NanoSail-D: The Small Satellite That Could!

Three years from its initial design review, NanoSail-D became the first solar sail vehicle to orbit the earth and just the second sail ever unfurled in space when it successfully deployed its sail on January 20th, 2011. NanoSail-D was jointly designed and built by NASA engineers from the agency's Marshall Space Flight Center in Huntsville, AL, and NASA's Ames Research Center in Moffett Field, CA. Key sail design support was provided by ManTech/NeXolve Corp. in Huntsville. The NanoSail-D experiment is managed by Marshall and is jointly sponsored by the Army Space and Missile Defense Command, the Von Braun Center for Science and Innovation and Dynetics Inc. The ground operations center for the project was located at Santa Clara University, with beacon packets received from amateur radio operators around the world.

The NanoSail-D mission had two main objectives. The first objective was to eject a nanosatellite from a microsatellite, and second, was to deploy its sail from a highly compacted volume and validate de-orbit capability. The first two objectives were successfully achieved and analysis of its de-orbit capability is in process. Another aspiration of the project was to increase awareness of solar sails to the general public. The outpouring of support from the amateur radio operator community proved to be invaluable in tracking and receiving data for analysis. In addition, NanoSail-D has been an exciting target for both novice and veteran sky watchers to view and photograph. Many people have seen NanoSail-D’s solar sail flares -- brief but intense flashes of light caused by sunlight glinting harmlessly from the surface of the sail.

This paper presents an overview of the NanoSail-D project and insights into how the team overcame many of the setbacks along the way. Many lessons have been learned during these past three years and are discussed in light of the phenomenal success and interest that this small satellite has generated.

NanoSail-D: The Small Satellite That Could!

Dean C. Alhorn, Joseph P. Casas
NASA Marshall Space Flight Center
Marshall Space Flight Center, AL 35812; 256-544-9093
dean.alhorn@nasa.gov, joseph.casas@nasa.gov

Elwood F. Agasid
NASA Ames Research Center
Moffett Field, CA 94035-1000; 650-604-0558
elwood.f.agasid@nasa.gov

Charles L. Adams
Gray Research, Inc.
655 Discovery Dr., Suite 300, Huntsville, AL 35806; 256-961-7572
charles.l.adams@nasa.gov

Greg Laue
ManTech International Corporation/NeXolve Corporation
655 Discovery Dr, Huntsville, AL 35806; 256-971-7846
greg.laue@Nexolve.com

Dr. Christopher Kitts
Robotic System Laboratory, Santa Clara University
500 El Camino Real Drive, Santa Clara, CA 95053; 408-554-4382,
ckitts@engr.scu.edu

Sue O'Brien
Rotorcraft Systems Engineering and Simulation Center, University of Alabama Huntsville
301 Sparkman Drive, Von Braun Research Hall, Huntsville, AL, 35899; 256-824-6133
obriens@uah.edu

ABSTRACT

Three years from its initial design review, NanoSail-D successfully deployed its sail on January 20th, 2011. It became the first solar sail vehicle to orbit the earth and the second sail ever unfurled in space.

The NanoSail-D mission had two main objectives: eject a nanosatellite from a microsatellite; deploy its sail from a highly compacted volume and low mass system to validate large structure deployment and potential de-orbit technologies. These objectives were successfully achieved and the de-orbit analysis is in process.

This paper presents an overview of the NanoSail-D project and insights into how potential setbacks were overcome. Many lessons have been learned during these past three years and are discussed in light of the phenomenal success and interest that this small satellite has generated.

NanoSail-D was jointly designed and built by NASA's Marshall Space Flight Center and NASA's Ames Research Center. ManTech/NeXolve Corporation also provided key sail design support. The NanoSail-D experiment is managed by Marshall and jointly sponsored by the Army Space and Missile Defense Command, the Von Braun Center for Science and Innovation and Dynetics Inc. Ground operations support was provided by Santa Clara University, with radio beacon packets received from amateur operators around the world.

INTRODUCTION

Almost three years ago the first NanoSail-D flight unit was launched into space. Unfortunately the Falcon-1 launch vehicle failure in August of 2008 caused another setback in the history of solar sailing. The first NanoSail-D mission was over and the backup flight unit was put into cold storage. NanoSail-D had joined the Planetary Society's Cosmos-1 as the next solar sail vehicle to not make it into space.

Fast forward to December 2010.

The second NanoSail-D flight unit had overcome its own obstacles and was launched into space aboard the Fast Affordable Science and Technology SATellite (FASTSAT). Although NanoSail-D2 was not the first to deploy a sail in space, that honor belonged to JAXA's Ikaros; it was to be the first sail vehicle to orbit the Earth. After commanding the FASTSAT satellite to begin the ejection sequence, the initial data received indicated that NanoSail-D2 had ejected. Unfortunately, upon further analysis and data received from the satellite-tracking operators, there was no new object in the orbital path of FASTSAT. Evidently, something had gone wrong and NanoSail-D2 was stuck inside the P-POD mounted on FASTSAT.

Forty-two days after it was commanded to eject, the stuck NanoSail-D2 unit freed itself from FASTSAT and entered orbit by itself. The small satellite was now orbiting the Earth and transmitting its radio, telling everyone it was alive, but no one was listening. Finally, the ground team received and decoded the signals. NanoSail-D2 was operating as designed. NanoSail-D2 unfurled its sail on January 20th, 2011.

This paper presents an overview of the NanoSail-D2 project and insights into how the team overcame many of the setbacks along the way. Many lessons have been learned during these past three years and are discussed in light of the phenomenal success and interest that this small satellite has generated. NanoSail-D2 achieved its goals and became the small satellite that could!

PROJECT INCEPTION

The NanoSail-D project owes its existence to previous work performed under the NASA In-Space Propulsion (ISP) technology project. This project produced two competing large sail design projects. Each of the two competing design teams produced a 20m x 20m scalable solar sail system and deployed the sail in the Plum Brook Station vacuum chamber at NASA's Glenn Research Center. Unfortunately, the solar sail in-space propulsion project was terminated and the hardware from these demonstrations placed into storage.

Following the end of the solar sail ISP technology project, the MSFC sail development team was looking to utilize the leftover solar sail hardware in a smaller class research satellite. Consequently, at this time, cubesat satellites were becoming more prevalent and thus the CubeSail project was started at MSFC. The primary goal of this ambitious project was to deploy a small solar sail in a 3U cubesat form-factor in low earth orbit.

The CubeSail team formed in May 2007 and together with the company NeXolve Corporation, a division of ManTech International Corporation, the conceptual design of CubeSail started to develop. The CubeSail design effort continued until late 2007 when the team was offered a slot to launch the sail subsystem on the upcoming third launch of the SpaceX Falcon-1 rocket in 2008. The team partnered with NASA's Ames Research Center (ARC) and the NanoSail-D project commenced. The greatest challenge for this effort was that the team had to design, develop and deliver the sail deployment hardware to California by the end of April 2008 for integration and testing of the satellite components.

TEAM FORUMULATION

To reduce costs and to deliver the system on schedule, NanoSail-D was designed using as much leftover hardware from previous flight and non-flight projects as possible. The sail material for NanoSail-D was harvested from one of the ISP solar sail programs. Ames and its small satellite contractors provided the electronic bus from leftover GeneSat hardware, updated the internal software to operate NanoSail-D and led this initial NanoSail-D mission.

NeXolve designed and manufactured the NanoSail-D sail deployment system. The Rotorcraft group at the University of Alabama in Huntsville (UAH) provided the electronics for the sail activation Interface board (SAIB). In addition, UAH performed the nanosatellite structural analysis. Gray Research provided key technical support and the Santa Clara University (SCU) in California operated the mission control center. The California Polytechnic State University (Cal-Poly) manufactured the Poly-Picosatellite Orbital Deployer (P-POD) and assisted in testing the satellite. Design-Net engineering provided launch integration support.

