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NANOSAIL-D: A SOLAR SAIL DEMONSTRATION MISSION

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ABSTRACT

During the past decade, within the United States, NASA Marshall Space Flight Center (MSFC) was heavily engaged in the development of revolutionary new technologies for in-space propulsion. One of the major in-space propulsion technologies developed was a solar sail propulsion system. Solar sail propulsion uses the solar radiation pressure exerted by the momentum transfer of reflected photons to generate a net force on a spacecraft. To date, solar sail propulsion systems have been designed for large spacecraft—in the tens to hundreds of kilograms mass range. Recently, however, MSFC has been investigating the application of solar sails for small satellite propulsion. Likewise, NASA Ames Research Center (ARC) has been developing small spacecraft missions that have a need for a mass-efficient means of satisfying deorbit requirements. Hence, a synergistic collaboration was established between these two NASA field Centers with the objective of conducting a flight demonstration of solar sail technologies for small satellites.

The NanoSail-D mission flew onboard the ill-fated Falcon Rocket launched August 2, 2008, and, due to the failure of that rocket, never achieved orbit. The NanoSail-D flight spare is ready for flight and a suitable launch arrangement is being actively pursued. Both the original sailcraft and the flight spare are hereafter referred to as NanoSail-D. The sailcraft consists of a sail subsystem stowed in a three-element CubeSat. Shortly after deployment of the NanoSail-D, the solar sail will deploy and mission operations will commence. This demonstration flight has two primary technical objectives: (1) to successfully stow and deploy the sail and (2) to demonstrate deorbit functionality. Given a near-term opportunity for launch on Falcon, the project was given the challenge of delivering the flight hardware in ≈6 mo, which required a significant constraint on flight system functionality. As a consequence, passive attitude stabilization of the spacecraft will be achieved using permanent magnets to detumble and orient the body with the magnetic field lines and then rely on atmospheric drag to passively stabilize the sailcraft in an essentially maximum drag attitude.

This paper will present an introduction to solar sail propulsion systems and an overview of the NanoSail-D spacecraft.

Keywords: solar sail, NanoSail-D, CubeSat.

INTRODUCTION

Solar sail propulsion utilizes the solar radiation pressure exerted by the momentum transfer of reflected light. The integrated effect of a large number of photons is required to generate an appreciable momentum transfer. Therefore, a large sail area is required. And since acceleration is inversely proportional to mass for a given thrust force, the mass of the sailcraft must be kept to a minimum.

Figure 1 illustrates how the solar radiation pressure is utilized for propulsion. Incident rays of sunlight reflect off the solar sail at an angle θ with respect to the sail normal direction. Assuming specular reflection from a perfectly flat sail membrane, there will be two components of force: one in the direction of the incident sunlight and the second in a direction normal to the incident rays. When the force vectors are summed, the components tangent to the sail surface cancel and the components normal to the surface add to produce the thrust force in the direction normal to the sail surface. For a perfect 40 m × 40 m square sail at 1 AU from the Sun, the solar radiation thrust force is ≈0.03 N.

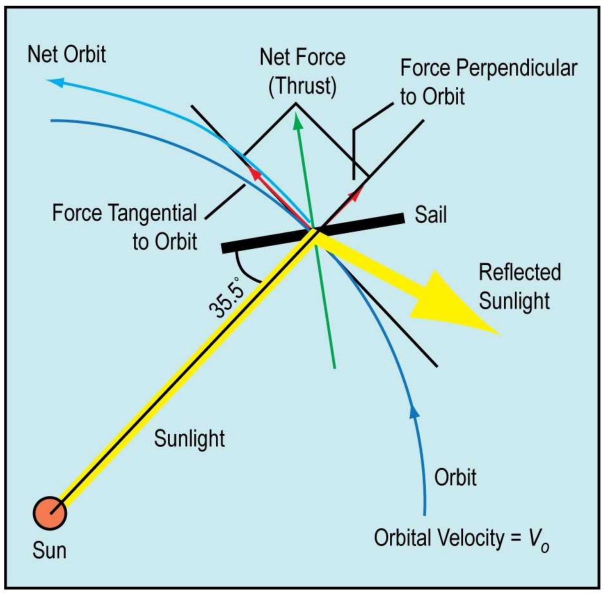

Fig. 1. Solar radiation thrust force

NANOSAIL-D OBJECTIVES

The objectives of the Nanosail-D project are primarily programmatic, with several technology goals to be serendipitously demonstrated:

1. Establish ARC-MSFC collaborative relationship for future small satellite initiatives. (Comment: MSFC is known for developing NASA's "large" space missions. A partnership with ARC would help diversify the MSFC science portfolio.)

2. Deploy first solar sail leveraging work by MSFC approved under the Science Mission Directorate In-Space Propulsion Technology Program.[1] (Comment: The hardware from the solar sail ground demonstration program was in storage and NanoSail-D provided an opportunity to use the hardware and the MSFC expertise developed in the program to fly a relatively low-cost demonstration.)

3. Demo orbital debris mitigation technology—drag sail. (Comment: When flown in low-Earth Orbit, the aerodynamic drag experienced by the NanoSail will exceed solar photon thrust, resulting in a rapid deorbit of the sail spacecraft. If a similar sail were stowed on a spacecraft and deployed at the end of its life, it might serve as a lightweight deorbit system.[2])

4. Ground imaging to reduce spacecraft instrumentation. (Comment: The NanoSail-D is very small and it was impossible to place much diagnostic instrumentation onboard. With ground imaging, it would be possible to confirm solar sail deployment and attitude, etc.)

PERFORMANCE

Solar sail performance is typically specified in terms of characteristic acceleration that is defined as the acceleration from solar radiation pressure at a distance of 1 AU from the Sun. It is both a function of the reflective efficiency of the sail as well as the total system mass and reflective area. To date, solar sail propulsion system design concepts have been investigated for large spacecraft in the tens to hundreds of kilograms mass range, consequently requiring sail areas in the thousands of square meters or larger range.[3] Recently, however, MSFC has been investigating the application of solar sails for small satellite propulsion. If the payload mass can be substantially reduced, then similar characteristic acceleration performance can be achieved with substantially smaller sails, thus reducing the technical risk and cost associated with the sail propulsion system. Moreover, these propulsive solar sails can be doubly utilized to deorbit a small satellite to meet the end-of-mission disposal requirements without the need of a dedicated chemical propulsion system that would otherwise incur parasitic mass and volume impacts. At the same time, ARC has been developing small spacecraft missions that could benefit from this mass-efficient propulsion and deorbit capability. Hence, a synergistic collaboration was established between these two NASA field Centers with the objective of conducting a flight demonstration of solar sail technologies for small satellites.

