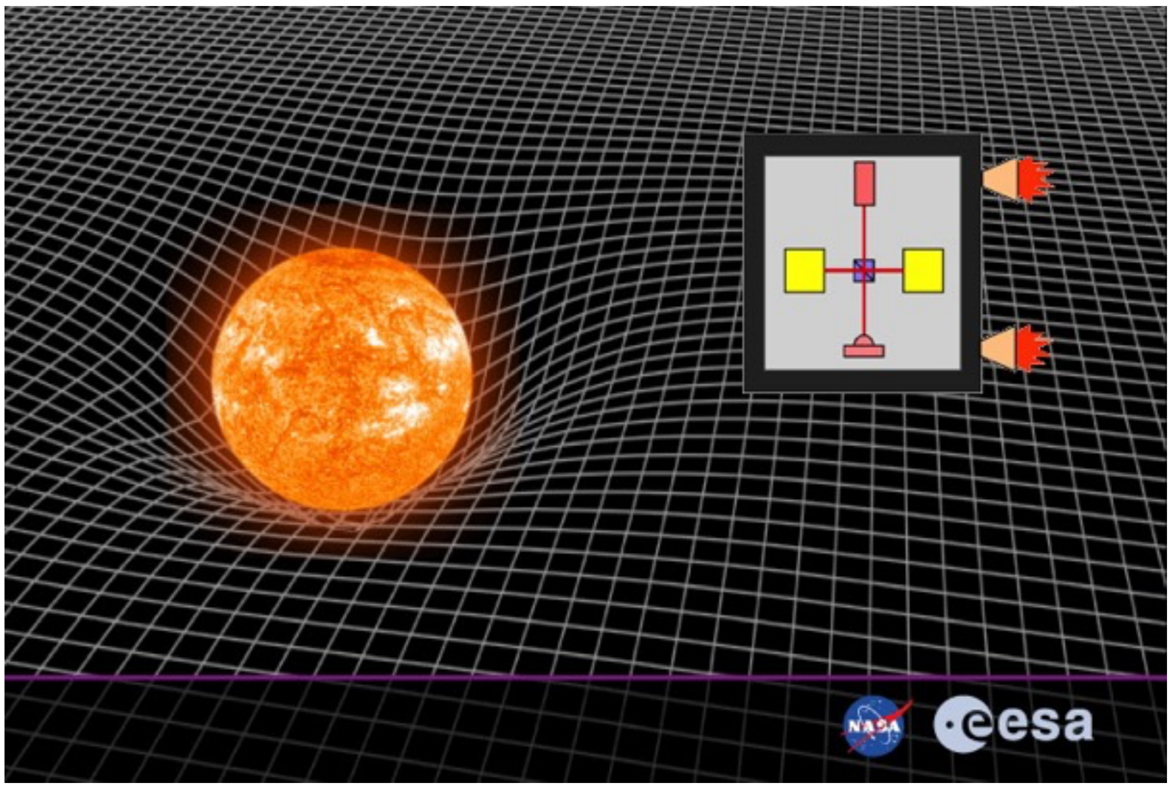
Overview of ST7-DRS Results

CURT CUTLER
Jet Propulsion Laboratory, California Institute of Technology

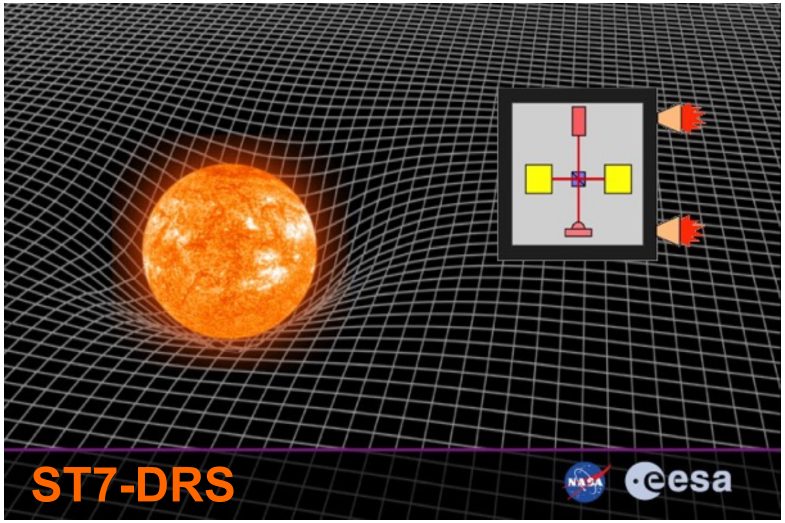


ST7-DRS Project Overview

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

Salient Features

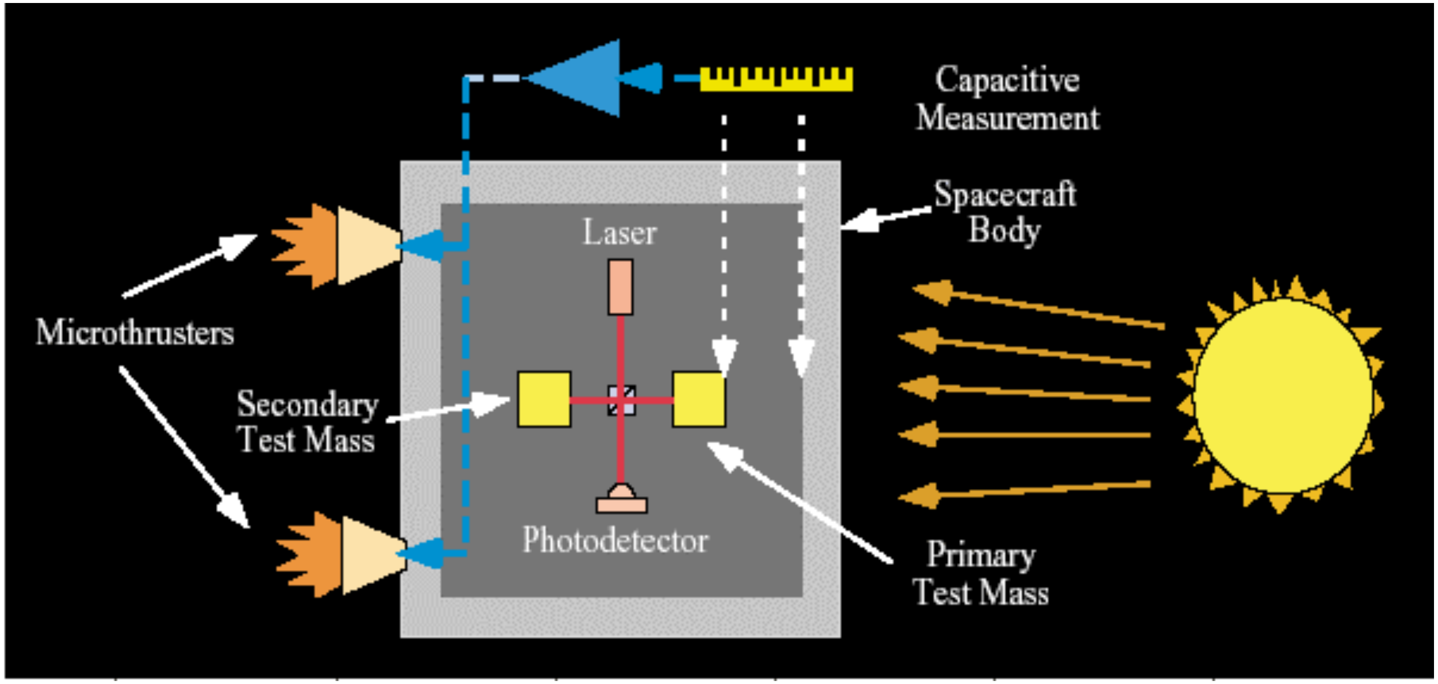
- Project Category: 3 Risk Class: C
- DRS flies on the ESA LISA Pathfinder spacecraft
- Sun-Earth L1 halo orbit
- Drag-free satellite to offset solar pressure
- Payload delivery: July 2009
- Launch date: December 2015
- Operational life: 60 days
- Data Analysis: 12 months



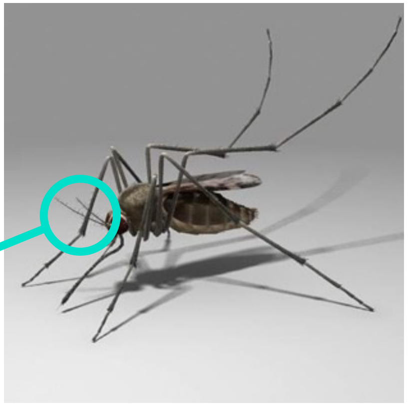
Technologies

- 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 inertial sensor, DRS will validate that a test mass follows trajectory determined by gravitational forces only within 3×10^{-14} $m/s^2/\sqrt{Hz}$ over frequency range 1 mHz to 30 mHz

Main S/C Disturbance: Solar Pressure



~ 0.1 μN



≈ 30 μN

Table of Key Dates

Event	Date	Event	Date
LPF Launch	03 Dec '15	Thruster-4 Anomaly	27 Oct '16
Transfer Phase Commissioning (10d)	02 Jan '16	Start:Hybrid Propulsion	29 Nov '16
Arrival at L1	22 Jan '16	End:Primary Mission	06 Dec '16
Experiment Phase Commissioning (10d)	27 Jun '16	Start:Extended Mission	20 Mar '17
Cluster-2 DCIU Anomaly	09 Jul '16	End:Extended Mission	30 Apr '17
Start:Primary Mission	15 Aug '16	Decommissioning Activities	13 Jul '17

