Colloid Micro-Newton Thrusters For Precision Attitude Control

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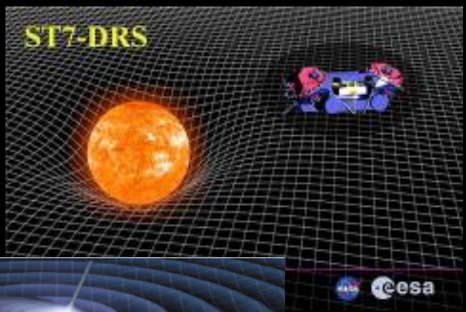
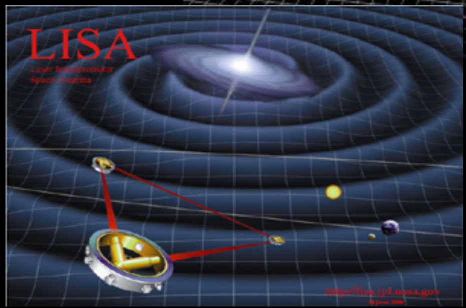
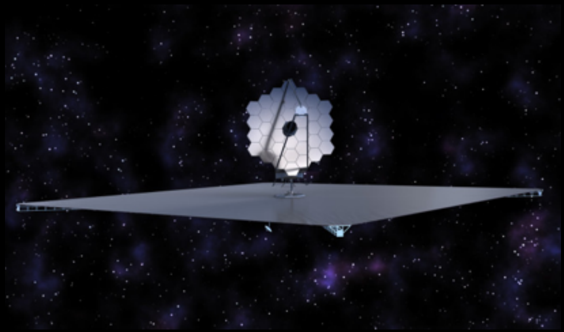
Vlad Hruby and Nathaniel Demmons, Busek Company, Inc.



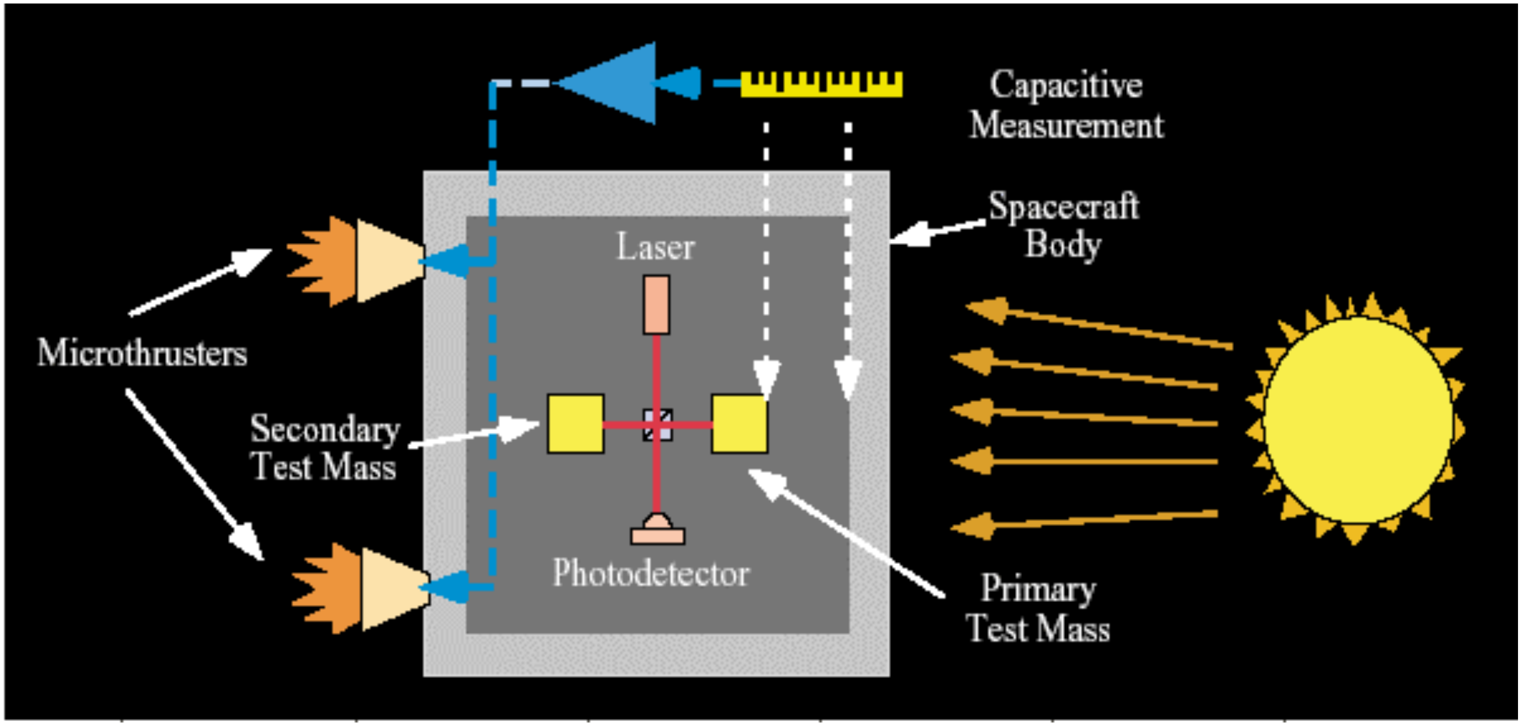


April 7, 2017

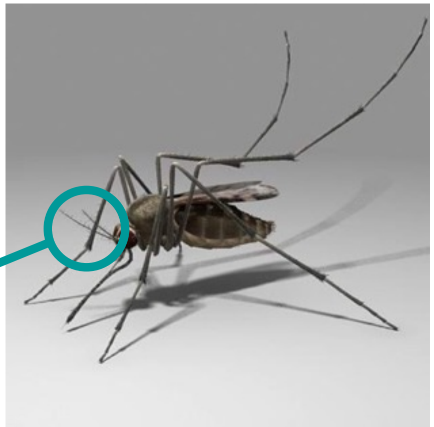


Cleared for Public Release
CL#17-2067

Main S/C Disturbance: Solar Pressure



~ 0.1 μN



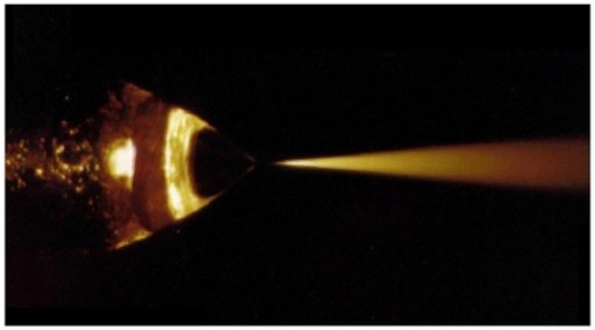
≈ 30 μN

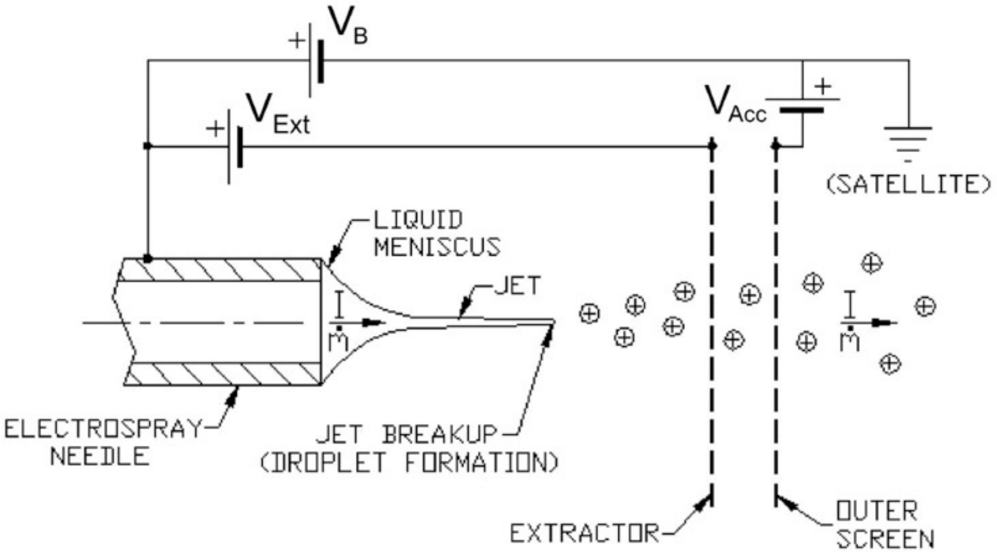
Colloid Thruster Technology

- **Colloid Thrusters emit charged droplets that are electrostatically accelerated to produce thrust**

$$\text{Thrust} \propto I_B^{\,1.5} \cdot V_B^{\,0.5}$$

- **Current and voltage are controlled independently by adjusting the flow rate and beam voltage**
- **Precise control of I_B (~ µA) and V_B (~ kV) facilitates the delivery of micronewton level thrust with better than 0.1 µN precision**
- **The exhaust beam is positively charged, well-defined (all charged particles), and neutralized by a cathode/electron source if needed**





Images courtesy of Busek Co.

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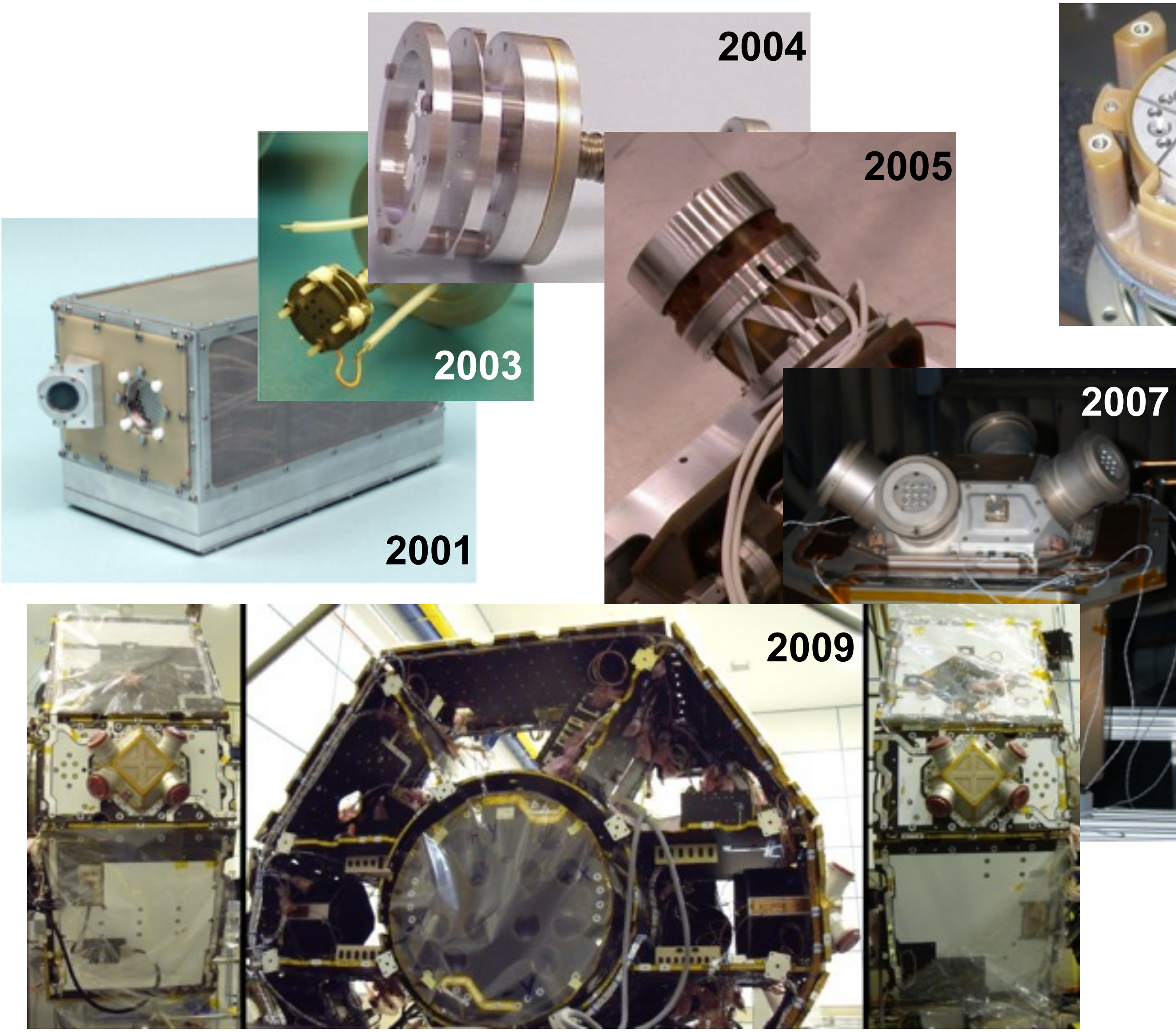
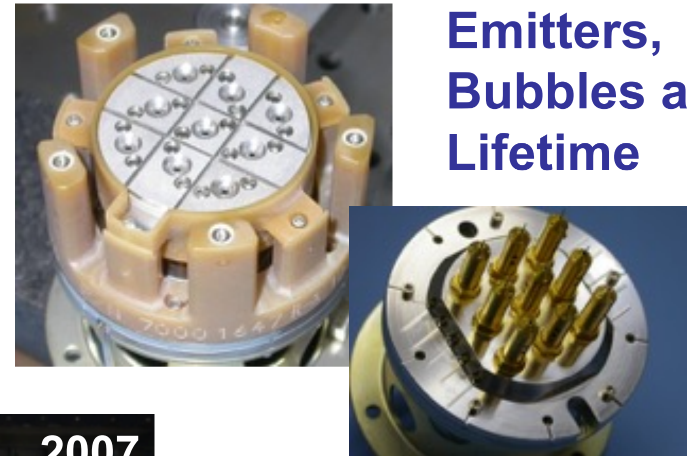
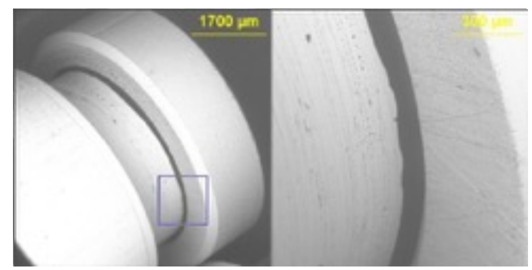
Colloid Thruster History and Technical Challenges

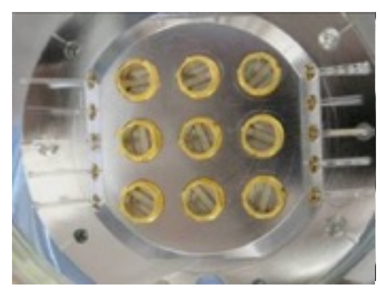


Emitters, Bubbles and Lifetime



Microvalve Manufacturing





Seals and Materials

ST7 and LISA Thruster Requirements

Requirement	ST7	LISA	Demonstrated
Thrust Range	5 to 30 μN	5 to 30 μN*	4.35 to 35.8 μN§
Thrust Precision	≤ 0.1 μN	≤ 0.1 μN	0.08 μN (0.01 μN calculated)
Thrust Noise	≤ 0.1 μN/√Hz (5 Hz control loop)	≤ 0.1 μN/√Hz (5 Hz control loop)	≤ 0.01 μN/√Hz (3e-5 – 3 Hz) ≤ 0.1 μN/√Hz (3 – 4 Hz)
DRS Drag-Free Bandwidth	$1x10^{-3}$ to $3x10^{-2}$ Hz	$3x10^{-5}$ to 1 Hz	$3x10^{-5}$ to 4 Hz
Control Loop Bandwidth	$1x10^{-3}$ to 4 Hz	$3x10^{-5}$ to 4 Hz	$3x10^{-5}$ to 4 Hz
Thrust Command Rate	10 Hz (≤ 0.1 s latency)	TBD	10 Hz (0.1 s latency, 0.4 s settle time)
Thrust Range Response Time	≤ 100 s	TBD	< 10 s
Specific Impulse	≥ 150 s	TBD	≥ 150 s (≥ 200 s typical)
Operational Lifetime	≥ 2,160 hours (90 days)	≥ 40,000 hours (~5 years)†	3478 hours during FLT 2B (245 Ns of total impulse and 113 g of propellant)
Plume Half Angle	≤ 35° (includes 95% of beam current)	TBD	< 23° (includes 95% of beam current)

* The LISA thrust range requirement may be lower for the science phase and higher for tip-off recovery

† The LISA mission has an operational goal of 8.5 years that will require an additional 3.5 years worth of consumables

§ By calculation a range of approximately 3-50 μN is possible within the nominal operational constraints of the thruster

