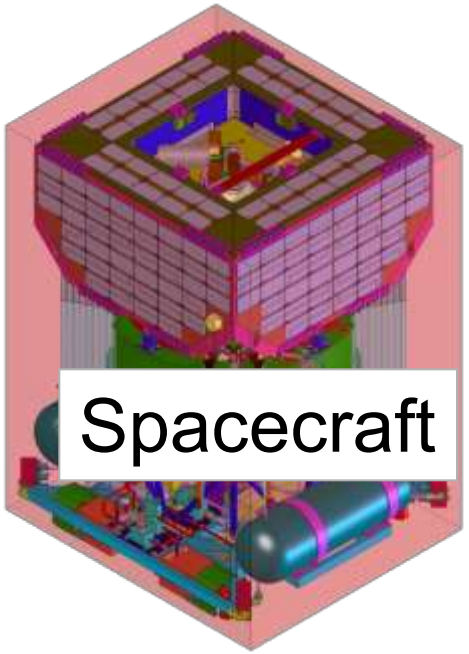

Deployed

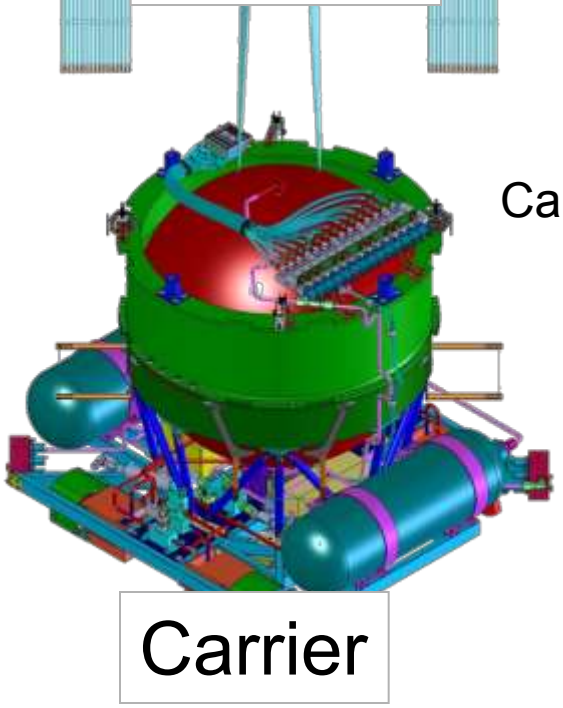
Sunjammer Mechanical Design



Sailcraft:

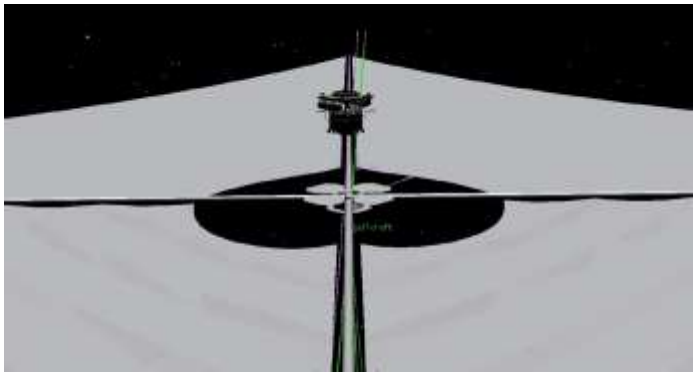
- Avionics
- Sail Softgoods
- Antennas
- Solar Array





Carrier:

- Support Structure
- Inflation System
- Propulsion System
- Separation System
- Primary Batteries