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**

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**

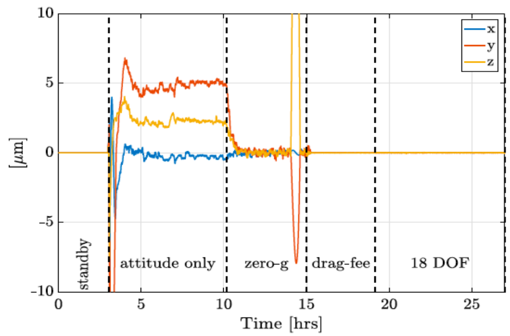
✓ 3. **DRS shall perform flight qualification of a Colloid Micro-Newton Thruster. DRS shall demonstrate a Colloid Micro-Newton Thruster in a space environment at any thrust level**
   - *Being a technology demonstration project, the majority of the challenge is to mature this technology to a point that 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**

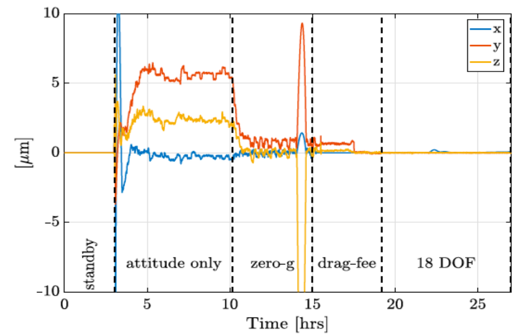
✓ **Minimum Mission Success: DRS shall deliver a flight qualified Colloid Micro-Newton Thruster, producing any measurable thrust on-orbit, verified through analysis of telemetry.**

DCS behavior during typical mode transition sequence from handover to the 18 DOF science mode.

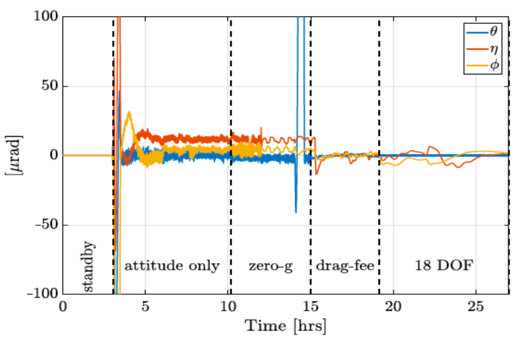
Plots show measured positions and angles of both the reference (RTM) and non-reference (NTM) test masses; angles of the spacecraft (S/C)