NANOSAIL-D SYSTEM OVERVIEW

The NanoSail-D mission was launched onboard a Falcon 1 launch vehicle in August 2008. The NanoSail-D, a CubeSat-class satellite, consisted of a sail subsystem stowed in a CubeSat 2U volume integrated with a CubeSat 1U volume bus provided by ARC. Shortly after deployment of the NanoSail-D from a Poly Picosatellite Orbital Deployer (P-POD) ejection system, the solar sail was to have deployed and mission operations commence. Unfortunately, the launch vehicle failed during ascent and the NanoSail-D never had the opportunity to deploy.

Given a near-term opportunity for launch, the project was met with the challenge of delivering the flight hardware in ≈6 mo, which required a significant constraint on flight system functionality. As a consequence, the baseline spacecraft functionality is limited to passive attitude control with no ground command capability and only minimal health and status telemetry sent to the ground. No onboard camera or instrumentation are to be utilized to image the deployed sail or measure the attitude dynamics since these functions require considerable software and avionics infrastructure that was beyond the scope of the project budget and schedule.

The stowed configuration of the NanoSail-D spacecraft is illustrated in Figure 2. The spacecraft bus, provided by ARC, is configured with a flight-proven computer, power supply, S-band radio, and ultra-high-frequency (UHF) beacon radio. Passive attitude control is provided by permanent bar magnets that are installed in the bus closeout panels. The spacecraft bus occupies the upper one-third volume of the 3U-sized CubeSat-class spacecraft.

The solar sail subsystem occupies the lower two-thirds volume of the spacecraft. Sail closeout panels provide protection for the sail and booms during the launch phase of the mission. These panels have spring-loaded hinges that will be released onorbit, under the command of the spacecraft bus. Figure 3 shows the fully deployed NanoSail-D in a ground test.

ManTech SRS, in Huntsville, Alabama, was responsible for design, development, and testing of the sail subsystem for NanoSail-D. Though the sail subsystem was to be utilized as a drag device for the current mission, all the essential components of the sail subsystem are scalable to >40 m^2 sail missions and were merely truncated due to the aggressive timeline of the current mission.

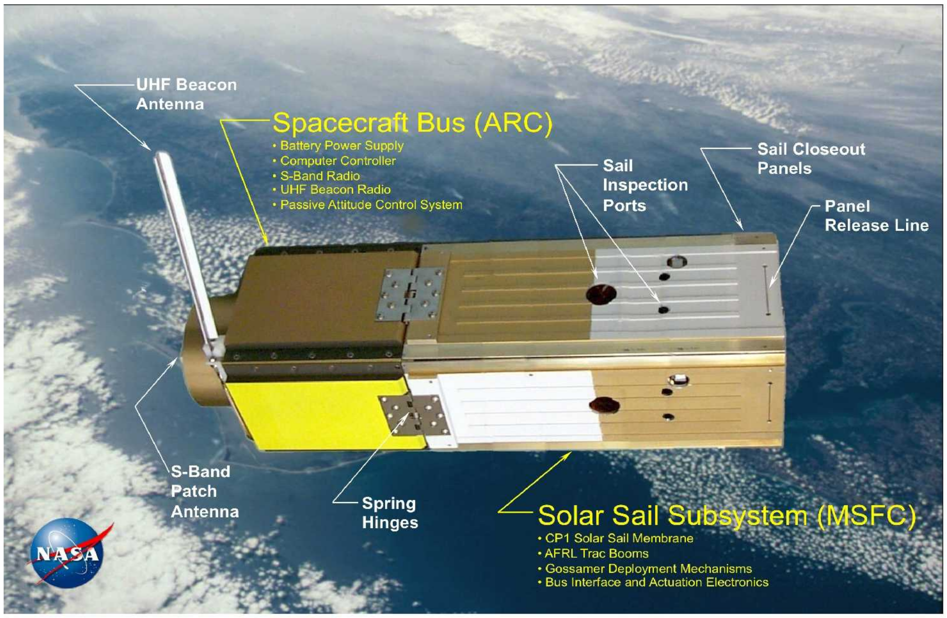

Fig. 2. On-orbit stowed configuration

Fig. 3. NanoSail-D ground deployment test

Due to the aggressive time constraints of the mission (from inception to launch in <6 mo), the sail subsystem was purposely designed to be as modular as possible with the sail subsystem divided into two primary components—the sail assembly and the boom mechanical assembly. Dividing the subassembly allowed for (1) separate relevant functional testing of the sail mechanical assembly and the boom mechanical assembly during the development of the system and (2) complete testing of the entire sail subassembly (deployment functionality) prior to integration with the Nanosail-D bus and release electronics. This basic approach allowed for quick incorporation of lessons learned and design modifications during the development at the subsystem and subassembly level without affecting the activities/design of any other components. Once assembled, the sail subassembly consisted of a standalone unit that bolted to the bus and connected to the release electronics. Launch operations consists of a simple, timed, two-actuation system. The initiating event consists of a burn-wire release of the door panels. The door panels protect the sail material and help to constrain it for the launch environment and ascent venting. The sail membranes, fabricated from aluminum-coated CP-1 material, are z-folded and rolled onto a sail spool. The trac booms, developed by the Air Force Research Laboratory, are also rolled onto a boom spool. The stored strain energy of the rolled booms provides the driving force to simultaneously deploy both the booms and the sail quadrants.

Mission data are to be comprised by radar cross-sectional area data, optical images, and orbital elements. Radar cross-sectional area data and optical images are to be obtained by the U.S. Army's Reagan Test Site. These data may enable estimation of a lower bound on the deployed sail area (lower bound only because the sail plane was likely not normal to the line of sight during data acquisition, hence, the projected area normal to the line of sight was to be measured). Estimation of the deployed area will be difficult during initial phases of the mission when the sail is to be "tumbling" about the Earth's magnetic field lines during part of the orbit and passively stabilized in the maximum drag orientation near perigee. Hence, the estimation of the deployed area from orbit data will depend on the latter phases of the mission when the orbit circularizes and the sail passively stabilizes due to aerodynamic torque in a relatively constant local vertical/local horizontal attitude. In the event that the sail does not stabilize prior to reentry, orbital analysis will allow an estimation of an average ballistic coefficient that may be correlated to an average area.

NANOSAIL-D FLIGHT DEMONSTRATION MISSION OPERATIONS

Seventy-two hours after deployment of the NanoSail-D from the P-POD ejection system, the solar sail will deploy and mission operations will commence as described in Table 1.