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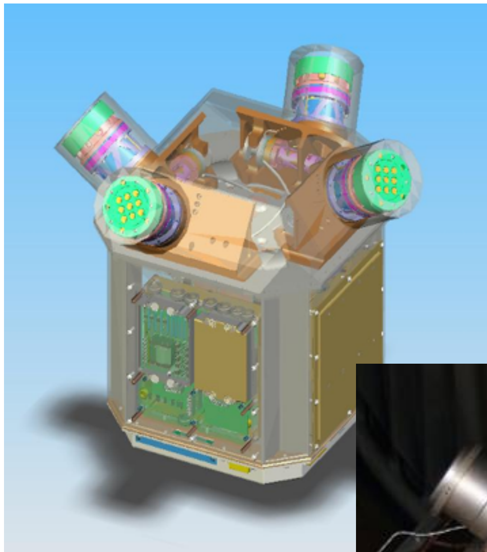
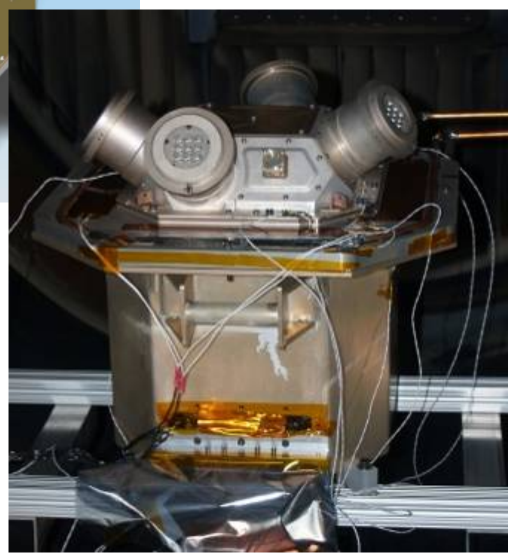
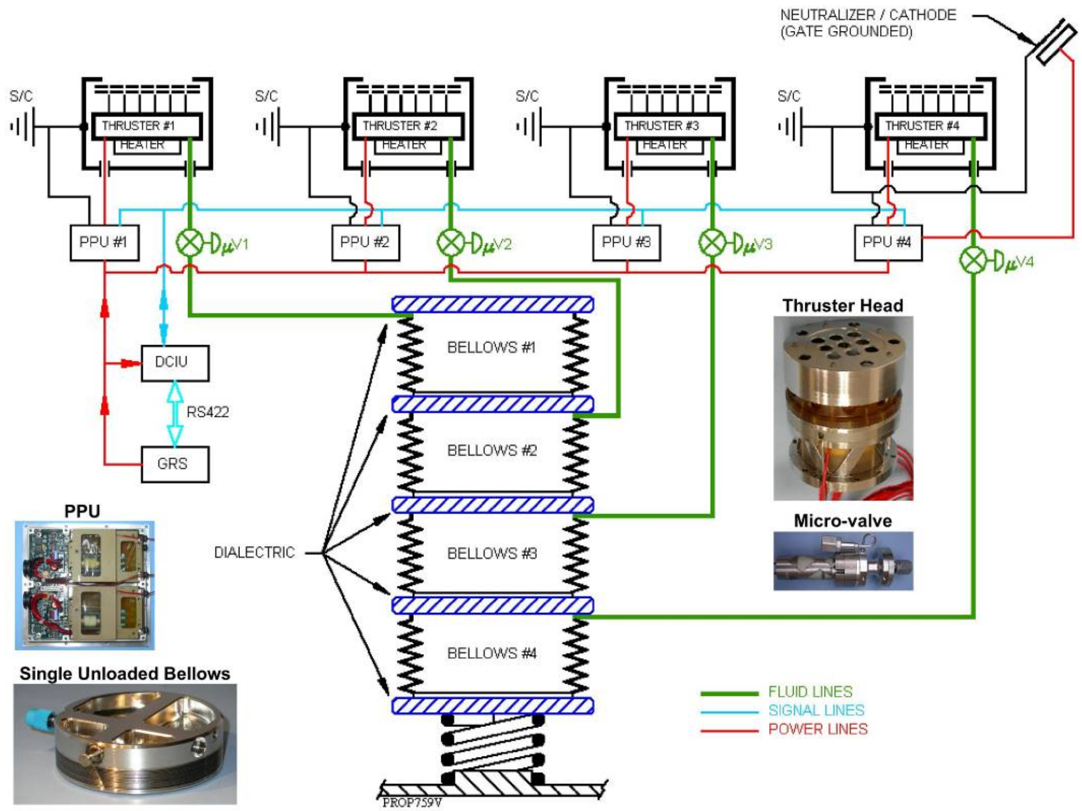
ST7 Microthruster System Architecture

Cluster with 4 Thruster Systems





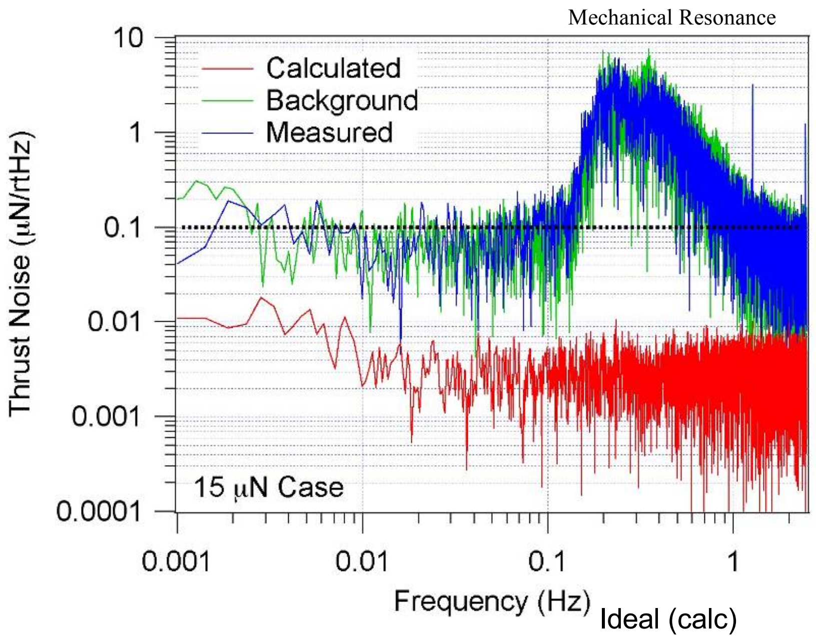


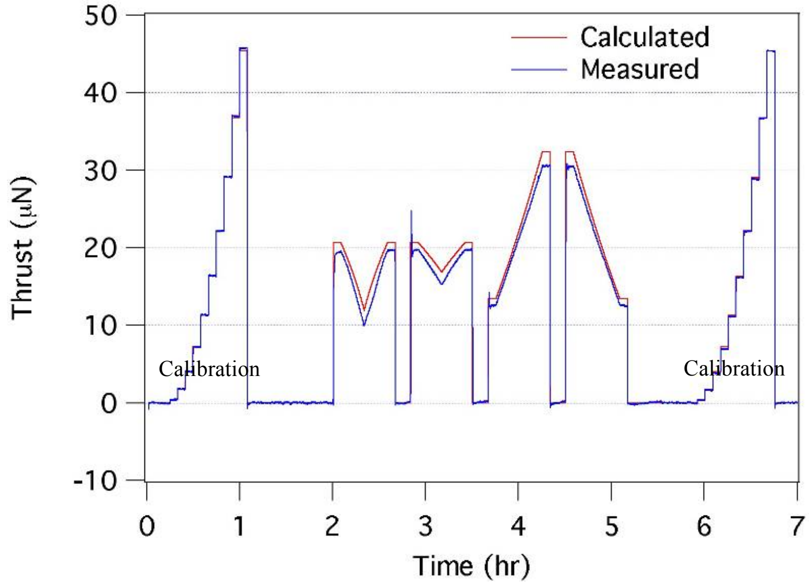
- **ST7-DRS has 2 clusters with 4 thrusters per cluster**
- **All 8 thruster systems are identical**
- **There is one DCIU and neutralizer per cluster**
- **Thrust range: 5-30 μN from each thruster head**

A single thruster system includes:

- **Thruster Head (including heater)**
- **Microvalve (precision flow control)**
- **Bellows (propellant storage)**
- **PPU (high-voltage converters)**

Thrust Stand Measurements Complete





- **Colloid thruster resolution and thrust noise now verified by direct measurement**
- **Predicted thrust relation matches well to measured data**
- **Busek's magnetically levitated thrust stand has remarkable resolution and background noise characteristics**
  - **<0.1 μN resolution, ~0.1μN/√Hz equivalent background noise from 0.005 to 0.1 Hz**
  - **Older JPL and Busek torsional pendulum microthrust stands have 2x lower resolution with actual thrusters**

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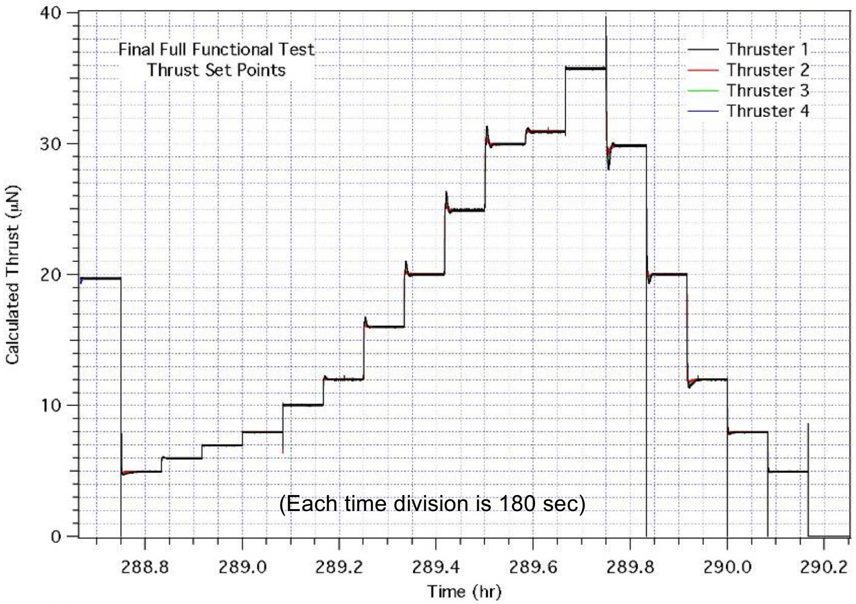
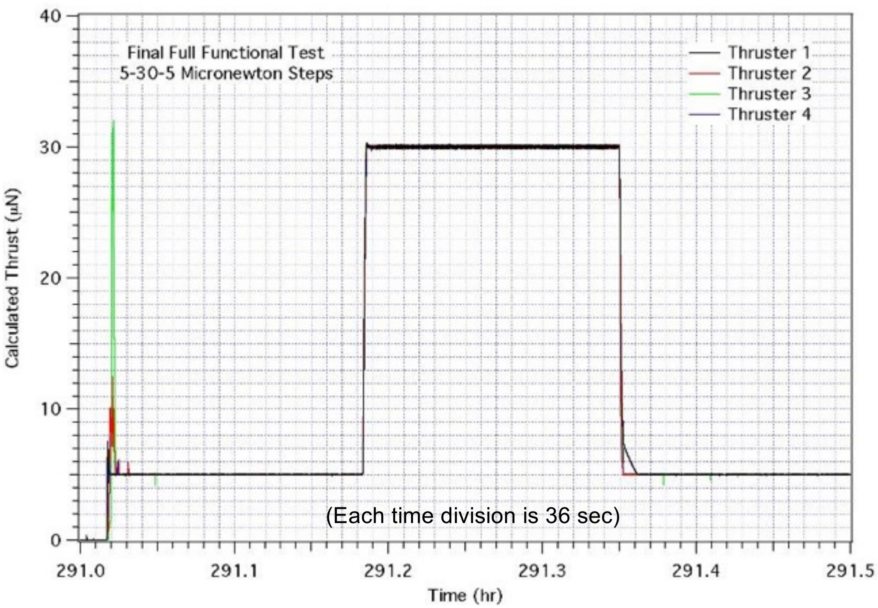
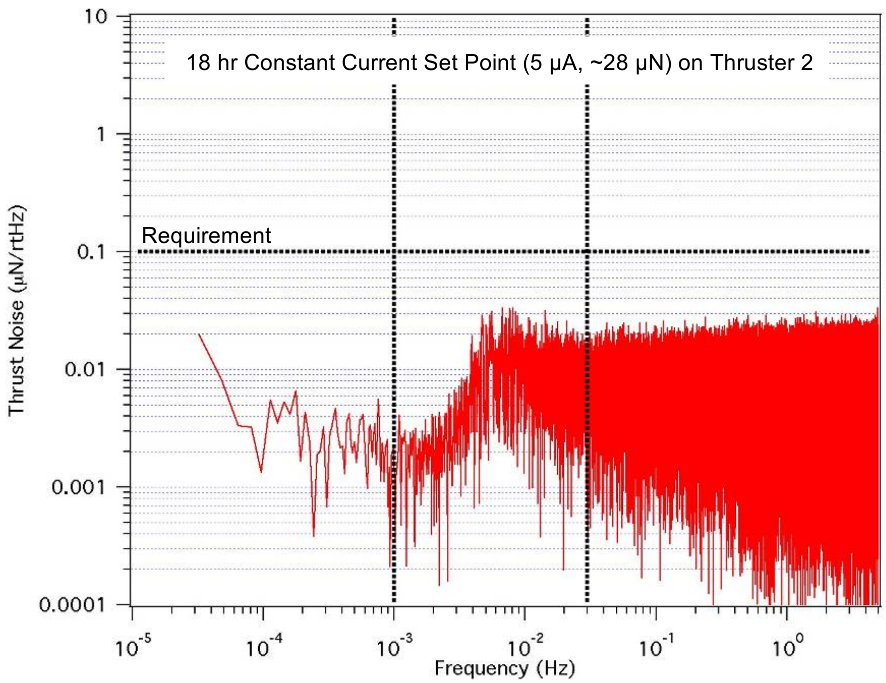
Cluster 1: Passed Full Functional Test





- At the end of the TVAC environmental test, Cluster 1 went through a full functional test at 20°C on all four thrusters and the cathode
- All colloid thruster systems passed through the final acceptance test without incident



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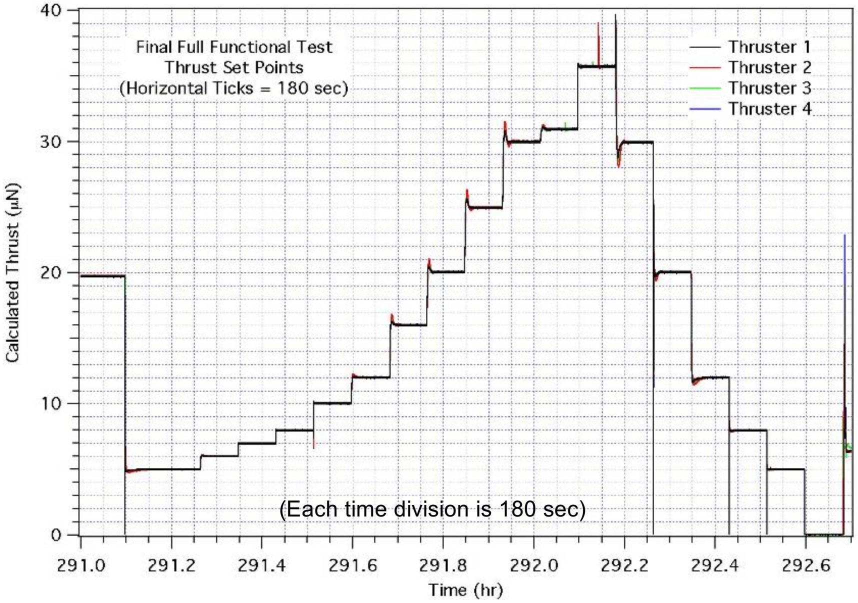
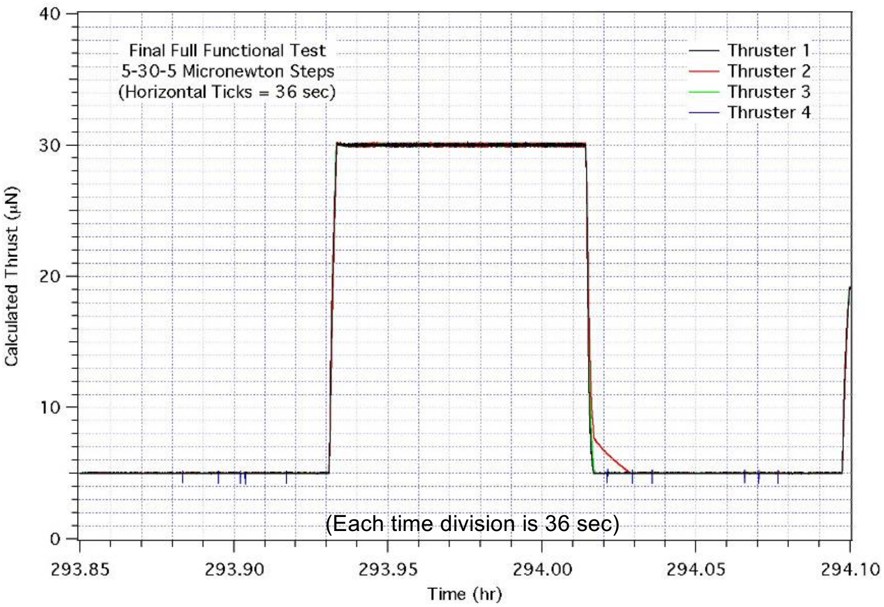
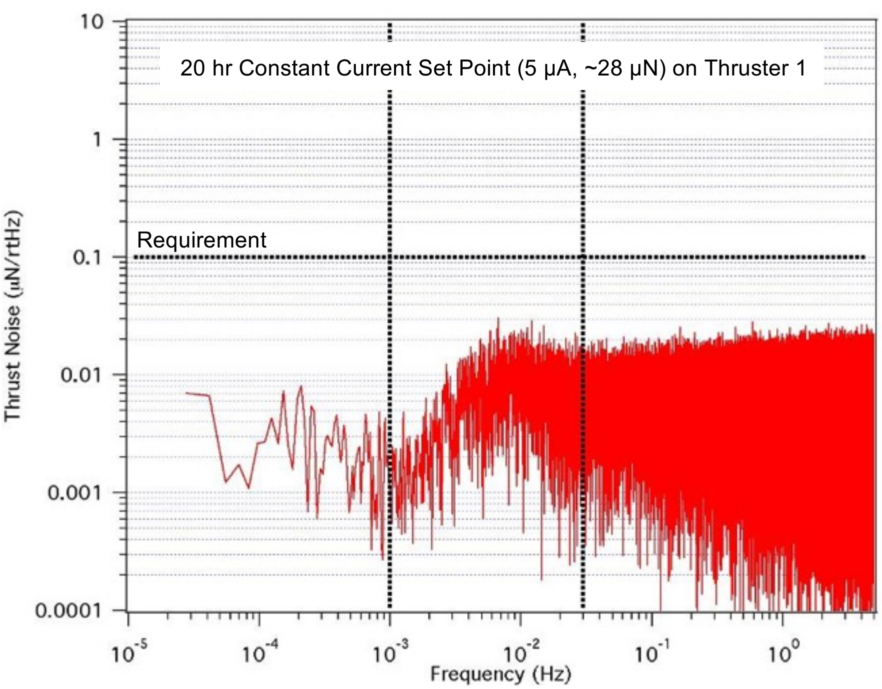
Cluster 2: Passed Full Functional Test





- **At the end of the TVAC environmental test, Cluster 2 went through a full functional test at 20°C on all four thrusters and the cathode**
- **All colloid thruster systems passed through the final acceptance test without incident**



