Colloid Micro-Newton Thrusters for the Space Technology 7 Mission and Beyond

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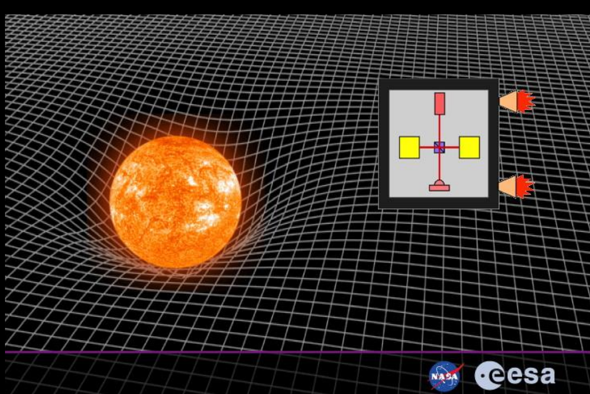
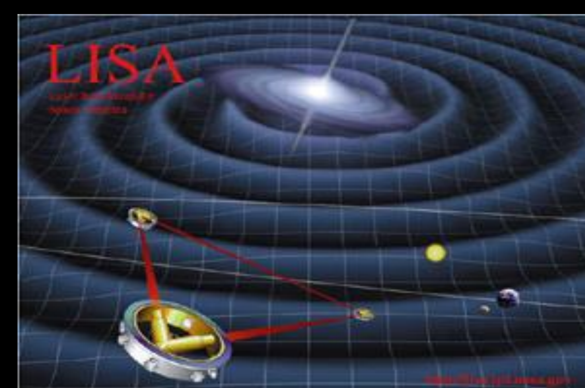


L3 Study Team

March 10, 2016

Combination of previously cleared material



Executive Summary

- Colloid thrusters are at TRL 7 – Thruster checkout commissioning successfully completed on LISA Pathfinder
- Experience on LISA Pathfinder to date:
  - Thrusters were stored with propellant loaded for 8 years
  - Startup took longer than we expected for one thruster
  - Bubble dissipation took longer than expected, but progressed
  - All thrusters passed functional test and were considered as viable backup to cold gas for post-separation despin and tip-off cancelation
- Colloid thrusters are capable of meeting all requirements for LISA/eLISA
  - Exact configuration (number of thrusters, pointing, etc,) and maximum thrust level needs study and will drive cost
  - We need larger propellant tanks and full redundancy, both of which have system-level impacts, but work has been done on both these areas with an estimate of TRL 5 for future flagship applications
- Key future activities:
  - Configuration and propellant loading considerations for future missions to prevent bubbles
  - Lifetime model validation and verification with long-term testing

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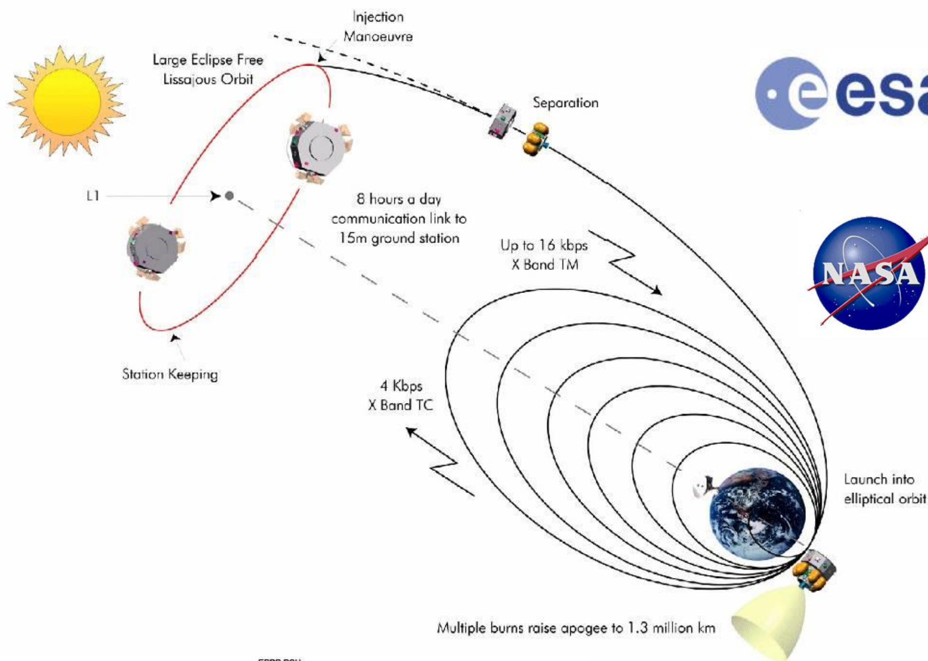
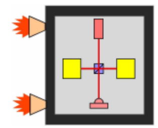
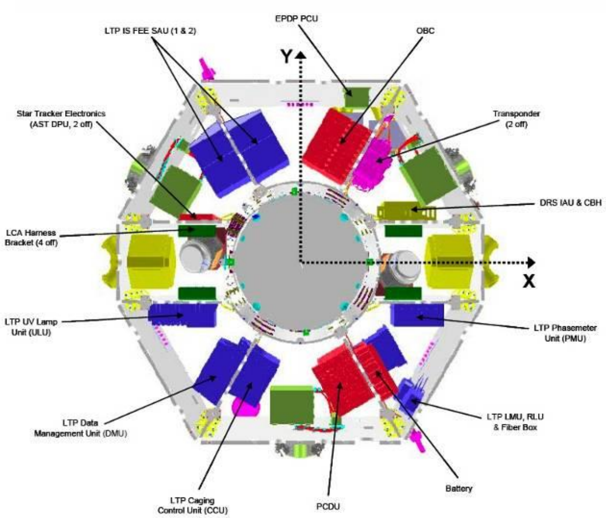
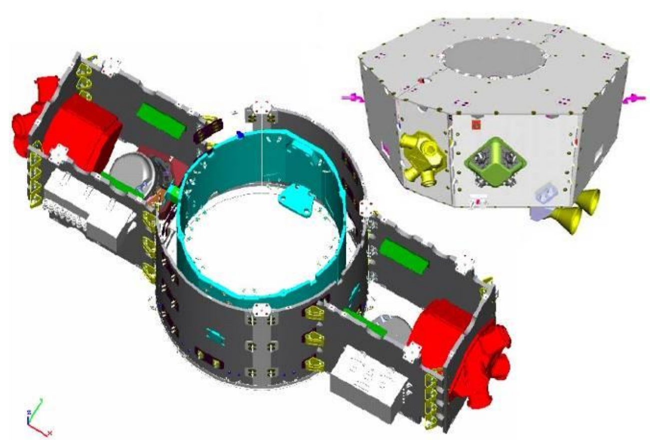
ST7 and LISA Pathfinder Mission





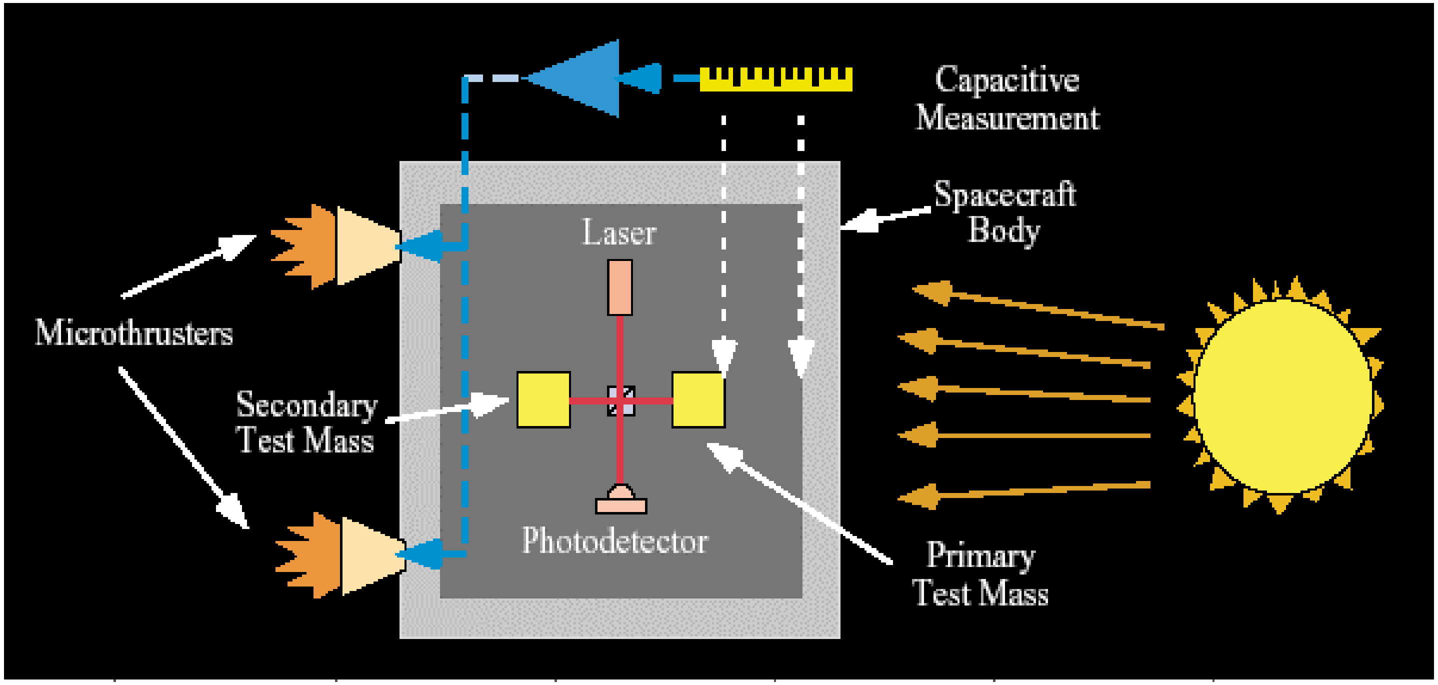
ST7-DRS

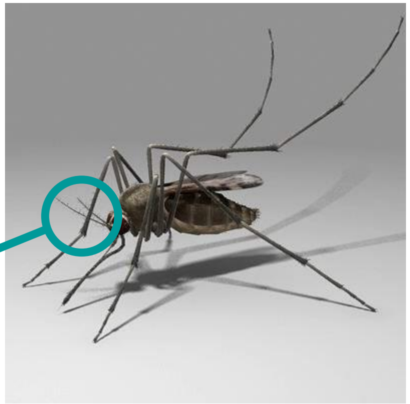




- New Millennium Program technology demonstration mission for drag-free and precision formation flying
- LISA Pathfinder Mission
  - ESA mission to launch in 2015
  - Six month mission to demonstrate technologies necessary for LISA
- LISA Technology Payloads
  - NASA Space Technology 7 (ST7) delivered thruster flight hardware to ESA in July 2009
  - ESA LISA Test Package (LTP) integrated in 2009

ST7-DRS Mission





~ 0.1 µN

≈ 30 µN

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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

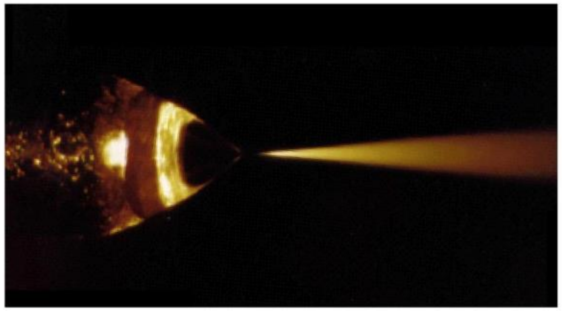
§ By calculation a range of approximately 3-50 μN is possible within the nominal operational constraints of the thruster