Table 1. NanoSail-D on-orbit operations sequence

Event	Hours	Minutes	Seconds	Comments
Falcon-1 launch	0	Launch minus 45	0	
NanoSail-D ejection from P-POD; beacon on	0	0	0	Assume launch plus 45 min
Beacon operating	6	0	0	
Beacon off period	66	0	0	
Panels open	72	0	0	
Booms/sails deploy	72	0	15	
Optical confirmation of deployment	73	44	0	Assumed time (one orbit after sail deployment; orbit period 1:34)
S-band on; listen at 30 s "on" and 30 s "off"	75	0	0	
Deorbit	120	10	0	Assumed 4 days after deployment

Passive attitude stabilization will be achieved using permanent magnets in the sailcraft bus to initially detumble and orient the body with the magnetic field lines. The magnets are located on opposite sides of the bus with the north-south axes of the magnets oriented perpendicular to the long axis of the spacecraft. The body will be free to rotate about the magnetic field lines as the permanent magnets align with the Earth's magnetic field. Since the orbit plane inclination was to be <10º, the magnetic field lines will be approximately normal to the orbit plane and gravity gradient torques and aerodynamic torques will tend to passively stabilize the sailcraft in an essentially maximum drag attitude (where the sail plane normal vector is approximately pointed in the velocity vector direction).

CONCLUSIONS

The NanoSail-D would have been the first on-orbit solar sail deployment demonstration. Unfortunately, due to the launch vehicle failure, it never had the opportunity to deploy. MSFC is now working to obtain a launch for the flight spare, which is identical to the original spacecraft used in the August 2008 launch attempt.

REFERENCES

[1]L. Johnson, R.M. Young, and E.E. Montgomery, "Recent Advances in Solar Sail Propulsion Systems at NASA," *Acta Astronautica*, Vol. 61, 376–382, 2007.

[2]P.C.E. Roberts and P.G. Harkness, "Drag Sail for End-of-Life Disposal from Low Earth Orbit," *Journal of Spacecraft and Rockets*, Vol. 44, No. 6, November–December 2007.

[3]V. Lappas, M. Leipold, A. Lyngvi, et al., "Interstellar Heliopause Probe: System Design of a Solar Sail Mission to 200 AU," AIAA Guidance, Navigation, and Control Conference and Exhibit, San Francisco, California, August 15–18, 2005.

NanoSail-D: A Solar Sail Demonstration Mission

6^{th} IAA Symposium on Realistic Near-Term Advanced Scientific Space Missions

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Dr. Mark Whorton, Andy Heaton, Robin Pinson: NASA George C. Marshall Space Flight Center

Greg Laue: ManTech SRS Technologies

Charles Adams: Gray Research

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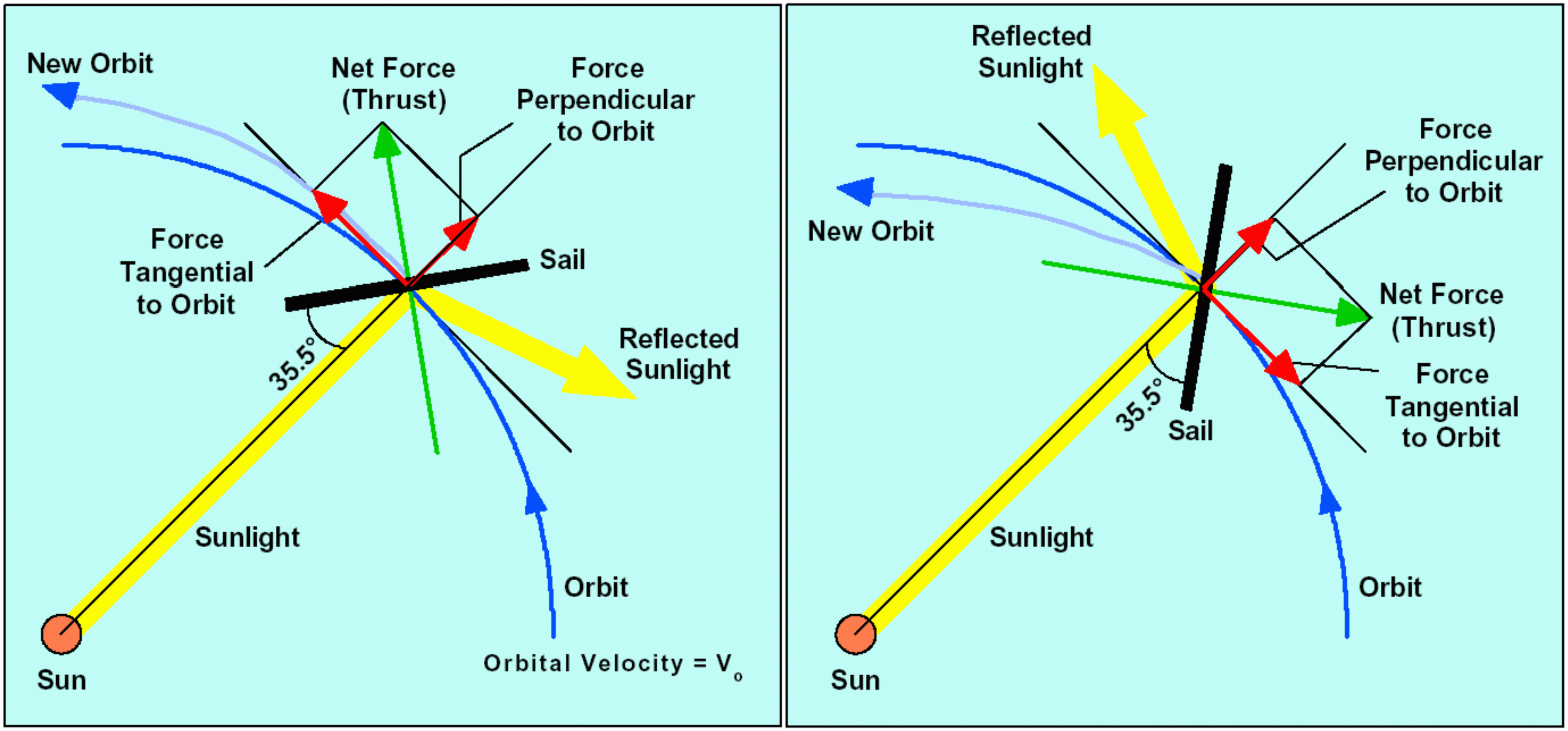
SOLAR SAIL Propulsion Fundamentals

- 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]



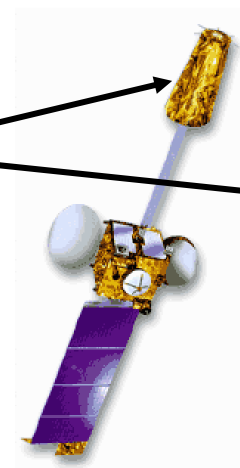
Solar Sail Technology History

NanoSail

Used Since 1962

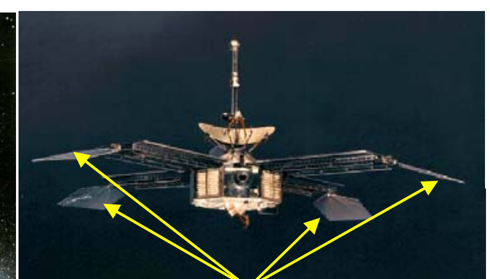
- Solar Sailing was initially developed at JPL as a measure to save the Mariner 10 mission which had lost a large portion of its propellant margin when the star tracker locked on to floating debris instead of Canopus. The mission went on to flyby Venus and three encounters with Mercury. Its successful 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.