DESIGN AND DEVELOPMENT

The NanoSail-D team was given the authority to proceed and the design effort commenced in the first week of 2008. In less than two weeks the team developed the basic design and layout of the satellite system. Over the next two months, the team would finalize the design and begin manufacturing of the system components. Testing of early prototypes would be important to verify the deployment concept.

Key to the success of this rapid project would be the ability to integrate the various components from the partners located in separate areas of the country. Two main interfaces were identified as the electrical and mechanical interfaces. The development methodology was to allow the individual partners to operate and design as independently as possible while being constrained by the two simple interface requirements.

The electrical requirement was primarily defined by the existing capability of the Ames GeneSat bus. The GeneSat bus had much more functionality that was needed for operating the NanoSail-D system. Thus, the bus electronics were simplified to reduce power consumption and provide the necessary power to deploy the panels and the sail. No new electrical functions needed to be developed. Electrical redundancy was considered, but not technically feasible due to the existing capabilities of the GeneSat bus. Therefore, the NanoSail-D electrical interface requirement was a simple schematic on a single letter size piece of paper.

The NanoSail-D mechanical interface requirements were similar in that the existing GeneSat design dictated the physical connections. A single mechanical plate was the structural interface between the GeneSat bus and the sail subsystem. Although this design method is not mass efficient, it allowed the team to work independently and thus simplified the interface.

It was very beneficial, that prior to the NanoSail-D development project, an existing team had some time to work through the preliminary sail deployer design. A preliminary computer model existed for the sail subsystem from the CubeSail effort. Thus a rapid prototype was quickly generated to verify the concept. Also, using the solid model, an early engineering unit was manufactured to understand the dynamics and ability to deploy a sail. Figures 1, 2 and 3 are pictures of the first sail sub-system engineering model and the initial sail deployment.

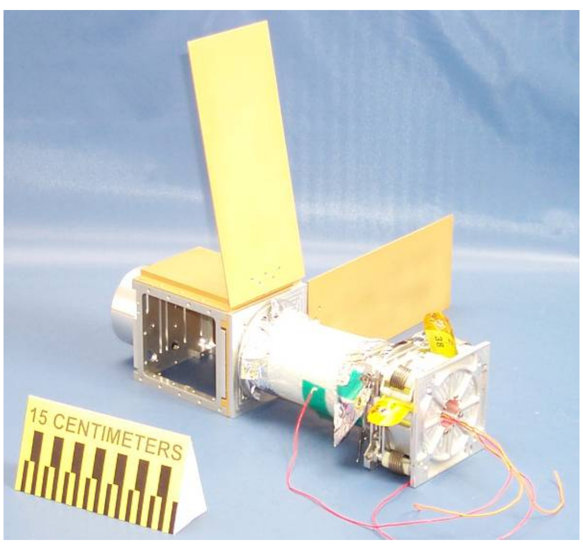


Figure 1: NanoSail-D Sail Sub-system Engineering Model

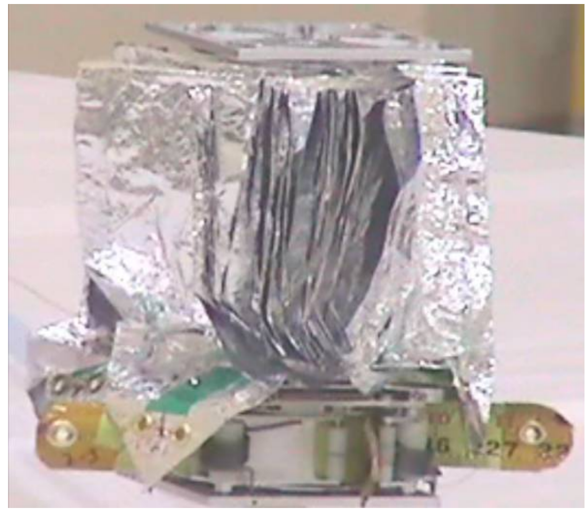


Figure 2: Initial Sail Deployment Unit

Figure 3: Initial Sail Deployment Test

A critical component of the NanoSail-D design was the booms, which pull the sail off the sail spool and support the fully deployed sail. As shown in Figure 1, the initial prototype utilized carpenter tapes for the booms. Unfortunately, carpenter tapes exhibit a phenomenon by which the tape will buckle if the load is too great. If this were to happen in orbit, the sail would lose its structural integrity and collapse. This behavior is exhibited in the third panel in Figure 2. The carpenter tape booms cannot support their own mass and therefore are bending off the edge of the table.

NeXolve engineers knew about a novel type of boom developed by the Air Force Research Laboratory (AFRL) in Albuquerque, NM. The AFRL Triangular Rollable And Collapsible (TRAC) boom had the stiffness to deploy and support itself and the fully unfurled sail. Figures 4 and 5 are pictures of a TRAC boom sample. It was not known if the booms could be manufactured in time for integration and testing. Therefore, an alternate design proceeded in parallel utilizing the TRAC booms. Less than a month before shipment, the TRAC booms finally arrived. The TRAC booms were quickly incorporated into the flight system and deployment testing started.

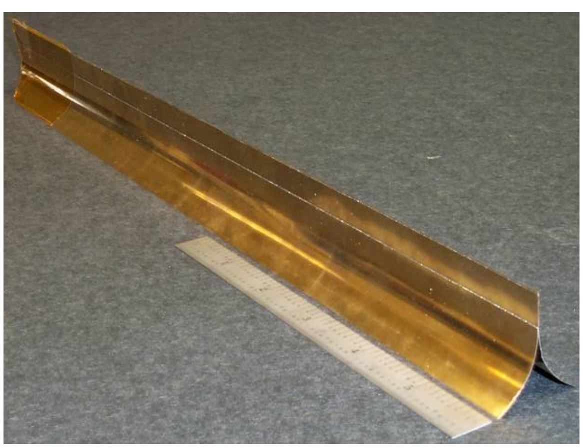


Figure 4: AFRL TRAC Boom Sample

Figure 5: AFRL TRAC Boom – End View

Several boom deployment tests were executed and the system performed as expected. Another crucial test was to determine if the system would operate after random vibration and ascent vent testing. These tests were performed less than a week before the system was shipped to Ames for integration. The final deployment test would determine if NanoSail-D would be ready on time. After a successful deployment test, the NanoSail-D flight unit was repacked and readied for shipment to Ames. A second backup unit was also quickly assembled and together the two systems were transported to California. Figure 6 is a picture of a completed flight sail deployer sub-system. (Note the four panels and the Kapton bumpers, which keep the sail from billowing and contain it during launch and ejection from the P-POD.)

NanoSail-D: The Small Satellite That Could!

Dean Alhorn, Joseph Casas
Elwood Agasid, Charles Adams,
Greg Laue, Dr. Christopher Kitts, Sue O'Brien

Small Satellite Conference
Logan, UT
08-10-2011

MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, AL

NASA

Ames Research Center
Nanosatellite Mission Office

Dynetics

VCSI
INNOVATION · RESEARCH · COLLABORATION

Space & Missile
Defense Command

NEXOLVE
ManTech
International Corporation

SPACE DEVELOPMENT & TEST WING
Space Test Program

AIR FORCE RESEARCH LABORATORY

Rotorcraft Systems Engineering and Simulation Center
UAH
RSESC

GRAY RESEARCH, INC.
Technical Excellence • Customer Satisfaction

Santa Clara University

L&M Electronics

CAL POLY

JE JACOBS SVERDRUP

DEFOUW ENGINEERING

uarc
University Affiliated Research Center

UC SANTA CRUZ
NASA Ames Research Center

AE
ASRC Engineering

“Twenty years from now you will be more disappointed by the things you didn't do than by the ones you did do. So throw off the bowlines. Sail away from the safe harbour. Catch the trade winds in sails. Explore. Dream. Discover.”