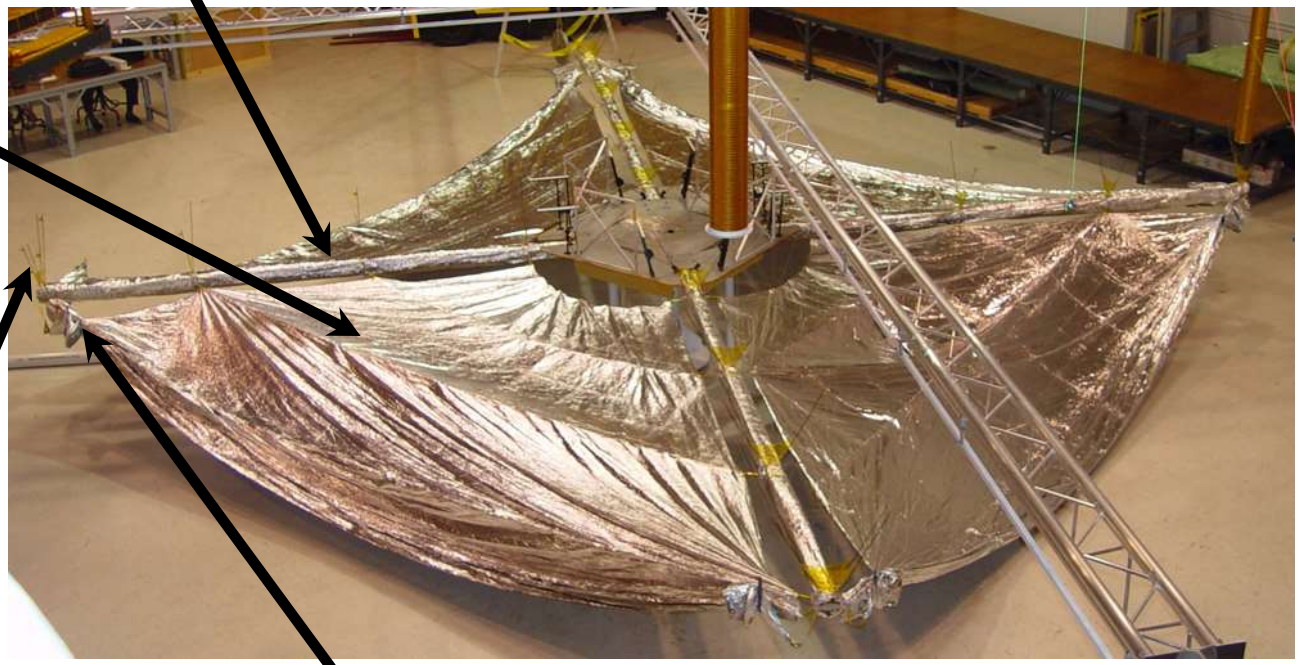


Carrier is jettisoned after deployment

Demonstration Objective 1 : Deployment

Boom deploys linearly, base first, segment-by-segment

Sail is pulled out by boom, stripe-by-stripe

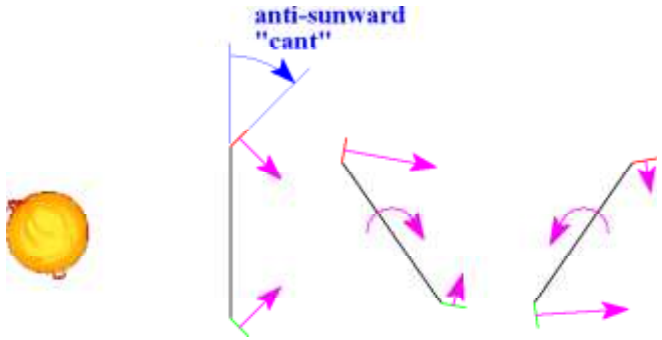


Line management devices control the spreader system

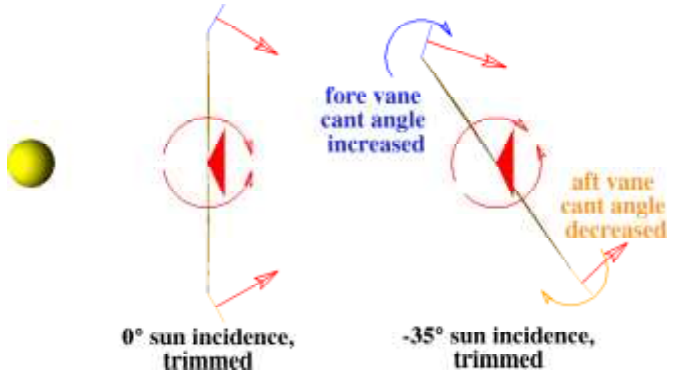
Membrane manage devices control the sail

- Deployment viewed via camera boom
- May be logos on the sail
- Jettison may be viewed from carrier

Demonstration Objective 2: Attitude Calibration



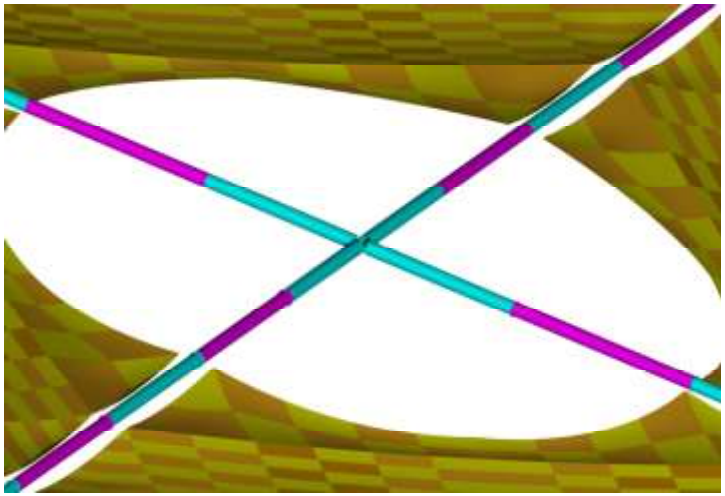
Passive stability due to vane cant or mainsail billow (effective shuttlecock)