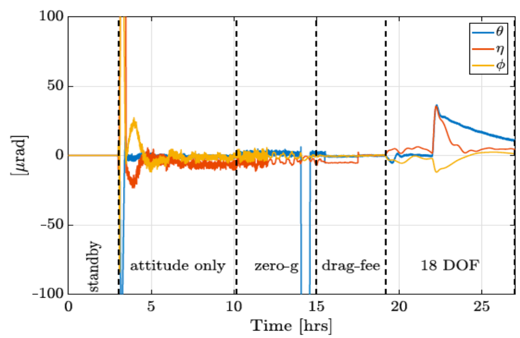
RTM positions



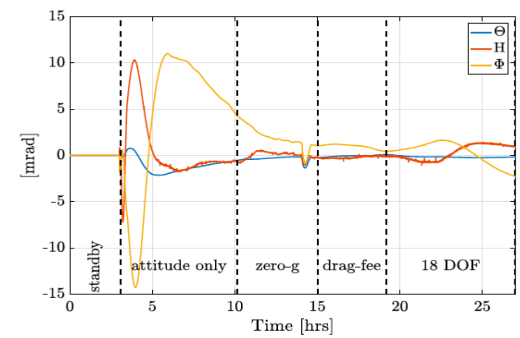
NTM positions



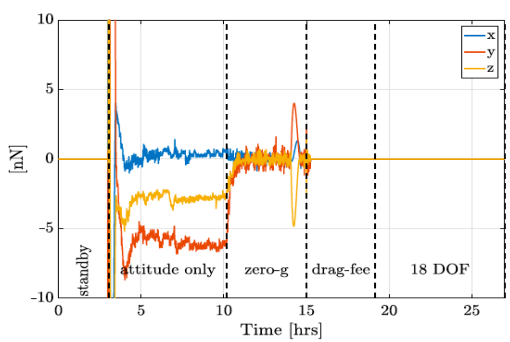
RTM angles



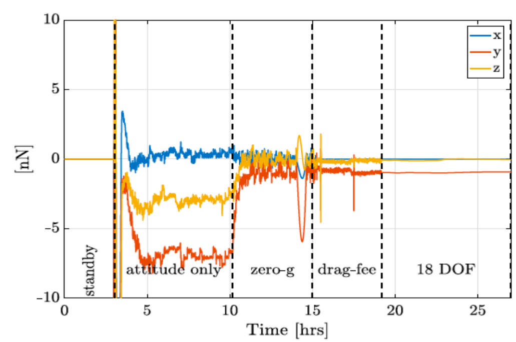
NTM angles



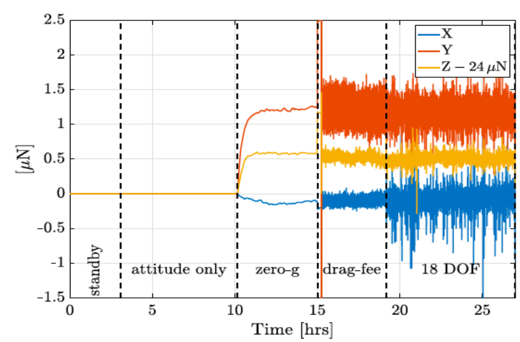
SC angles



RTM forces

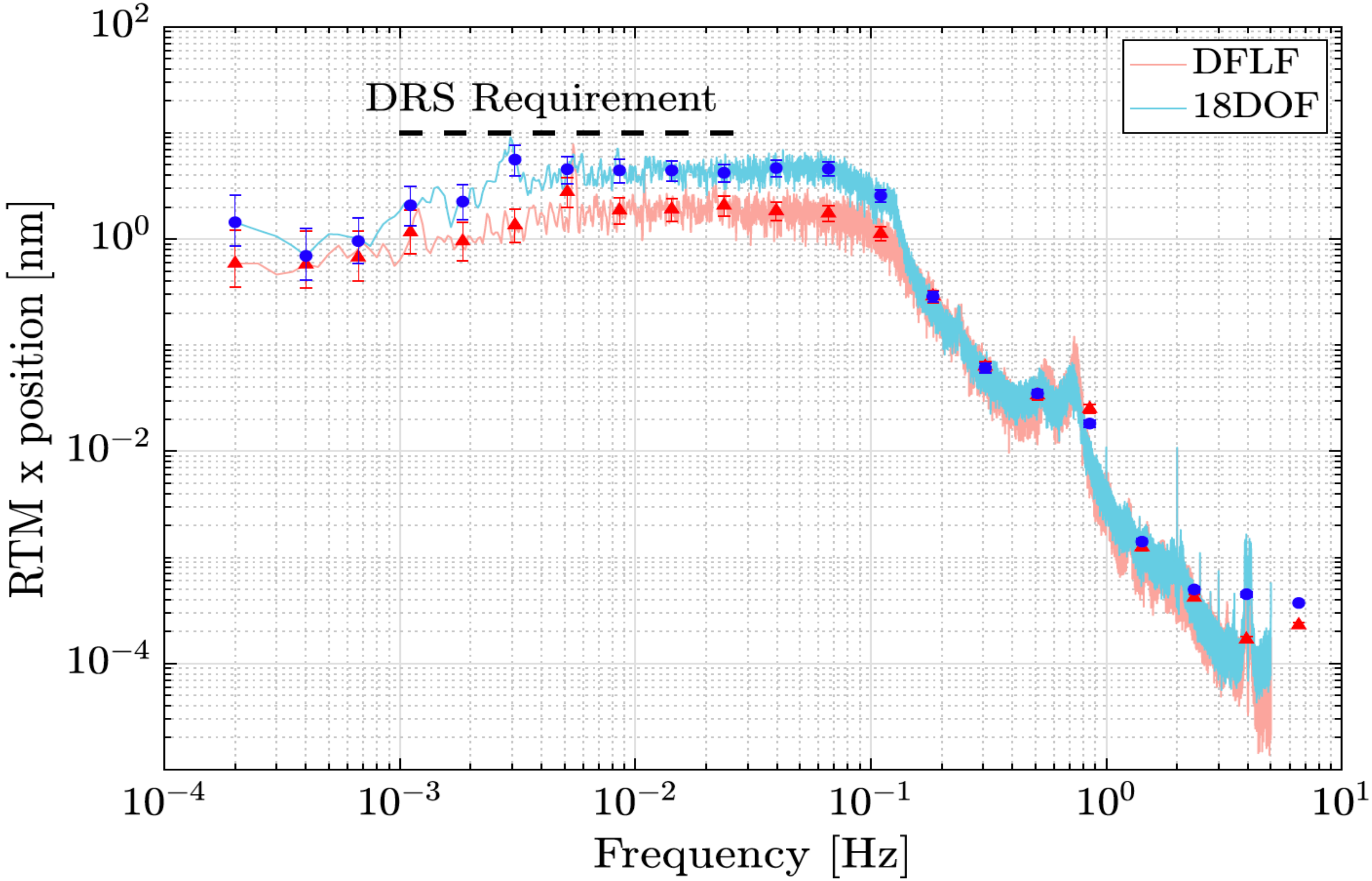


NTM forces



SC forces