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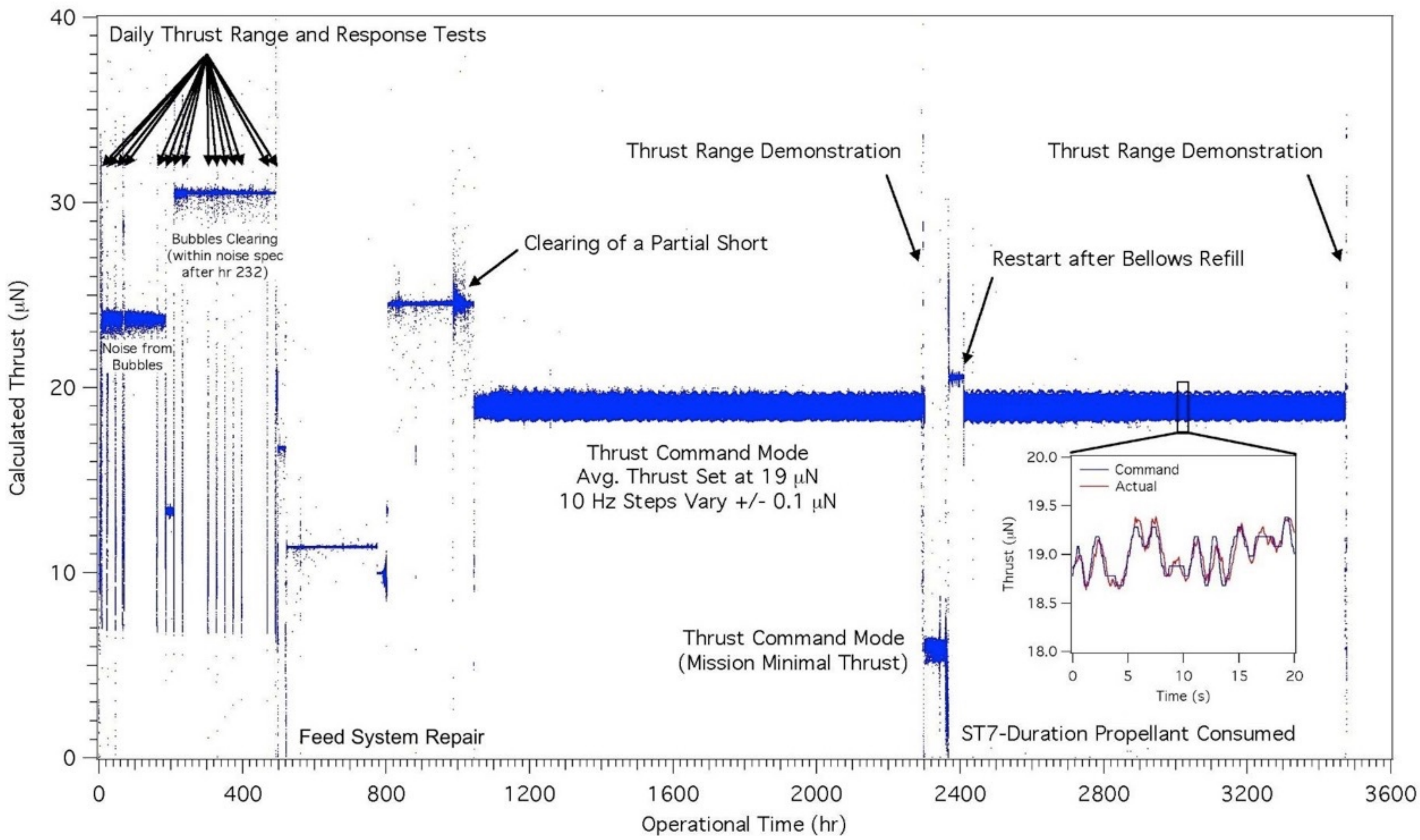
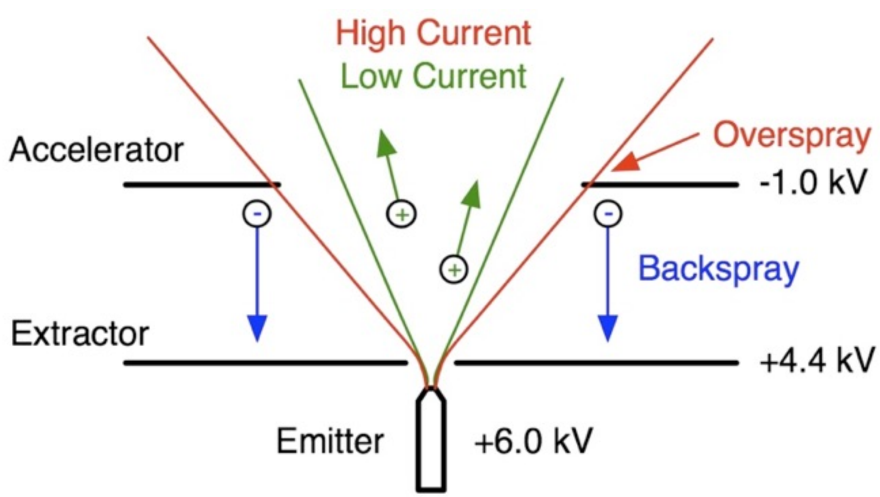
Formal Life Test of Colloid Microthruster

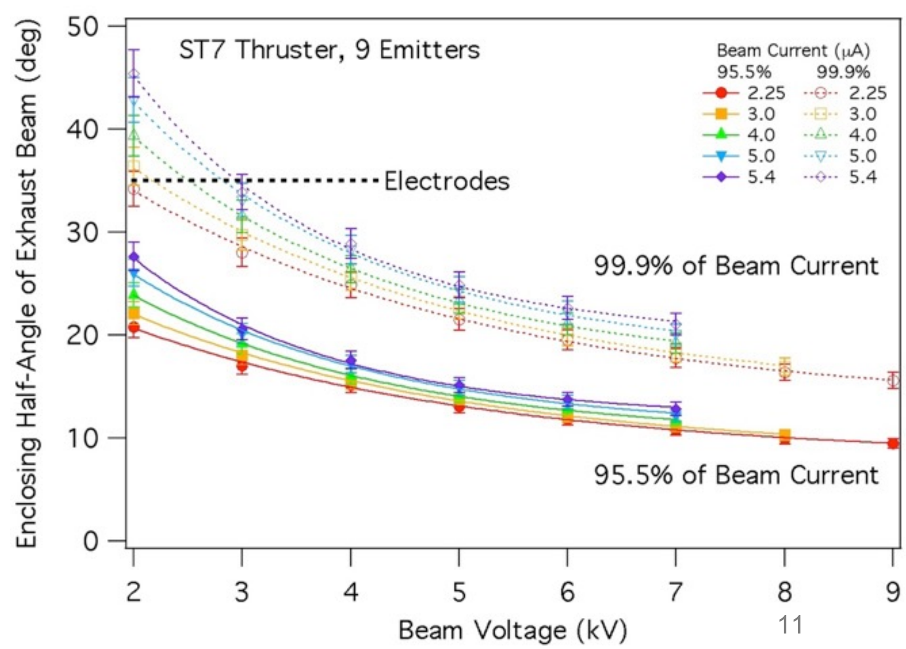


- **<u>Requirements:</u> >60 day (1440 hours) mission, 90 day + 50% (3240 hours) lifetime, expected 140 Ns of impulse**
- **FLT 2B operated for 3478 hours including more than 90 days in thrust command mode, producing 245 Ns total**

Beam Divergence and Thruster Lifetime

- Beam divergence losses are typically small (assuming a uniform distribution of q/M in the plume)
- During ST7 development, no beam propagation models were available, all design work done empirically, which led to significant impingement on accelerator electrode at high currents
- LISA work between 2009 and 2012 developed beam models and showed that thruster lifetime should be ~5 years at normal operating conditions
- Work continues to optimize the grid gaps and diameters to reduce impingement all together and extend lifetime





COLLOID THRUSTERS ON LISA PATHFINDER – ST7-DRS

Space Technology 7 Disturbance Reduction System

BUSEK

Colloid Micro-Newton Thrusters

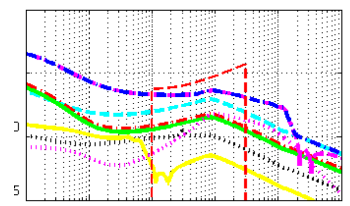
Life-Test complete with 3,400 hrs. of operation

Passed all proto-flight qualification level testing

Broad Reach Engineering
Space Flight Hardware & Vehicle Design

Integrated Avionics Unit

Goddard
SPACE FLIGHT CENTER



Dynamic Control System

Drag-Free Control Software and Analysis

JPL

Project Management

Thruster Development

C&DH Software

Structures

Cabling/Harness

I&T and ATLO Support

Operations

Instrument Delivery
June 20, 2008

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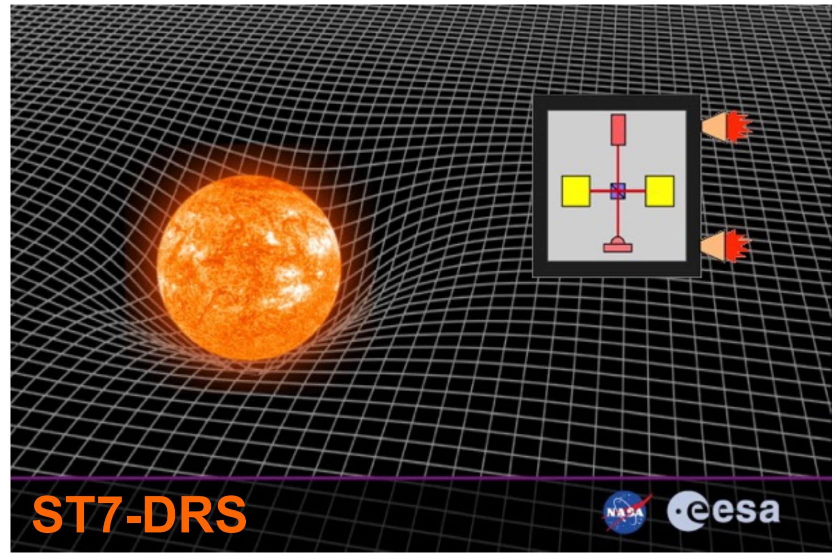
Project Overview

Space Technology 7 - Disturbance Reduction System (ST7-DRS)

Salient Features

- Project Category: 3 Risk Class: C
- DRS flies on the ESA LISA Pathfinder spacecraft
- Sun-Earth L1 halo orbit
- Drag-free satellite to offset solar pressure
- Payload delivery: July 2009 – COMPLETE
- Launch date: December 2015
- Operational life: 2 months
- Data Analysis: 12 months



Technologies

- The Disturbance Reduction System (DRS) will validate system-level technologies required for use on future gravity and formation flying missions.
- The key new technologies are gravitational reference sensors and microthrusters.
  - DRS will validate spacecraft position control to an accuracy of ≤10 nm/√Hz over frequency range of 1 mHz to 30 mHz (Precision Flight Validation Experiment)
  - With LISA Pathfinder GRS, DRS will validate that a test mass follows trajectory determined by gravitational forces only within 3×10^{-14} m/s^2/√Hz over frequency range 1 mHz to 30 mHz

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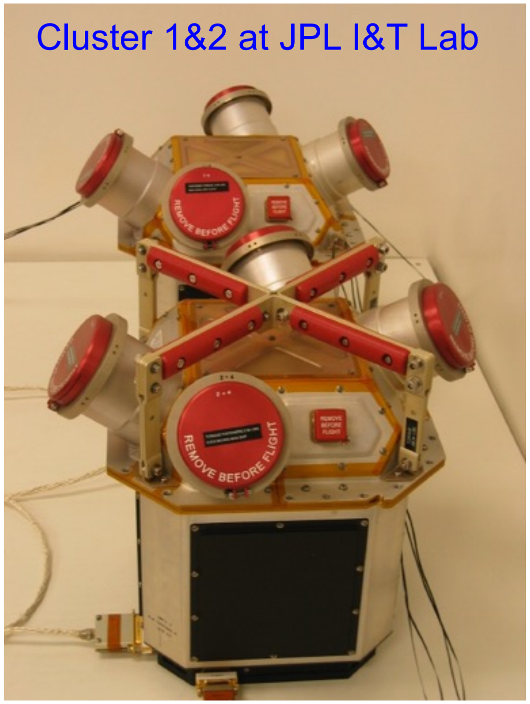
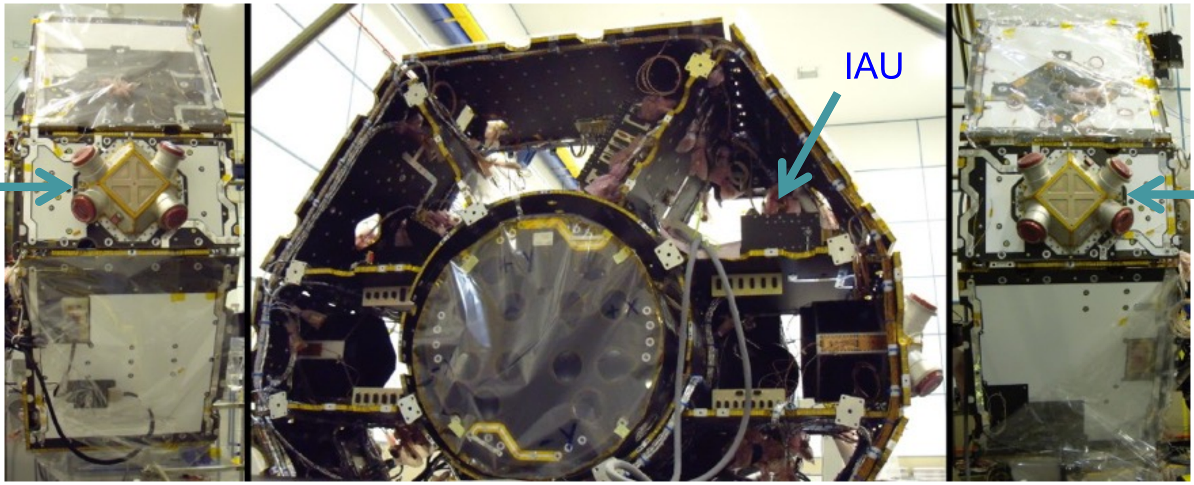
Both Flight Clusters Delivered to JPL and ESA



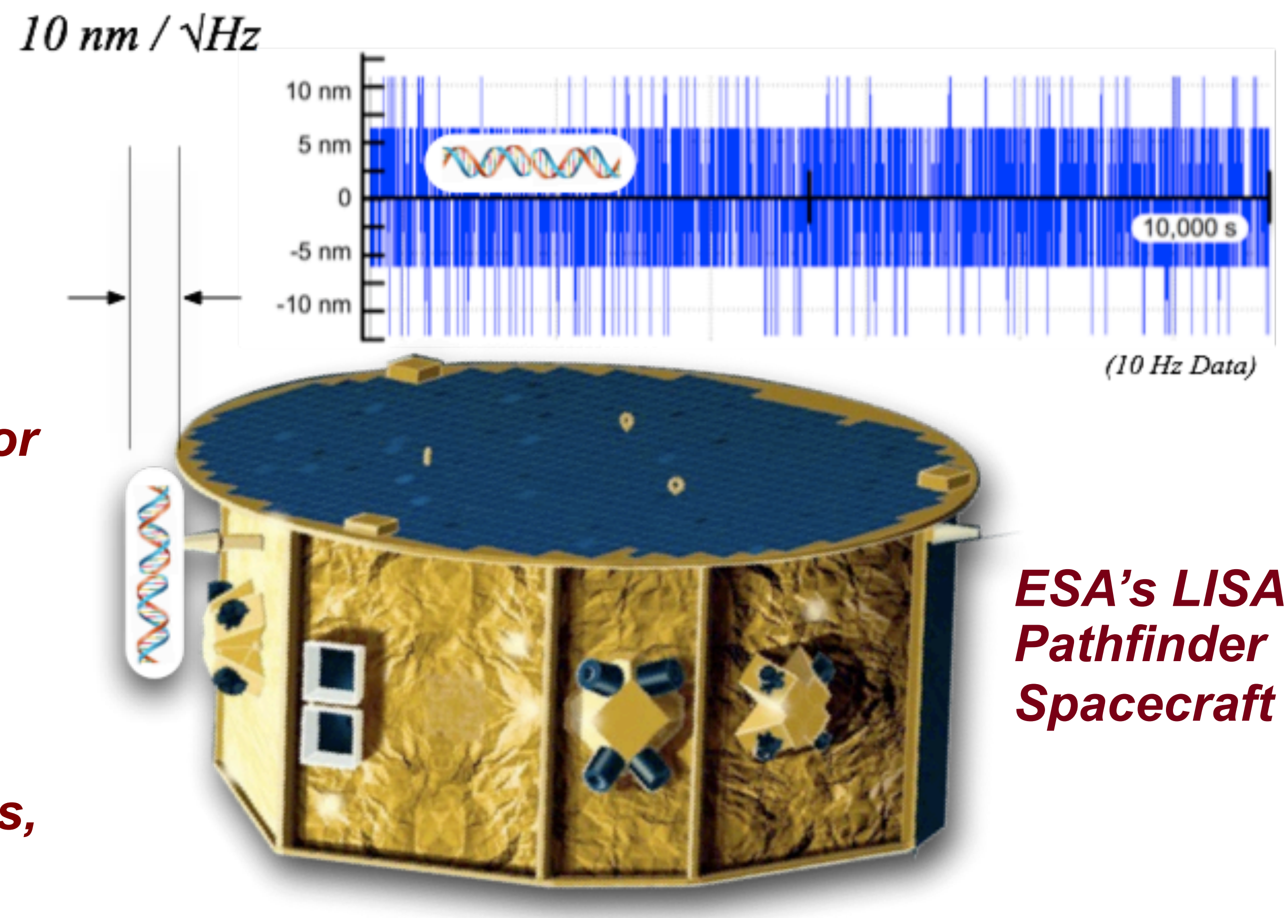
- Cluster 1 delivered to JPL in February of 2008
- Cluster 2 delivered to JPL in May of 2008
- Full DRS flight hardware and EM testbed units delivered to ESA in July 2009
- Full functional tests completed Sept. 2009
- DRS integration onto LISA Pathfinder Spacecraft completed November 2009
- Challenge remaining for LISA:
  Demonstrate thruster lifetime



Precision Spacecraft Control Enables Gravitational Wave Measurement

ST7 has developed the lowest continuous thrust, precision propulsion and control system ever qualified for flight in the US!