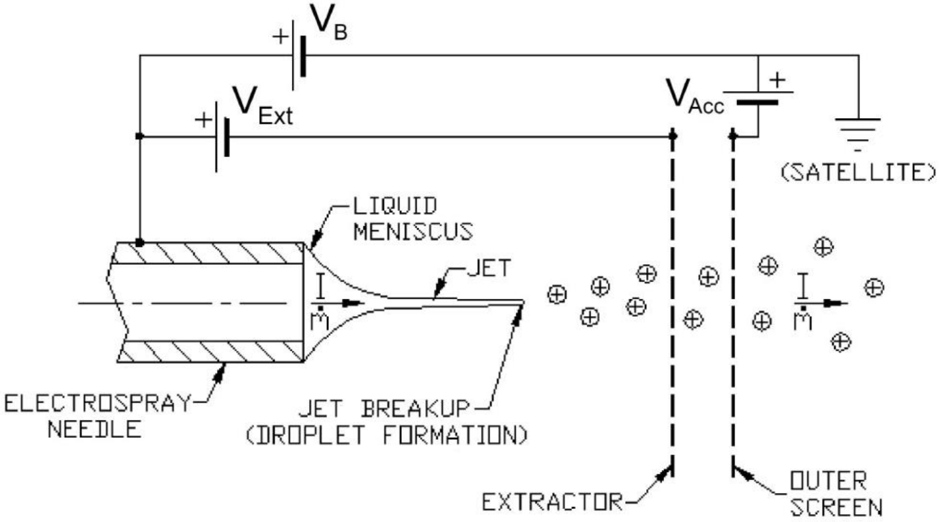
Colloid Thrusters

- **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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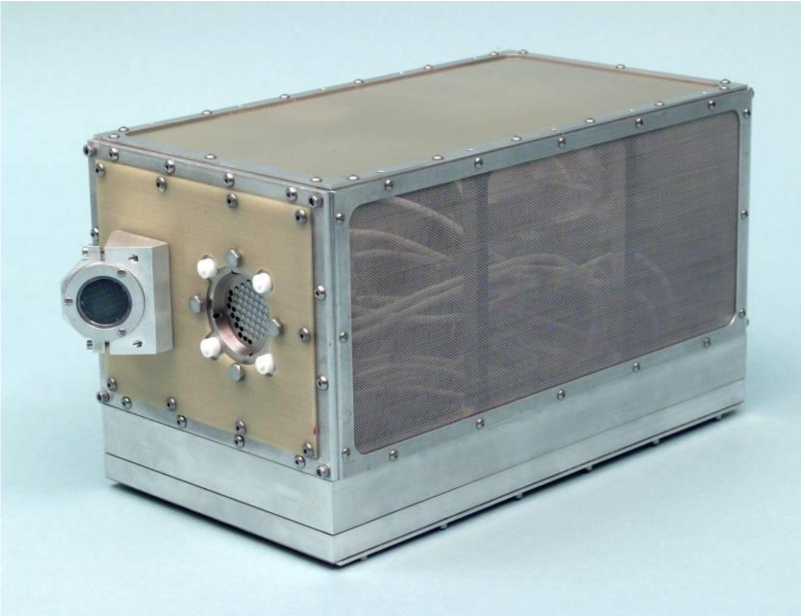
Early Busek Colloid Thruster Development

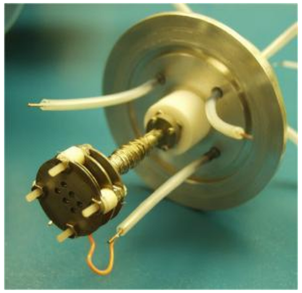
- 1998: The use of colloid thrusters for micropropulsion applications is proposed. NASA awards a Phase I SBIR contract to Busek.
- 1999: Successful completion of NASA Phase I results in a Phase II award. Experimental tools for the investigation of colloid thrusters, including a torsional micro-Newton 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.



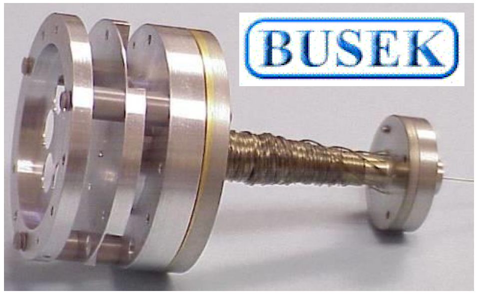
Busek Colloid Microthruster Prototype (2001)
- 56 needles, 1 propellant feed system
- Separate extractor and accelerator grids
- Integrated DC-DC HV converters and DCIU
- Carbon nanotube neutralizer
- I_{sp}: > 500 s; Thrust: 1-20 μN
- Total mass: 2 kg; Total power: 6 W

[†] 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

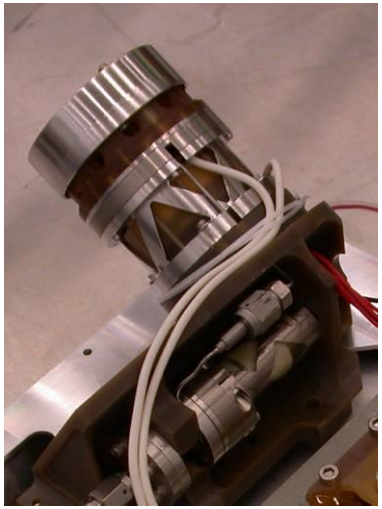
Thruster Technical Challenges



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

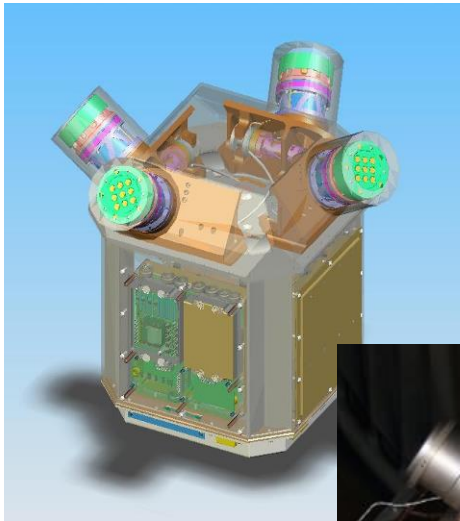
- Colloid Thruster Development Timeline:
  - Busek and JPL began work on Colloid Thrusters in 1998 with a NASA Phase I SBIR
  - ST7 work began in late 2002 with a 6-emitter Prototype Model completed in 2004 along first direct thrust stand measurements at Busek by PDR
  - First 9-emitter EM model failed 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

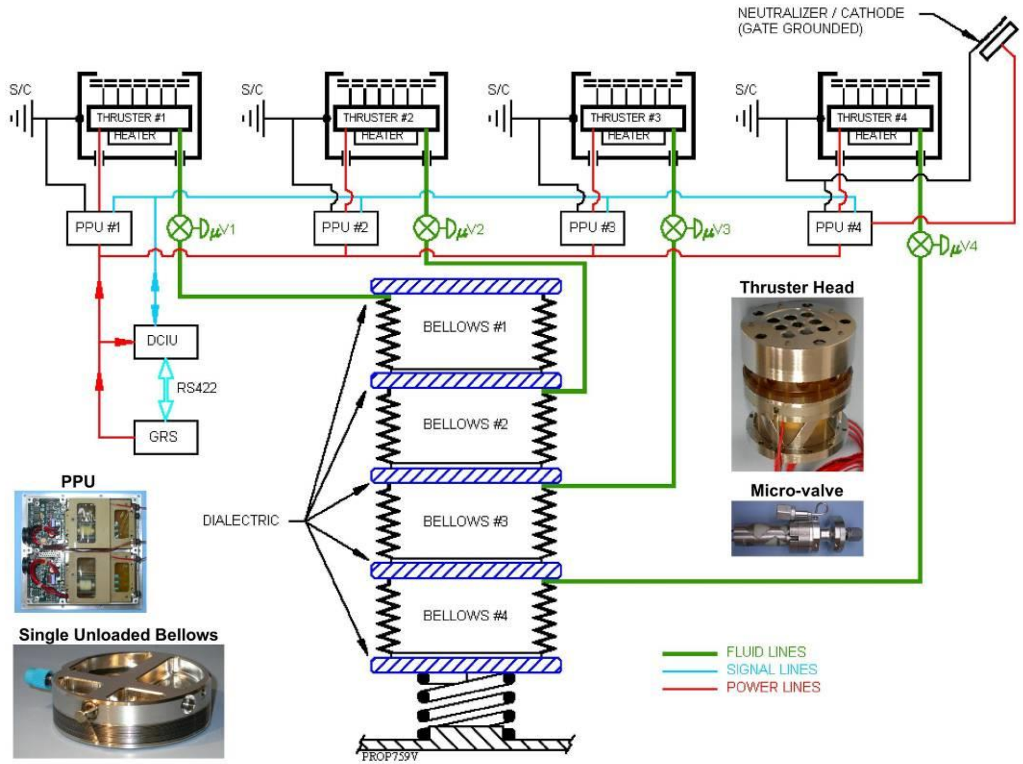
Scales in a Precision Colloid Thruster

- 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

ST7 Microthruster System Architecture

Cluster with 4 Thruster Systems





JPL
BUSEK

- **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)**

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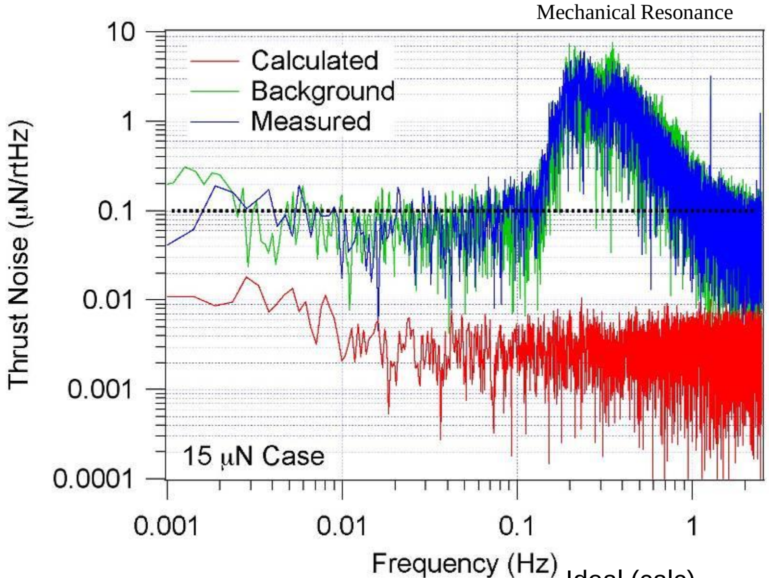
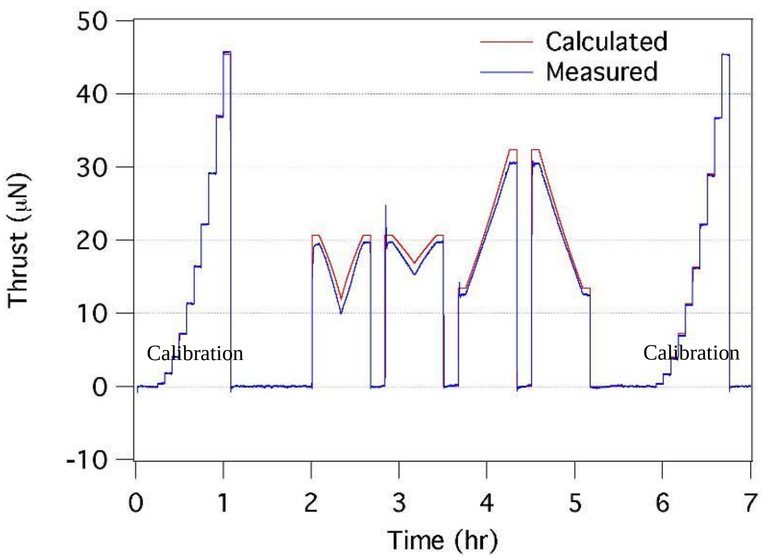
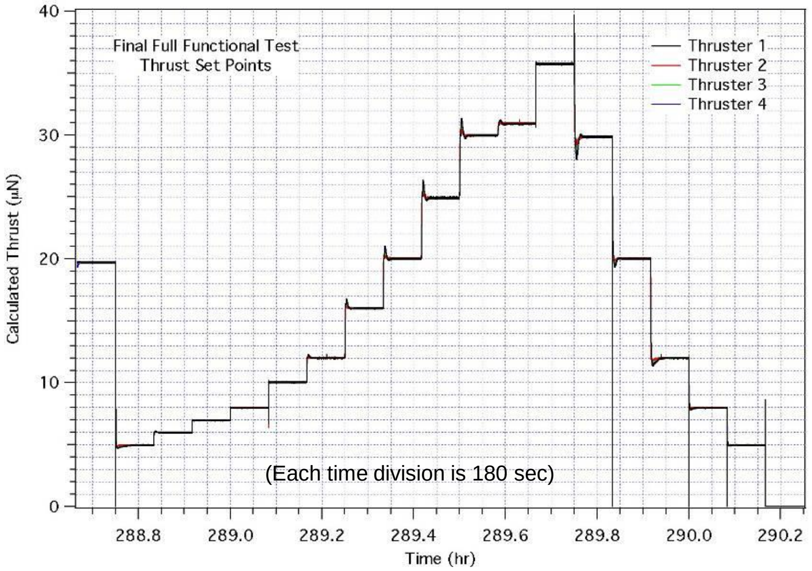
Thrust Stand Measurements Complete