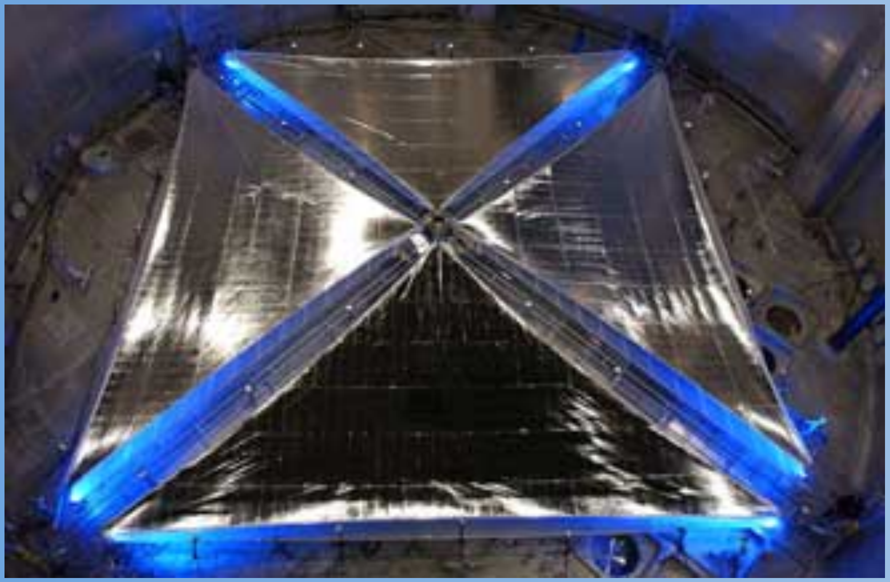
-Mark Twain

Navigo spatio

-Dean Alhorn

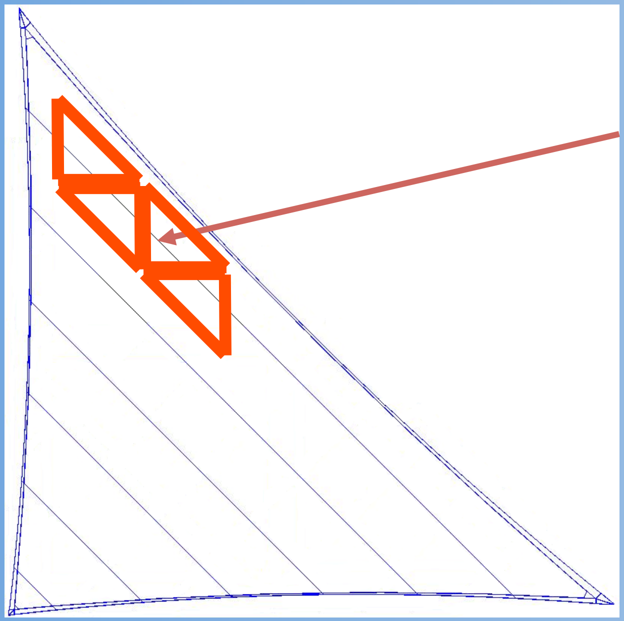
NanoSail-D Pre-History

NanoSail-D



NASA In-Space Propulsion (ISP) Technology Program
ISP program completed 2007

ATK Solar Sail System Ground Demonstrator –
Four quadrant, 20-meter solar sail system fully deployed during testing at NASA Glenn Research Center's Plum Brook facility in Sandusky, Ohio.



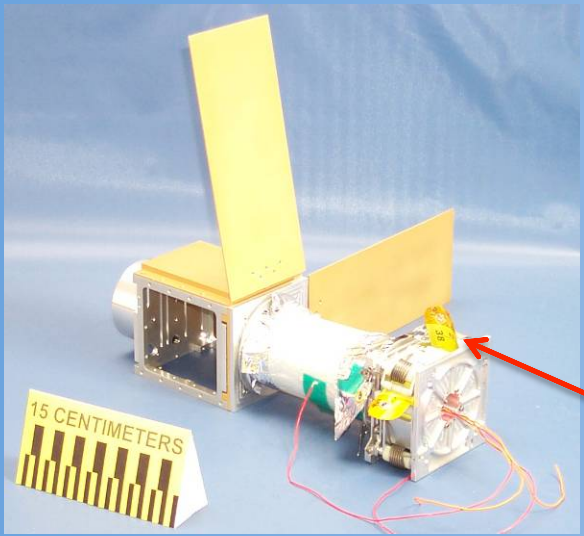
NanoSail-D quadrants (12 total) harvested from existing 20-meter ISP solar sail.

NeXolve/ManTech – subcontractor for ATK

NanoSail-D Timeline - 2008

- CubeSail effort 05/07 – 12/07
- NanoSail-D ATP 01/08 for delivery late April 2008
- Design, built and tested two flight units in 4 months!
- SN001 and SN002 delivered to ARC for integration 04/21
- Final integration completed, 05/05
- Flight units delivered to Kwajalein, 06/08
- SN001 integrated into P-POD on launch vehicle 06/09
- Falcon 1 third launch, 08/03
  - Falcon 1 vehicle failed to achieve orbit, total loss of NanoSail-D SN001
- NanoSail-D SN002 returned to ARC and placed in controlled storage

NanoSail-D Early Prototype



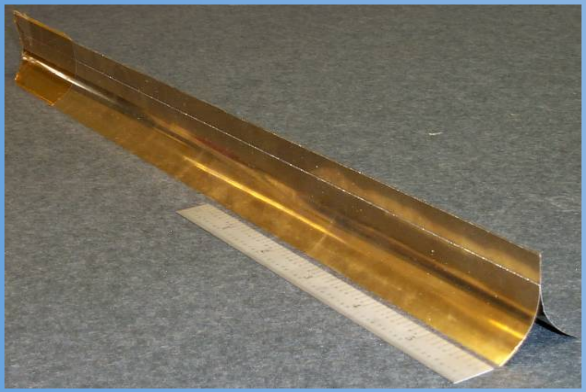
Early NanoSail-D Sail Subsystem Prototypes

Carpenter tape booms

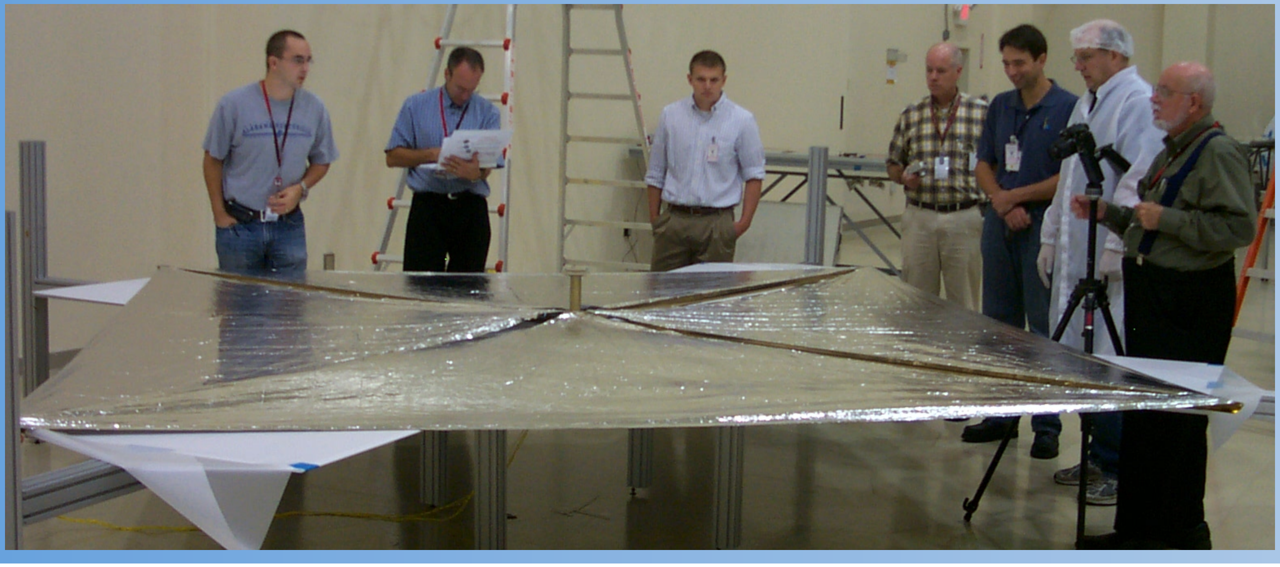
First deployment of NanoSail-D prototype

Note: Carpenter tape booms sagging under own weight.