Future applications include space-based gravitational wave and exoplanet observatories, large structure control, and formation flying



ESA's LISA Pathfinder Spacecraft

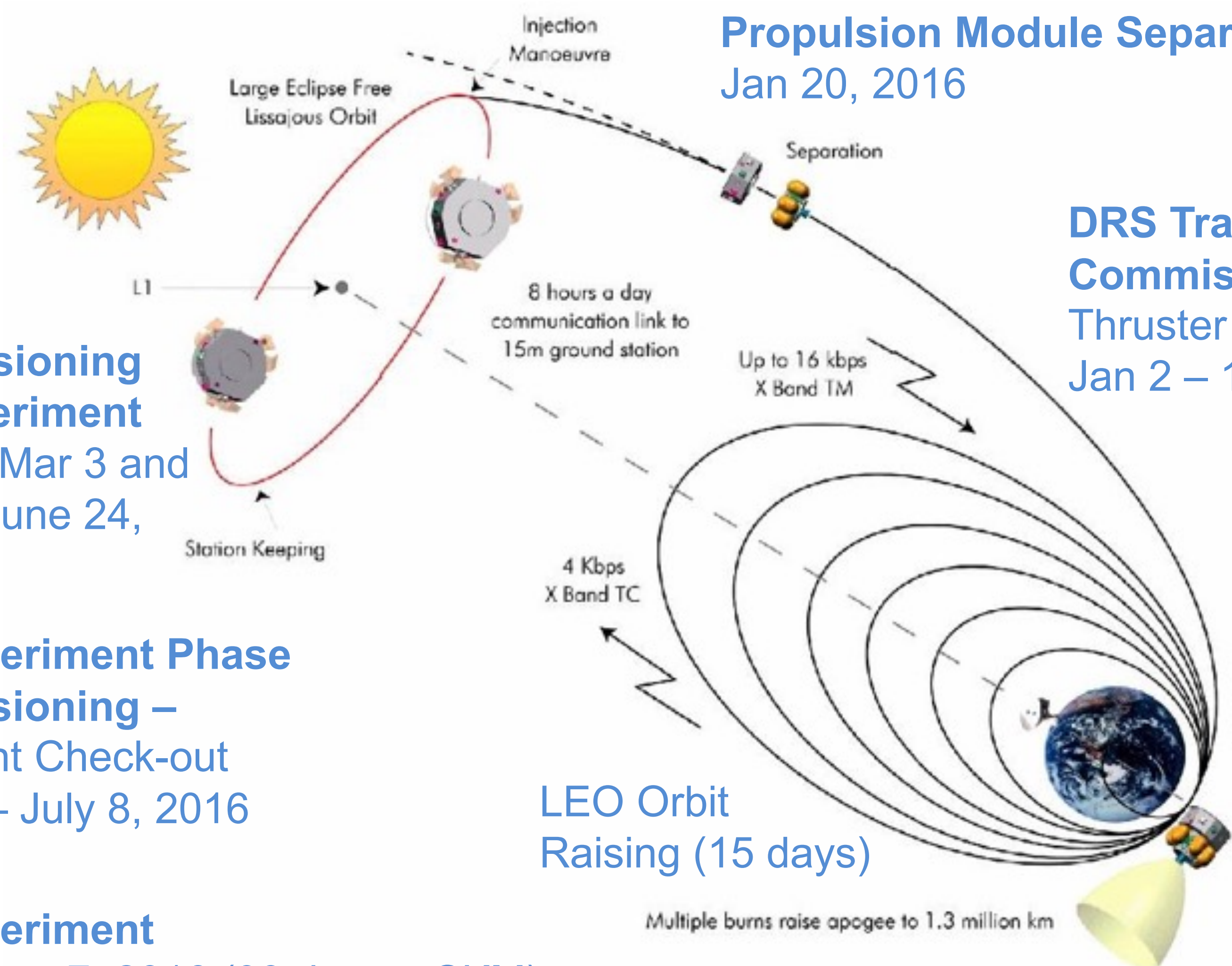
When DRS is active, S/C position noise is comparable to the diameter of a DNA Helix (2 nm)!

LISA Pathfinder Launch!

Launch from
French Guiana
December 3, 2015

Long duration storage of colloid thruster propellant (8 years in tanks) raised some concerns, but in the end a useful demonstration for future missions

Overall Mission Profile



Propulsion Module Separation
Jan 20, 2016

DRS Transfer Phase Commissioning –
Thruster Check-out
Jan 2 – 10, 2016

LTP Commissioning and Experiment
Jan 27 – Mar 3 and Mar 4 – June 24, 2016

LEO to L1 Transfer (23 days)

DRS Experiment Phase Commissioning –
Instrument Check-out
June 27 – July 8, 2016

LEO Orbit Raising (15 days)

LAUNCH
Dec 3, 2015

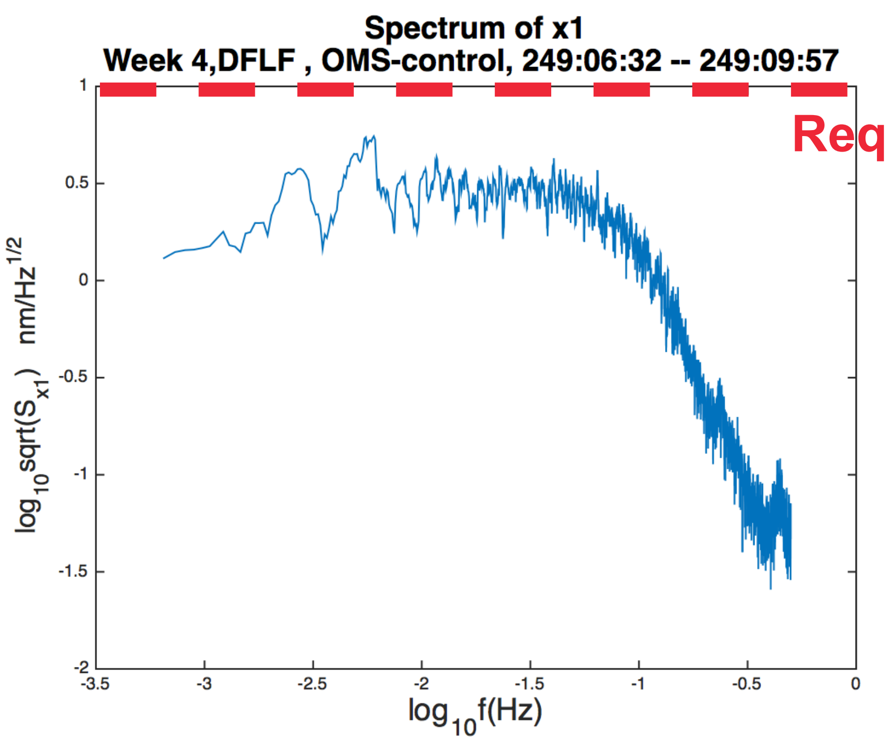
DRS Experiment
July 9 – Dec 7, 2016 (90 days + SKM)

Extended Mission through mid-July 2017

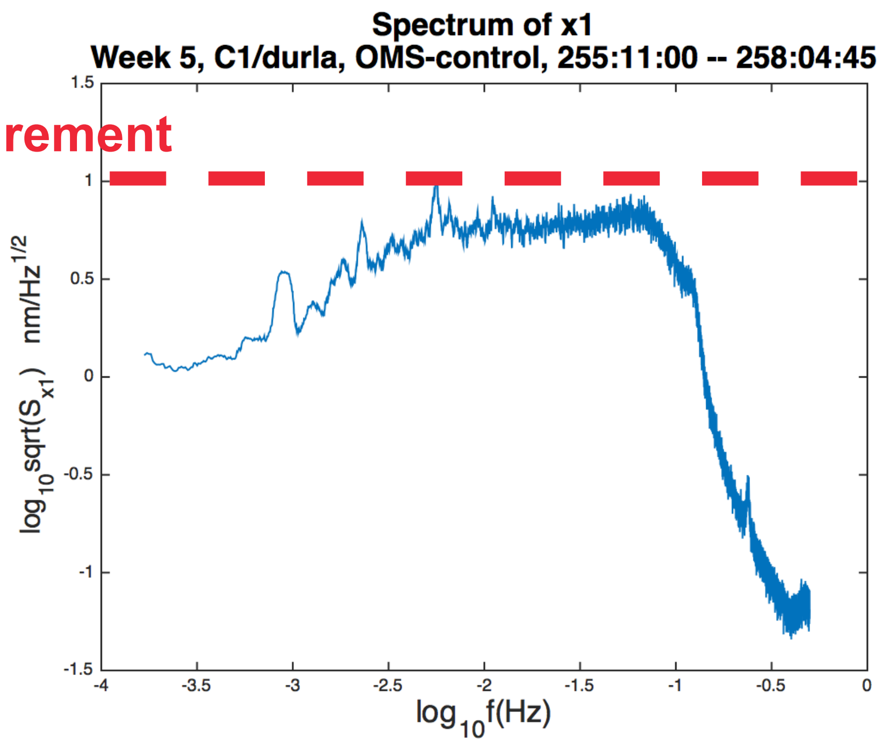
Results from Drag-Free Operation

Results Show Meeting L1 Requirement, <10 nm/√Hz position stability

Position Noise in Drag-Free Mode

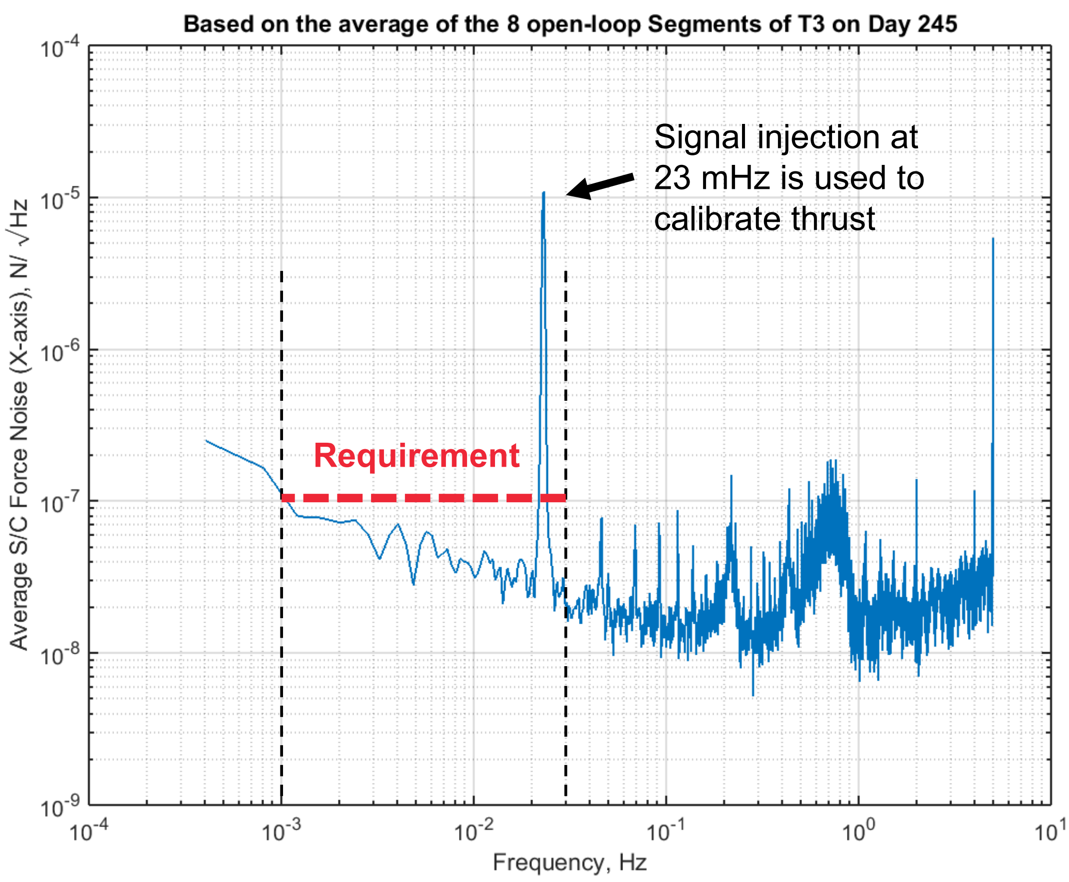


Position Noise in Science Mode



Thrust Noise Measurements

Results Show Meeting L1 Requirement, <0.1 µN/√Hz System-Level Thrust Noise



ST7-DRS Level 1 Requirements

Requirement	Full Success Criteria	Original Minimum Goals
Position control; 1-30 mHz	10 nm/√Hz	100 nm/√Hz
Drag-free sensor*	5 nm/√Hz	50 nm/√Hz
Propulsion system noise; 1-30 mHz	0.1 μN/√Hz	0.5 μN/√Hz

After successful commissioning, all L1 Requirements are looking good

✓ 1. DRS shall demonstrate ability to control spacecraft position within 10 nm/√Hz on the sensitive axis over a frequency range of 1 mHz to 30 mHz
   - Derived from LISA requirement of necessary position noise along sensitive axis
   - Requires LTP position sensing noise to be ≤ 5 nm/√Hz

✓ 2. DRS shall demonstrate a spacecraft propulsion system with noise less than 0.1 μN/√Hz over a frequency range of 1 mHz to 30 mHz

✓ 3. DRS shall perform flight qualification of a Colloid Micro-Newton Thruster. DRS shall demonstrate a Colloid Micro-Newton Thruster in a space environment at any thrust level
   - Being a technology demonstration project, the majority of the challenge is to mature this technology to a point that it can be qualified for flight. **This will be 90% of the success for this project**. Due to the long storage and ATLO period of DRS, any in-flight operation of the thrusters is considered a success, even if the system is not operating completely as intended

✓ 4. The project shall document and archive design, fabrication, test and flight demonstration data relevant to the qualification and infusion of DRS systems into future missions requiring DRS technology

✓ **Minimum Mission Success:** DRS shall deliver a flight qualified Colloid Micro-Newton Thruster, producing any measurable thrust on-orbit, verified through analysis of telemetry.

Open Issues, Lessons Learned from Pathfinder and Future Plans

- We experienced 3 issues with the colloid thruster on orbit:
  - Thruster 1 Bubbles – microvalve response reduced
  - Cluster 2 DCIU PROM – 1 of many routines in PROM damaged
  - Thruster 4 Propellant Bridge – ran at extreme conditions
- Through on-orbit experience, all issues were dealt with effectively and the mission continues even today!
- Key lessons learned:
  - Microvalve manufacturing and repeatability – already improved through 3 Phase II SBIRs and a NASA APD SAT to bring a fully redundant feed system to TRL 5
  - Thruster operations – new processor, memory and software update required
  - Thruster lifetime and reliability – new lifetime models, electrode designs, and long duration testing is required
- Future Plans:
  - NASA has created a L3 Study Office charged with developing technologies for a US contribution to an ESA-led LISA mission, including microthrusters
  - Over the next 5 years, a flagship-class colloid thruster system will be brought to TRL 6 including starting a 6-yr long-duration life test

FUTURE NASA APPLICATIONS

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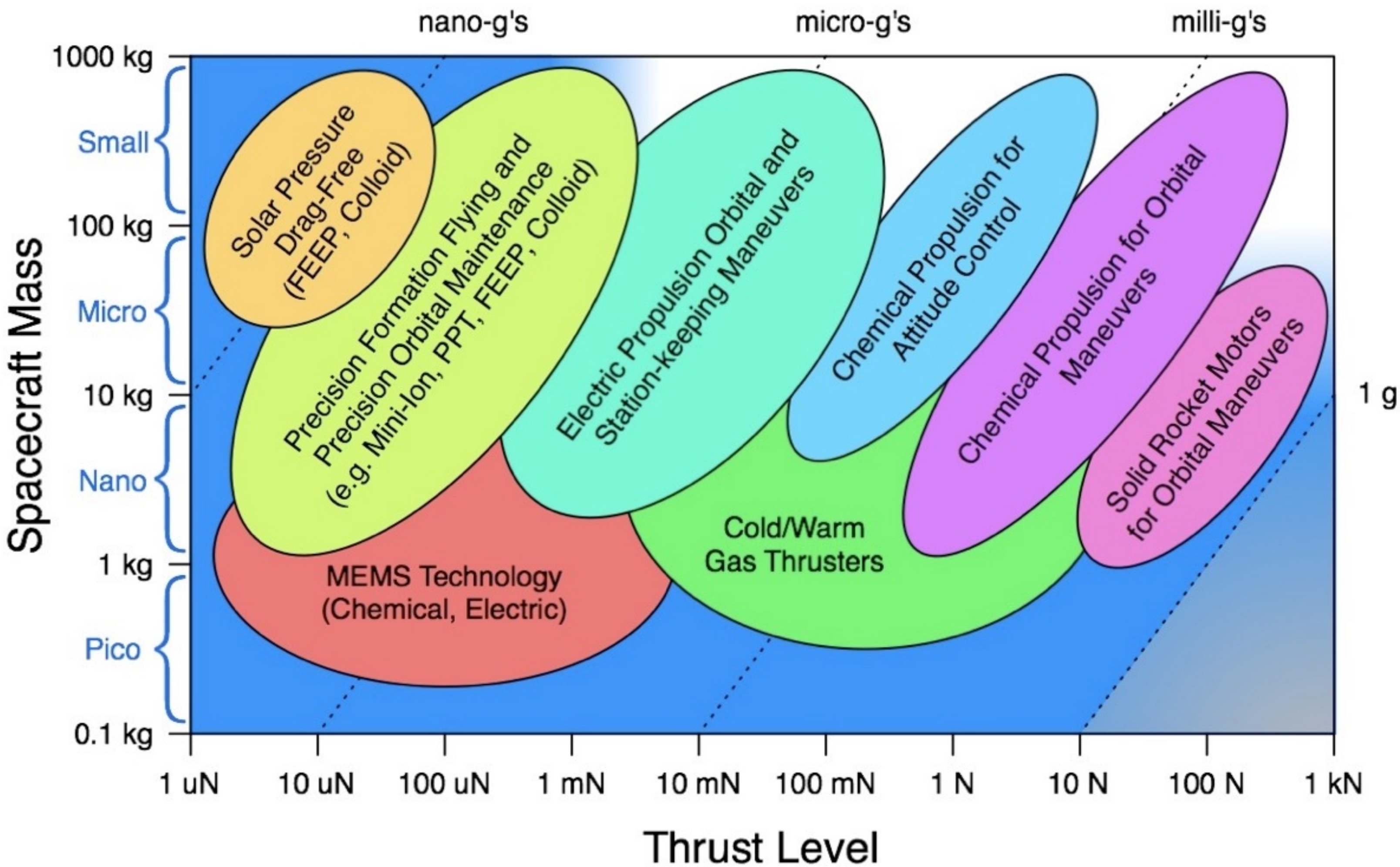
Spacecraft and Propulsion Requirements and Capabilities