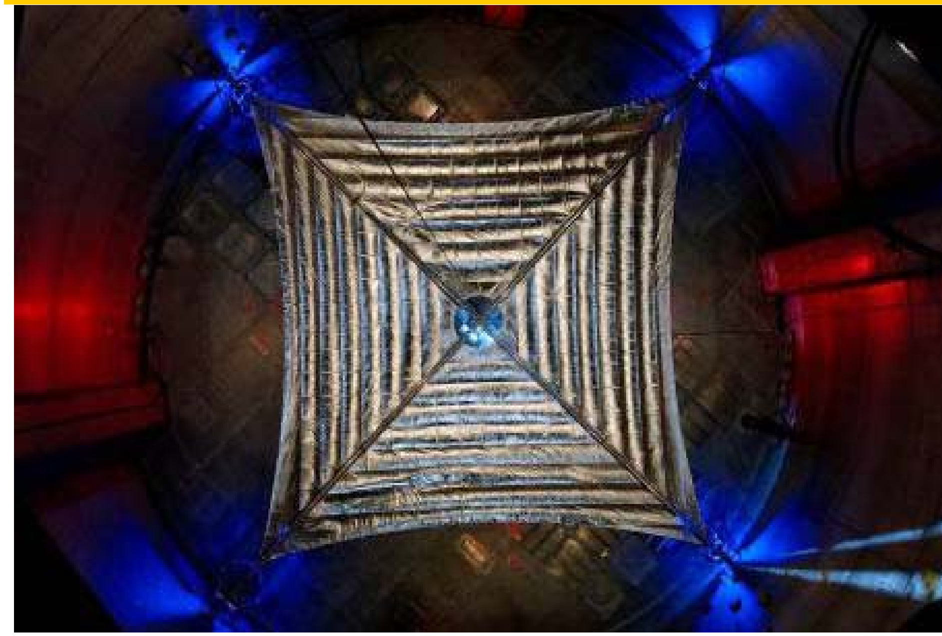
[Stowed Sail] (1991

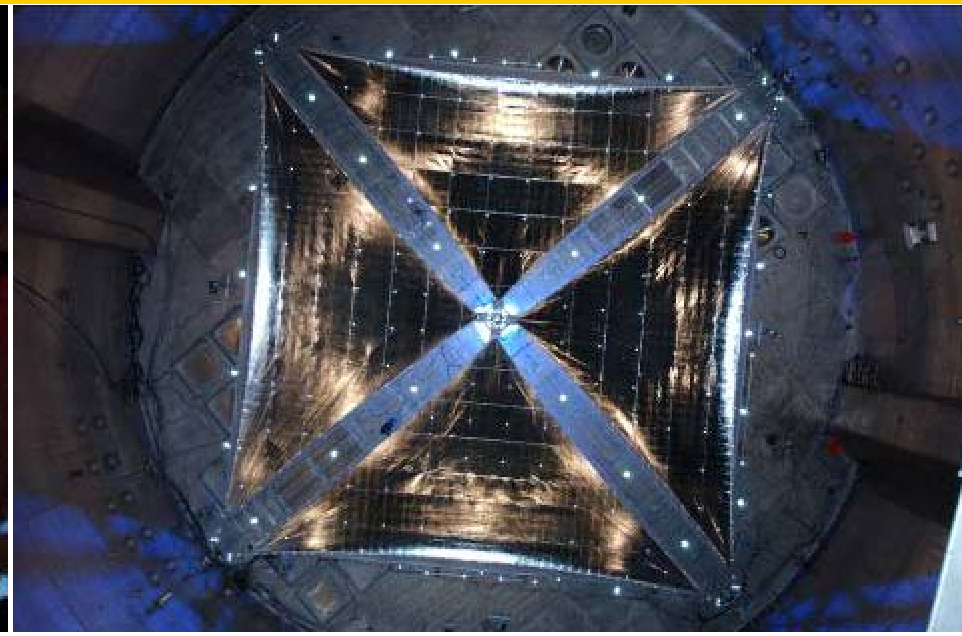
Mariner 2 Dacron Solar Sail (1962)



solar sails on Mariner IV (1964)

Solar Sail Propulsion Technology Status in 2005





- **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.**
  - **Preparing for 40-m space flight validation mission**

NanoSail-D

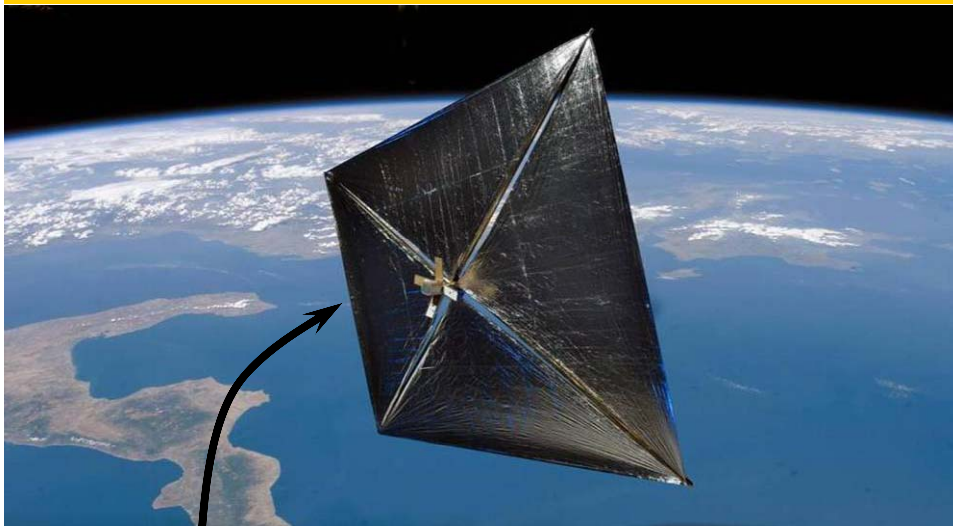
Solar Sail Propulsion Technology Status in 2008

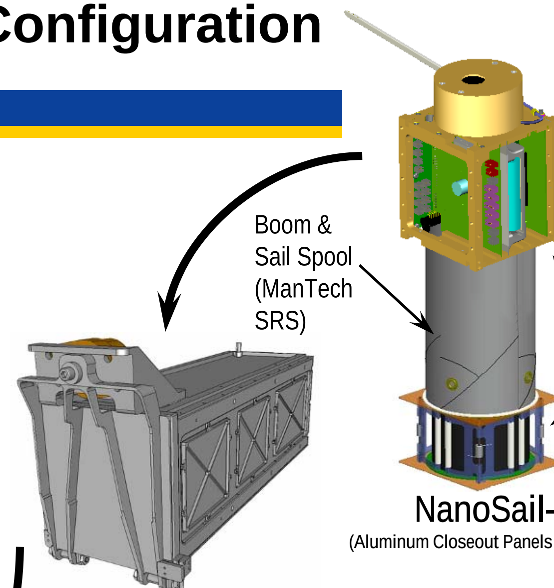
- Zero funding for solar sail technology within NASA
- No further technology work planned
- No flight validation mission flown
- So, I asked the question, “What can we do – cheaply – with the hardware and expertise we’ve acquired (~$30M) – to further advance solar sail technology?”
- The answer?