Retrimming sail attitude using the vanes

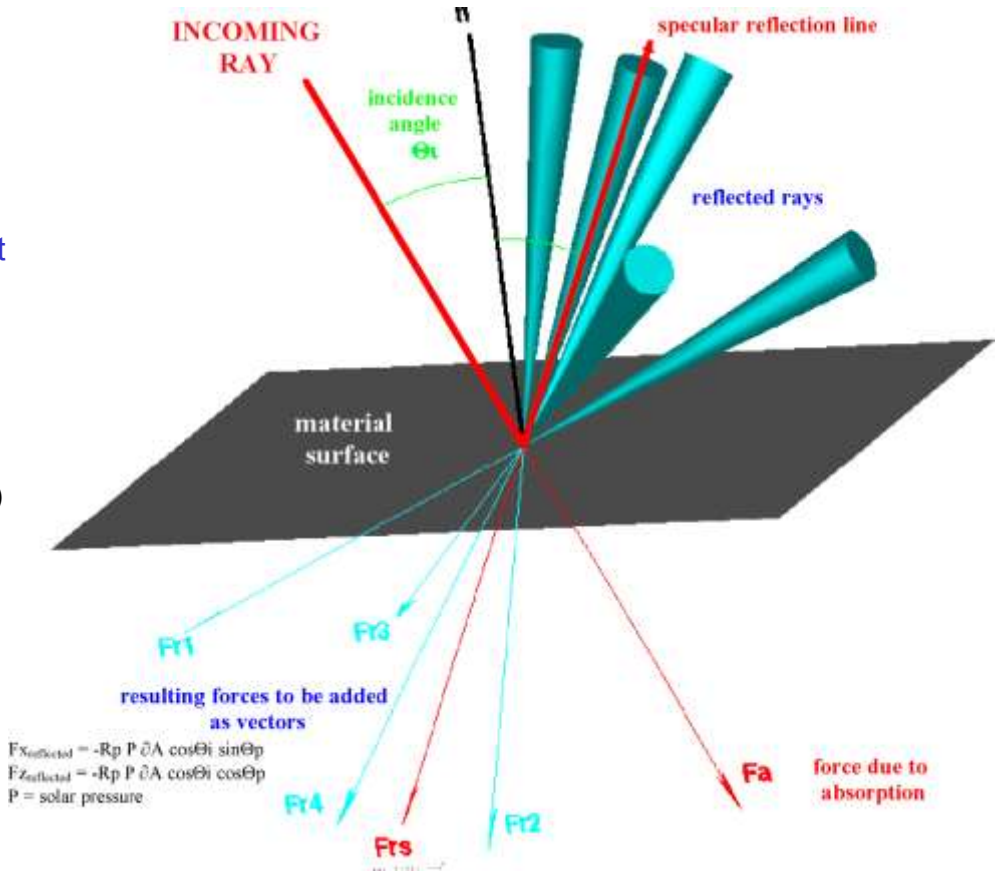
- Requires knowledge of sail restoring moments
- Moments are primarily due to shape
- Beam bend and photoflexibility are other factors
- Sail shape is gridded, each element a flat plate
- L'Garde's elemental force model applied to plates

- Still, gossamer structure will have errors
- Vanes oversized for bias moments
- Moments will be calibrated post-deploy
- Calibration procedure will fulfil NASA attitude control requirement