NanoSail-D Flight Booms



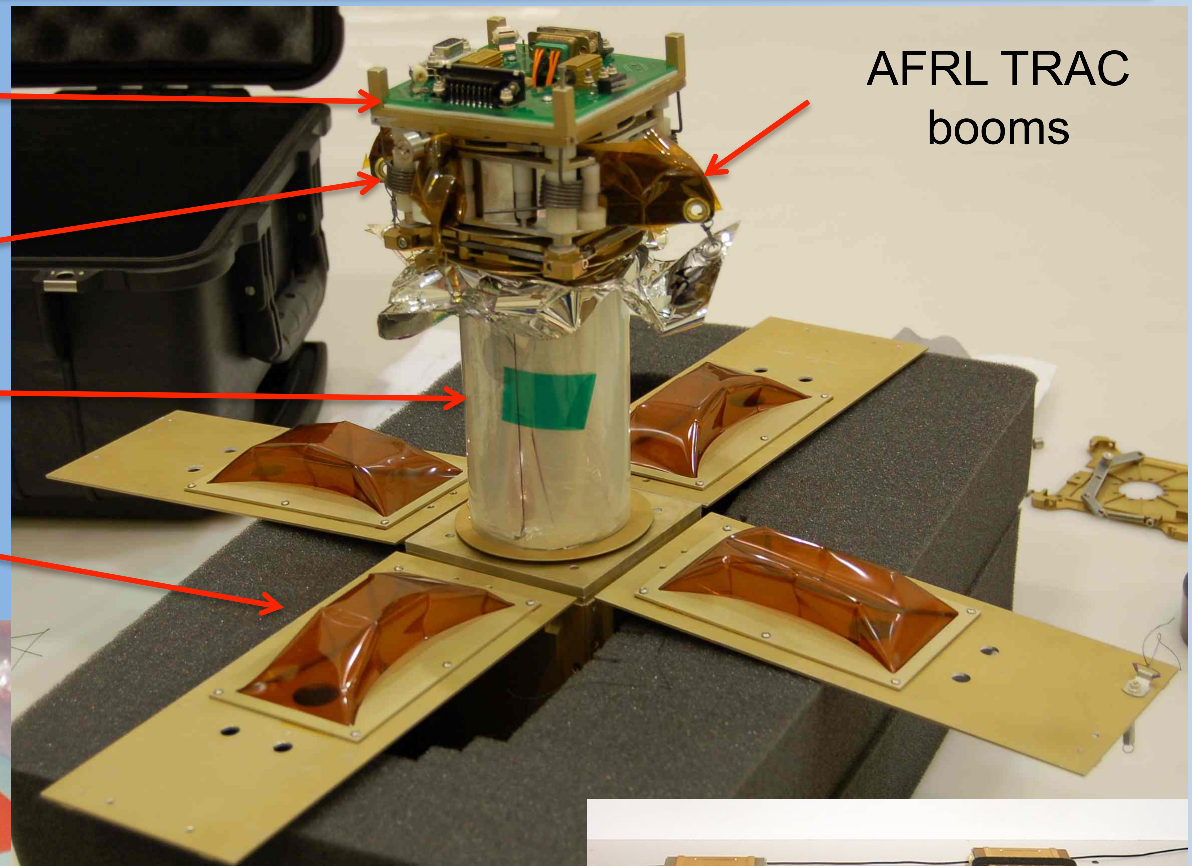
Triangular Rollable And Collapsible (TRAC) Boom
T_z critical = no torsional buckling mode
Developed by Air Force Research Laboratory (AFRL)
Contact: Jeremy A. Banik



Greg Laue/NeXolve holding 2.7m boom

NanoSail-D

NanoSail-D System Components



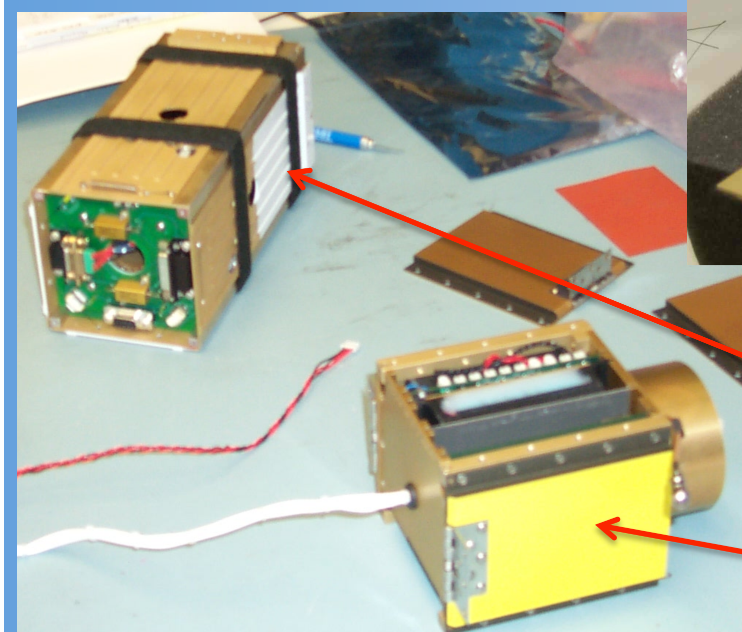
Sail Activation Interface Board (SAIB) - UAH

Boom and sail deployer mechanisms - NeXolve

$10m^2$ Sail
4 quadrants

Panel doors with Kapton bumpers

AFRL TRAC booms



NSD sail subsystem stowed configuration

Modified GeneSat bus – ARC

NSD Flight units 1 & 2

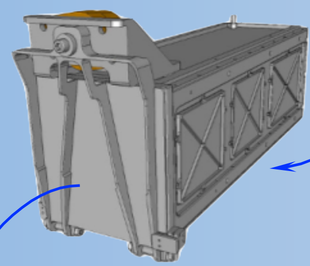
NanoSail-D

NanoSail-D SN001 Mission Synopsis

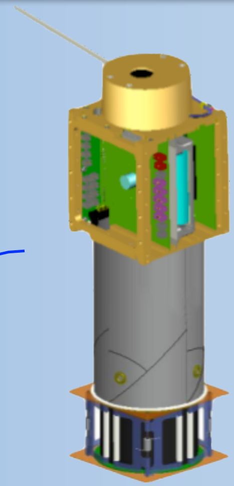
NanoSail-D SN001 Mission 01/08 – 08/08

- Primary Objective
  - Sail Stow & Deploy
- Secondary/Opportunity
  - Ground Imaging
  - De-orbit Maneuver
- Relevance: Future low cost, nanosat science & technology missions will be more capable with the addition of flight proven technologies in:
  - Gossamer deployable structures
  - De-orbit systems