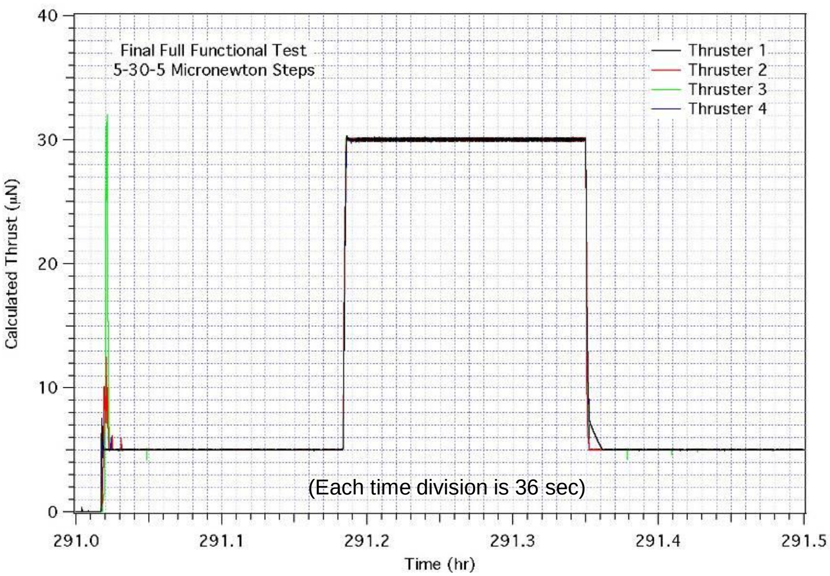




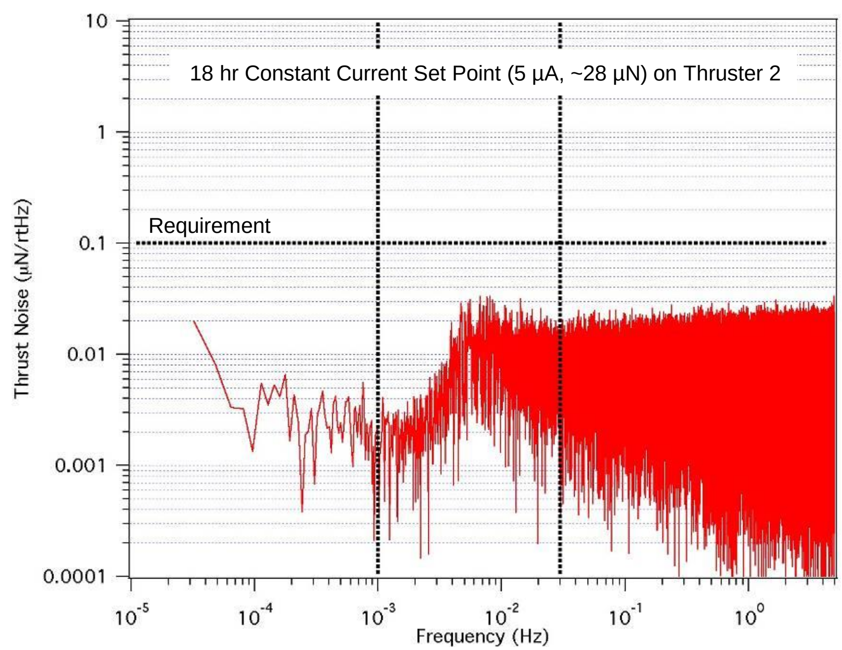
- **Colloid thruster resolution and thrust noise now verified by direct measurement**
- **Predicted thrust relation matches well to measured data**
- **Busek's magnetically levitated thrust stand has remarkable resolution and background noise characteristics**
  - **<0.1 µN resolution, ~0.1µN/√Hz equivalent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

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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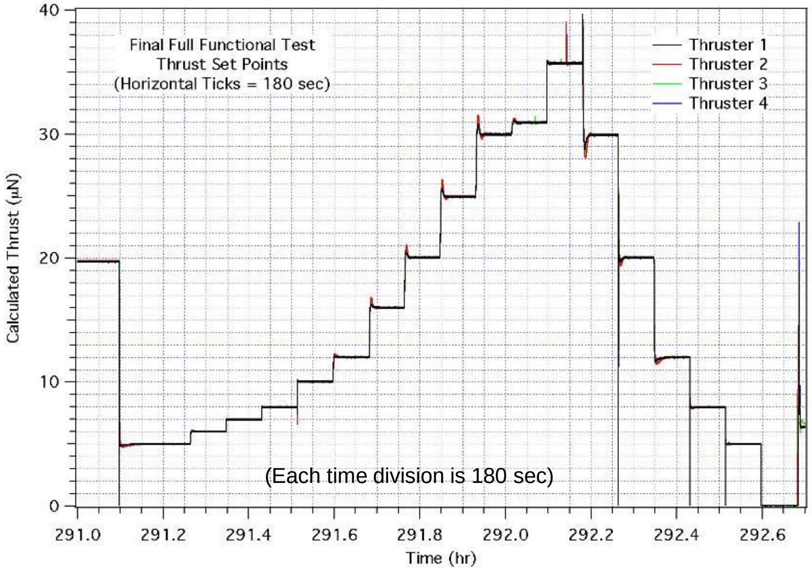
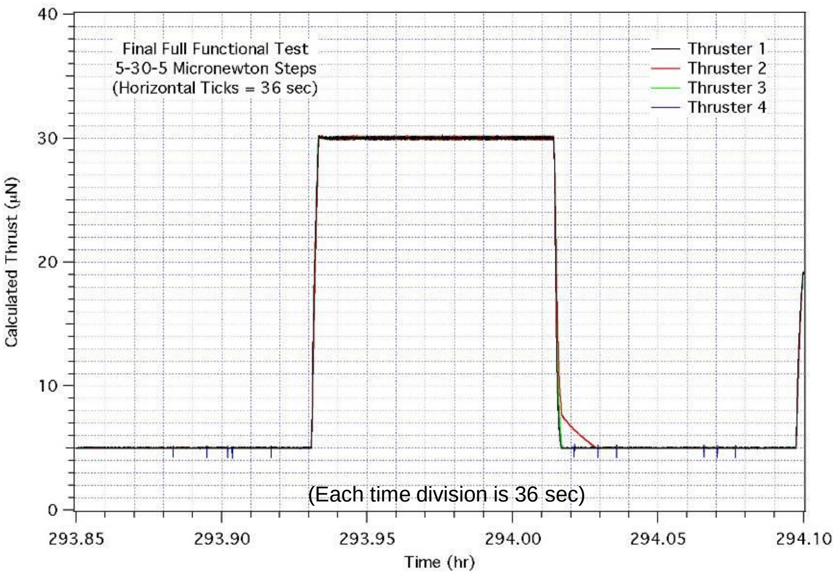
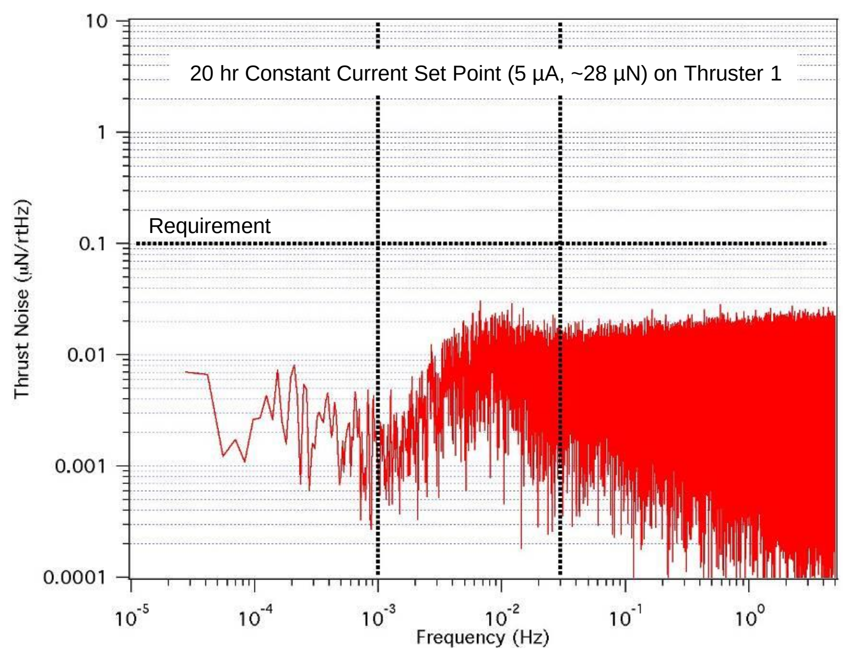
Cluster 2: Passed Full Functional Test





- 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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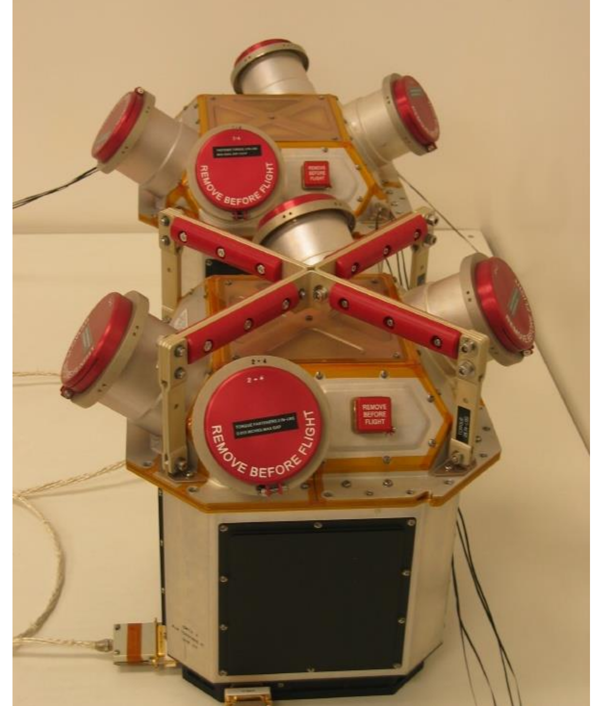
Both Flight Clusters Delivered to JPL