Demonstration Objective 3: Thrust Calibration & 30-Day Maneuver

- Thrust is not heavily affected by shape (flat plate often used in trajectories)
- Major effect is what surface wrinkles do to the force of reflected light
- Optics model adds “specular” and “diffuse” forces as scalars, and assumes diffuse force is normal to the surface
- Using real data for pragmatically low-stress membranes (not mirror-like specularity), optics model would predict poor performance (specularity = 0.40 to 0.55)
- Using the same bi-directional reflectance data, but actually vector-summing forces due to each and every ray reflected into the hemisphere above the sample shows good performance (propulsive reflectivity Rp=0.85 ÷ ρ=0.89 = 0.96)
- L’Garde uses data at $\theta_{incidence}$ = 25°, mild & heavy wrinkles, and assumes derived propulsive reflectivity (Rp) is constant (as specularity is constant with θi in the optics model), and that “propulsive zenith” (θp) varies mildly with attitude (θp = 25.7° @ θi = 25° vs. diffuse thrust normal (0°) and no forward scatter of “specular” rays in the optics model)
- Seeking interested experimenters to take data at more incidence angles



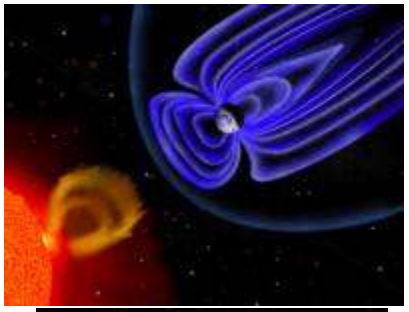
- Thrust calibration using ranging, and ensuing 30 day maneuver, will satisfy NASA nav requirements
- Demonstration Objective 4 will be to then fly out to sub-L1
- Magnetometer and plasma sensor to demonstrate solar wind can be measured from the sail
- After six months of degradation, sail will be recalibrated

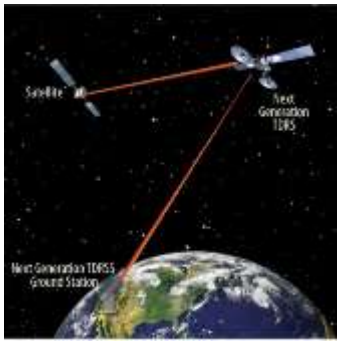
Demonstration Objectives Verified

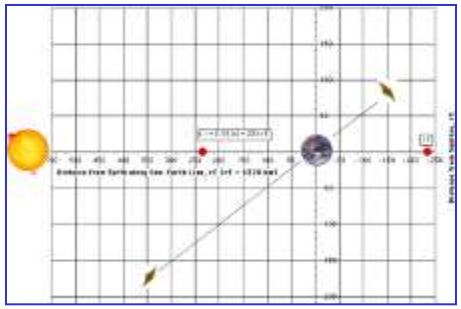
1. Demonstrate segmented deployment of a solar sail
   - ✓ Verified with onboard imaging system
   - ✓ Data relayed to ground
2. Demonstrate attitude control plus passive stability and trim using beam-tip vanes.
   - ✓ Calibration effort will verify controllability and stability.
3. Execute a navigation sequence with mission-capable accuracy.
   - ✓ Sunjammer will be flown on a navigation sequence that future users are interested in.
4. Fly to and Possibly Maintain Position at sub-L1 and/or Pole Sitter Positions
   - ✓ Real time Infusion. This mission profile will demonstrate the validity of using solar sails to monitor space weather at pseudo Lagrange points.
   - ✓ Data will be relayed to the ground and analyzed by NOAA, UCL, and ICL.

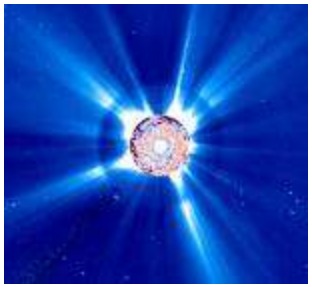
Other Infusion Opportunities

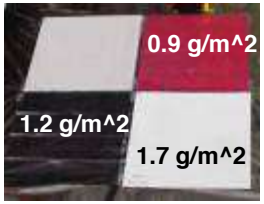
- NASA
  - Heliophysics
  - Communication
  - ADR/ODR
- NOAA
  - Storm Warning
  - Communication
- DoD
  - STP
  - Communication
  - ADR/ODR
- SSHI (Commercial Entity)
  - Celestis Payloads
  - Advertising Rights

