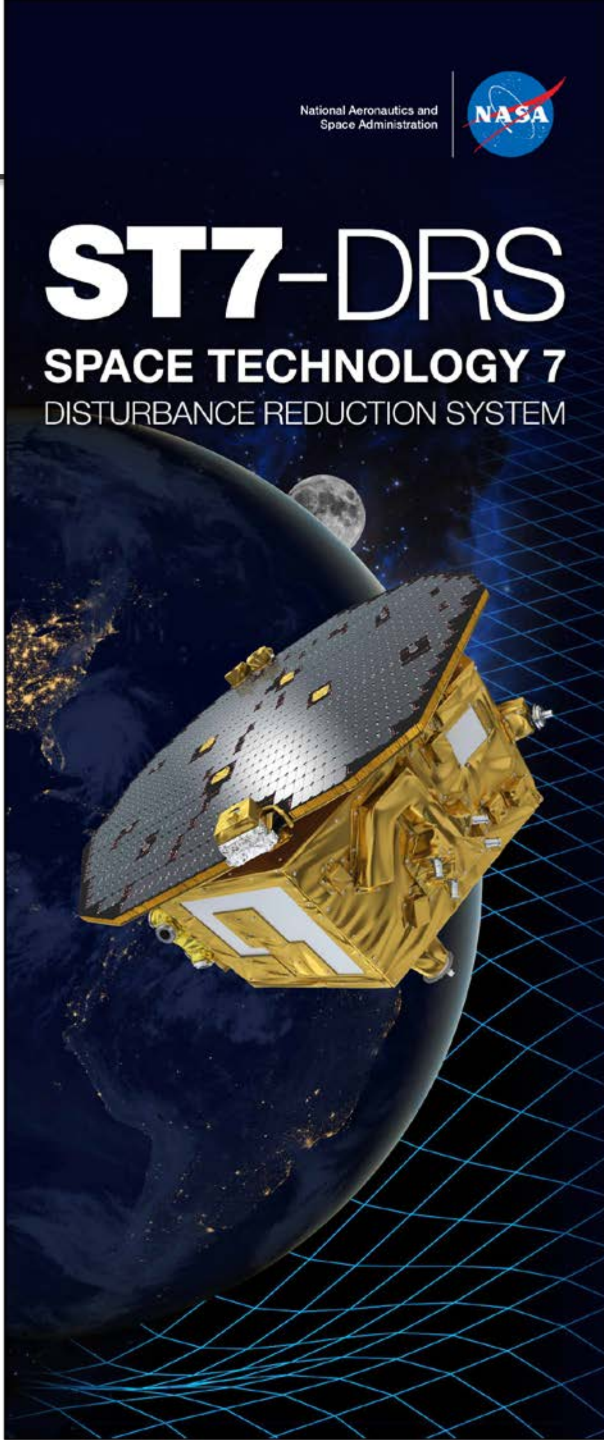
Drag-Free Performance of the ST7 Disturbance Reduction System Flight Experiment on the LISA Pathfinder

Peiman Maghami[1], James O'Donnell Jr.[1], Oscar Hsu[1], John Ziemer[2], Charles Dunn[2]