- 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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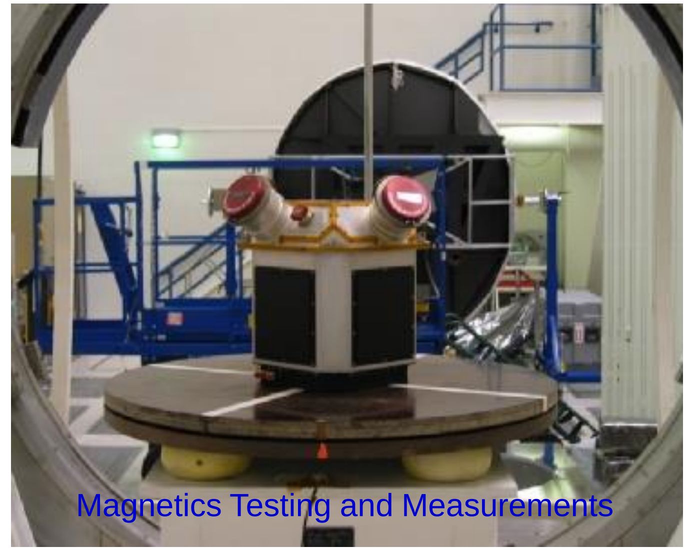
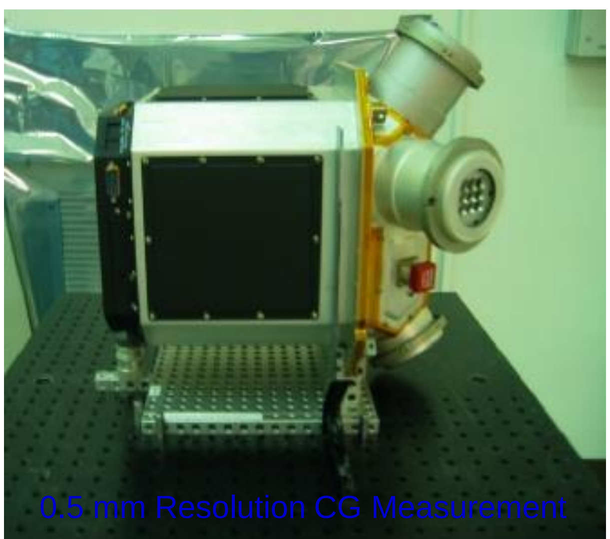
I&T Activities at JPL

Safe-to-Mate and IAU Integration



Magnetics Testing and Measurements



0.5 mm Resolution CG Measurement

EMI/EMC Testing and Measurements with IAU

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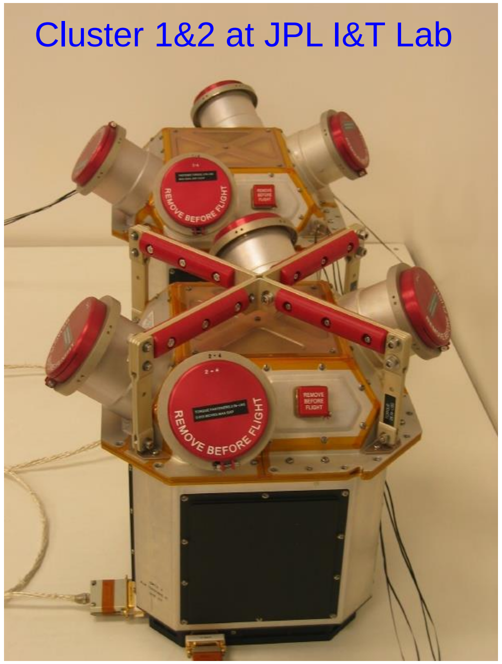
Both Flight Clusters Delivered to JPL and ESA

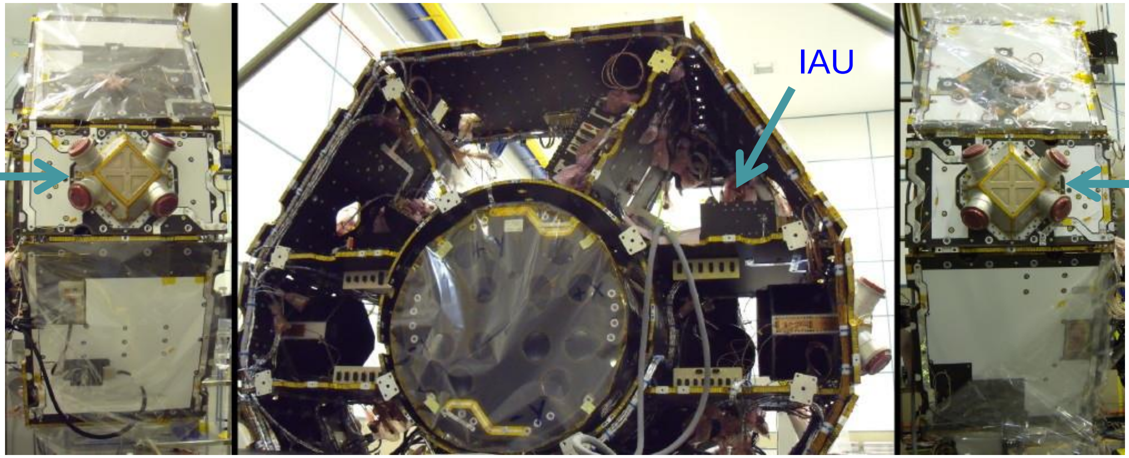
Cluster 1&2 at JPL I&T Lab



- 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 any future Gravity Wave Observatory:

Demonstrate thruster lifetime

LISA Pathfinder Spacecraft



Additional Activities Post-Delivery to ESA (Pre-Launch)

- Ran DRS full functional test (thrusters on and disabled) through S/C and ESA ground data system multiple times
- Passed through S/C-level environmental tests (vibration and thermal vacuum)
- Passed multiple, periodic leak-checks on all flight thruster heads at Astrium – no leaks for 8 years!
- Completed long-duration materials testing to certify shelf-life for late 2015 launch
- Passed polarity check with thrusters enabled to 2 kV
- Installed thermal blankets on both clusters
- Worked well with ESA / Airbus team

LISA Pathfinder Commissioning
All DRS Success Criteria Passed

- ✓ IAU Check-out
- ✓ Thruster Power Cycle
- ✓ Thruster Impedance Test
- ✓ Thruster Start-up
- ✓ Bubble Dissipation
- ✓ Thruster Full Functional Test (all 8 thrusters)
- ✓ A / B Side Power Check-Out
- ✓ ESA Thrust Command Mode Demonstration
- ✓ Thruster Safe Shutdown
- ✓ A / B Side Communications Check-Out

Notes:

- Thruster 1 still has a bubble in the feed system, but it is small enough for us to pass thruster response time tests
- Cathode test was not part of our success criteria, but we will retry in June

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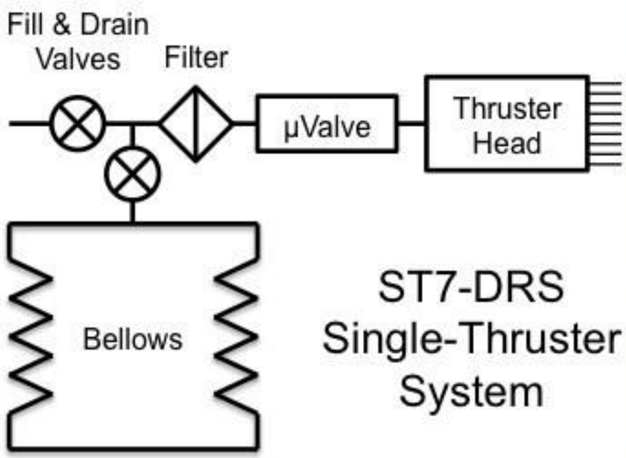
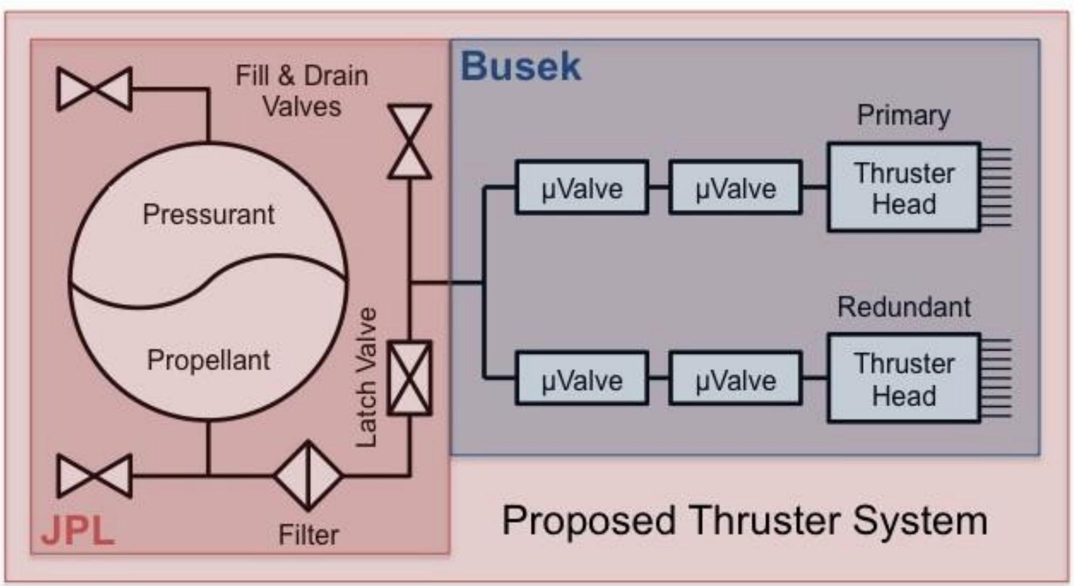
PCOS SAT Task: Colloid Thruster Feed System Development





- **The ST7-DRS propellant feed system includes**
  - **Bellows tank, 100 mL**
  - **Spring pressurized**
  - **Microvalve flow control**
- **Issues:**
  - **Not enough capacity for GWO or eLISA**
  - **Heavy (scaled bellows)**
  - **Microvalve manufacturing**
  - **Single string**
- **Solutions:**
  - **Spherical blow-down tank**
  - **New microvalve (Busek)**
  - **Dual string configuration**
- **Funded in FY13 – FY14**

Colloid Microthruster Propellant Feed System

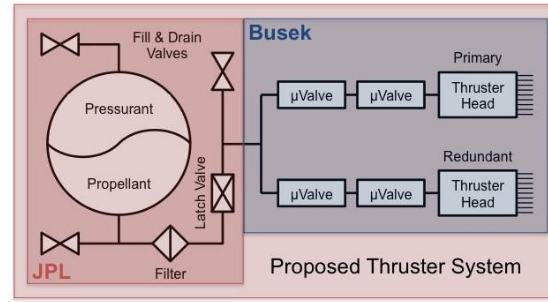
PI: John Ziemer/JPL

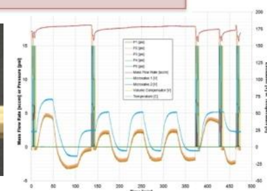
Objectives and Key Challenges:

- Replace the heavy (up to 15 kg) spring-loaded bellows design from ST7 with a light-weight pressurized diaphragm tank (≤1 kg)
  - O1: Design tank and feed system with full redundancy
  - O2: Design, fabricate, and test stainless steel diaphragm tank
- Use the new Busek Microvalve (Phase II SBIR and Phase IIe) to reduce complexity while providing redundancy
  - O3: Design, fabricate, and test new Busek Microvalves
  - O4: Integrate and test feed system components to TRL 5

Significance of the Work:

- A new, flight-like, fully redundant, higher capacity colloid thruster feed system at TRL 5 can support any gravity wave observatory concept
- A clear path to TRL 6 once the mission and system are defined