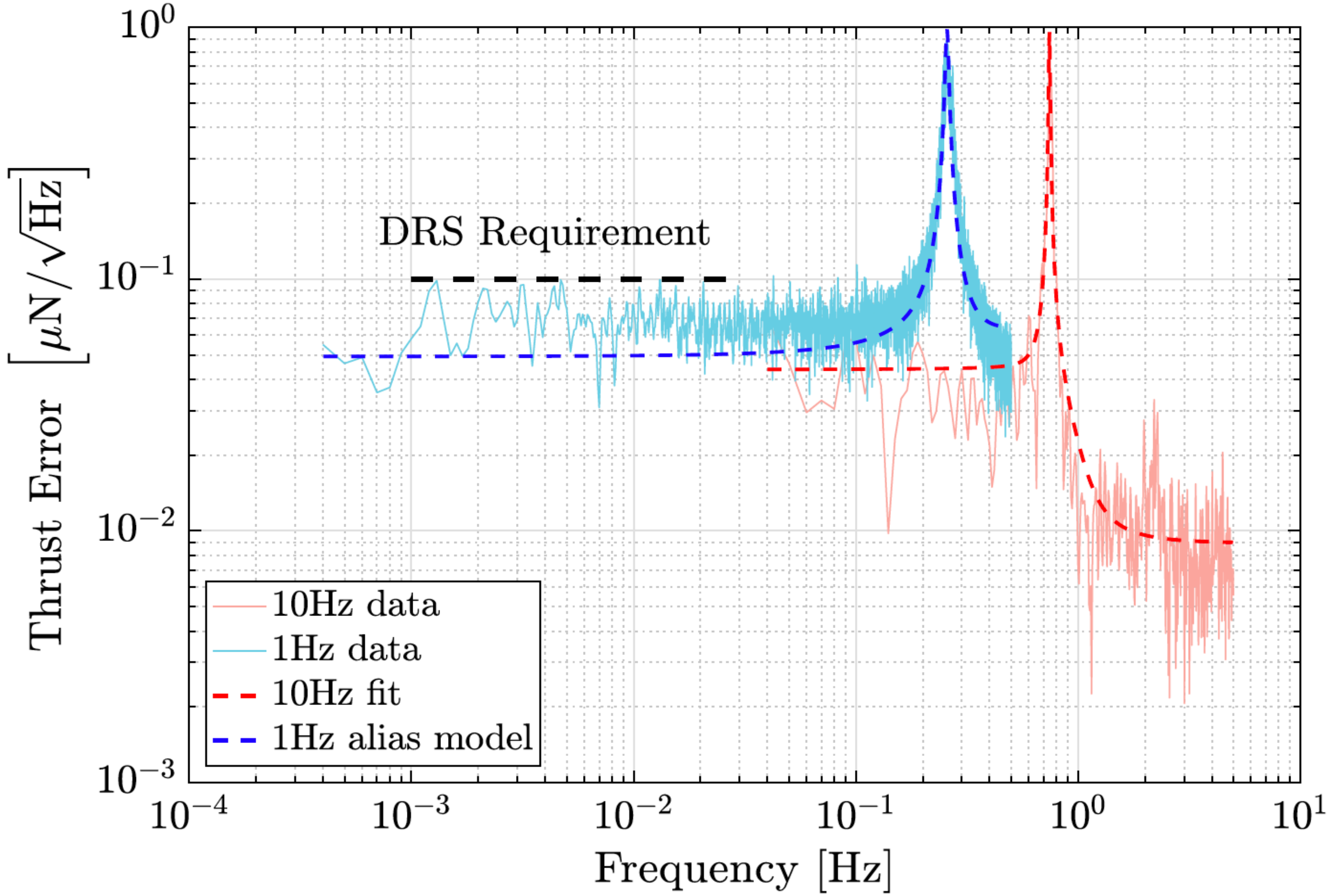
Demonstration of <10 nm/√Hz position stability



Amplitude spectral density of the measured RTM S/C position along the x-direction for a 20.7 hr run in the drag-free low-force (DFLF, red) mode beginning on 2016-08-22 and a 31.1 hr run in the 18 degree-of-freedom (18DOF, blue) mode beginning on 2016-10-22.