NanoSail-D

NanoSail-D

NanoSail-D Mission Configuration



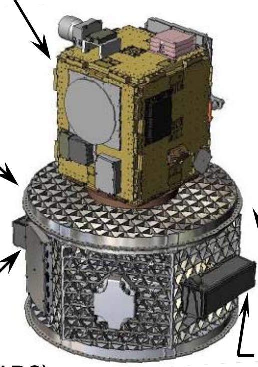


NanoSail-D
(Aluminum Closeout Panels Not Shown)

PPOD Deployer
(Cal-Poly)

Stowed Configuration

SpaceX Falcon-1



Ride Share Adapter
(Space Access Technology)

Launched : August 2, 2008
Launch site: Omelek Island, RTS (Kwaj)
Orbit: 685 X 330 km, 9º inclination
De-Orbit Period: 5 - 14 days

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

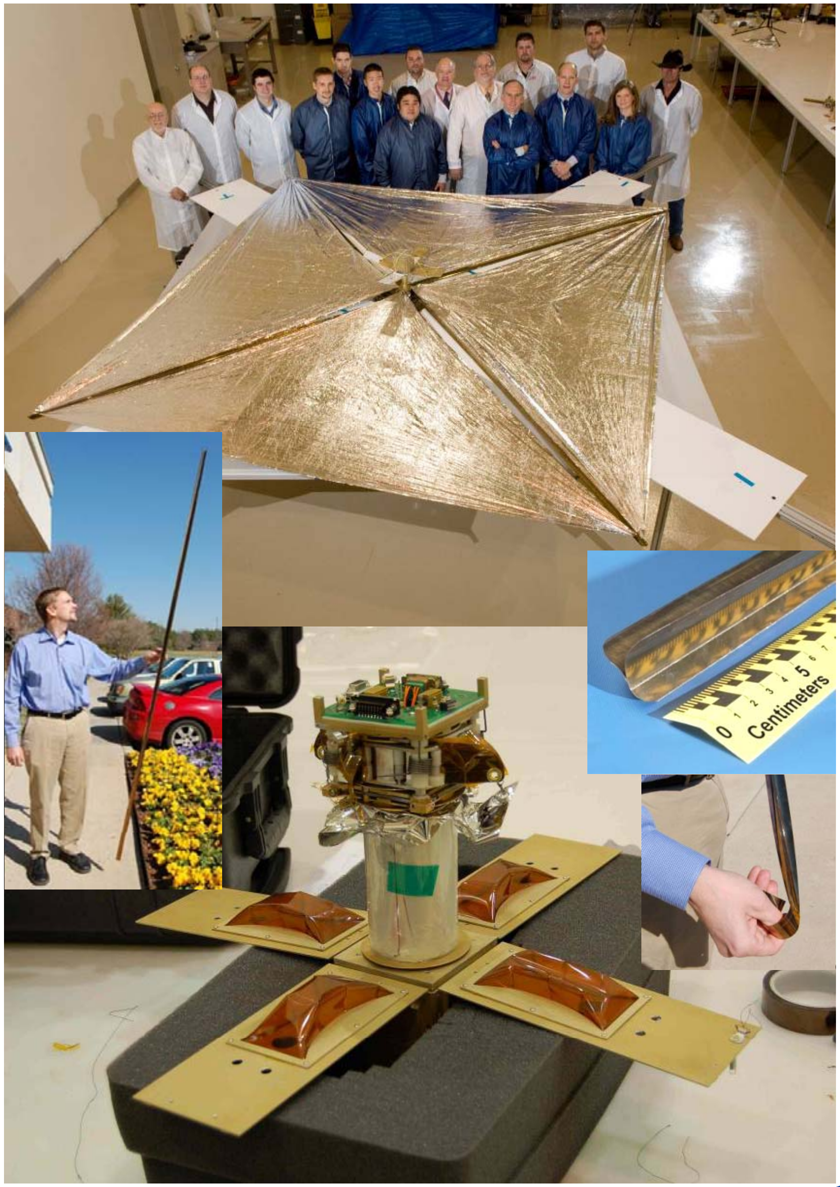
Project Overview

- **Minimum Success Criteria**
  - Design, fabrication, test and delivery of a flight-ready satellite to the launch site within budget on an extremely tight 6 month schedule.

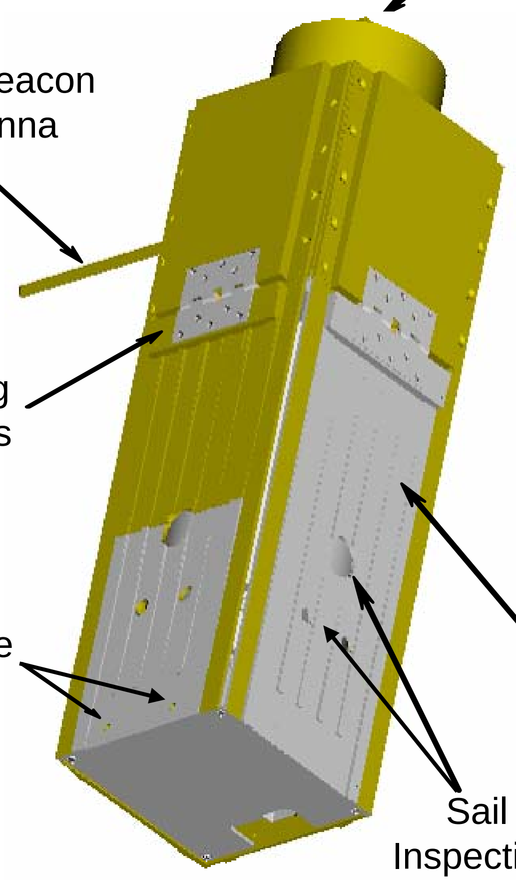
- **Full Success Objectives**
  - Primary: First solar sail deploy in space
  - Secondary
    - *Solar Sail performance assessment*
    - *Drag sail assessment*
    - *Pioneer new project processes*