Approach:

- Teaming arrangement between flight tank vendor Keystone, Busek for the Microvalve, and JPL to manage, perform I&T
- Use standard liquid-fed propulsion flight design guidelines and practices – the new technology is in the assembled pieces working together, not the propulsion engineering approach
- Four tasks related to each objective, plus a management task, each with a JPL expert lead
- Hold peer reviews at each meaningful milestone: requirements definition, design, and test

Key Collaborators:

- Busek Co., Inc. on Microvalve and systems engineering
- Keystone Engineering on flight-like tank manufacture and test
- JPL electric / chemical propulsion and flight propulsion groups

Development Period:

- Jan 2013 – Jan 2015

Accomplishments and Next Milestones:

- Tank fabrication and TRL 5 tests are complete
- Microvalve fabrication and environmental tests are complete
- Redundant Microvalve subassembly including accumulator and volume compensator has been fabricated and tested for TRL 5
- Complete feed system has been integrated and tested in a relevant, laboratory environment to reach TRL 5
- Integrated tests spanned expected beginning to end of life operating conditions, including testing redundant configuration

Application:

- Drag-free gravity wave observatories
- Remove reaction wheels - precision pointing of exo-planet observatory and next generation space telescopes
- Small spacecraft main propulsion

TRLin = ***3-4*** *TRLcurrent* = ***5*** *TRLtarget* = ***5***

Previous LISA Work

- Focused on developing Lifetime models
  - Based on multiple single-emitter 3000 hour and accelerated tests
  - Studied primary failure mode: propellant deposition on electrodes
  - Model suggests 40,000 hour lifetime for ST7 thruster head as is
    - Largest uncertainty comes from transient events and passing bubbles
    - Requires longer term test with full thruster head for validation
    - Modeling suggested improvements that could reduce propellant deposition nearly in half by small changes in electrode geometry (electrode capacity for propellant deposition could also be improved)
- Even older LISA work compared various options
  - FEEP, PPT, Laser Ablation, miniature ion, cold gas, etc.
  - If useful, this would need to be updated
  - No other option that can meet performance requirements, besides cold gas, is as mature as colloid thrusters

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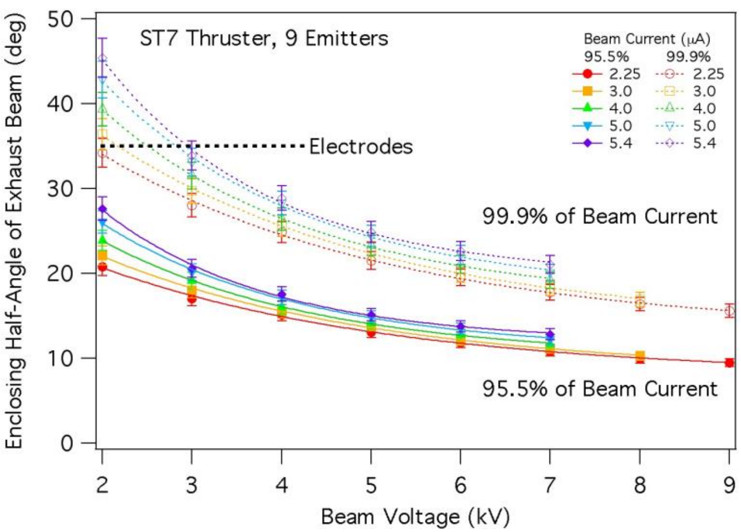
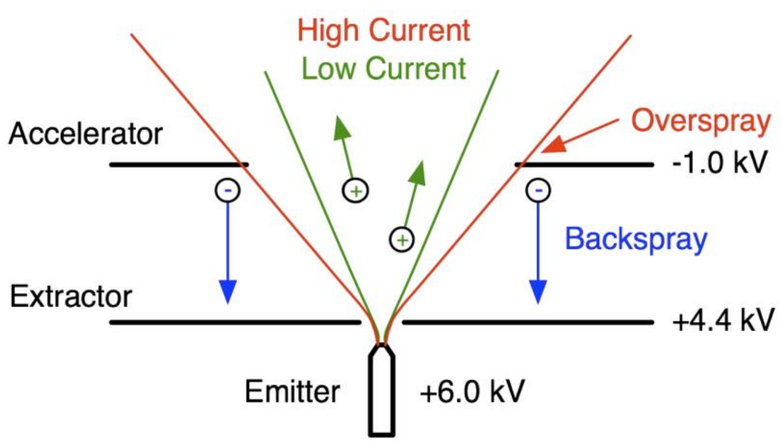
Lifetime of Colloid Microthrusters

- **ST7 and LISA projects have worked to determine, understand, predict, and correct lifetime limiting failure modes**
- **Key Lifetime Issues**
  - **Bubbles in the feed system restrict propellant flow and produce "overspray"**
    - **Prevention of bubbles from forming (propellant purity and system cleanliness)**
    - **Removal of any bubbles that form through "bubble eliminator" device**
    - **Use of proper start-up procedure to reduce likelihood and duration of bubbles**
  - **Overspray of propellant onto extractor and accelerator electrodes**
    - **New electrode geometry and materials to reduce overspray and reduce its impact**
    - **Optimization of extractor electrode design to further reduce/eliminate overspray**
    - **Special electrodes designed to handle a "lifetimes" worth of overspray without failure**





BACKGROUND MATERIAL

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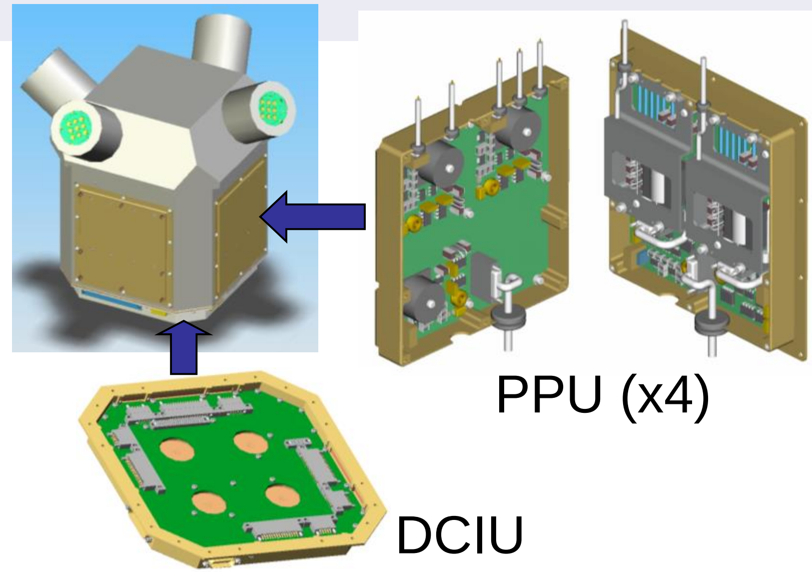
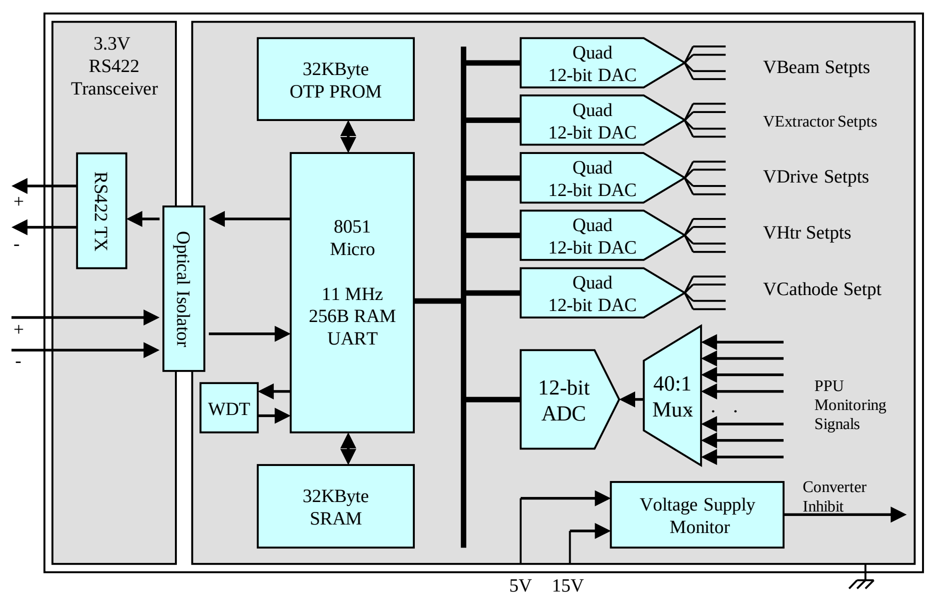
Microthruster Electronics

- Flight electronics provided by Assurance Technology Corp. (ATC)
- PPU (4 PPUs per cluster)
  - Currently second generation breadboard model built and tested, EM designed and in fabrication
  - PPU contains beam and extractor HV converters, accelerator and cathode supplies, and the micro-valve driver
- DCIU (1 DCIU per cluster)
  - Currently second generation breadboard model built and tested, EM designed and in fabrication
  - ADC Input Channels: 40 x 0-5 V 12 bit monitor channels
  - DAC Output Channels: 20 x 0-10 V 12 bit control channels
  - Communications: Digital to IAU, Analog to PPU





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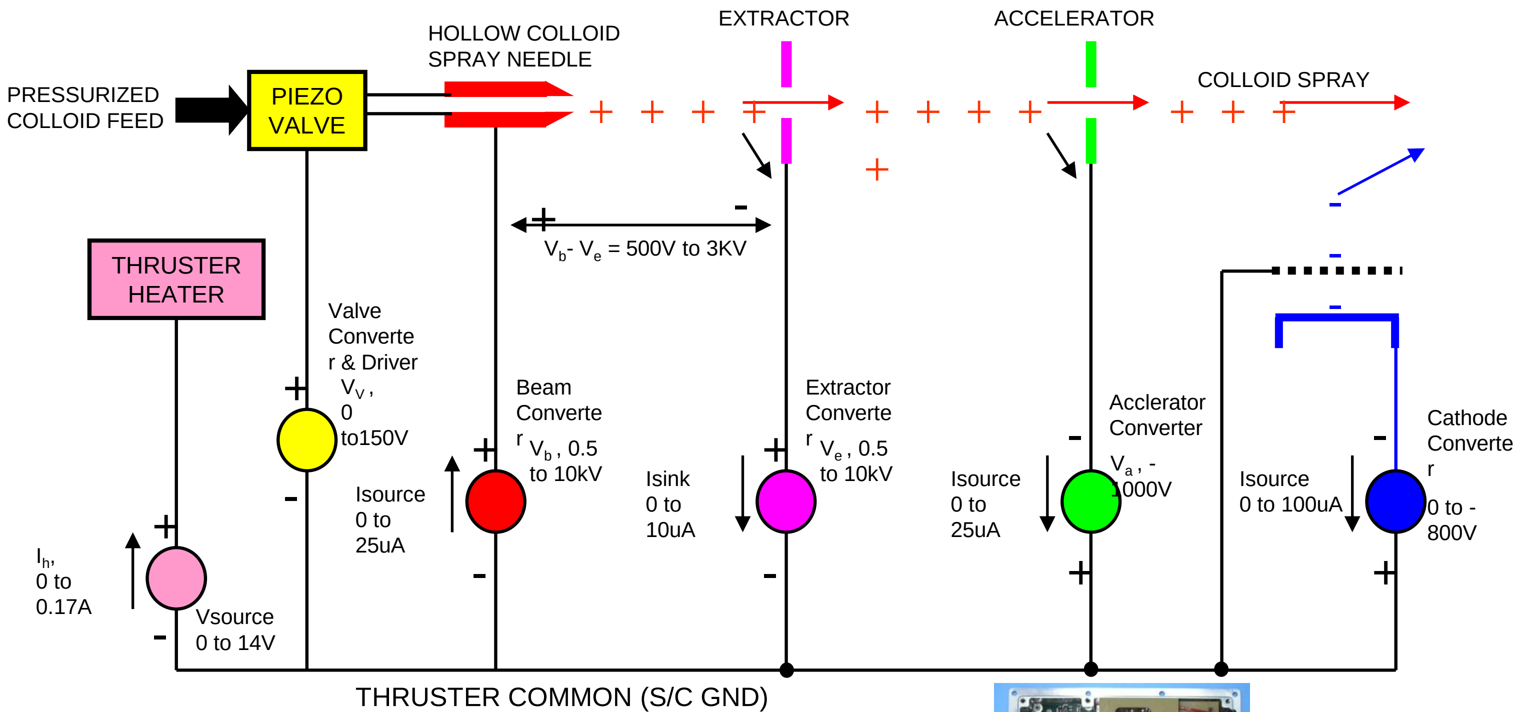
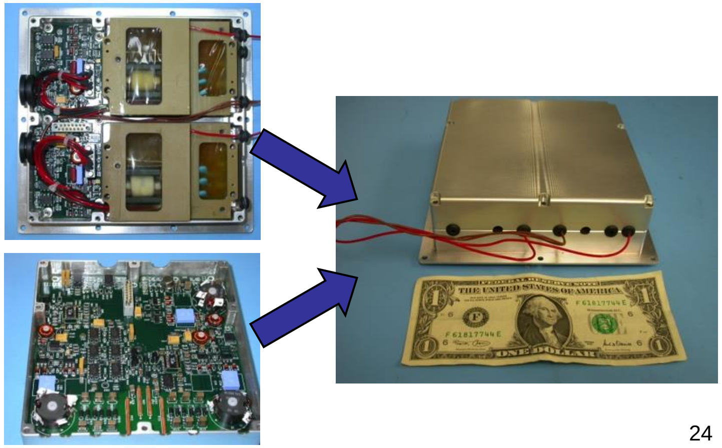
Thruster Power Processing Unit Schematic