Stowed Configuration



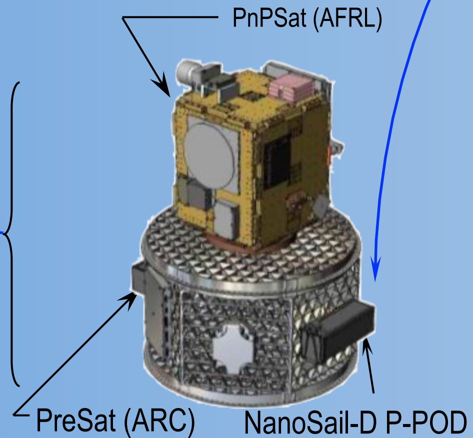
PPOD Deployer



NanoSail-D

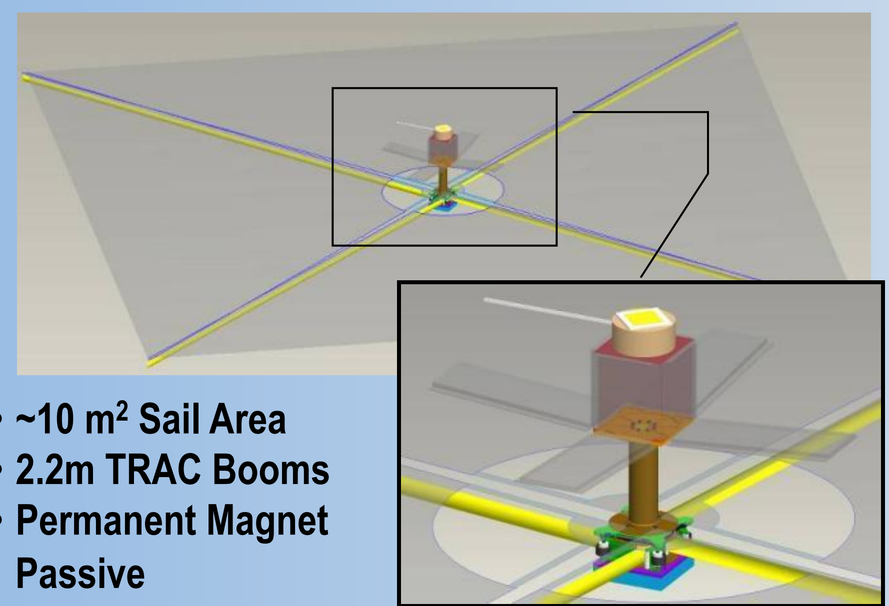
Panel Doors Not Shown

Falcon-1 (SpaceX)



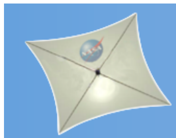
Ride Share Adapter
(Space Access Technology)

Launch Date: 3 August 2008
Launch Vehicle Failed to reach orbit.
Loss of NanoSail-D SN001



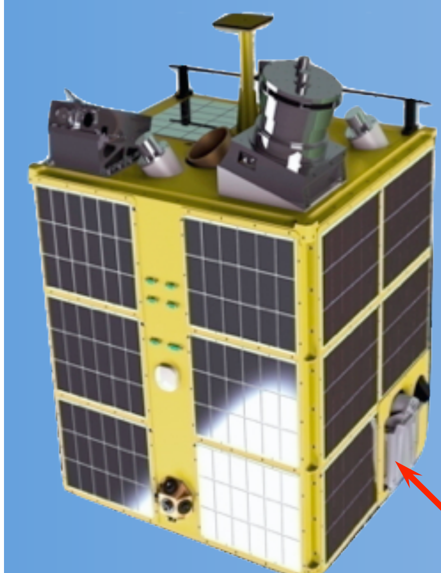
- ~10 m^2 Sail Area
- 2.2m TRAC Booms
- Permanent Magnet Passive Stabilization

Deployed Configuration

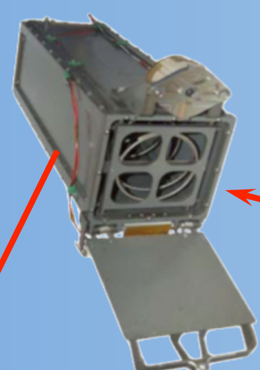


NanoSail-D2 — 2009

- **NanoSail-D was identified as payload candidate for flight on FASTSAT-HSV01 mission**
  - **NanoSail-D presented to the mid-SERB panel in April 2009**
    - **<u>Objective 1:</u> Demonstrate the capability of the FASTSAT-HSV spacecraft to launch a nanosatellite while minimizing recontact.**
    - **<u>Objective 2:</u> Demonstrate the capability to deploy a highly compacted solar sail/boom system and to validate de-orbit functionality.**
  - **Received ATP to refurbish SN002 unit for STP-26 mission. (7/09 - 2/10)**



FASTSAT-HSV01



Poly-Picosatellite Orbital Deployer (P-POD)

NanoSail-D (On-orbit stowed configuration)

NanoSail-D (On-orbit deployed configuration)

10

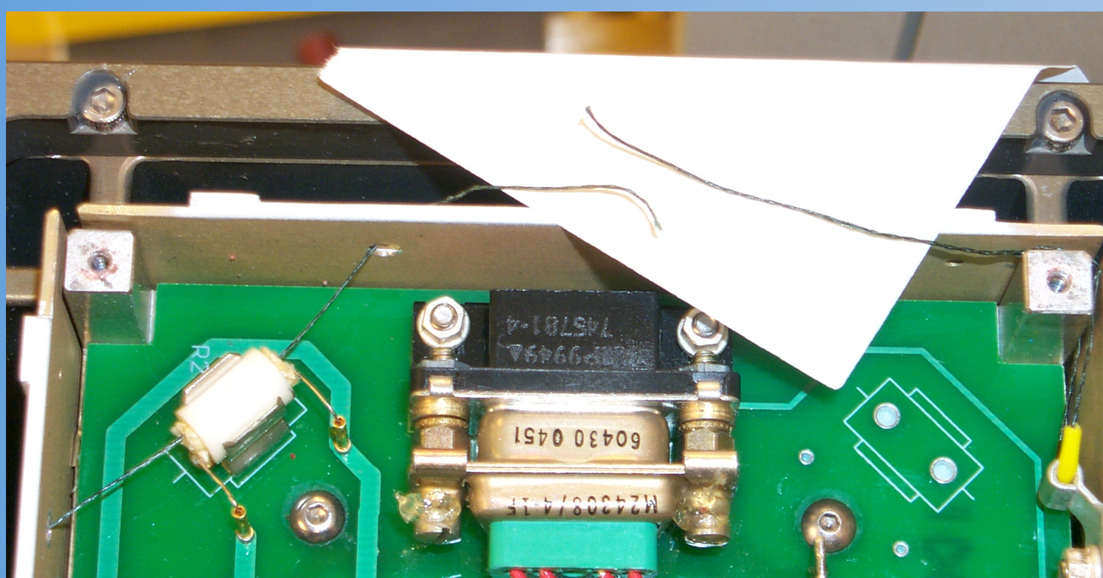
NanoSail-D

Refurbishment Problems

Sail did not deploy after being in storage for over a year.

Cause was stuck boom spool.

Redesigned & remanufactured spool bushings, cleaned spool parts.