- **Deliverables**
  - Primary Solar Sail Payload Assembly
  - Spare Solar Sail Payload Assembly
  - Payload Mockup for ARC Bus development
  - Poly PicoSat Orbital Deployer

- **Sponsors**
  - MSFC Center Director
  - ARC Center Director



Major Milestones

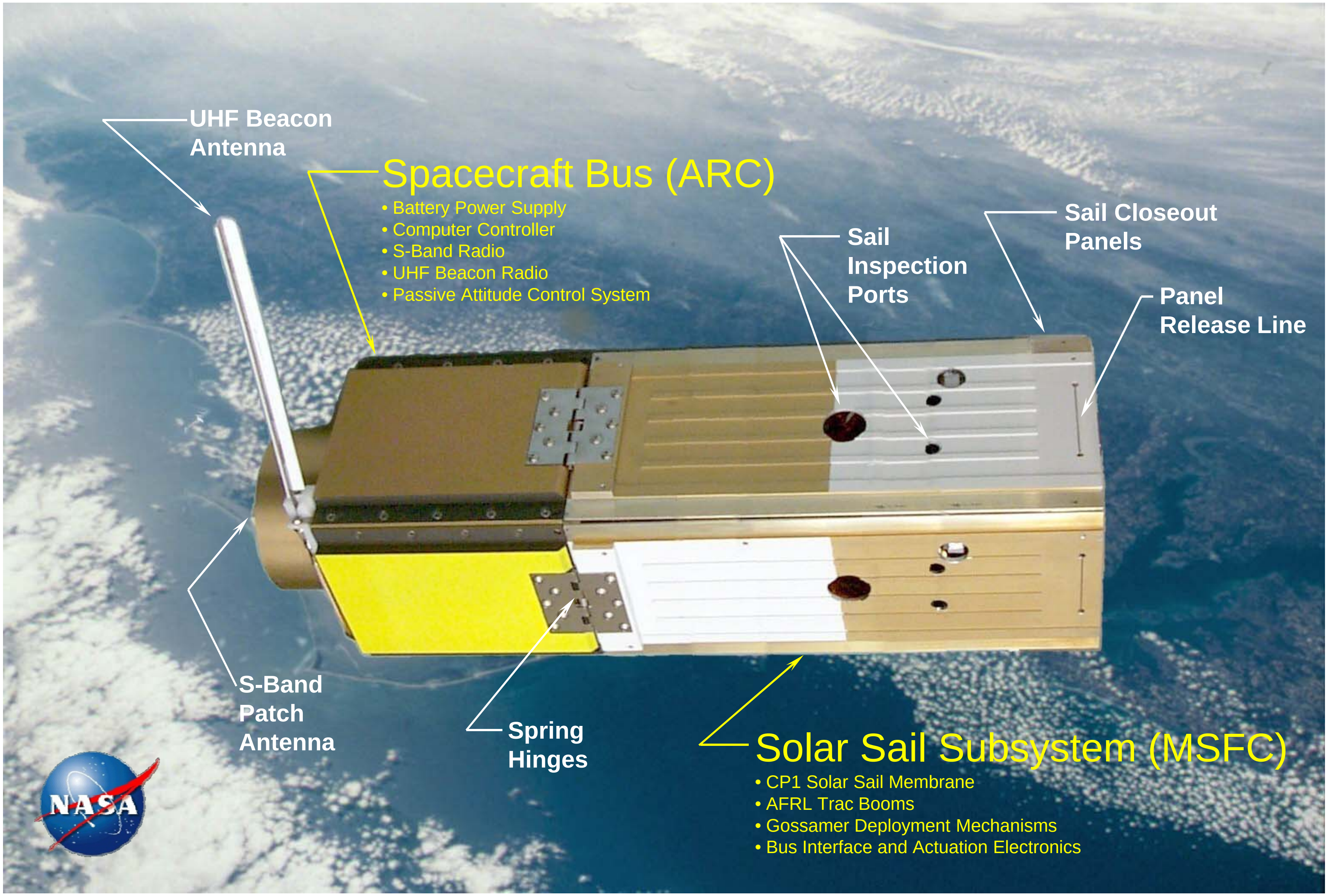


Stowed Configuration

- Project Milestones
  - Final Design Audit - 1/17/08
  - MSFC System Acceptance - 4/17/08
  - Sail payload delivery to ARC - 4/21/08
  - Bus-payload integration and flight certification at ARC
    - Integration & checkout – 4/21-24
    - Satellite environmental testing - 4/25 - 5/6
    - Mission simulations completed - 5/10
  - FRR at ARC – 5/13/08
  - ORR at ARC– 6/9/08
  - PM&PI travelling to Kwajalein
  - NSSTC/1048 mission center set-up
  - Launch 8/2 – 8/15