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)**

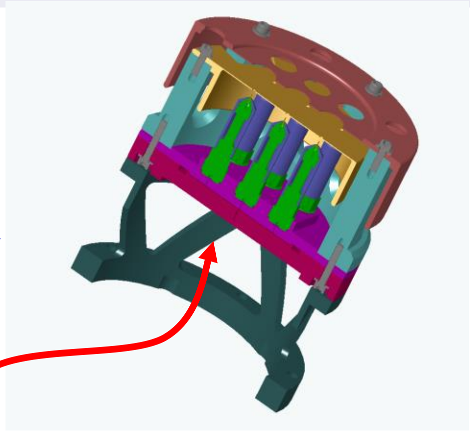


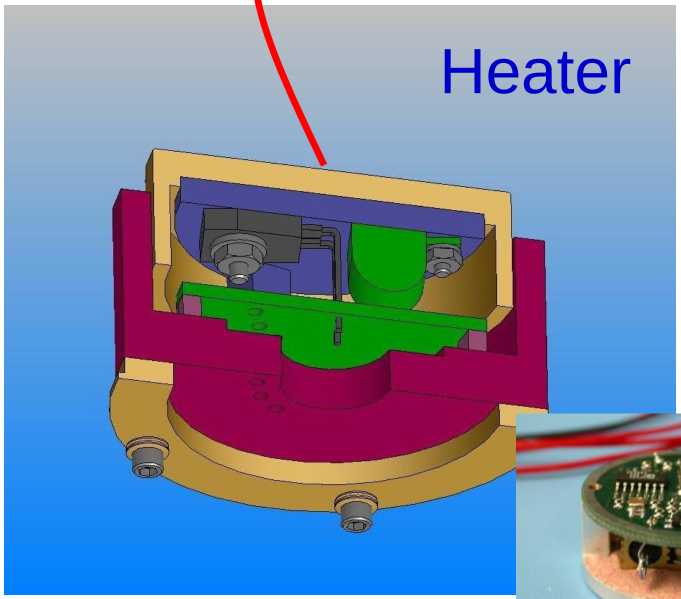
Thruster Heater Design

- **<u>ST7-DRS Requirements:</u>**
  - **-15ºC to 50ºC non-operational temperatures**
  - **10ºC to 30ºC operational temperatures**

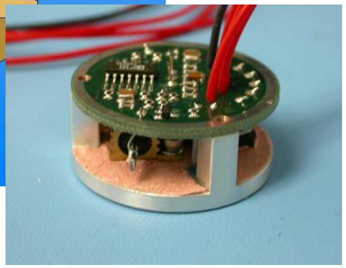
- Heater accelerates the transition from cold system off state and maintains constant temperature during operation
- P_{max} = 2.5 W, T_{max} = 50ºC
- Thermistor based feedback to DCIU that controls heater current
- Heater in thermal contact with thruster manifold, heating propellant and thruster
- Heater at ground potential, thruster at up to 10kV (< 1 nA leakage at 10 kV)
- Stable control demonstrated in vacuum
- Heat up rate at max power ~0.8ºC/min (25 min from –10 to +10C/min. off to min. on)

Thruster Head Assembly





Cross-sectional view of thruster heater



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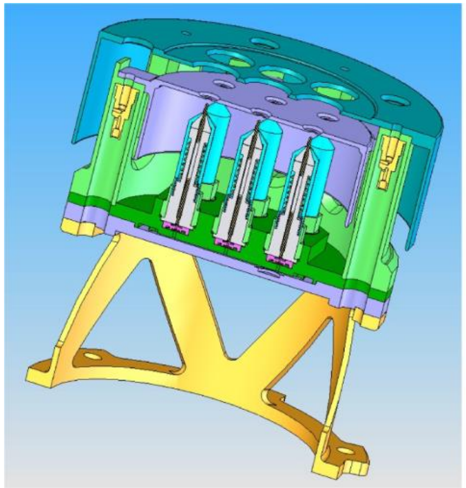
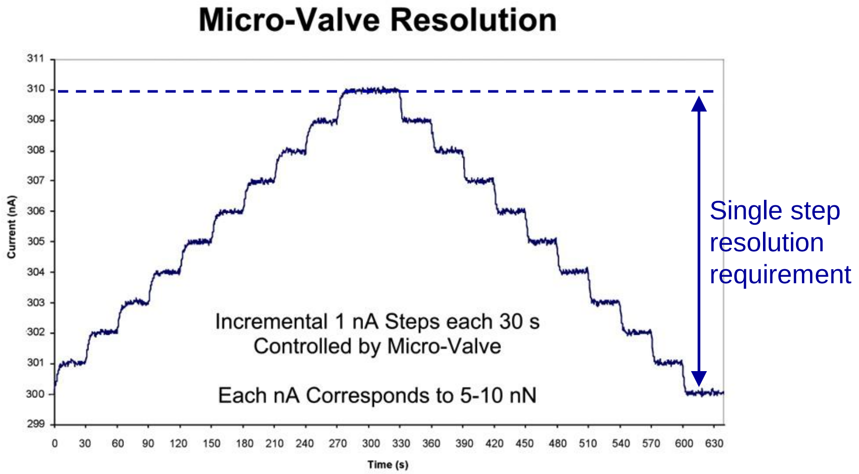
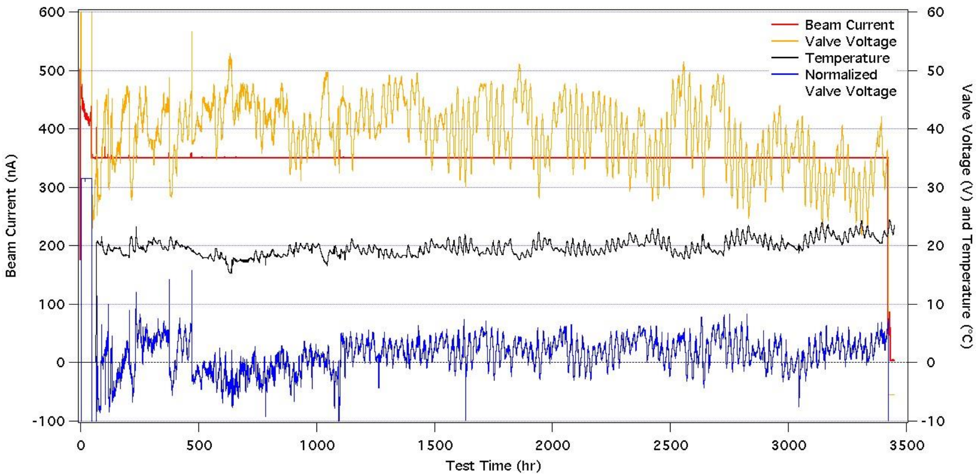
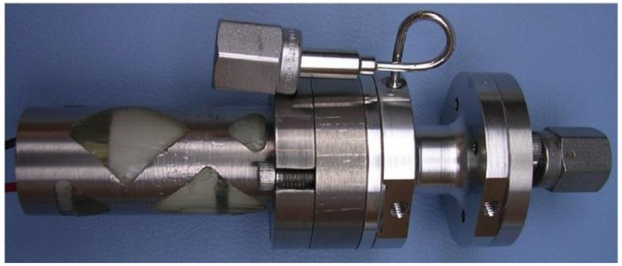
Thruster Head and Micro-Valve Performance



- **Thruster head and microvalve meet LISA performance requirements:**
  - **5-30 μN with < 0.1 μN resolution**
  - **< 0.1 $\mu N/\sqrt{Hz}$ thrust noise**







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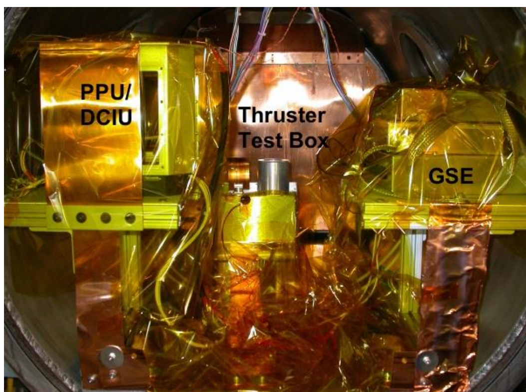
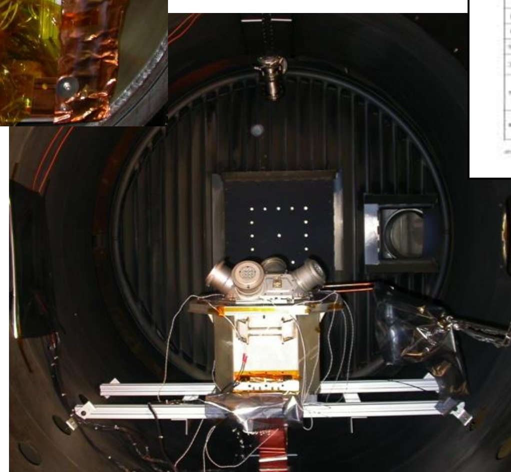
Requirements V&V