Micropropulsion Mission and Technology Space



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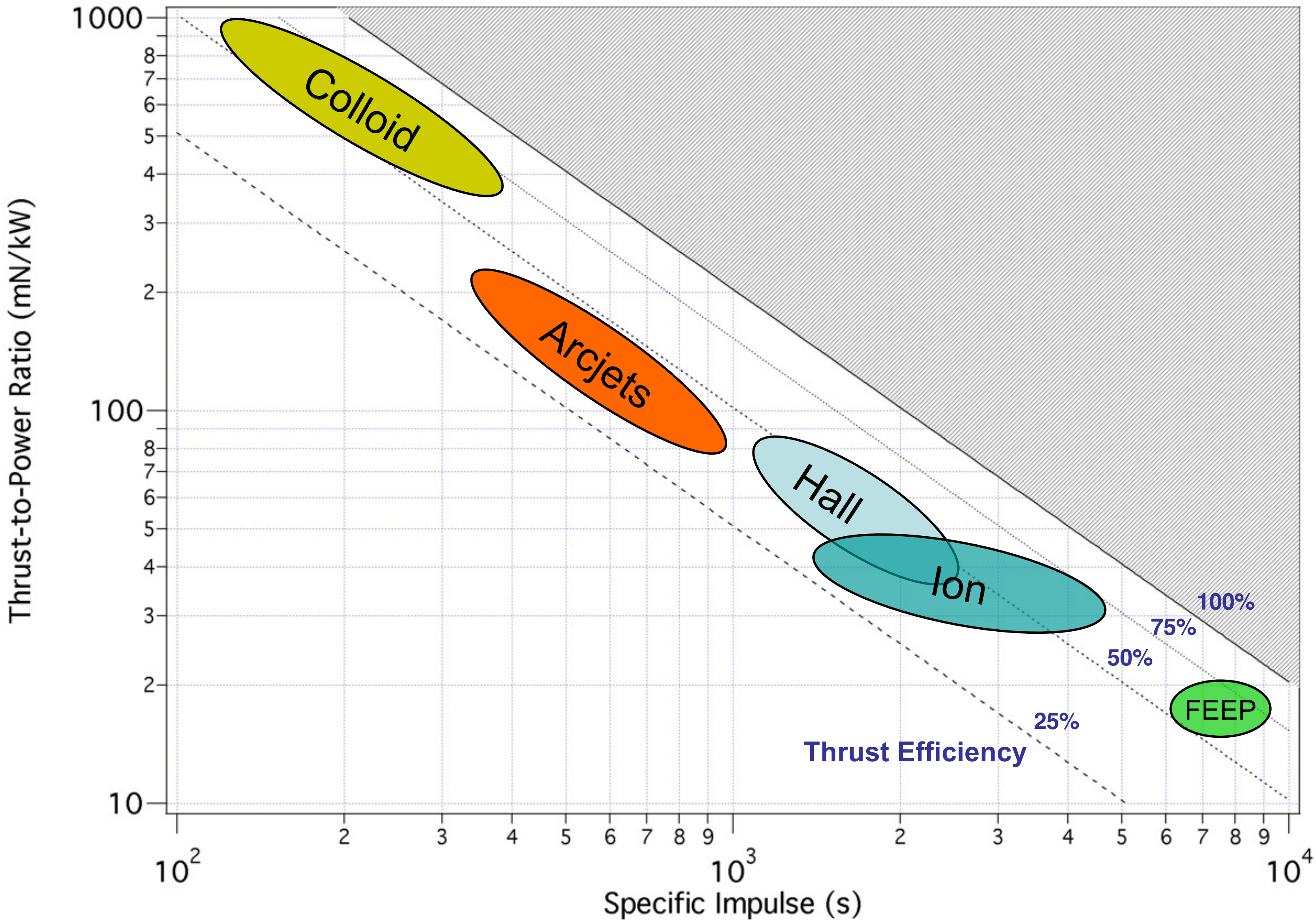
Flight Qualified Electric Propulsion Systems



Three New NASA Mission Scenarios

I. Drag-free constellation maintenance
   - Gravity wave observatory
     - Laser Interferometer Space Antenna (LISA)
   - Derived thrust profiles for multiple mission modes and functions

II. Drag-free precision orbit maintenance
   - Earth observing radar satellite with repeat tracks
     - Interferometric Synthetic Aperture Radar (InSAR)
   - Derived thrust requirements for 30 m Earth-fixed orbital tube

III. Precision pointing
   - Exoplanet observatory
     - ACCESS
   - Derived precision pointing accuracy capability with electric thruster characteristics

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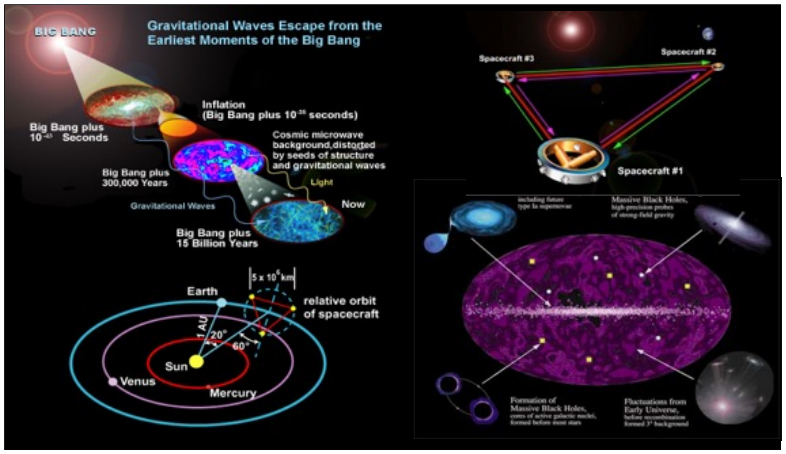
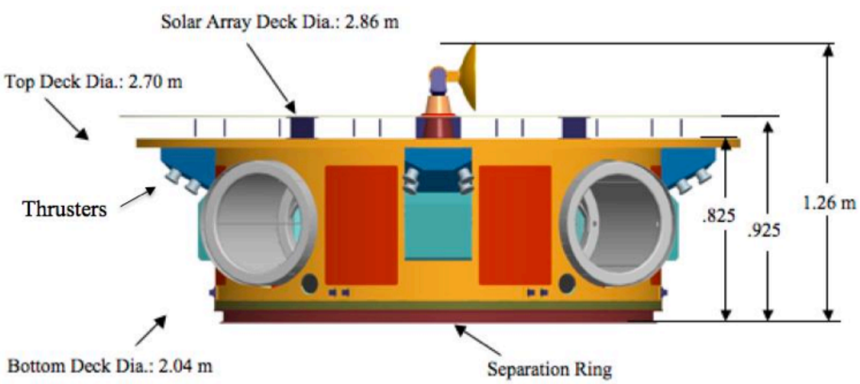
Laser Interferometer Space Antenna (LISA)





- **Detects gravitational waves by measuring the time-varying strain in length between spacecraft**
- **Orbit:** 3 independent, Heliocentric, 20° earth trailing orbits, equilateral triangular constellation with $5x10^6$ km +/- 1% arm lengths, constellation requires no active station keeping or maintenance over the mission lifetime
- **3 spacecraft separated by 5 million km**
  - Distance between spacecraft must be maintained to within ~10 nm
  - Requires
    - 10's of μN level thrust
    - 0.1 μN thrust resolution
    - <0.1 μN $Hz^{-1/2}$ thrust noise
- **Spacecraft must operate in "drag-free" environment**
  - Thrusters must counteract minute disturbances of solar wind, radiation, and photon pressure
- **Mass: 400 kg per sciencecraft**
- **Lifetime: >5 years**
- **Both colloid and cold gas thrusters have been demonstrated on LISA Pathfinder/ST7 and one of them will be selected for LISA**

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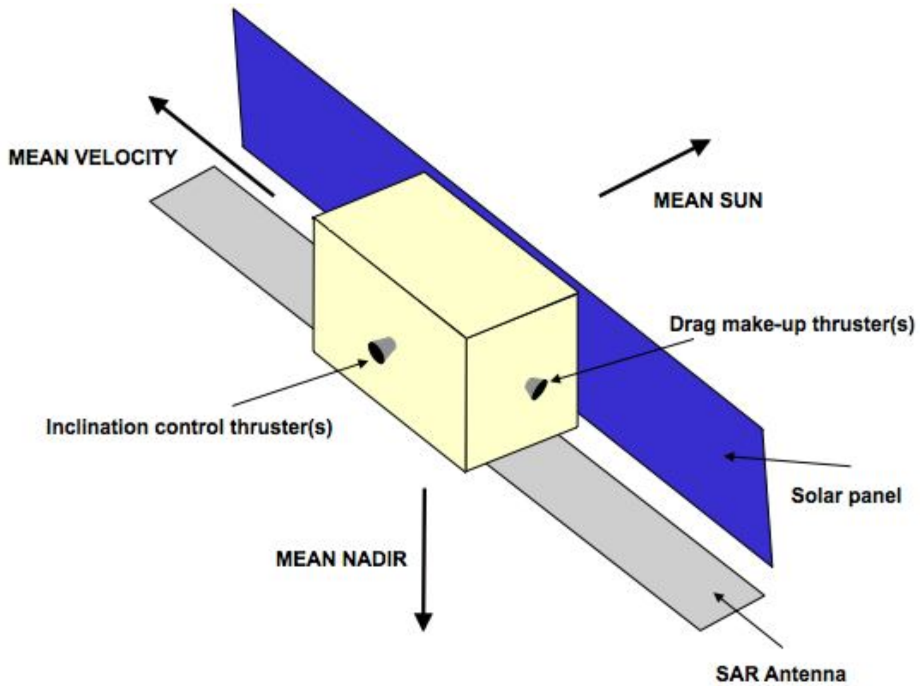
Earth observation spacecraft



InSAR spacecraft model

- 1000 kg "quiet" spacecraft:
  - Attitude control performed with reaction control wheels and magnetorods.
  - No moving appendages, fixed SAR antenna and fixed solar panel.
  - Passive thermal control.
  - Small frontal area: ~4 m^2
  - Lateral area: ~20 m^2
  - Thrusters aligned with the center of mass for minimum impact maneuvers:
    - Anti-velocity direction to perform drag compensation.
    - Normal (anti-sun) direction to perform inclination maintenance.
- Mission Applications
  - Repeat track "orbit tubes"
  - Improve detection of moving objects
  - Earth monitoring: ice and water boundaries

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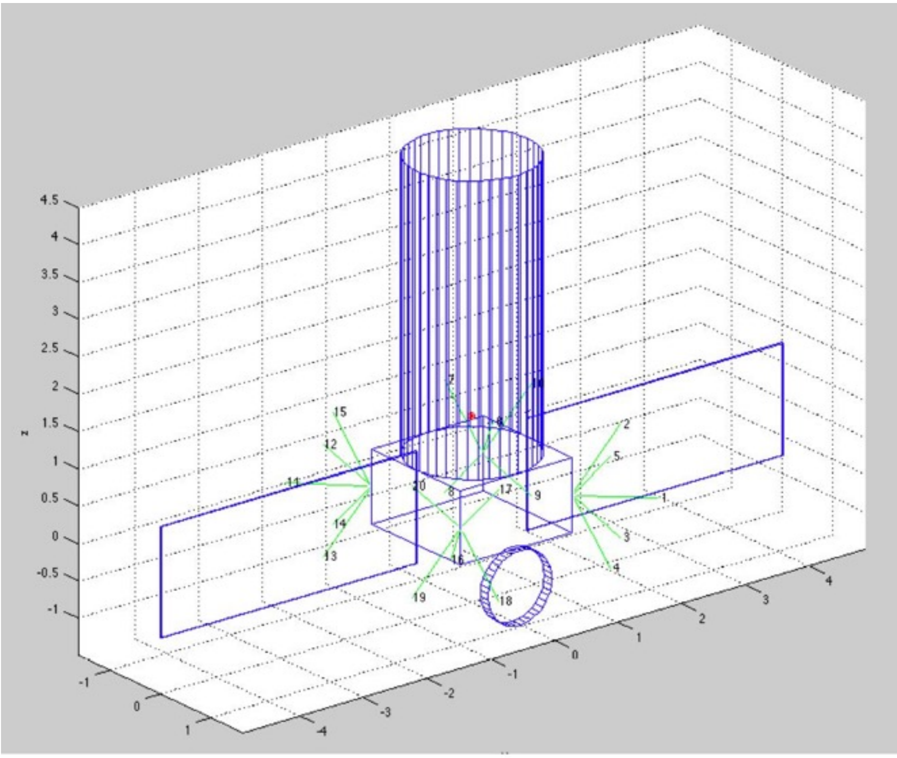
Thrust Requirements for 30 m Earth-fixed Orbital Tube Maintenance

Orbit cycle		9	9	1	1
Orbits per cycle		134	134	15	16
Inclination		97.79	97.79	97.655	96.58
Altitude range (Km)		600-628	600-628	565-594	273-302
10.7 cm solar flux level (sfu)		175	250	175	175
Tangential acceleration required for sinstantaneous drag control (km/s²)		5.6×10^{-11}	2.8×10^{-10}	8.5×10^{-11}	7×10^{-9}
Tangential thrust required for instantaneous drag control (mN)					
Spacecraft Mass	400 kg	0.022	0.112	0.034	2.8
	1000 kg	0.056	0.280	0.085	7.0
	4000 kg	0.220	1.120	0.340	28.0
Normal acceleration for annual + bi-weekly inclination control with thrusters in both (sun and anti-sun) directions (mN)		2.4×10^{-10} Km/s²			
Normal thrust for annual + bi-weekly inclination control with thrusters in both (sun and anti-sun) directions (mN)					
Spacecraft Mass	400 kg	0.096			
	1000 kg	0.240			
	4000 kg	0.960			

Precision Orbit Maintenance and Transfer Analyses Summary

- An acceleration level of 2.4×10^{-10} km/s^2 (normal) and 2.8×10^{-10} km/s^2 (tangential) will be required for practical use of low-thrust for orbit control and reduction of the control tube diameter to 30 m at the 600 km orbit altitude.
  - 2 normal and 1 tangential 0.3 mN thrusters for a 1000 Kg spacecraft
- The 1/16 orbit at 300 km will require thrust levels of 7×10^{-9} km/s^2, mostly for drag compensation.
  - 2 normal 3.0 mN and 1 tangential 7.0 mN thrusters for a 1000 Kg spacecraft
- Orbit change to a shorter repeat cycle will require hundreds of days at the thrust level needed for orbit control.
  - Could reduce to tens of days by using 10 thrusters or thruster with an order of magnitude higher thrust
    - 100 mN thruster could accomplish transfer within ~ 40 days.

Spacecraft and Requirements



Configuration and thruster placement modeled.

- ACCESS Exoplanet Observatory Mission Concept
  - Monolithic chronograph
  - ~2000 kg
- Pointing/attitude error requirement
  - Tip/tilt, x/y axes: 0.1 milliarcseconds (mas)
    - 50 x better than state-of-the-art
    - Hubble requirement: 5 mas
  - Roll axis: 5000 mas
- Desired slew rate
  - ~1.7 deg./min.
- Electric Propulsion ACS
  - 20 microthrusters
    - 4 clusters with 5 thrusters in each

EP approach also has mass advantages

Mass comparison of traditional and electric propulsion-based ACS for ACCESS-class mission.

Subsystem	Mass (kg)	
	Traditional	EP
4 HR-16 Reaction wheels	48	0
Thrusters	4.0	10
Propellant	105.4	7.3
Tank	29	0.8
Additional battery	0	19.5
Additional Solar Panel	0	2
EP Thruster Power Processing Unit	0	25
Active Hexapod	175.5	0
Propulsion System Sub-total	**361.9**	**64.6**
Dry subsystem mass without ACS and Hexapod	1798.1	1798.1
Wet mass	2160	1862.7
Total Propulsive “fuel Fraction” (%)	17	3
Mass Savings over Traditional (%)		**14**

- Mass savings of ~14 % with electric propulsion ACS
  - Without reaction wheels, hydrazine thrusters and associated vibration isolation hexapod
- If higher slew rates or station-keeping maneuvers are required, keeping the hydrazine system still has a next mass savings

Precision Pointing Analysis Summary

- The most stringent fine-pointing requirement of < 0.1 milliarcseconds can be met with electric-thruster attitude control.
  - A factor of 50 better than current SOA Hubble-class pointing
- A thruster with the simulated characteristics will allow:
  - The medium-level of actuation to be eliminated
  - Both reaction wheels and a hydrazine thruster system for momentum management to be eliminated, and
  - The active optics to be greatly simplified since the telescope can be pointed close to the fine-level requirement.
- Vibrations are expected to be less than 4 nm displacements with thrust profile approach.
- EP ACS mass is expected to be >10% less than standard approach.
- Higher-fidelity attitude control simulation is needed to fully explore the optimal requirements for an electric thruster-based attitude control system and characterize on-times and fuel consumption.

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Mission Scenario Micro-Newton Thrust Analysis Summary

- **4 – 30 uN with 0.1 uN thrust precision and 0.1 mN/√Hz thrust noise is enabling for a drag-free LISA constellation with 400 kg spacecraft.**
  - **BUSEK colloid thruster has been flight qualified and delivered for ST7 mission with this performance capability.**
- **10's-100's, and up to 1000s uN for orbit transfer with 1 – 10 uN thrust precision is enabling for 30 m Earth-fixed orbital tube maintenance.**
  - **Qsinetiq T5 thruster is providing 1-20 mN with 1-12 uN resolution for atmospheric drag makeup on the ESA GOCE mission (250 km altitude).**
  - **Smaller ion engines and electrospray thrusters are under development for the lower thrust level range capability.**
- **Micronewton thrust capability is enabling for exoplanet observatories requiring <1 miliarcsecond attitude accuracy.**
  - **Small ion engines are under development for this capability.**
  - **Electrospray thrusters have demonstrated this capability.**

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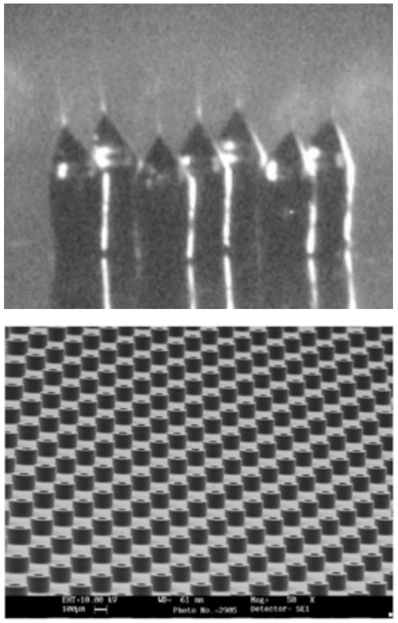
Future of Electrospray Thrusters

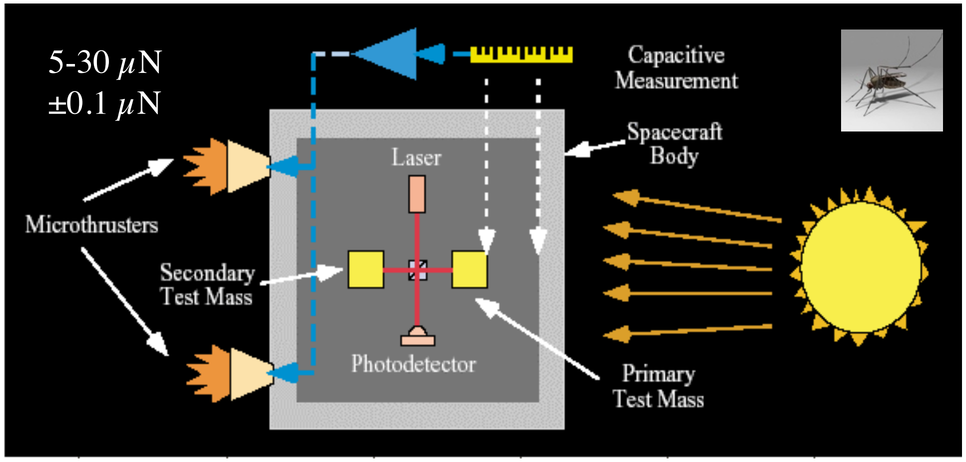


(*MEMS Colloid Thruster Images from J. Stark, et al, J. Propulsion and Power, 22(3), 2006*)