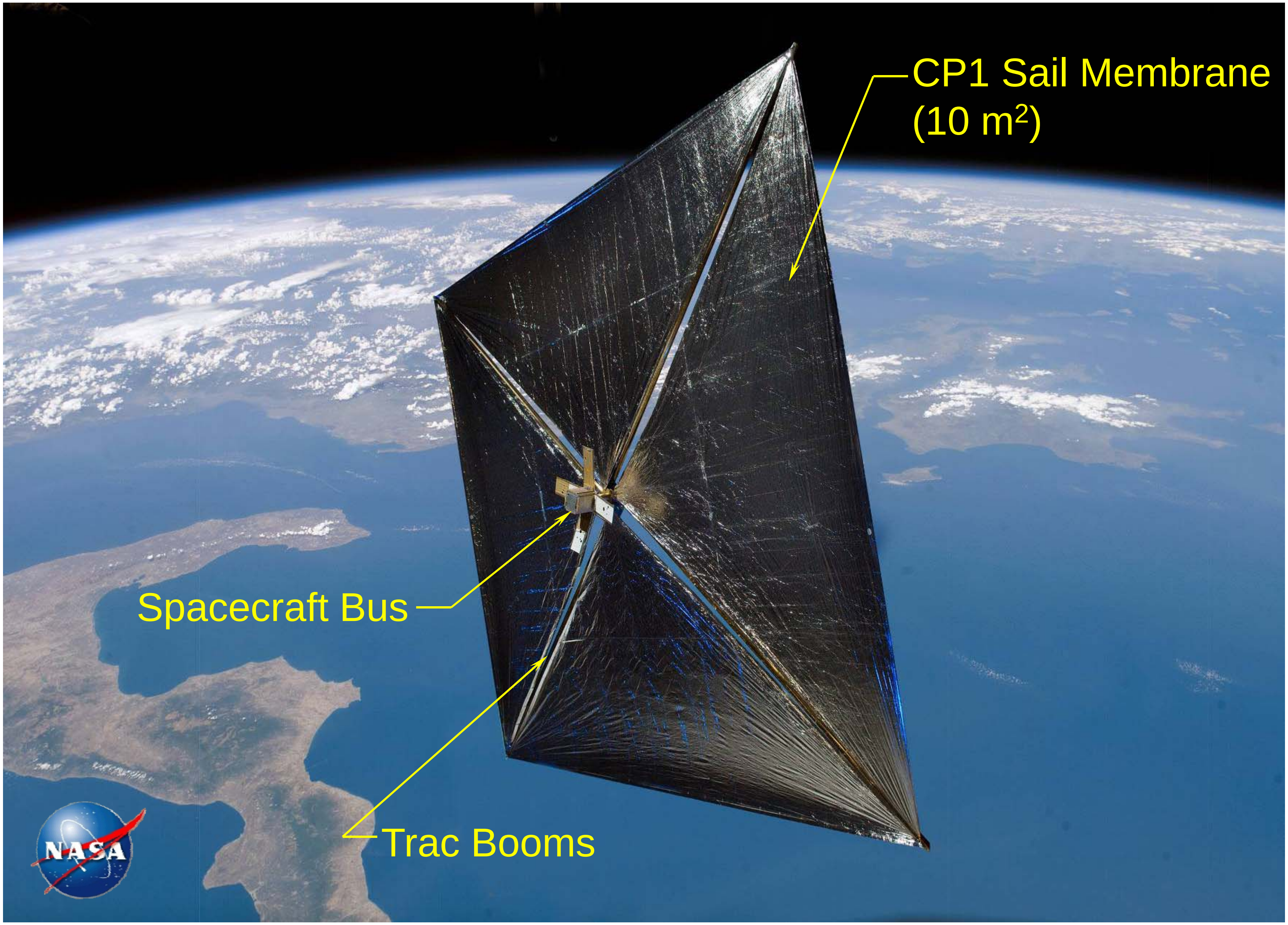
On-Orbit Stowed Configuration

NanoSail-D



Deployment Video

On-Orbit Deployed Configuration



Mission Milestones

Mission Event	*Time After Launch, L+ time (hr:min:sec)*	*Comments*
1. Falcon-1 Launch	00:00:00	
2. NanoSail-D Ejection from PPOD, UHF beacon on @ 10%	00:17:47	1067 seconds after launch.
3. Panels Open	72:17:47	72 hrs after ejection from P-POD.
4. Booms/Sails Deploy	72:18:02	15 seconds after panel opening.
5. S-band on, listen at 30 sec on, 30 sec off.	72:22:47	5 minutes after panel opening.
6. Optical Confirmation of Deployment (projected)	73:52:02	1 orbit after sail deployment (orbit period: 1 hr 34 min).
7. TLE Confirmation of Deployment (projected)	75:26:02	2 orbits after sail deployment.
8. Deorbit	168:18:02	Assumed 4 days after sail deployment.

Mission Dashboard

NanoSail-D

NanoSail-D Mission Dashboard

Mission Counter		Satellite Status		Ground Segment Status	
	0	***Payload Status***		***Kwajalein comm station***	In Transit
	Mission Phase	Panel	Stowed	. Station shipped 6/4	
	Pre-Launch Processing	Sail	Stowed	***El Salvador comm station***	Nominal
June 24 0900	**Launch Operations**	***Bus Health***		Station installed and verified	
	Pre-Sail Flight	Bus Temp	---	***CREST ops facility***	Nominal
T+72 hours	**Sail Deployed Powered**	Batt V	---	***SCU ops facility***	Nominal
~ T+100 hours	**Sail Deployed Unpowered**	Comm	---		
~ T+2 wks	**Satellite De-orbited**	CPU	---	***Photo of the Week*** - UCA antenna	

Event Summary (times in PDT)

- 6/4/08 0900: Satellite leaves Ames

Operational Notes (times PDT)

- Launch planned for 6/24 1900 from Reagan Test Site, Kwajalein Atoll

Drag Estimate from TLEs

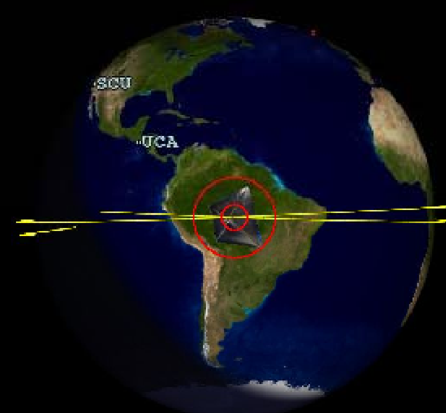
Post-launch, this will be a time history plot of the TLE drag term

Semi-Major Axis

Post-launch, this will be a time history plot of the semi-major axis (which will shrink over time)

Eccentricity

Post-launch, this will be a time history plot of the eccentricity (which will circularize over time)

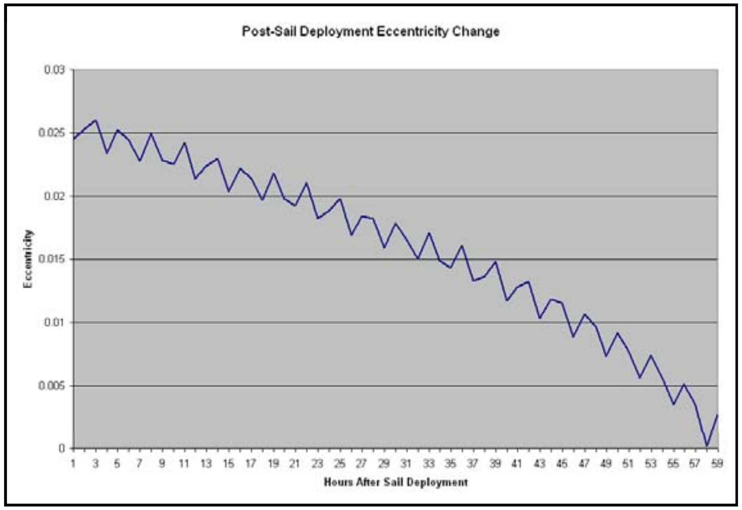


Santa Clara University Robotics Systems Laboratory

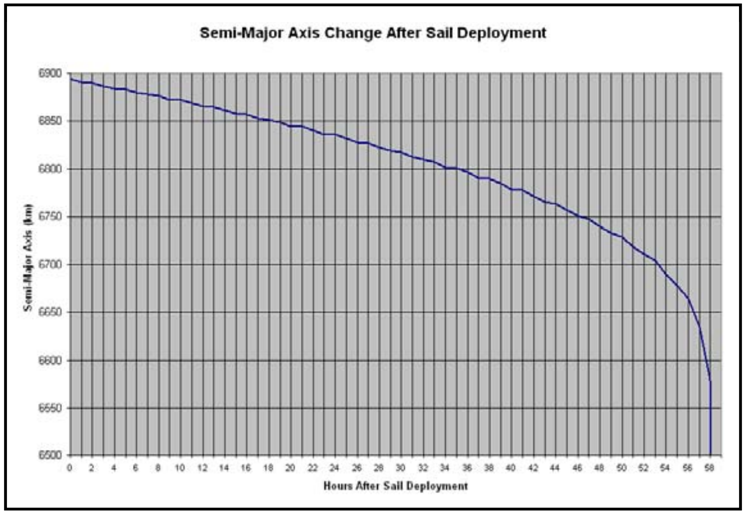
http://nanosaild.engr.scu.edu/dashboard.htm