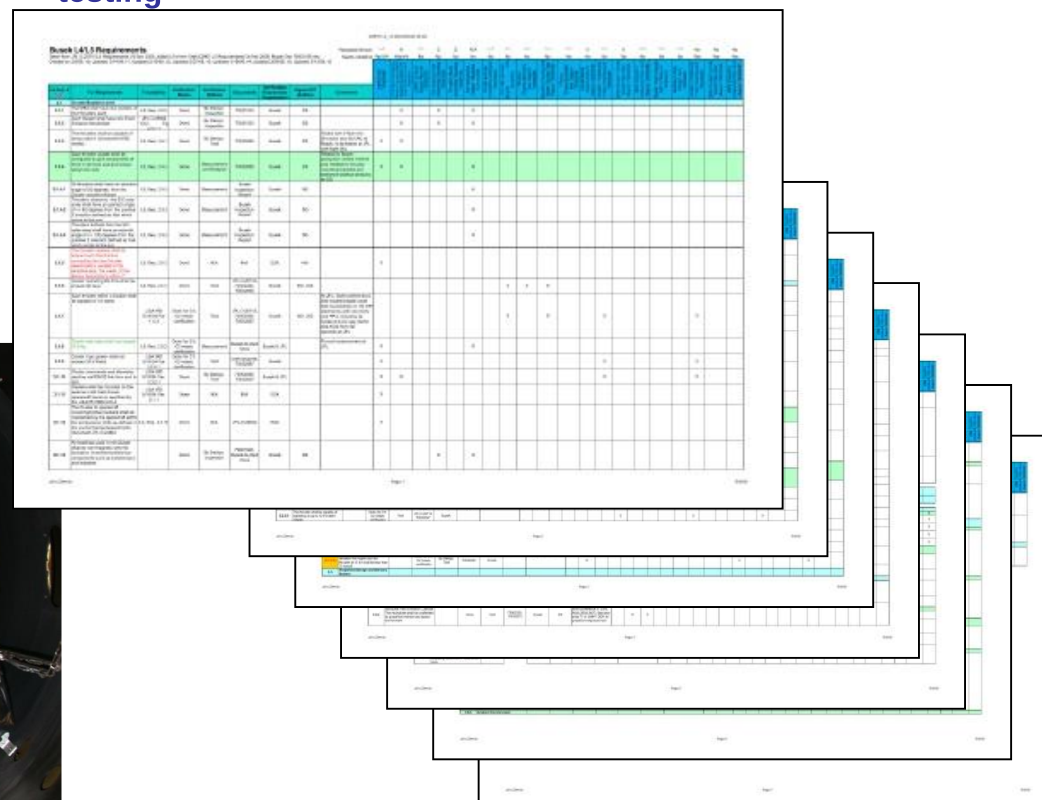
All requirements have been verified

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**







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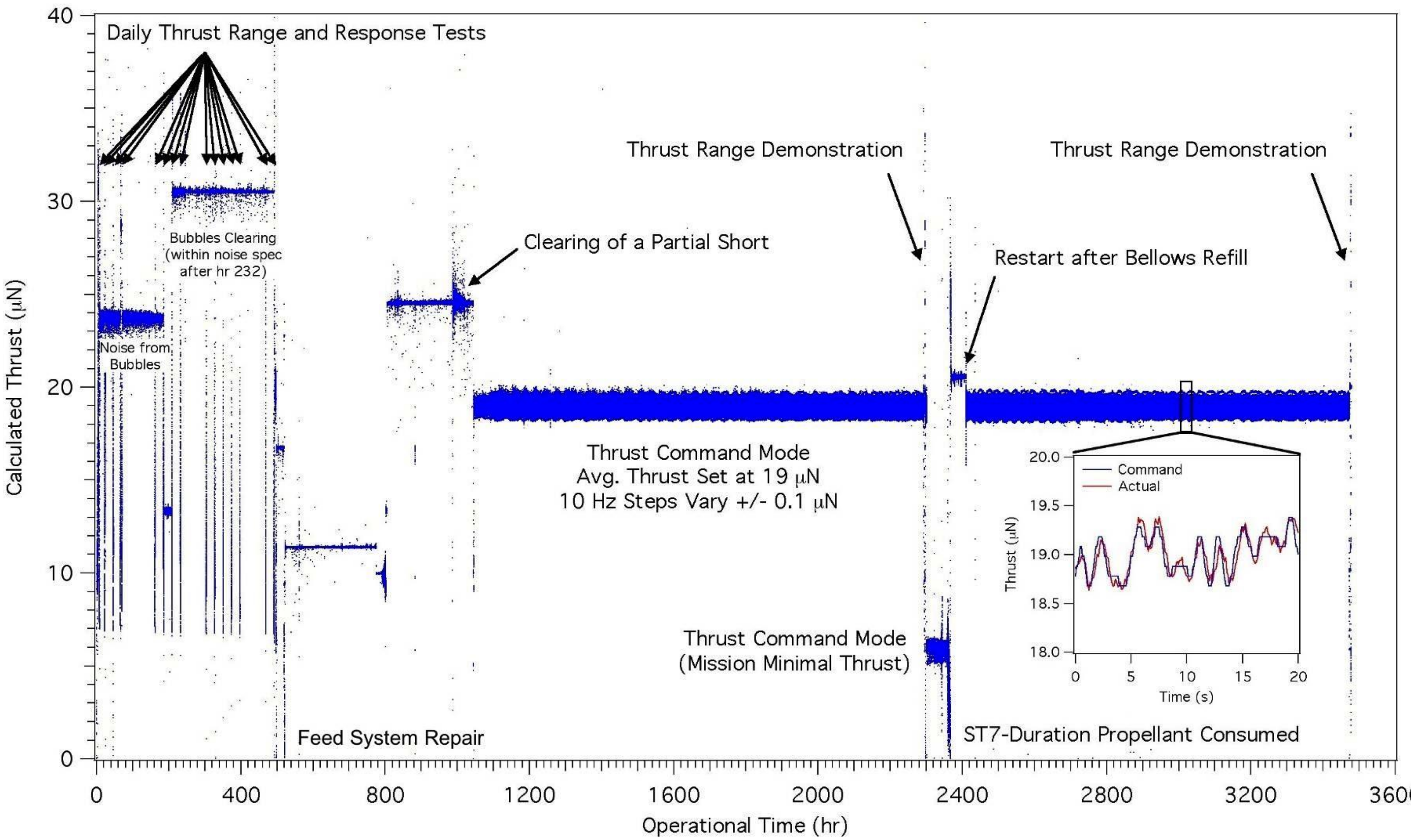
Formal Life Test of Colloid Microthruster



- **Requirements:** >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**

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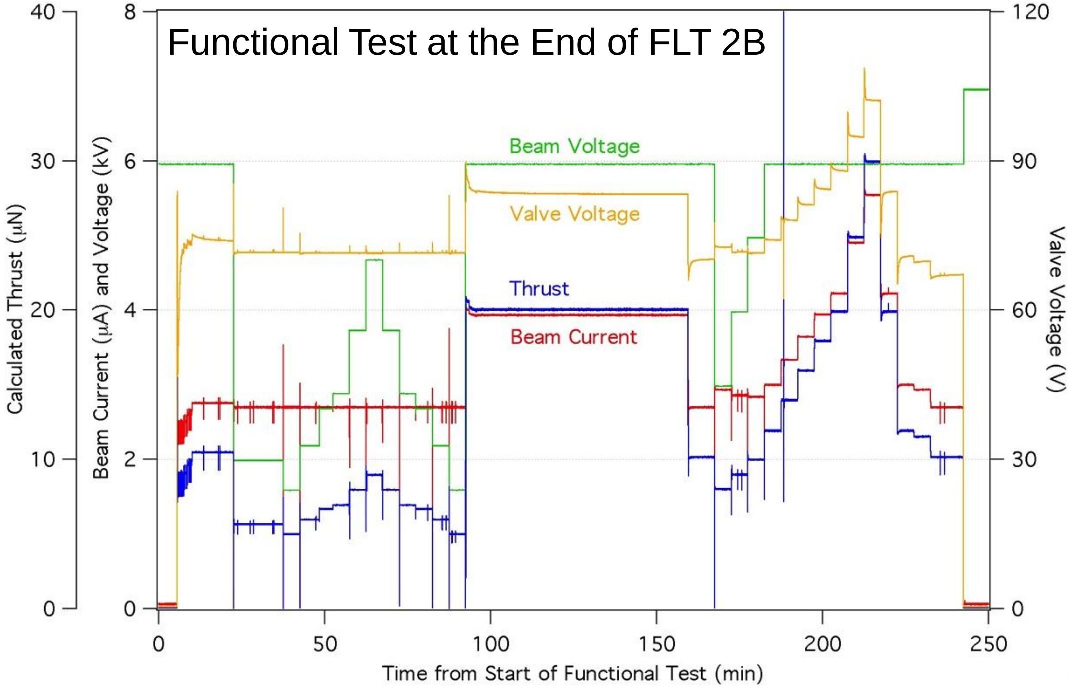
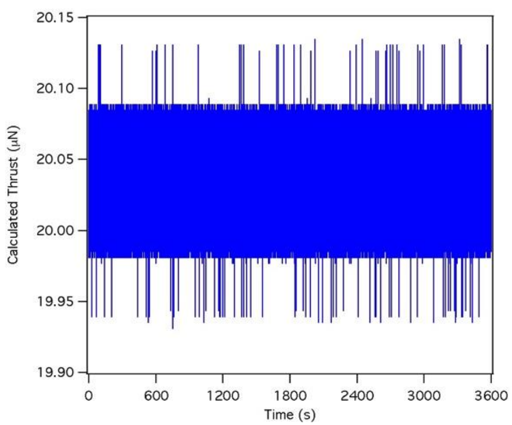
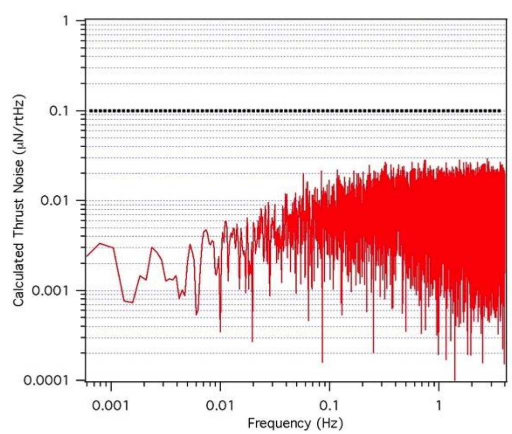
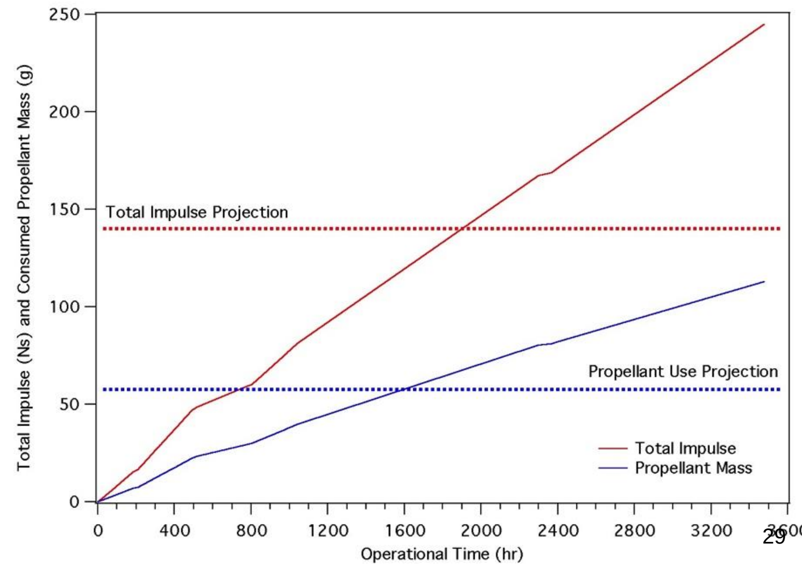
Performance of FLT 2B at EOT