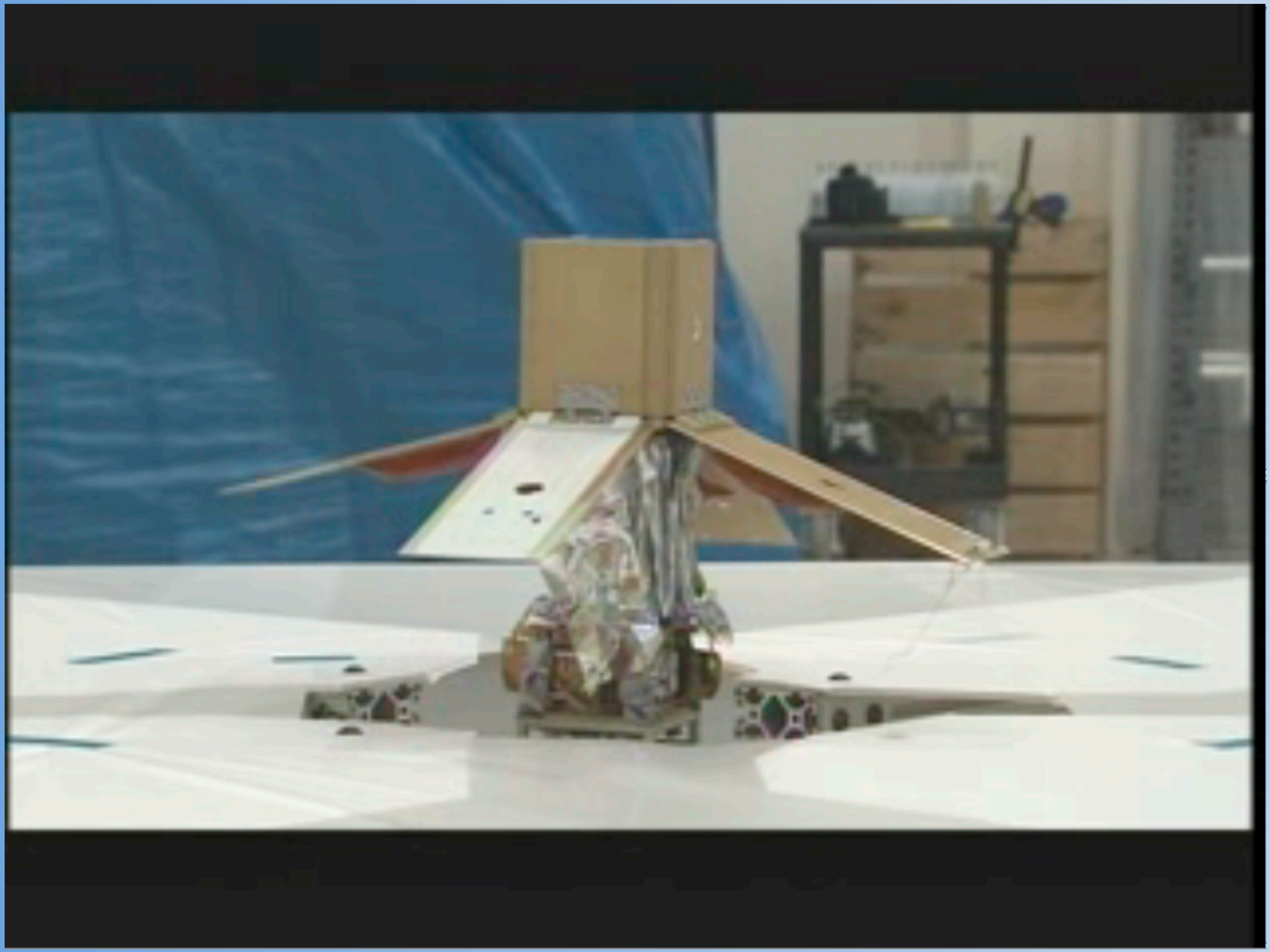
Door retention wire broke after shock testing.

Cause was improper routing of retention wire during assembly.

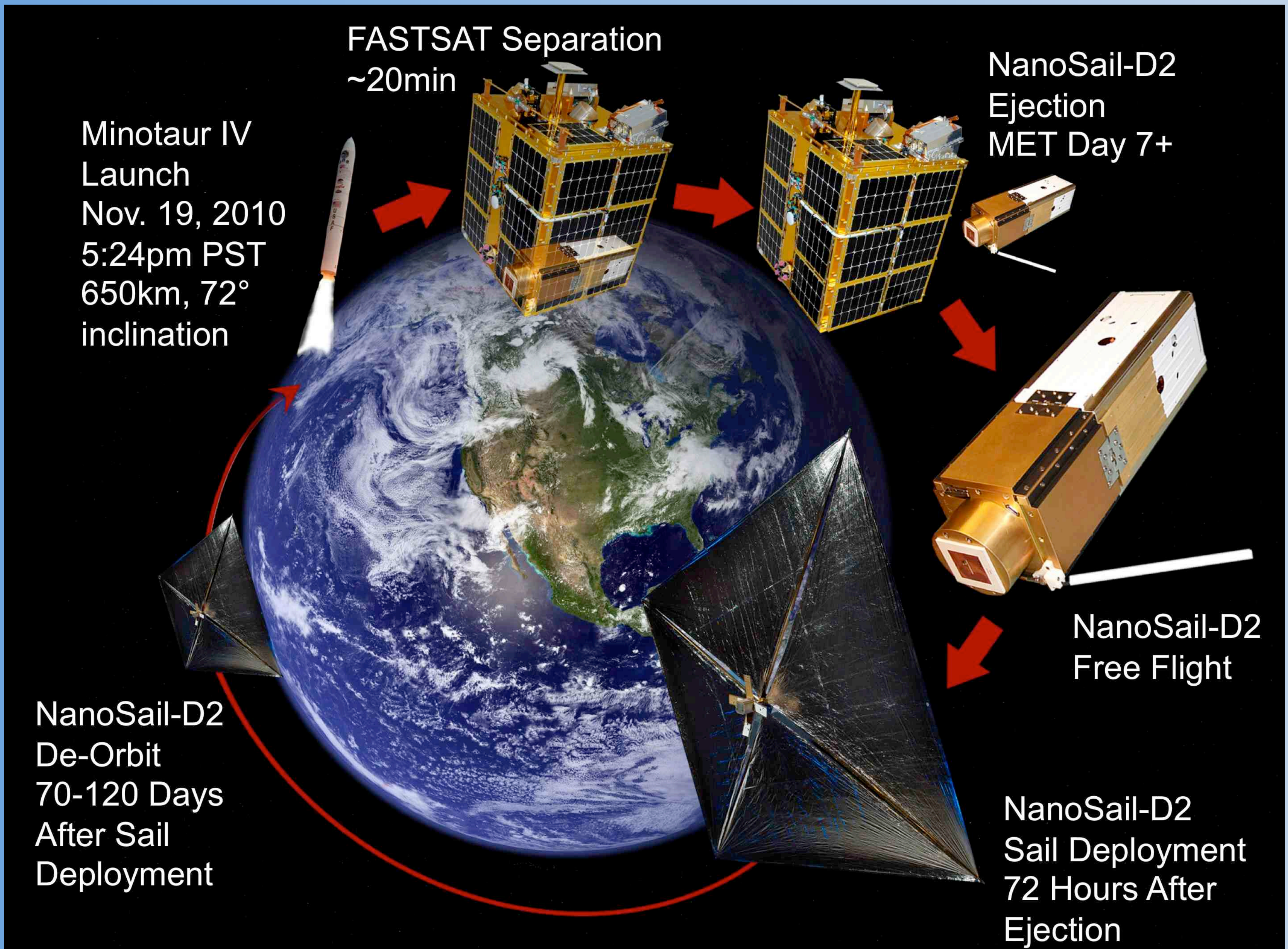
Corrected assembly process.

NanoSail-D

NanoSail-D Deployment Video



NanoSail-D2 Mission Timeline Plan



Smooth Sailing

Expect the unexpected with NanoSail-D

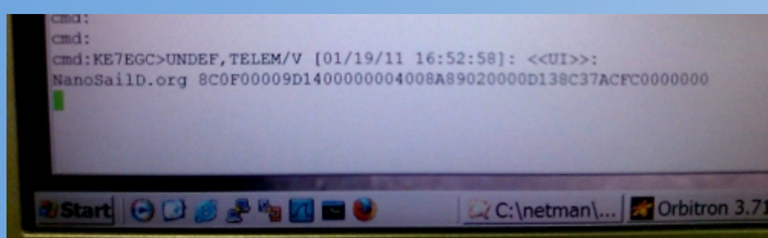
NanoSail-D

01/17/11 – Martin Luther King Day Federal Holiday – NanoSail-D2 leaves FASTSAT. (Liberation Day?)

01/18/11 – 10am FASTSAT Spacecraft Analysis (SPAN) noted an anomaly in the solar panel voltages and currents.

01/19/11 – 9:30am contacted JSpOC, confirmed another object in FASTSAT orbit.