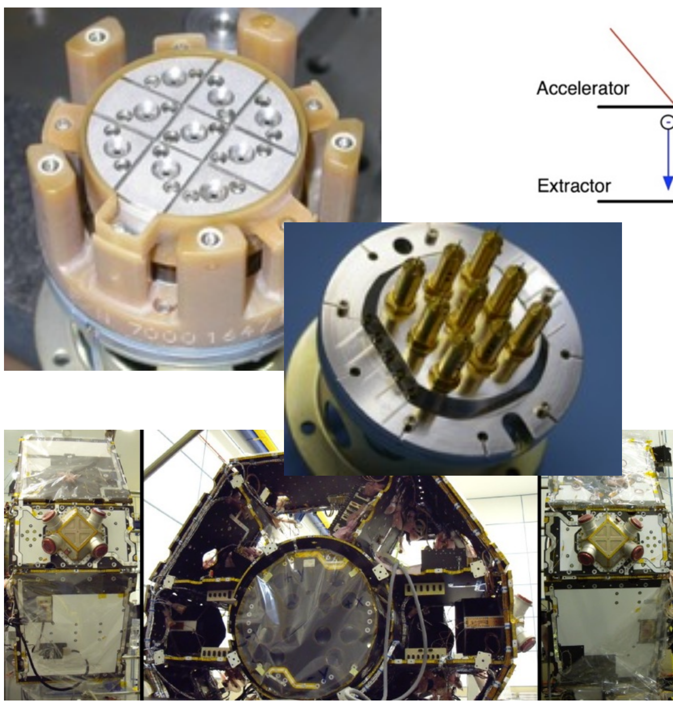
- **Measured performance in droplet mode at room temp. (~90% eff.):**
  - **0.1 - 0.5 μA per emitter**
  - **0.25 - 2.75 μN per emitter at 6 kV**
  - **Isp range of 450 - 200 s at 6 kV**
- **A 1 mN thruster would require:**
  - **4000 - 400 emitters**
  - **2.4 - 1.2 W (thruster head only) at 6 kV**
  - **Isp range of 450 - 200 s at 6 kV**
- **Similar arguments can be made for FEEPs or colloids running in ionic mode at higher Isp (2000-8000s)**
- **Thrusters are under development at JPL, Busek, and MIT**

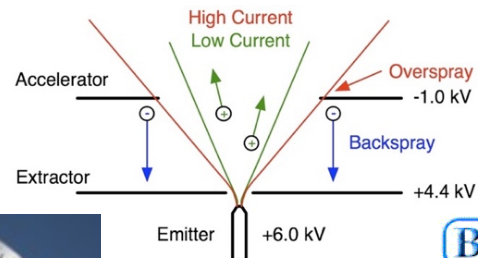
BACKUP SLIDES

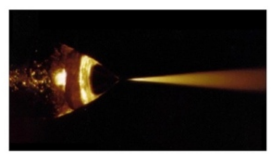
Colloid Microthrusters for Precision S/C Control

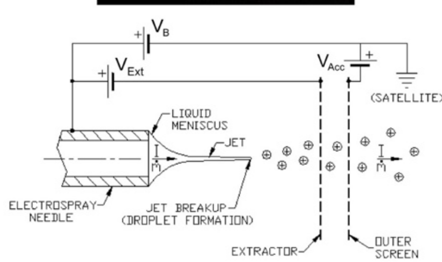


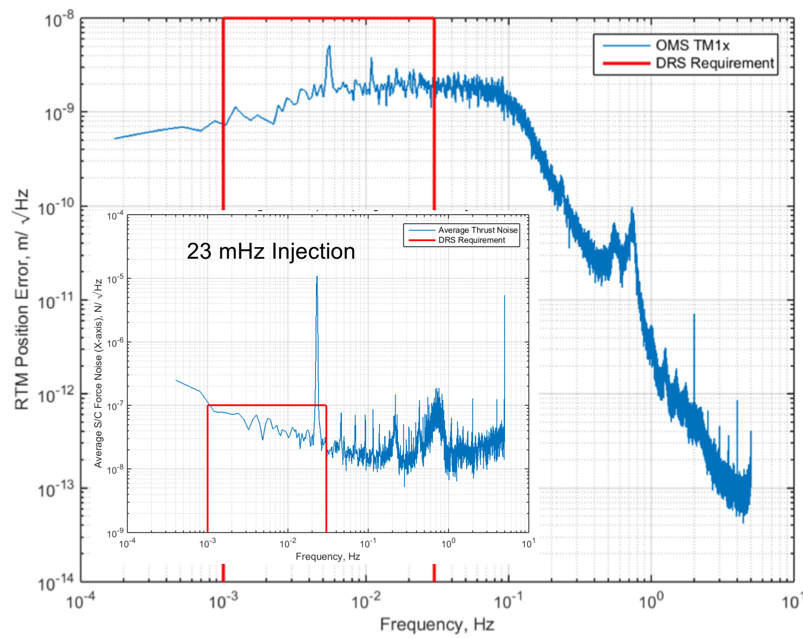
- Busek Colloid Microthrusters have been developed to TRL 7 by ST7-DRS on LISA Pathfinder and will continue to be developed for contribution to an ESA-led LISA mission
- Drag-free performance requirements (≤10 nm/√Hz) and models demonstrated on orbit
- 0.1 mas (50x better than Hubble) pointing w/o reaction wheels is possible using less mass
- Focus for LISA is on demonstrating thruster reliability (redundancy) and lifetime (4 years)











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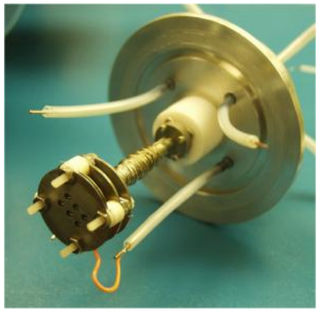
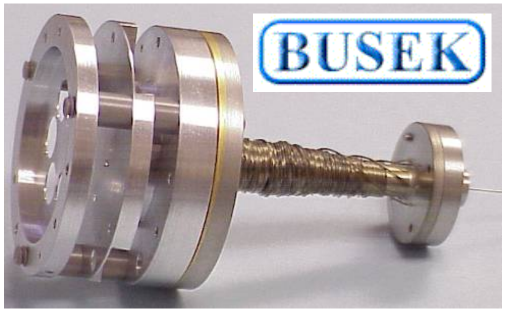
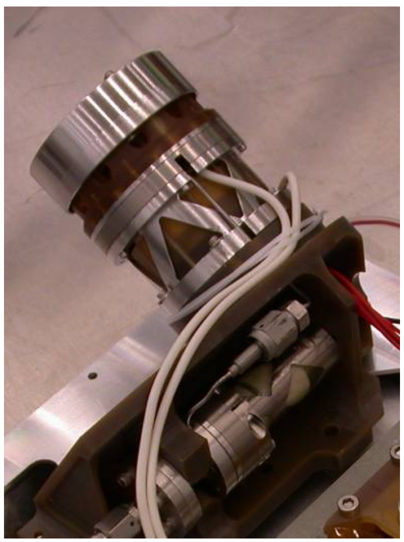
Thruster Technical Challenges



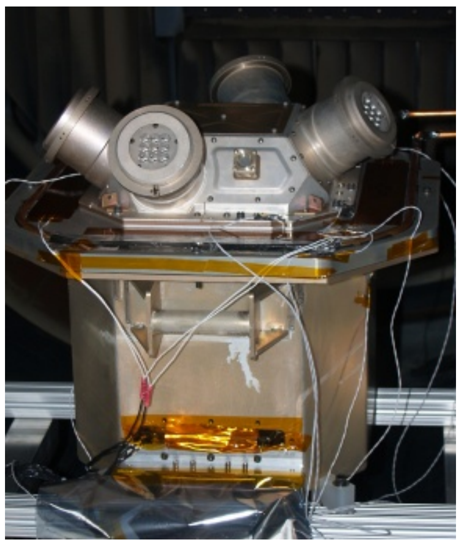
2003 Lab Model



2004 Prototype Model



2005 First EM Design
- Complete System
- 9-Emitter Thruster Head
- Microvalve Flow Control
- EM Electronics



2007 Flight Design
- 4 Thruster Systems in a Cluster
- 3400 hr Life Test Complete
- Thrust Stand Measurements and Environmental Testing Complete
- Flight-Hardware Delivered

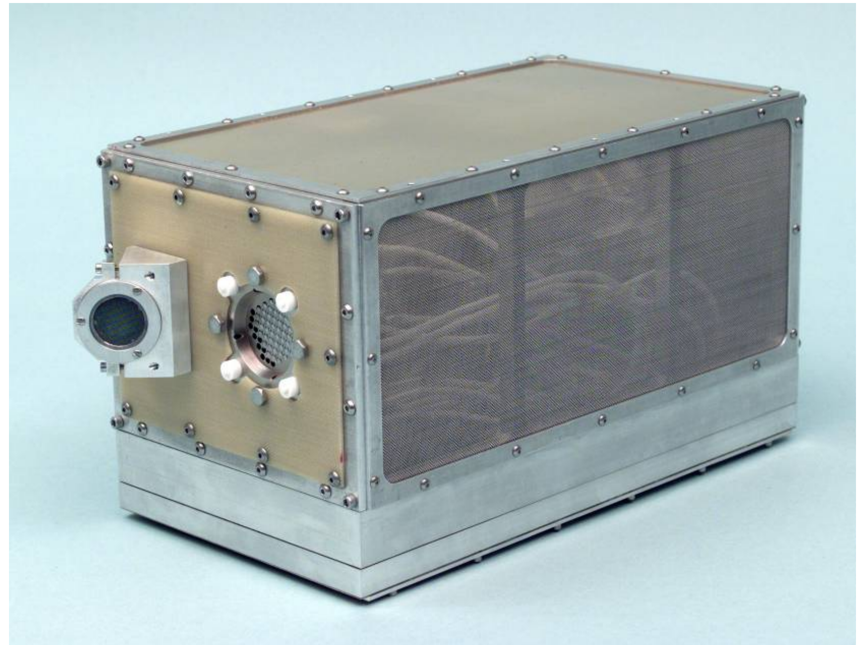
- Colloid Thruster Development Timeline:
  - Busek and JPL began work on Colloid Thrusters in 1998 with a NASA Phase I SBIR
  - ST7 work began in late 2002 with a 6-emitter Prototype Model completed in 2004 along first direct thrust stand measurements at Busek by PDR
  - First 9-emitter EM model failed after 500 hours of testing in late 2005; JPL became much more involved with an engineer on site at Busek
- Technical Challenges:
  - Excess propellant (overspray) and thruster lifetime
  - Bubbles in the feed system and thruster performance
  - Emitter design and fabrication
  - Microvalve thermal design and fabrication
  - Material compatibility with propellant

Scales in a Precision Colloid Thruster

- Thrust (30 μN max with 0.1 μN precision):
  - 30 μN is about the weight of a mosquito
  - 0.1 μN is about the weight of a mosquito antenna
- Beam Current and Flow Rate:
  - 10 nA precision at 10 kV (Terra-Ohm isolation)
  - 10 nL/s maximum flow rate (1 drop in 10 min)
  - Microvalve flow rate precision requirement: 25 pL/s

Early Busek Colloid Thruster Development

- 1998: The use of colloid thrusters for micropropulsion applications is proposed. NASA awards a Phase I SBIR contract to Busek.
- 1999: Successful completion of NASA Phase I results in a Phase II award. Experimental tools for the investigation of colloid thrusters, including a torsional micro-Newton balance, are developed.[†] Extensive study of different propellants and electrospray properties. [‡,¥,☒]
- 2001: JPL awards a contract to develop a colloid thruster prototype for the DRS project. The prototype is delivered, with an estimated Technology Readiness Level of 4[€].
- 2002: The DRS project is selected for NMP's ST7 mission. Busek is the DRS team member responsible for the Micro-Newton Thruster development.



Busek Colloid Microthruster Prototype (2001)

- 56 needles, 1 propellant feed system
- Separate extractor and accelerator grids
- Integrated DC-DC HV converters and DCIU
- Carbon nanotube neutralizer
- I_{sp}: > 500 s; Thrust: 1-20 μN
- Total mass: 2 kg; Total power: 6 W

† M. Gamero-Castaño et al. Paper IEPC-01-235, 2001
‡ M. Gamero-Castaño & V. Hruby. J. Prop. Power, 17, 977, 2001
¥ M. Gamero-Castaño & V. Hruby. J. Fluid Mech. 459, 245, 2002.
☒ M. Gamero-Castaño. Phys. Rev. Lett, 2003.
€ V. Hruby et al. Paper IEPC-01-281, 2001

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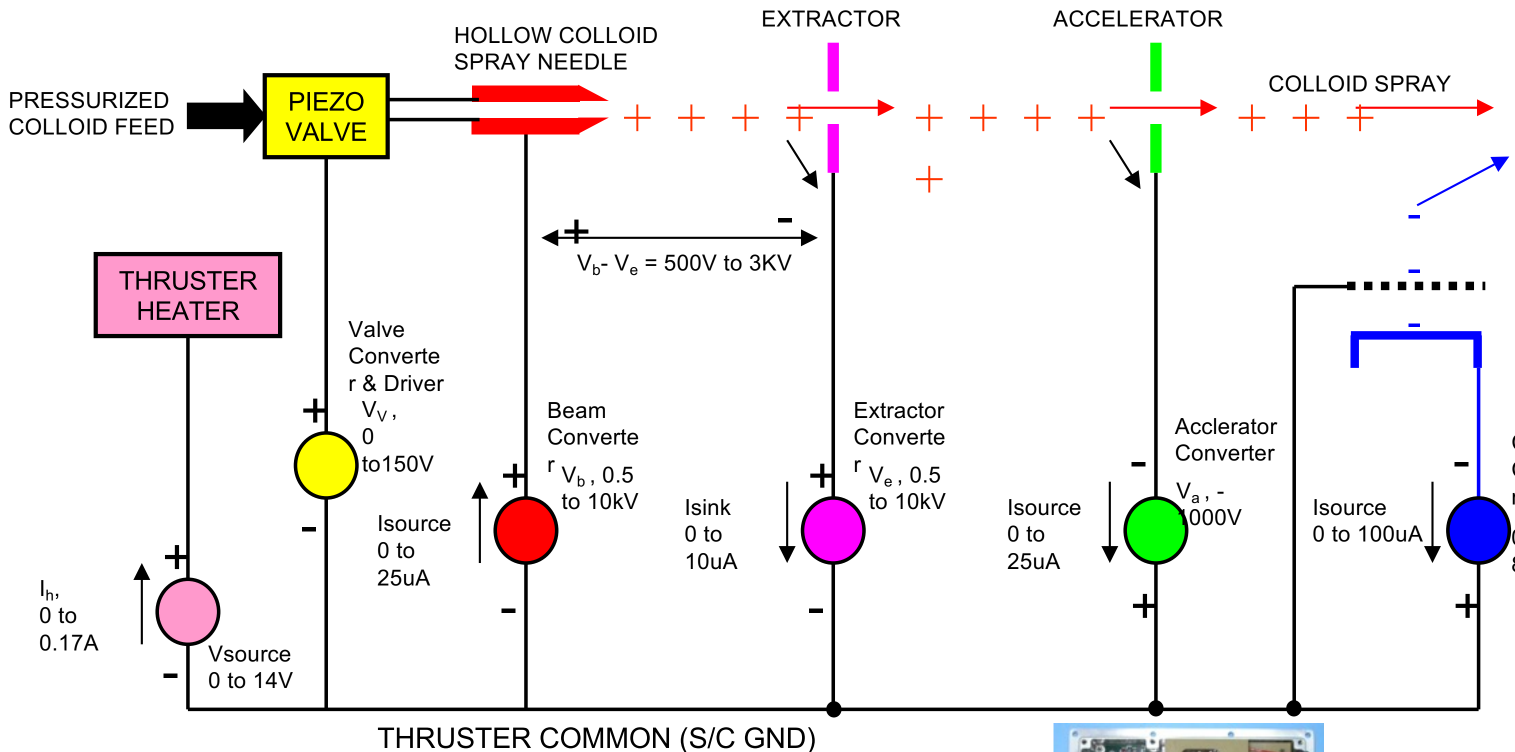
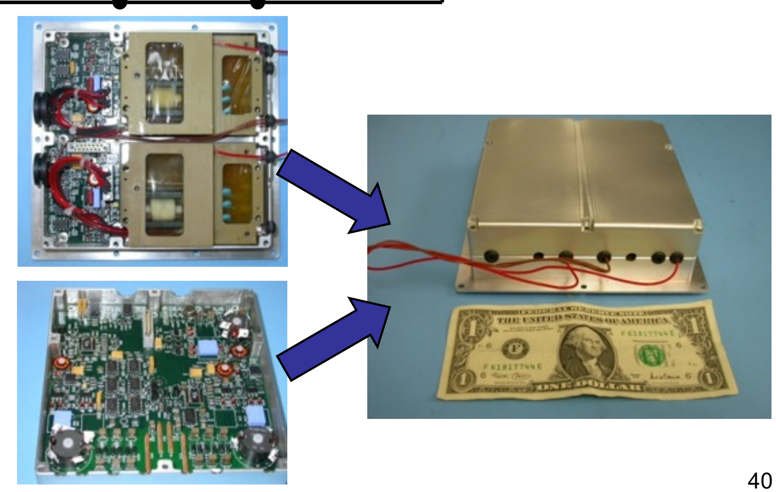
Thruster Power Processing Unit Schematic



CONTROLLED VARIABLES: V_b, $(V_b - V_e)$, V_v, I_h, I_c



- **PPU challenge is having two high voltage variable output DC-DC converters capable of providing 0.5 to 10 kV in a continuous range**
- **Flight hardware delivery in late 2006 by Assurance Technology Corporation (ATC)**