- 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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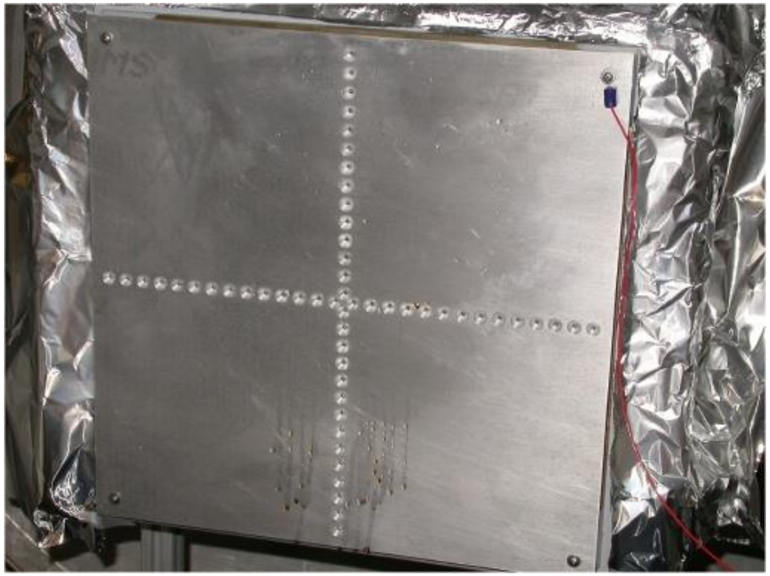
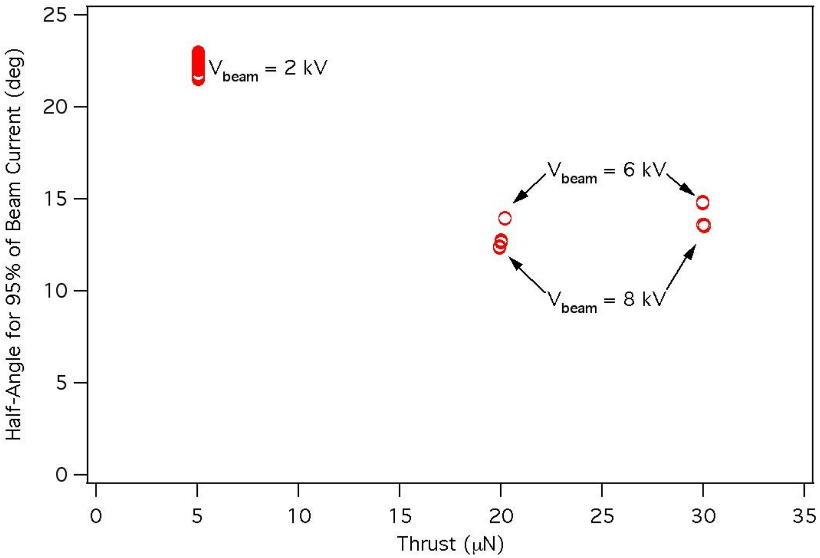
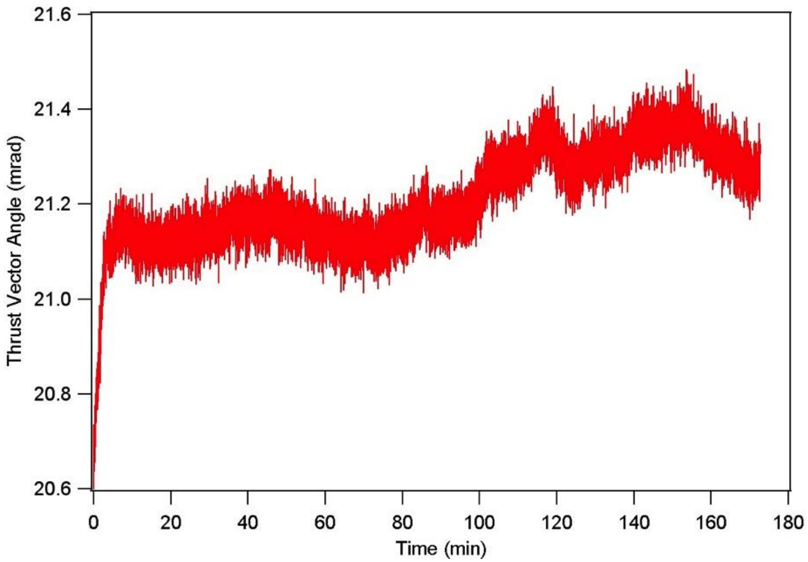
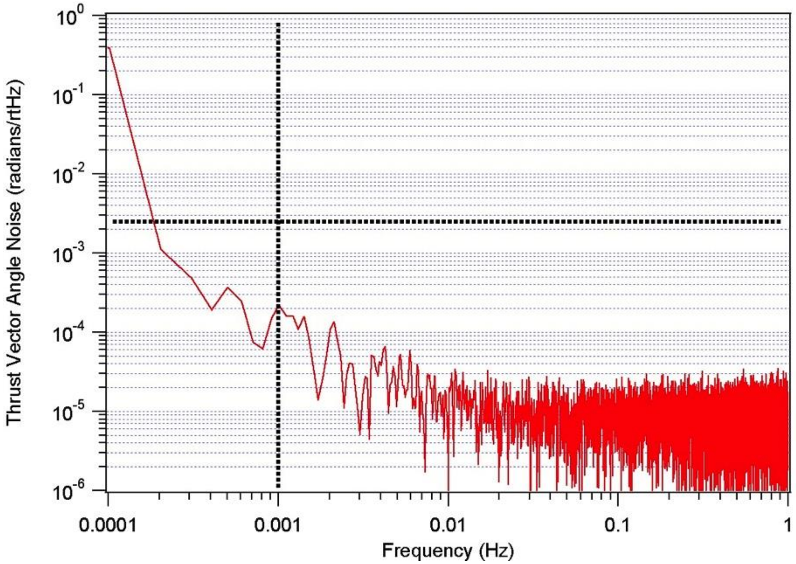
Exhaust Beam Profile and Stability









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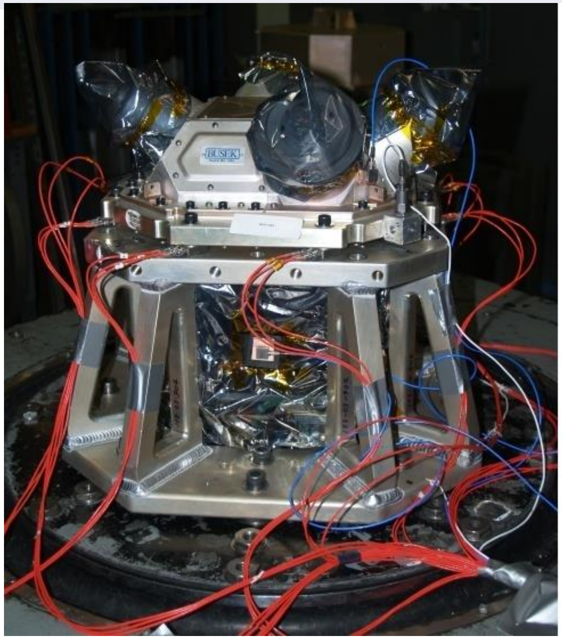
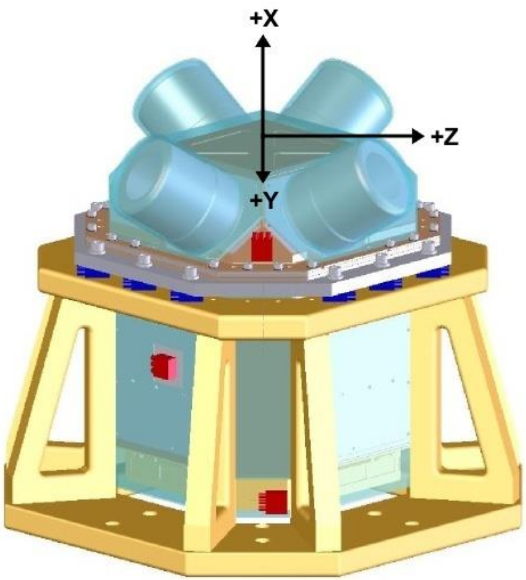
Dynamics Environmental Validation

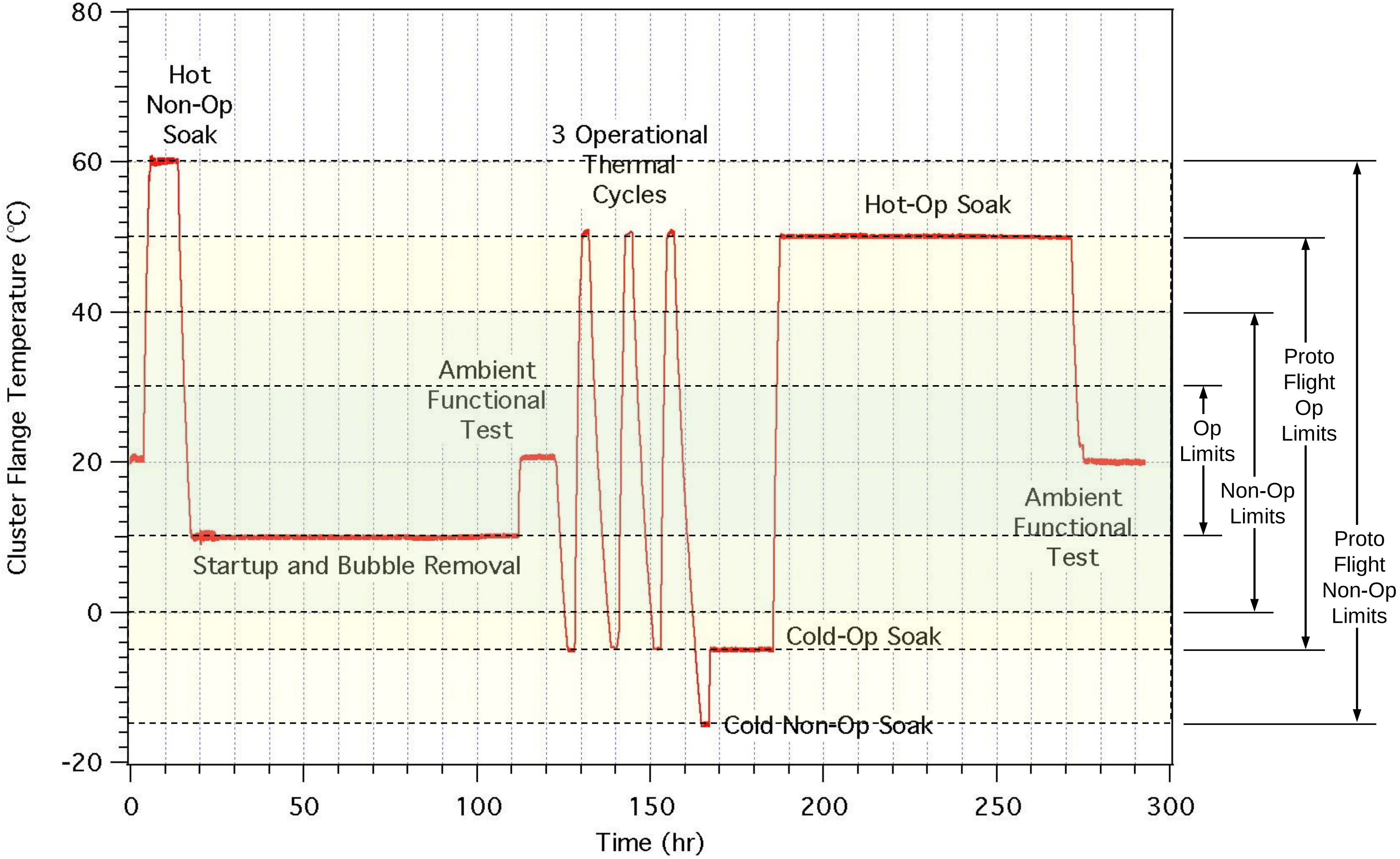




- Dynamics testing performed at the cluster level, preceded by some component-level and mock-up (mass equivalent with critical components) shock testing
- Sine, random, and quasi-static load testing was performed on both flight clusters
  - For sine load testing, Cluster 1 was tested to flight acceptance 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

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**

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 □N, T3/T4: 30 □N)**	**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