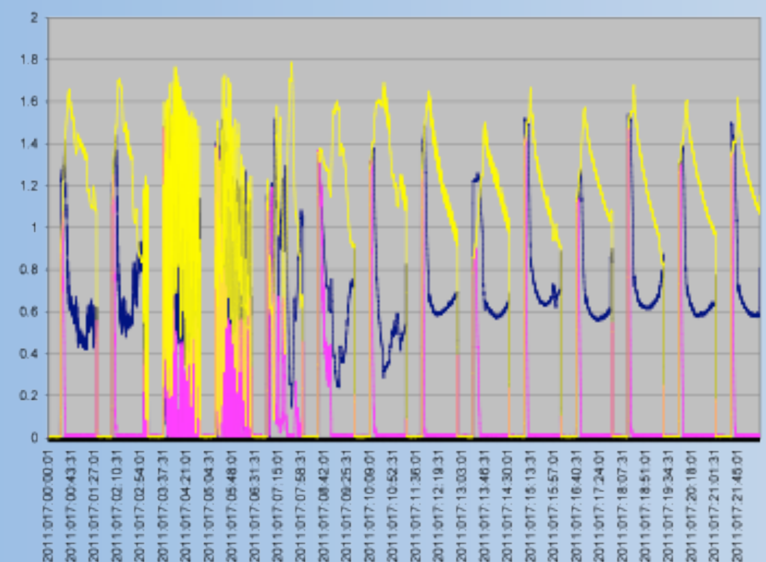
01/19/11 – 5:00pm NanoSail-D2 beacon first received at Marshall Amateur Radio Club.



01/20/11 – 9:00pm NanoSail-D sail unfurled.

01/21/11 –JSpOC confirmed sail deployment.

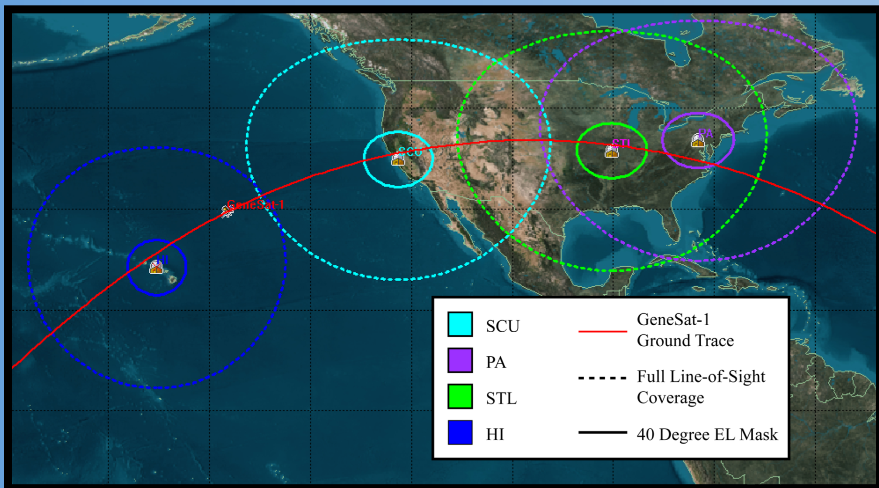
FASTSAT solar panel currents



Stan Sims, Dean Alhorn @ MARC

NanoSail-D

Santa Clara Ground Systems Team



SCU Beacon sites – SCU, STL, PA
(HI – not operational at launch time)

NanoSail-D Beacon Data – 64 bytes
1 sec. transmission every 10 sec.

Eventually received 469 beacon packets from 11 different countries in less than 48 hours.

NanoSail-D2 beacon audio
Captured by H. Hamoen/PA3GUO

NanoSail-D Summary Sheet

Beacon Format (Transmitted every 10 seconds continuously)
Flight 1: 437.269MHz, Network Addr: 6000, Encrypt Key: 6000, Unit Addr: 600, PW: 0x6666
Flight 2: 437.270MHz, Network Addr: 7000, Encrypt Key: 7000, Unit Addr: 700, PW: 0x7777

Size (bytes)	Field	Details
1	Software Version Number	Set to 120 for flight
1	Burn Time	Set to 15 for flight
2	Start Phase	Set to 0 for flight
2	Current Phase	30 second increments
1	Switch State	Real-time value of switch
1	Panel Deploy Status	Indicates panel deployed
1	Sail Deploy Status	Indicates sail deployed
2	Startup Counter	Number of satellite resets
1	Power Port	Subsystem power indicators. 138: Beacon ON, S-Band OFF 139: Beacon ON, S-Band ON
2	Battery Voltage	Volts= 0.0179*Counts - 3.9930
2	Temperature	Satellite bus temperature
3	Satellite Timestamp	Current satellite time (seconds)
3	Satellite Ejection Time	Time at last power up (seconds)
3	Sail Deployment Time	Time of start of burn sequence (seconds)

Mission Timeline (T=Elapsed Time, P=Current Phase)
T=00:05:00 (P=0010) : Deployment (Satellite ON, Beacon ON, S-Band OFF)
T=72:05:00 (P=8650) : Start of Burn Sequence
T=72:06:00 (P=8652) : Burn Panel Wire (1st attempt)
T=72:06:30 (P=8653) : Burn Panel Wire (2nd attempt conditional)
T=72:07:00 (P=8654) : Burn Panel Wire (3rd attempt conditional)
T=72:07:30 (P=8655) : Burn Sail Wire (1st attempt)
T=72:08:00 (P=8656) : Burn Sail Wire (2nd attempt conditional)
T=72:08:30 (P=8657) : Burn Sail Wire (3rd attempt conditional)
T=72:09:00 (P=8658) : S-Band ON
T=84:09:00 (P=8659) : Satellite OFF

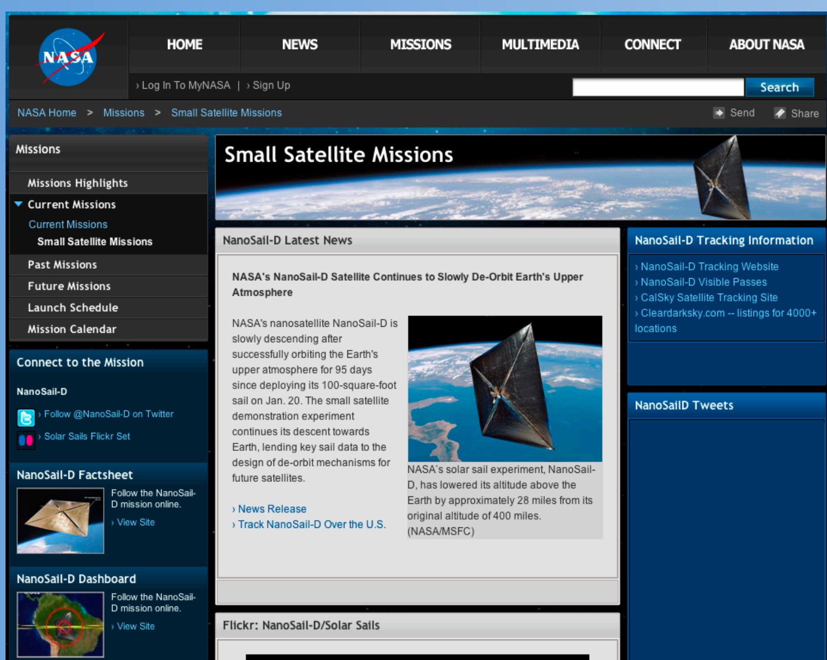
Contingency
IF (Panels or Sail did not deploy) AND (Startup Counter = 60)) THEN Goto P=8650
IF (Panels or Sail did not deploy) AND (Battery Voltage < 6.7V for 30 minutes) THEN Goto P=8650