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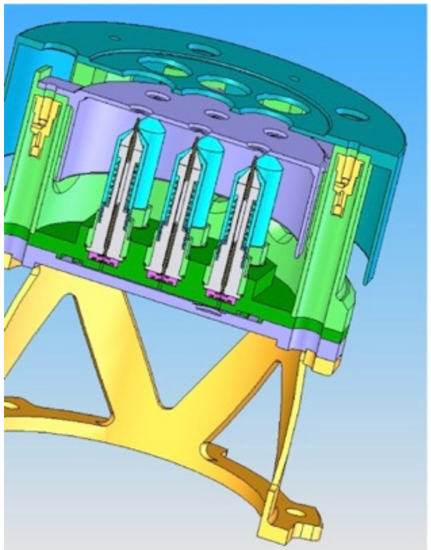
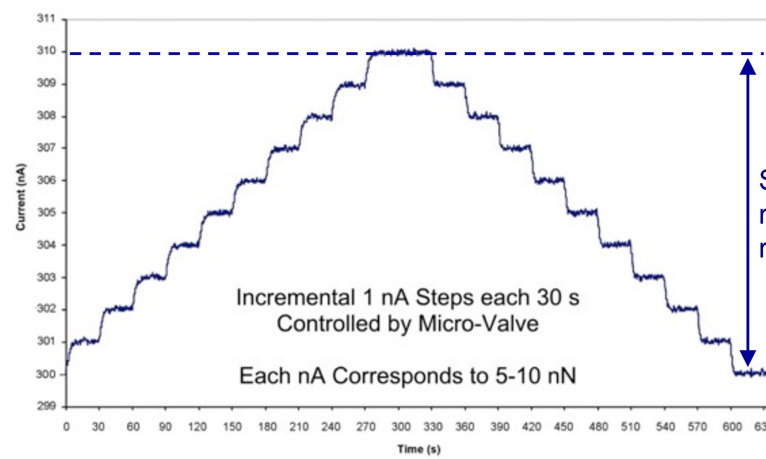
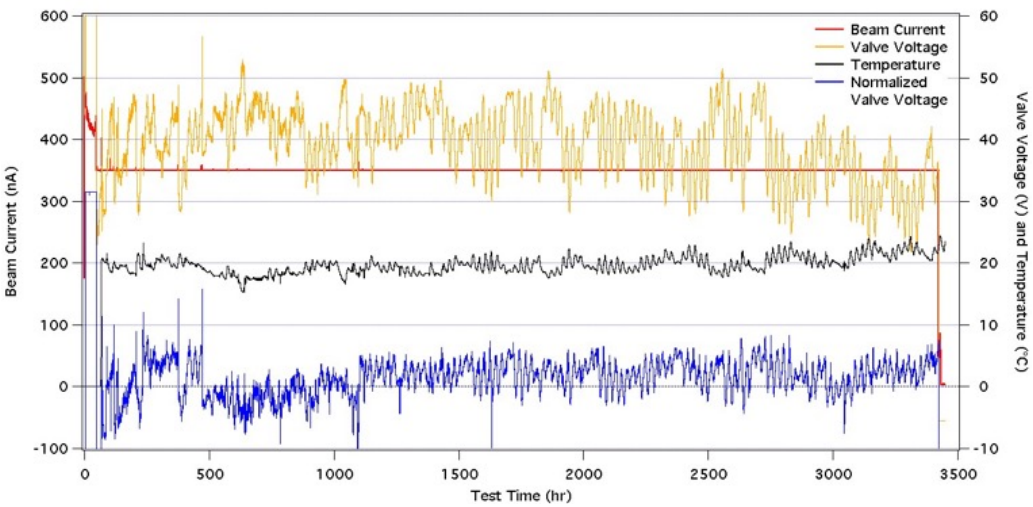
Thruster Head and Micro-Valve Performance

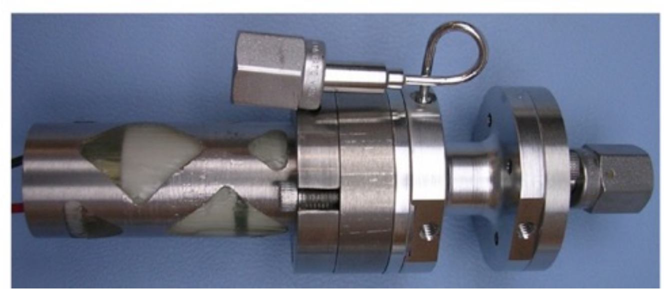


- **Thruster head and microvalve meet LISA performance requirements:**
  - **5-30 μN with < 0.1 μN resolution**
  - **< 0.1 μN/√Hz thrust noise**

Micro-Valve Resolution







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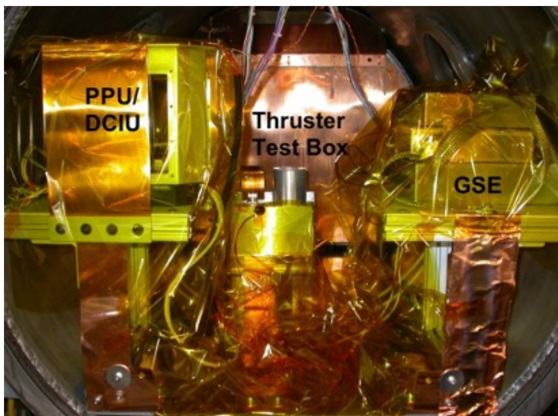
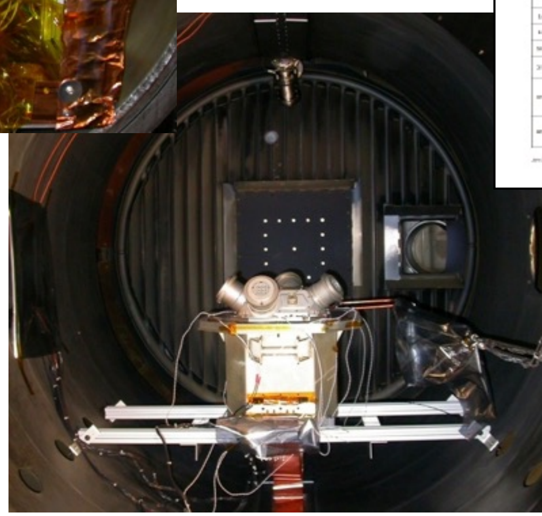
Requirements V&V

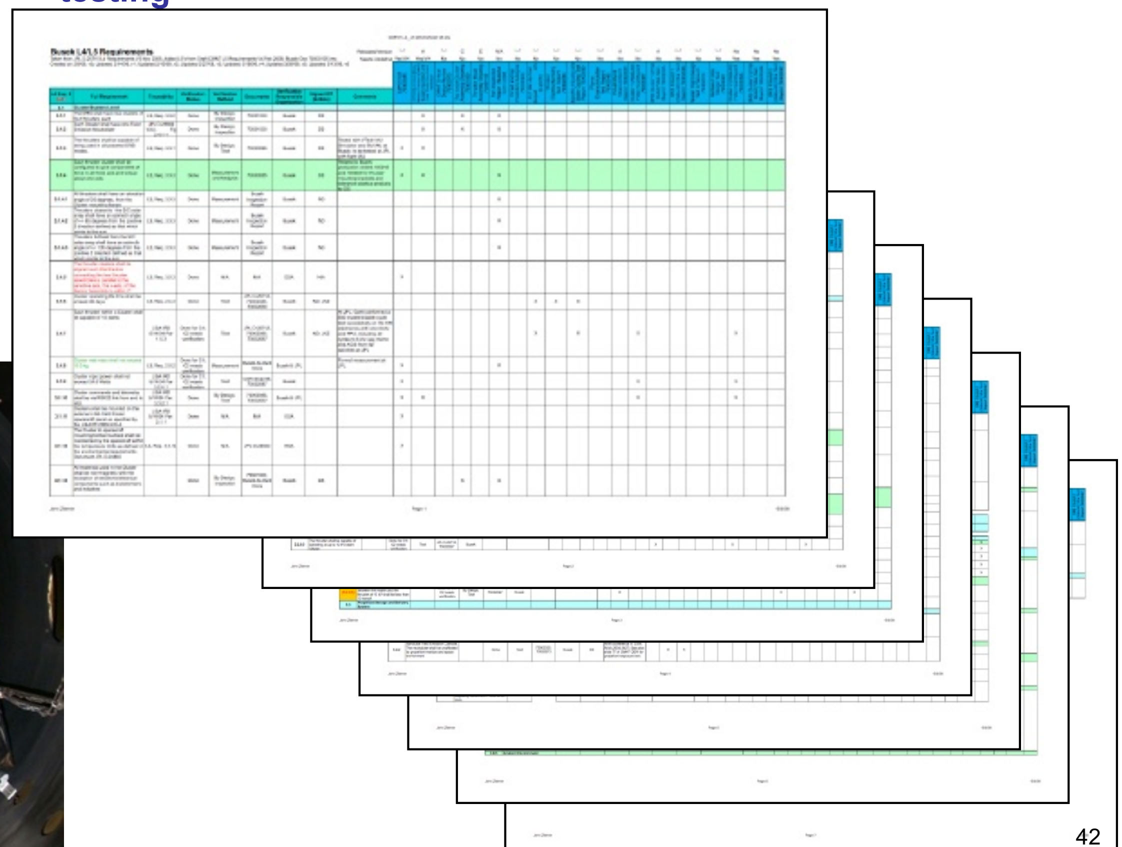
All requirements have been verified

Requirement	Box Level	Cluster Level
Thrust Range	✓	Partial
Thrust Precision	✓	Partial
Thrust Noise	✓	Partial
Thrust Response Time	✓	Partial
Specific Impulse	✓	Partial
Operational Lifetime	✓	
Plume Half-Angle	✓	
Environmental Dynamics		✓
Environmental Temperature	✓	✓

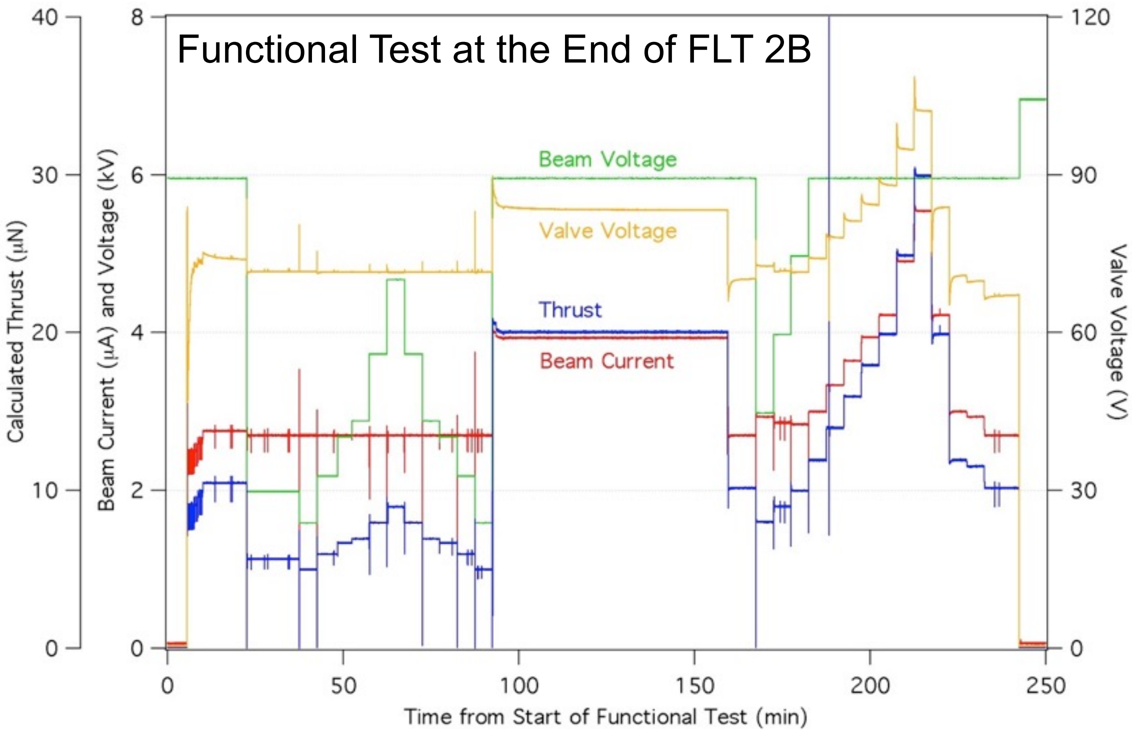
- **All L4 CMNT requirements have been verified**
- **Some requirements have been verified at the "box" level**
  - **A "box" is a complete flight-like single thruster system**
  - **A single thruster system is smaller, lighter and cheaper to test**
  - **Many of the performance requirements (thrust, lifetime, plume divergence) can be verified at the "box" level**
- **Both flight clusters went through protoflight-level dynamics and thermal qualification testing including full functional testing**



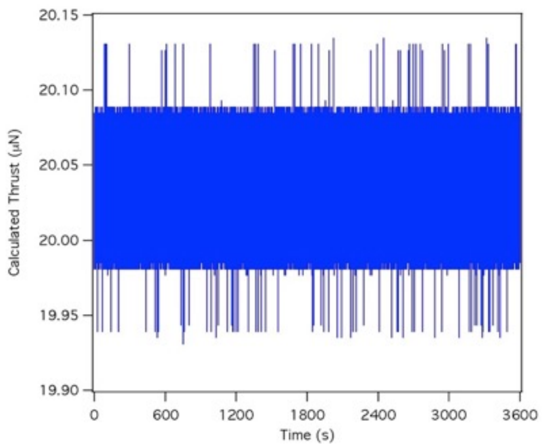


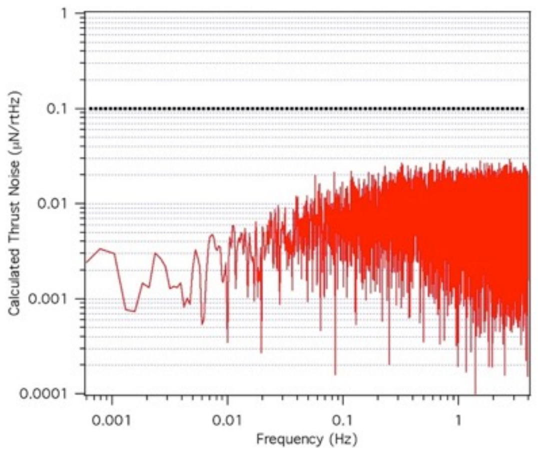


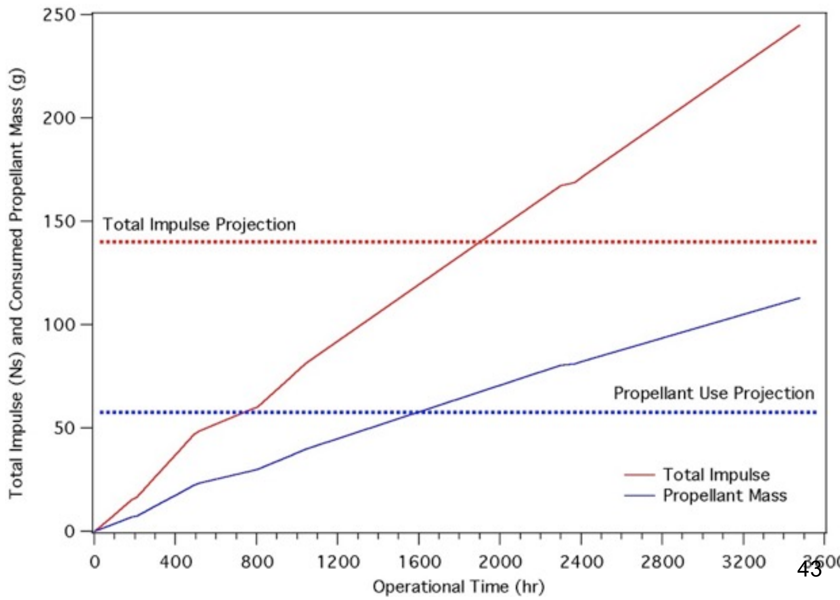
Performance of FLT 2B at EOT



- At the end of Formal Life Test 2B, a full functional test was performed
- Full thrust range was demonstrated along with thrust noise < 0.1 μN/√Hz
- Both total impulse and propellant throughput exceed projections by >50%







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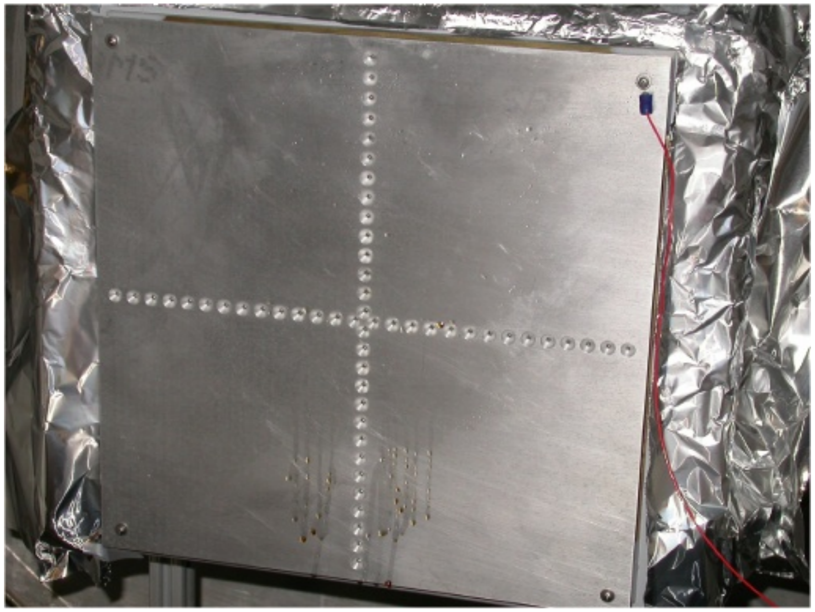
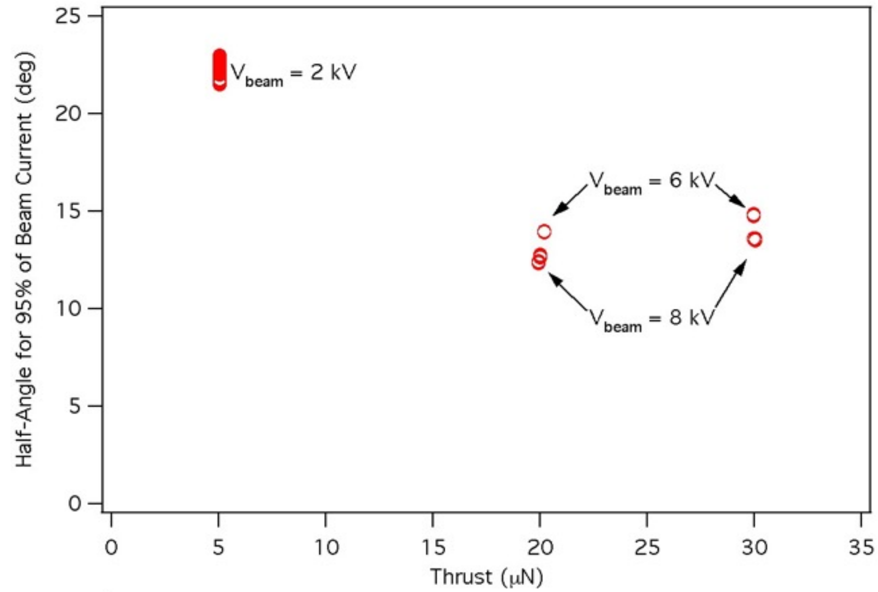
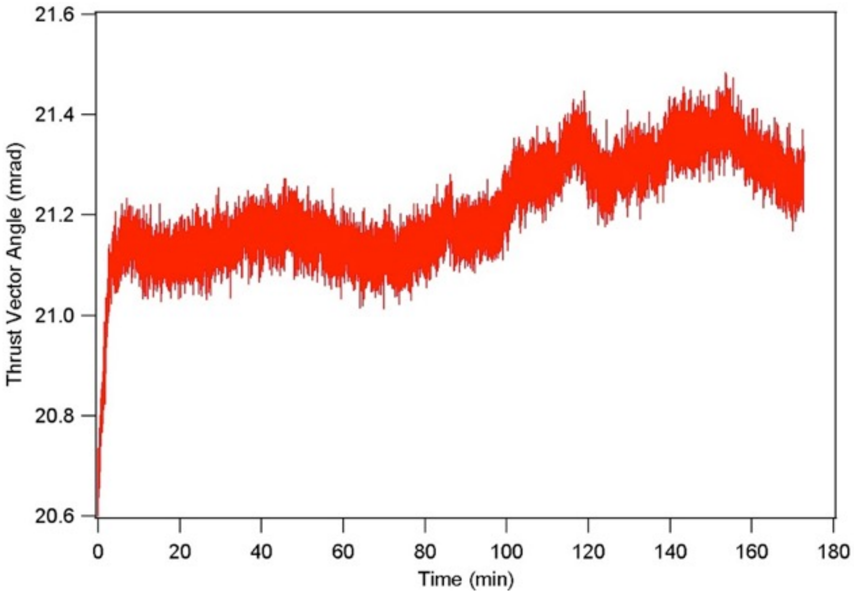
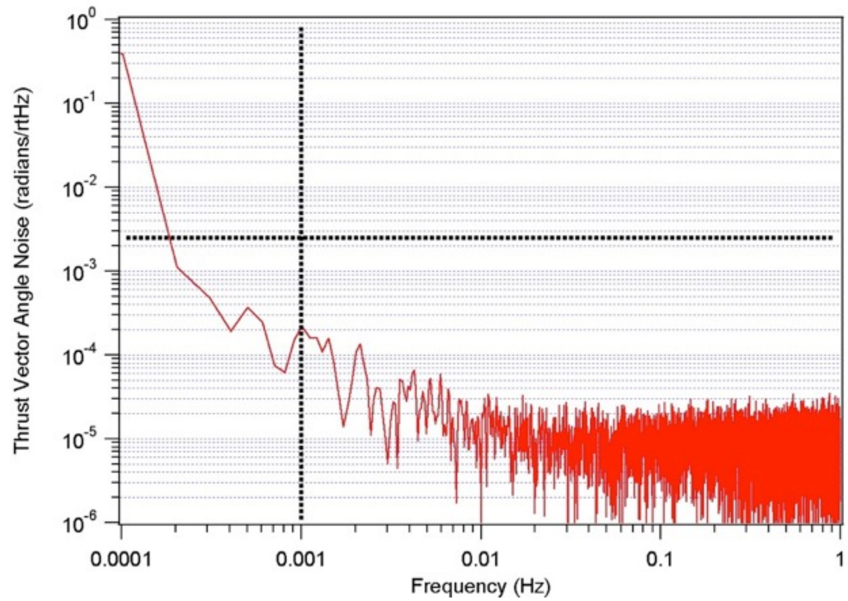
Exhaust Beam Profile and Stability