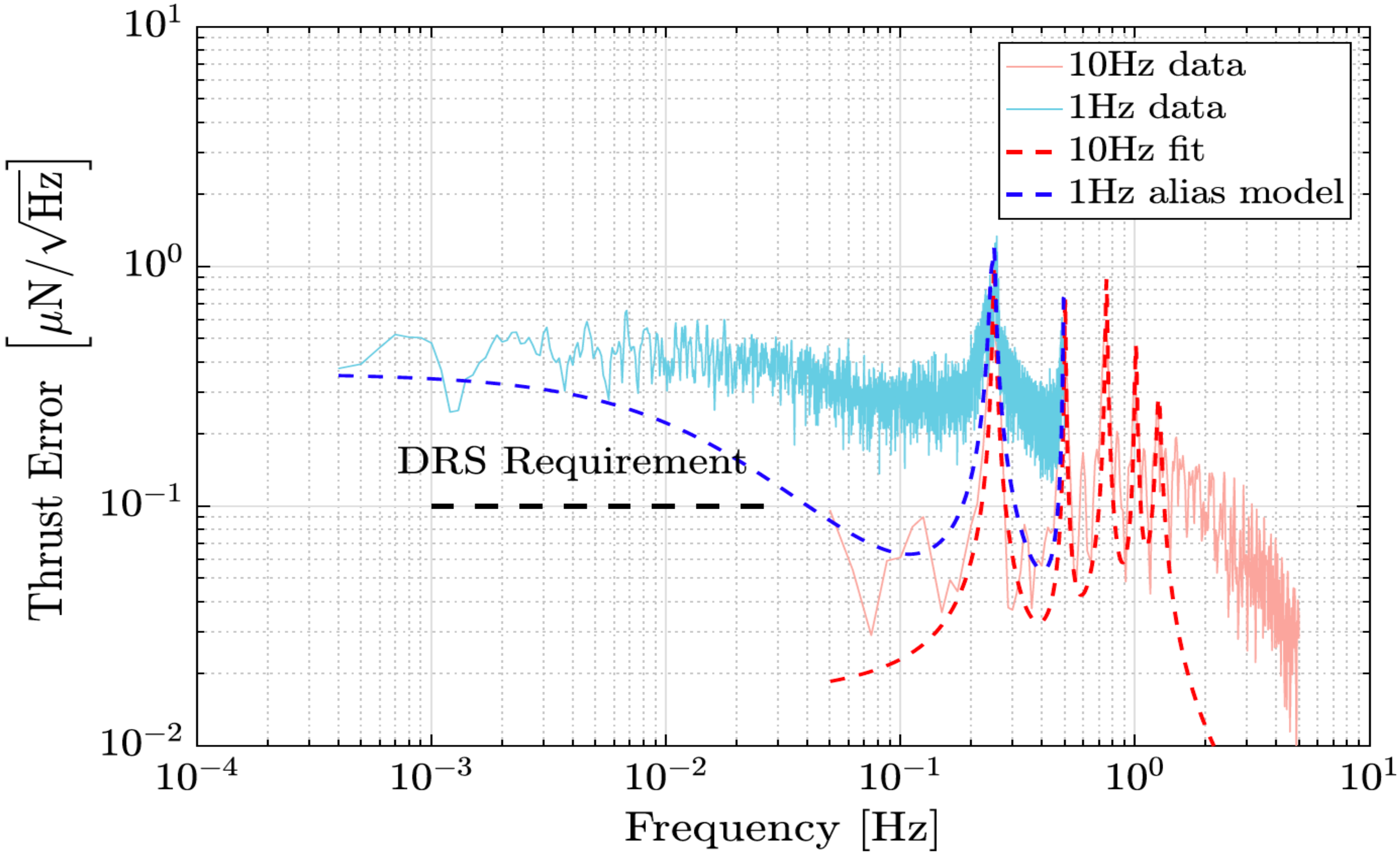
Demonstrating Thrust Noise <0.1 µN/√Hz

Method I: assume Thrust : $C_1\, I_B^{1.5}\, V_B^{0.5}$ and measure "uncommanded part" of fluctuations in rhs.



Measured thrust error (thrust command – modeled thrust) in CMNT#5 for an 8-hour period on 2017-04-24.

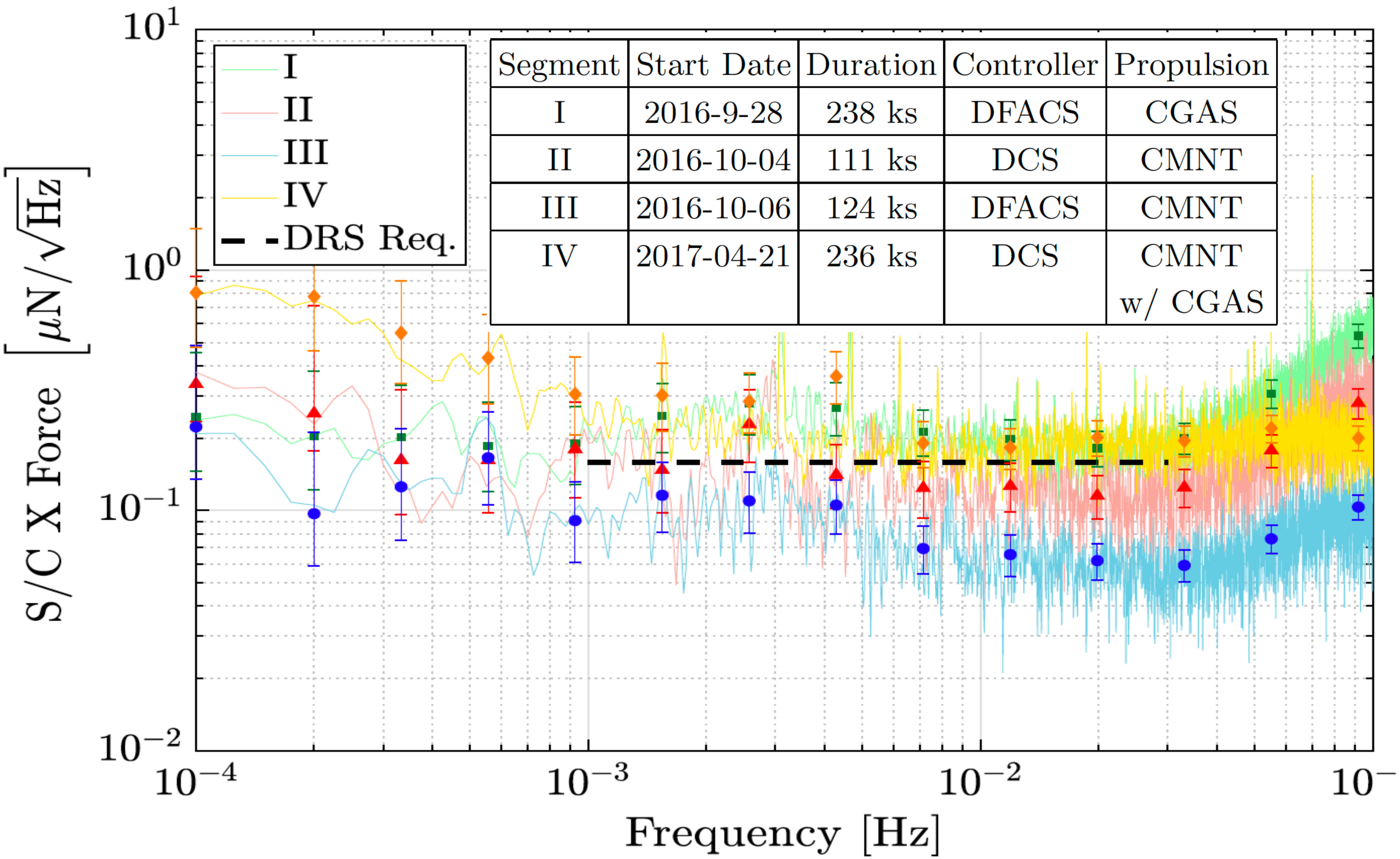
Thruster 1 (problematic in a few ways) is only one that failed to meet noise requirement