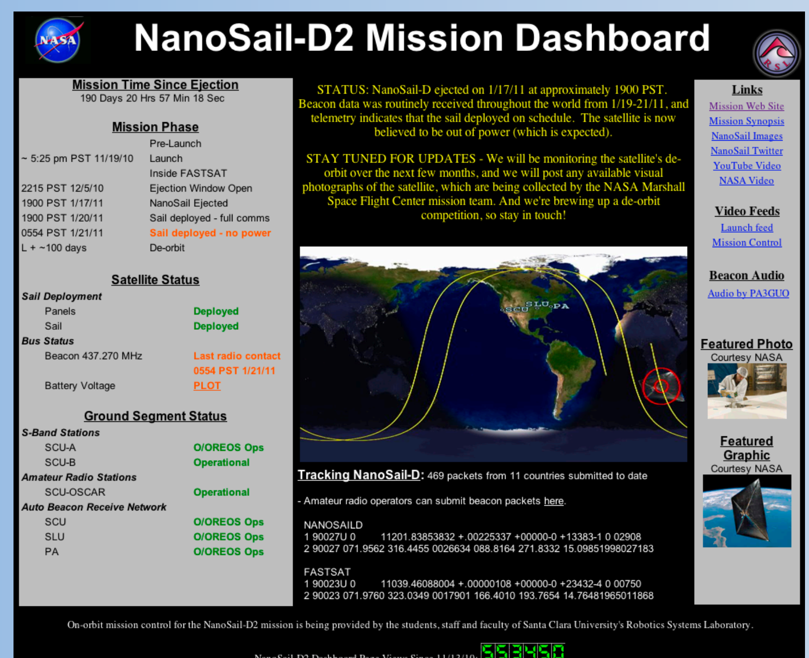
Ground Station Commands
Enable (BUS, 0x04) : Burn Panel Wire
Enable (BUS, 0x02) : Burn Sail Wire
GetPage(BUS, 0x1018) : Get Log File

NanoSail-D

Want more NanoSail-D?

- NanoSail-D Homepage
  - http://www.nasa.gov/mission_pages/smallsats/nanosaild.html
- NanoSail-D Mission Dashboard maintained by RSL @ SCU
  - http://nanosaild.engr.scu.edu/dashboard.htm
- NanoSail-D Twitter feed
  - http://twitter.com/nanosaild
- NanoSail-D Photo Contest – in conjunction with SpaceWeather.com
  - http://nanosail.org





NanoSail-D2 flying in the sky – 03/02/11

NanoSail-D

NanoSail-D

Conclusion

- Lessons Learned
  - Reusing flight hardware is possible, and reduces time and cost
  - Rapid development is possible with simple interfaces and clear roles.
  - Announce success after all data has been gathered and analyzed.
  - Second chances do happen, take full advantage of them.
  - Mission is not complete until all data indicates the contrary.
- Solar sailing is in its infancy but growing
  - Ikaros and NanoSail-D in space.
  - NanoSail-D to de-orbit in the next 6months
  - Several future sail projects are in works
    - Lightsail-1 – Planetary Society
    - CubeSail – University of Surrey
    - FeatherSail-2 – Solar sail project study at NASA/MSFC

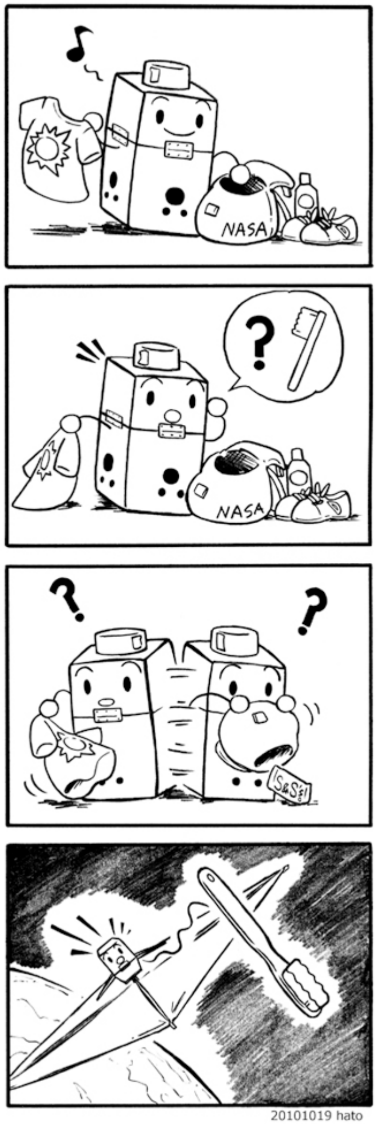
FeatherSail-2 (preliminary)

- Area ~ 871 m^2
  - Half the size of a football field!
- Areal Density ~ 41 g/m^2
- Mass ~ 50 kg
- Accelertion ~ 0.21 mm/s^2
- Potential Missions
  - Earth/Sun Pole sitter
  - Science measurements out of ecliptic
  - Near Earth Object (NEO) Rendevous
  - Interstellar travel

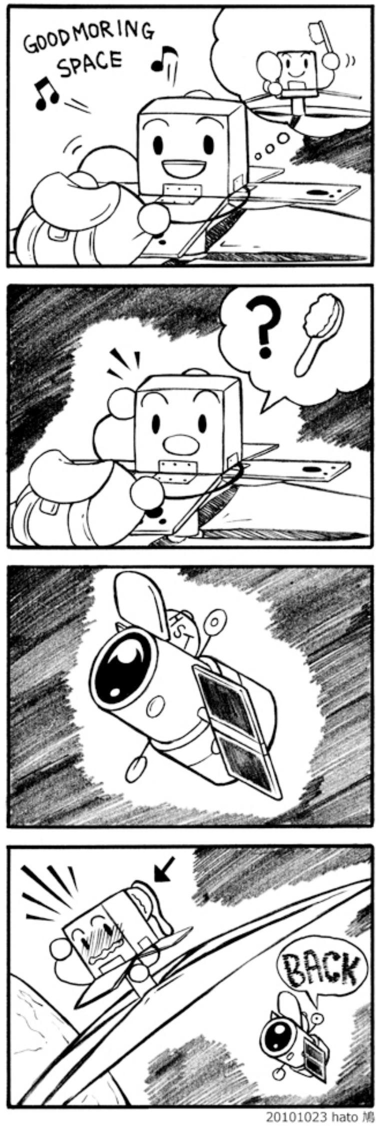
NanoSail-D

NanoSail-D the comic

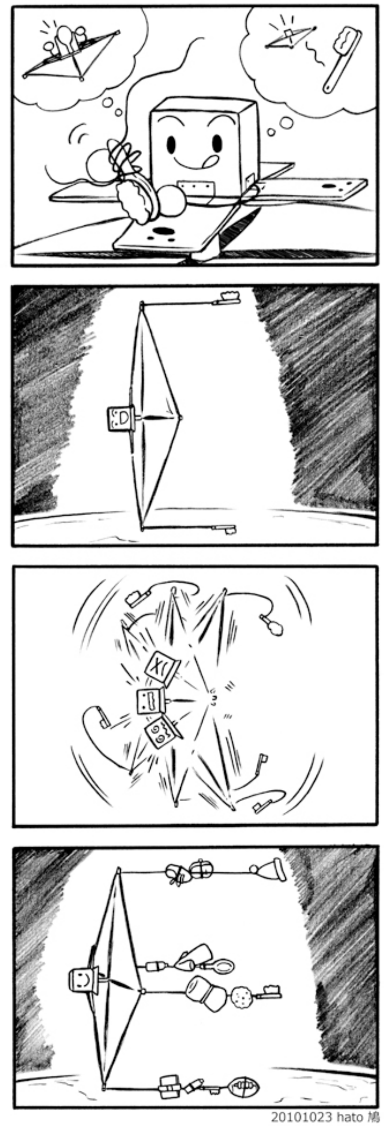
NanoSail-D toothbrush



NanoSail-D Brush#1



NanoSail-D Brush#2



NanoSail-D Sailing