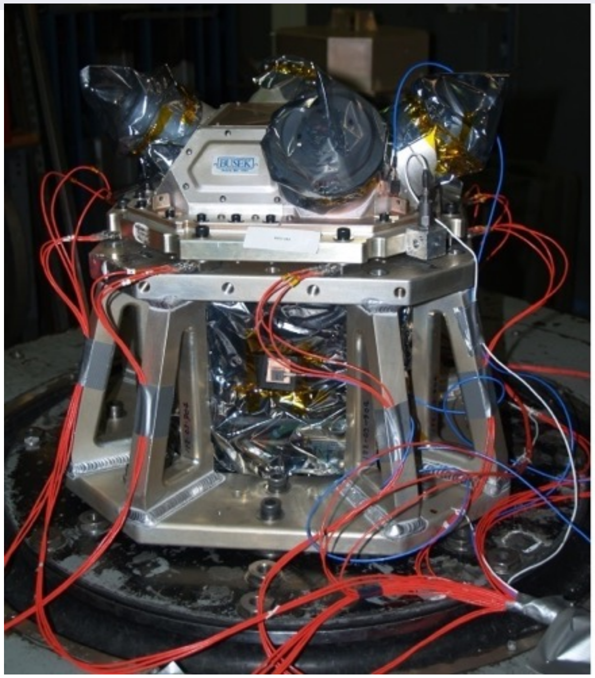


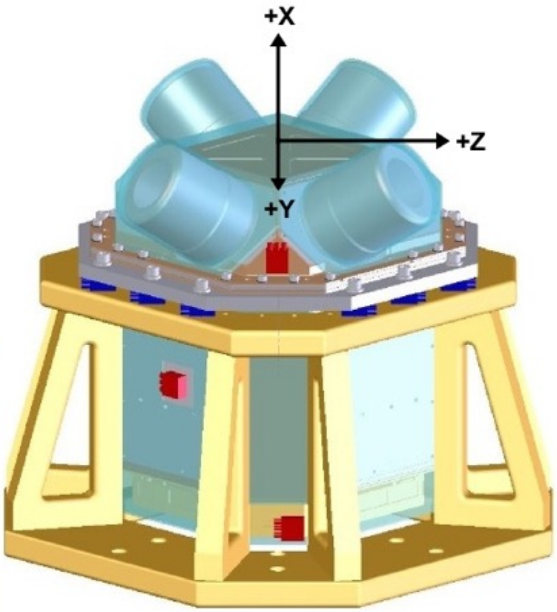






Dynamics Environmental Validation





- Dynamics testing performed at the cluster level, preceded by some component-level and mock-up (mass equivalent with critical components) shock testing
- Sine, random, and quasi-static load testing was performed on both flight clusters
  - For sine load testing, Cluster 1 was tested to flight acceptance levels (16 g); Cluster 2 tested to protoflight levels (20 g)
  - All other testing was performed at protoflight levels for both clusters
- Both clusters passed pre- and post- full functional testing

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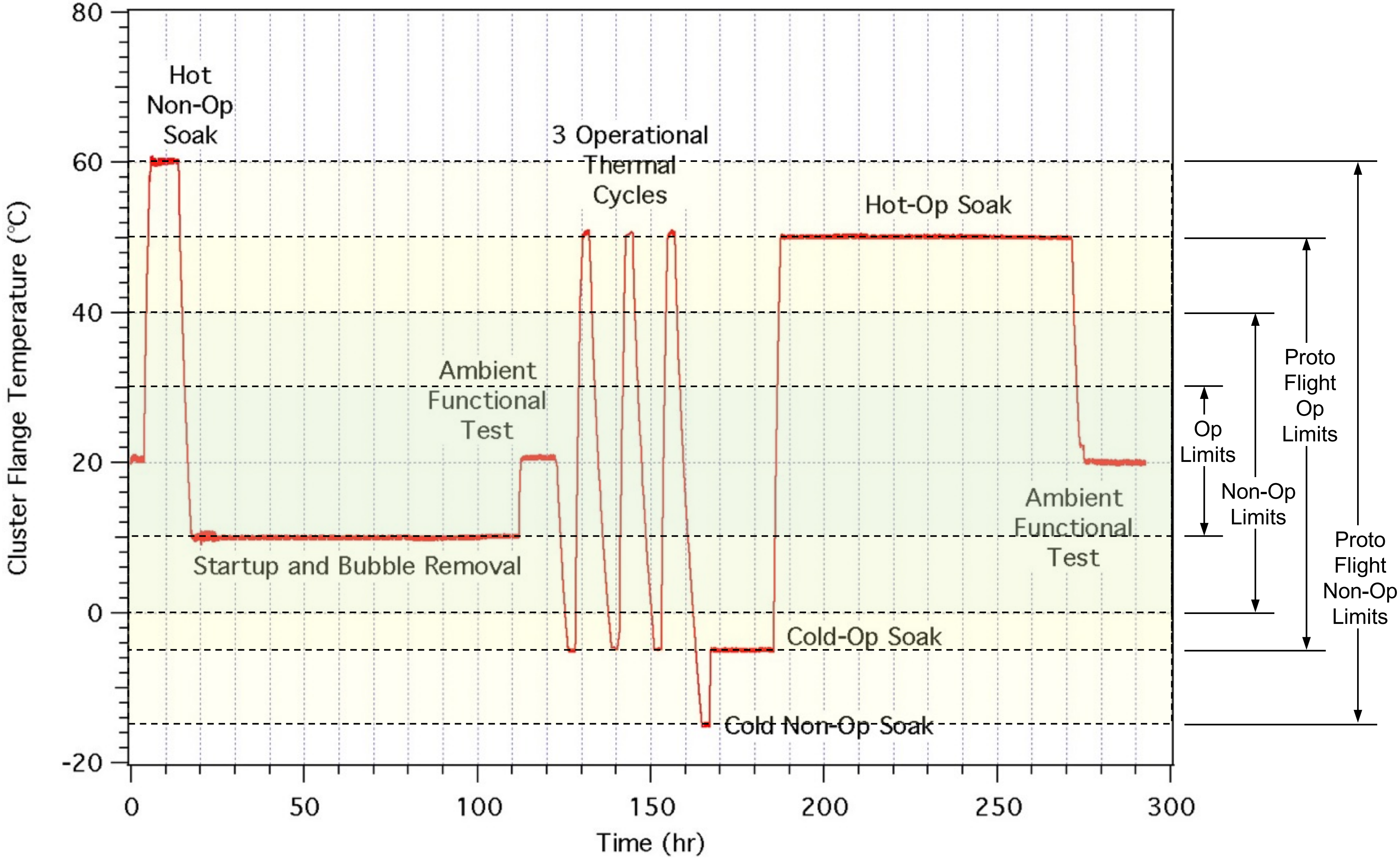
Thermal Vacuum Test Profile

Both Clusters Completed TVAC Testing Successfully



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Flight Cluster Test Summary

All requirements have been verified

Test	Levels/Requirements		Results
Card Level Random Vibe	**Lateral = 10.6 g, Longitudinal = 12.3 g**	✓	**All Cluster 1&2 electronics units passed**
Card Level TVAC	**2 cycles, -15º C to 65º C**	✓	**All Cluster 1&2 electronics units passed**
Valve Level Thermal Cycle	**-5º C to 50º C operating, -15º C to 70º C non-operating**	✓	**8 out of 8 flight microvalves passed**
Cluster Functional	**Full-Scale Response Time < 100 s, Thrust Range 5 to 30 µN**	✓	**Cluster 1&2 (all thrusters): Response Time < 10 s, Thrust Range = 4.35 to 35.8 µN**
Cluster Sine Vibe	**20 g PF, 16 g FA**	✓	**Cluster 1 completed FA level, no sine retest Cluster 2 completed PF level, no sine retest**
Cluster Random Vibe	**Lateral = 10.6 g PF, 8.48 FA Longitudinal = 12.3 g PF, 9.9 g FA**	✓	**Cluster 1 completed PF level and FA retest Cluster 2 completed PF level and FA retest**
Cluster TVAC	**-5º C to 50º C operating (4 cycles), -15º C to 60º C non-operating,**	✓	**Cluster 1 passed post TVAC full functional test after low temperature start up anomaly Cluster 2 passed post TVAC full functional test with no anomalies**
Cluster EMC	**B < 4 µT, E < 20 V/m**	✓	**Cluster 1&2 Completed measurements at JPL**

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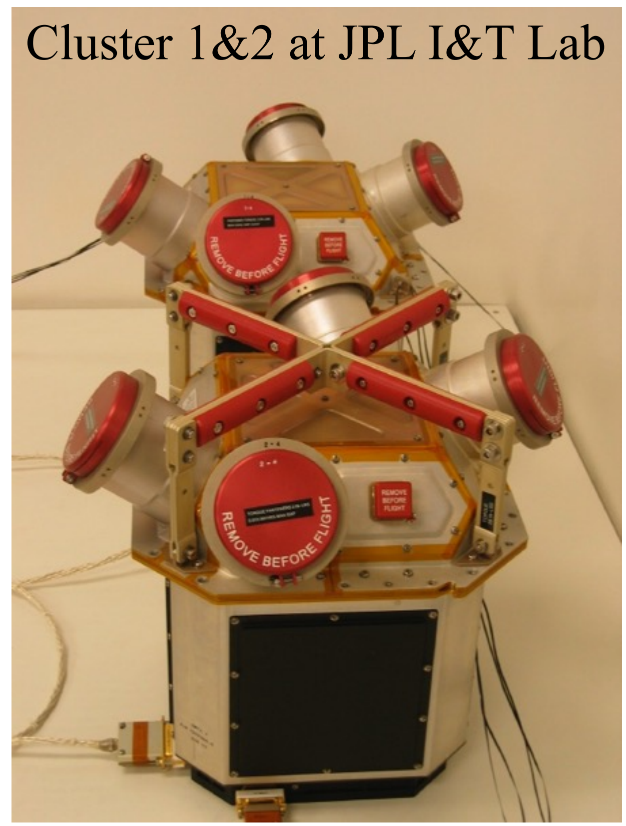
Both Flight Clusters Delivered to JPL

- Cluster 1 complete and delivered to JPL in February of 2008
- Cluster 2 complete and delivered to JPL in May of 2008



Cluster 1&2 at JPL I&T Lab

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As Delivered Both Clusters Meet Mass, Power, Propellant, and Electronics Allocations

	Mass (kg)	Power (Watts)	Remaining Propellant Load (Operational Days)	Operational Time	Single Command Processing Speed (msec)	Memory Reserve
Allocation/ Requirement	**31 kg Total**	**53 Watts Max Total**	**90 days (T1/T2: 20 µN, T3/T4: 30 µN)**	**60 days (1440 hours)**	**100**	**ROM 32.8 kB RAM 33.0 kB**
Cluster 1 Measured	**14.794**	**16.5 Nom 24.6 Max (as tested; 23.8 Max w/reduced heater power)**	**T1: 137.6 T2: 129.3 T3: 97.1 T4: 93.1**	**Thrusters: ~100 hours Electronics: 700-800 hours (3478 hours demonstrated in life test)**	**~75**	**ROM: 18.6 kB (58%) RAM: 518 B (98%)**
Cluster 2 Measured	**14.784**	**17.1 Nom 25.4 Max (as tested; 24.6 Max w/reduced heater power)**	**T1: 108.5 T2: 99.1 T3: 98.4 T4: 96.1**	**Thrusters: 150-200 hours Electronics: 500-600 hours (3478 hours demonstrated in life test)**	**~75**	**ROM: 18.6 kB (58%) RAM: 518 B (98%)**

Mass, Power, Data Processing Within Allocation

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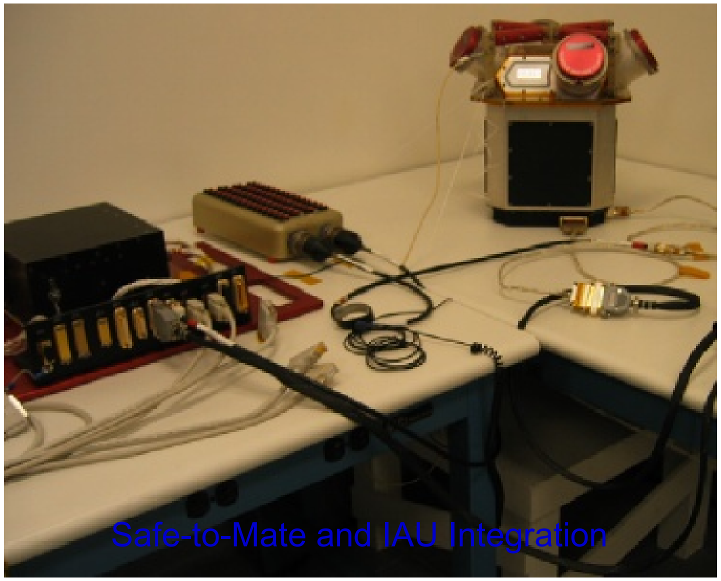
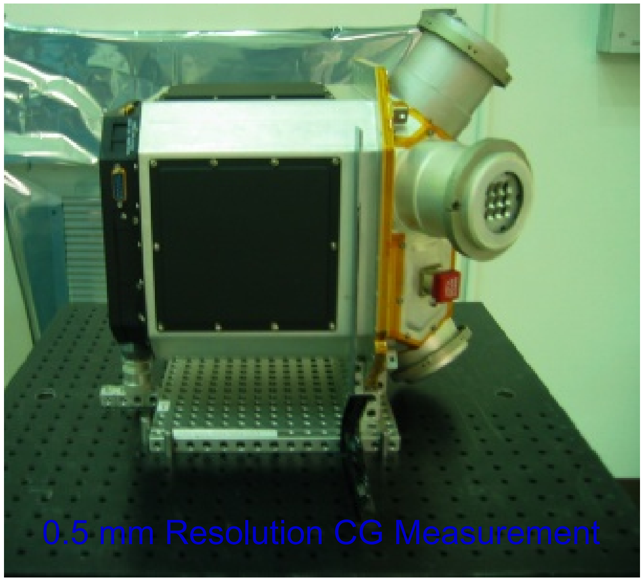
I&T Activities at JPL

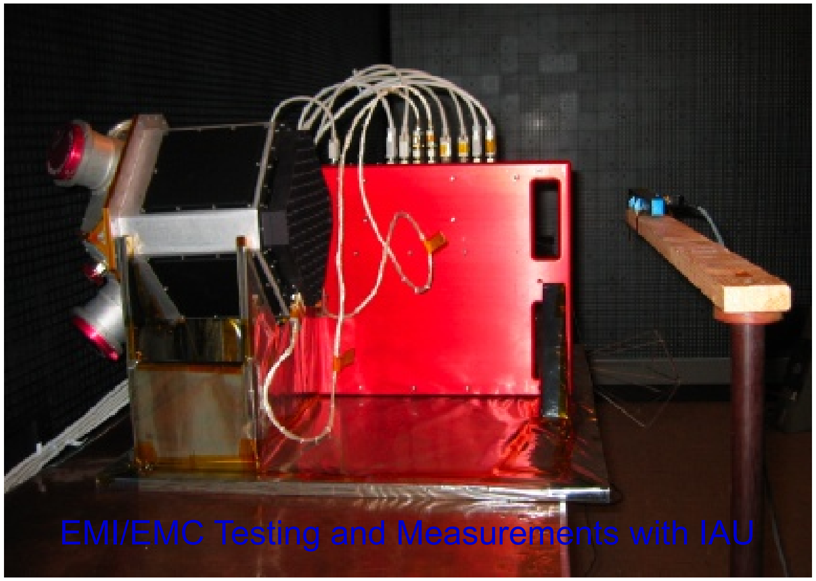


Safe-to-Mate and IAU Integration

Magnetics Testing and Measurements



0.5 mm Resolution CG Measurement



EMI/EMC Testing and Measurements with IAU