Same as previous slide, but for Thruster 1.

Demonstrating Thrust Noise <0.1 μN/√Hz

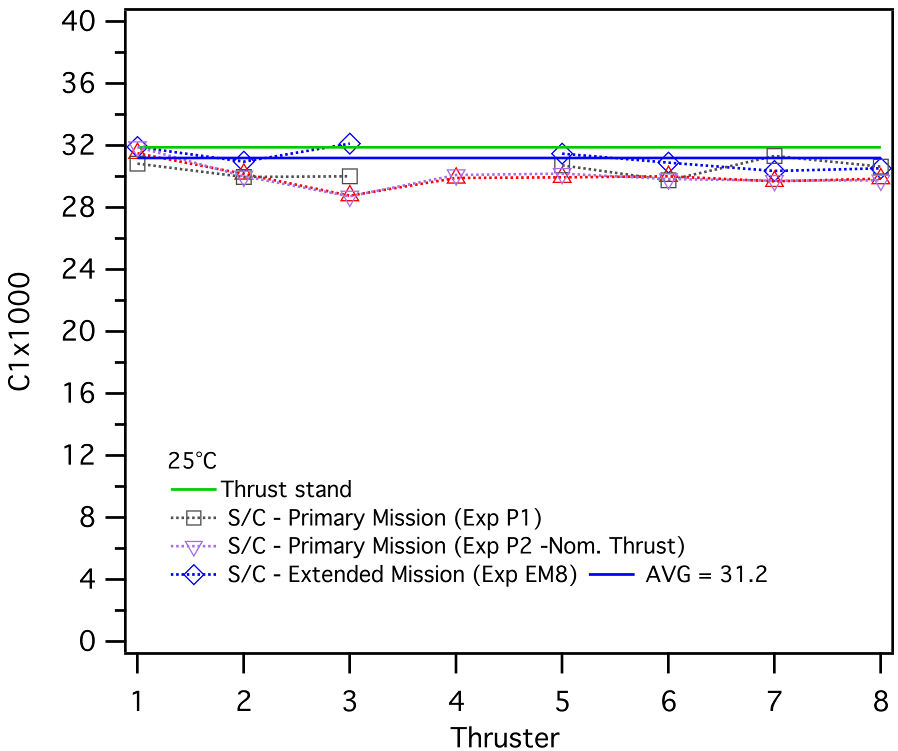
Method II: Measure S/C acceleration (here along x, the direction of TM separation).