NanoSail-D

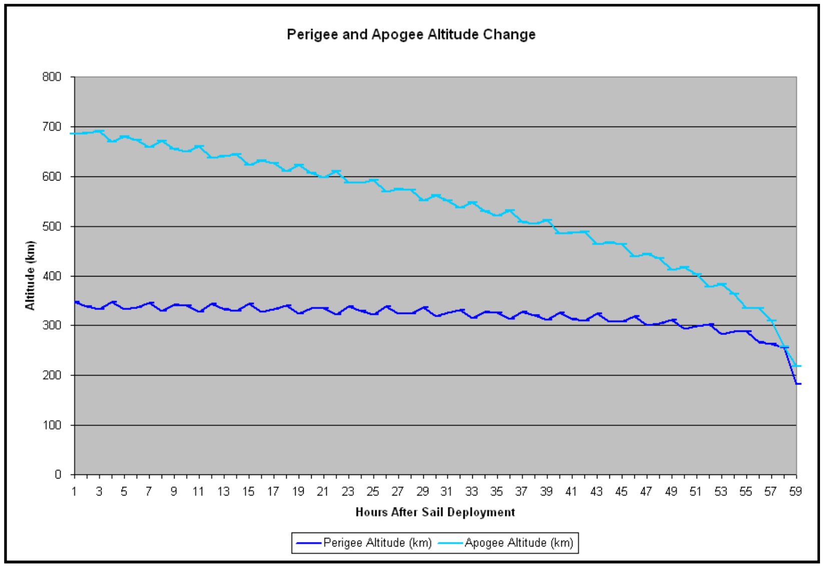
On-Orbit Performance Predictions



Eccentricity

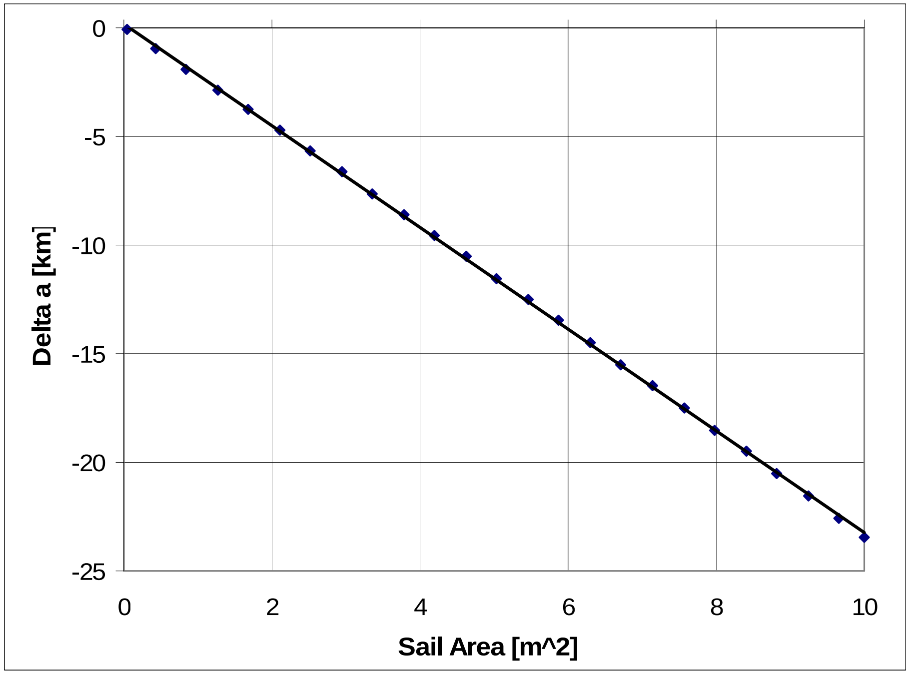


Semi-Major Axis



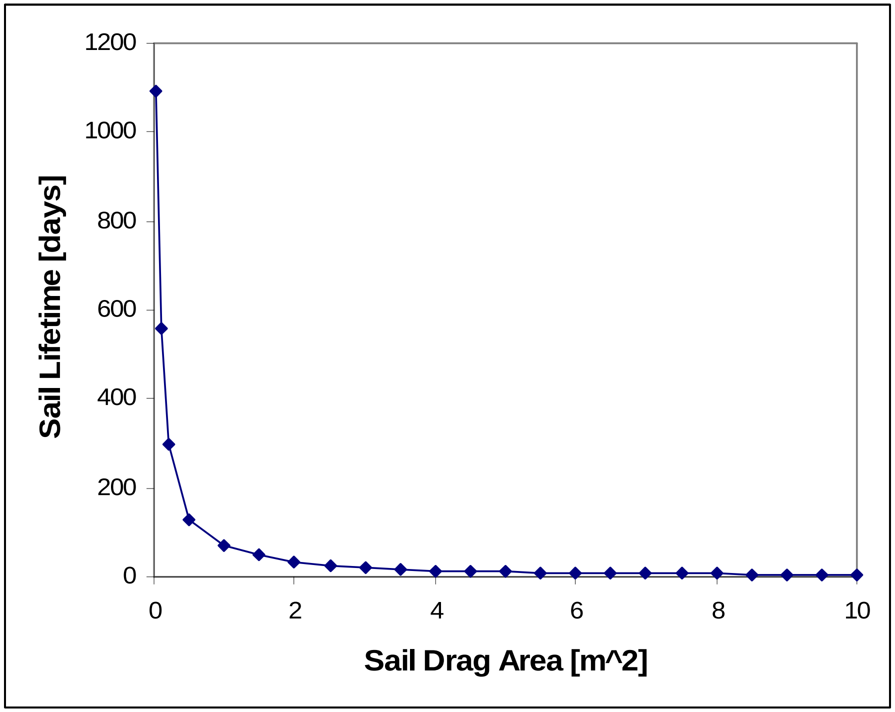
Perigee/Apogee Altitude

On-Orbit Performance Predictions



Orbit Decay as a Function of Sail Area (24 hr Time Period)*

Mission Duration as a Function of Sail Area*



* 330 km x 685 km orbit

Backup