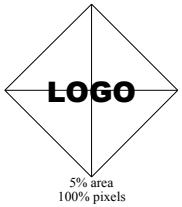


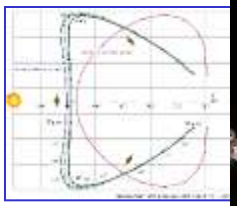




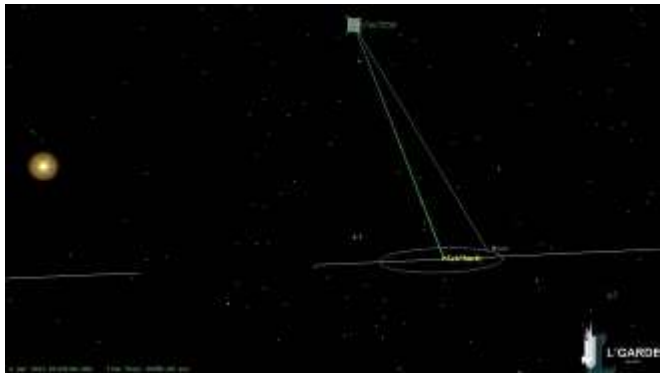




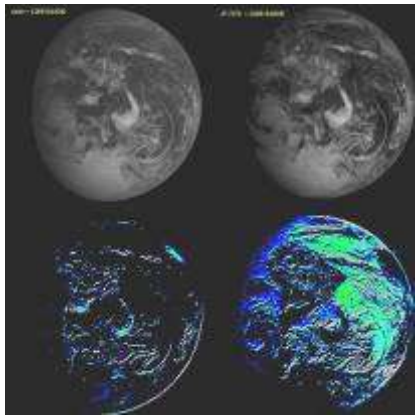




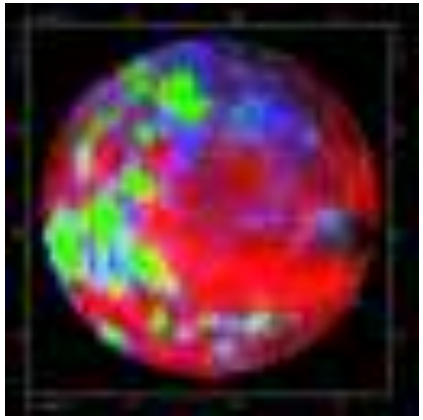
Other Near Term Tasks For Sails



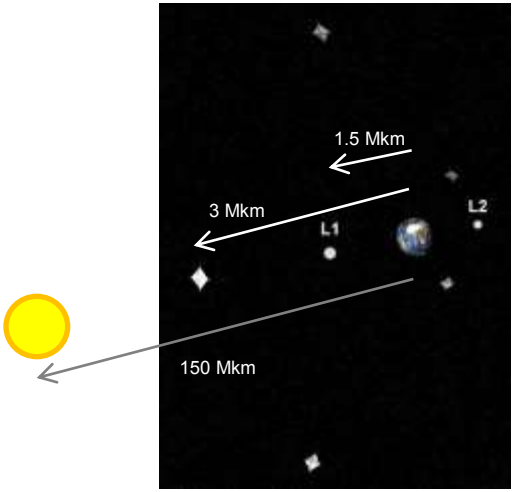
Northern “polesitter” providing continuous polar coverage of the Earth and moon



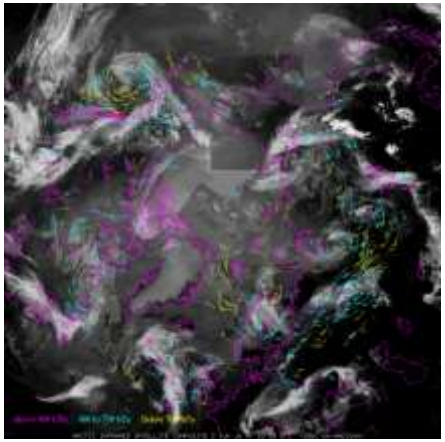
Aerosols & clouds (Galileo)



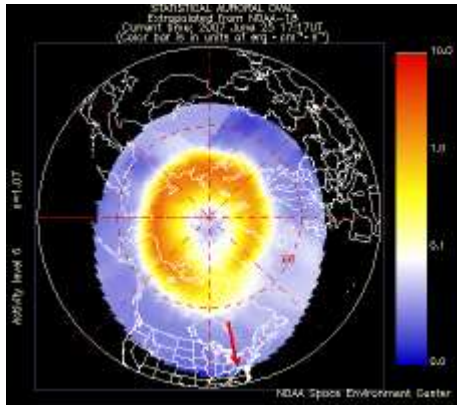
Near Infrared Mapping Spectroscopy (Galileo)



Family of artificial Lagrange orbits



Wind vectors from polar imagery (LEO & GEO composite)



UV auroral imaging (NOAA)

Lazzara, Matthew A., Alex Coletti, and Benjamin L. Diedrich. "The possibilities of polar meteorology, environmental remote sensing, communications and space weather applications from Artificial Lagrange Orbit." *Advances in Space Research* 48.11 (2011): 1880-1889.