Segment	Start Date	Duration	Controller	Propulsion
I	2016-9-28	238 ks	DFACS	CGAS
II	2016-10-04	111 ks	DCS	CMNT
III	2016-10-06	124 ks	DFACS	CMNT
IV	2017-04-21	236 ks	DCS	CMNT w/ CGAS

X-component of force derived from S/C acceleration

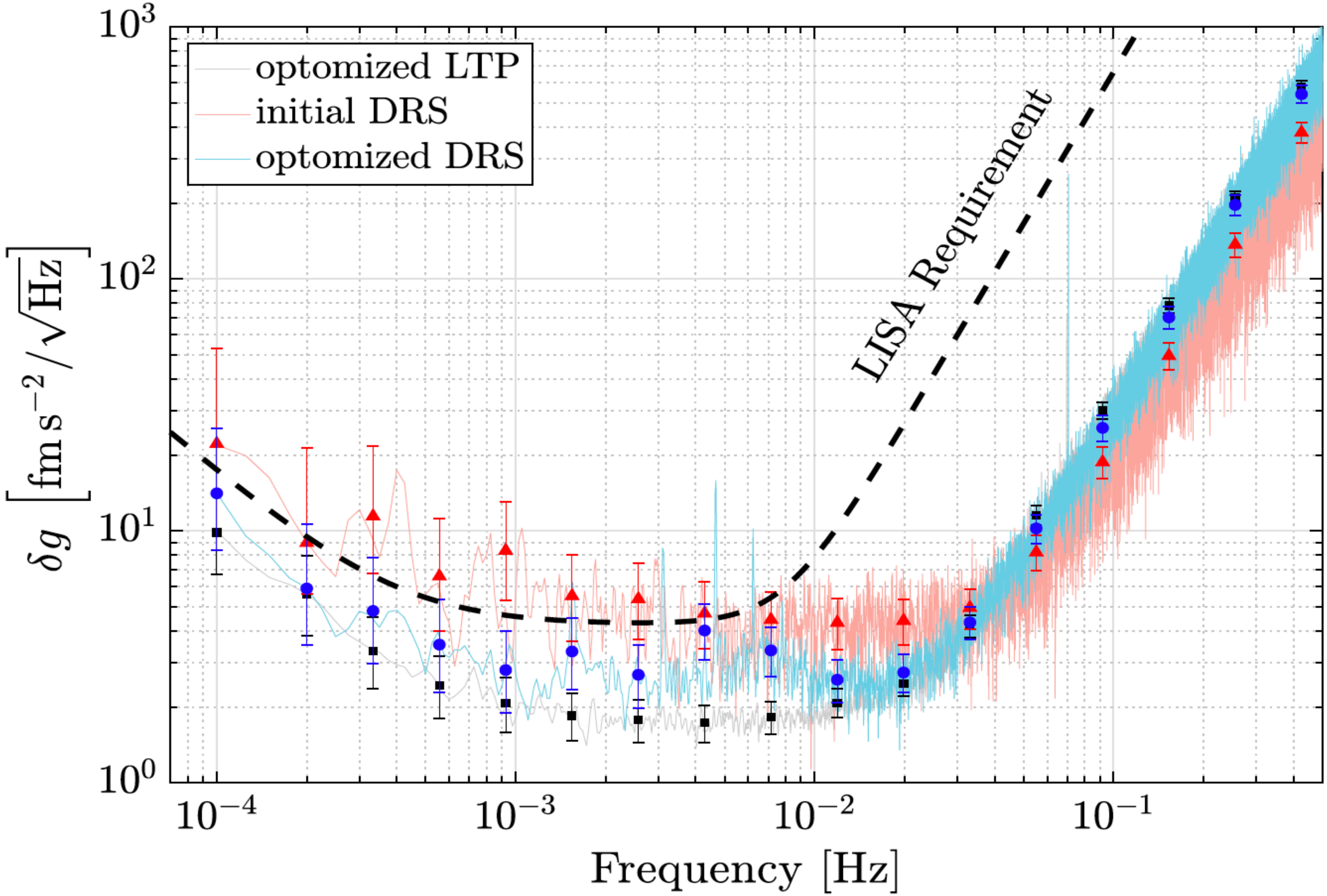
Thrust Coefficient Derived from Test Mass (High Resolution) Measurements in Extended Mission



Thr	C1x1000	+/-	Delay	+/-
T/S	31.9			
1	31.9	0.1	-0.48	0.02
2	30.9	0.1	-0.25	0.02
3	32.1	0.1	-0.12	0.01
4				
5	31.5	0.1	-0.13	0.02
6	30.9	0.1	0.02	0.02
7	30.4	0.1	-0.33	0.02
8	30.5	0.1	-0.48	0.02
Avg	31.2			

- **C_1 estimated from test mass measurements in wide range and high resolution mode differed in flight during primary and extended mission, and were lower than measured on the ground (although high resolution measurements were closer).**
- **Average C_1 estimated from thrust measurements in flight during extended mission differed from estimate from measurements on the thrust stand by only 2%.**
- **All propellant requirement studies for LISA are using a C_1 of 0.030 (conservative)**

δg measurements



Measured residual differential acceleration between Pathfinder's two test masses (g) for DRS operations and comparison with LTP configuration.

Summary and Future Plans

– The colloidal thrusters met all performance requirements. Because the propellant mass is much less than for cold-gas thrusters, they could represent an attractive alternative.

– NASA's LISA Study Office (charged with developing technologies for a US contribution to an ESA-led LISA mission) is supporting development of several technologies, including colloidal 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