[1] NASA Goddard Space Flight Center

[2] NASA/Caltech Jet Propulsion Lab

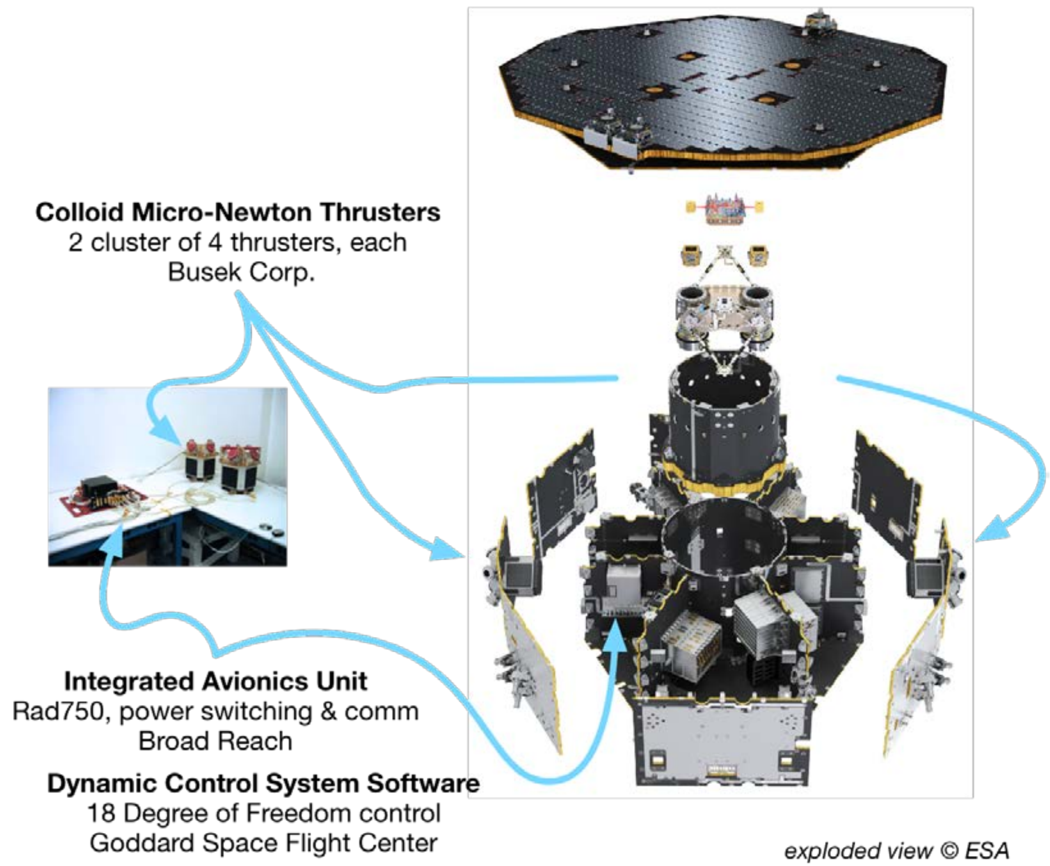


Outline

- LISA Pathfinder & DRS
- Disturbance Reduction System (DRS) Mission Timeline Highlights
- DRS Mission Modes
- Requirements and Goal
- Science Mode
- Drag-Free Performance
- Acceleration Performance
- Acknowledgements
- Concluding Remarks

LISA Pathfinder & DRS

- DRS is a NASA Contribution to the ESA LISA Pathfinder Mission
- Three Components:
  - Integrated Avionics Unit
  - Colloid Micro-Newton Thrusters
  - Dynamic Control System Software



exploded view © ESA

DRS Mission Timeline Highlights

- 2002 – DRS Project Started
- 2006 – DCS Control Design Completed
- 2008 – DRS Technology Package Delivered to LISA Pathfinder
- 2015 – DCS algorithms updated.
- December 3, 2015 at 04:04 UTC – Launch of LISA Pathfinder
- December 12, 2015 – Transfer to Sun-Earth L1 Point Begins
- **January 2-10, 2016 – DRS Thruster Checkout**
- January 22, 2016 – Arrive at L1 Point/Propulsion Module Separation
- March 1, 2016 – LISA Pathfinder Science Mission Starts
- June 24, 2016 – LISA Pathfinder Completes first operations Phase
- **June 27-July 7,2016 – DRS Instrument Checkout**
- **July 8, 2016 – DRS Thruster Anomaly**
- **August 8, 2016 – DRS Recommissioning Begins**
- **August 14, 2016 – DRS Experiment Phase Begins!!**
- **December 6, 2016- Last Day of Nominal Timeline**

DRS Mission Modes

<table>
<tr><th>DRS Mission Mode</th><th>Spacecraft Control Mode</th><th>Reference Test Mass Control Mode</th><th>Reference Test Mass Force Mode</th><th>Non-Reference Test Mass Control Mode</th><th>Non-Reference Test Mass Force Mode</th></tr>
<tr><td>Standby</td><td>Standby</td><td>DFS Standby</td><td>N/A</td><td>DFS Standby</td><td>N/A</td></tr>
<tr><td>Attitude Control</td><td>Attitude-Only</td><td rowspan="2">DFS Accelerometer</td><td rowspan="2">High Force</td><td rowspan="3">DFS Accelerometer</td><td rowspan="3">High Force</td></tr>
<tr><td>Zero-G</td><td>Accelerometer</td></tr>
<tr><td>Drag Free Low Force</td><td rowspan="2">Drag Free 1</td><td rowspan="2">DFS Drag Free 1</td><td rowspan="3">Low Force</td></tr>
<tr><td>18-DOF Transitional</td><td>Suspended Drag Free 1</td><td rowspan="2">Low Force</td></tr>
<tr><td>18-DOF</td><td>Science</td><td>DFS Drag Free 2</td><td>Suspended Drag Free 2</td></tr>
</table>

DFS: Drag-Free Sensor

DRS Requirements & Goal

Drag-Free Requirements

- ***The DRS shall maintain the spacecraft position with respect to the reference test mass, about the sensitive axis (X-axis of the LISA Technology Package (LTP) housing frames H1 or H2), to better than 10 nm/√Hz in the measurement bandwidth (MBW).***
  - Verified in the Drag-Free Low Force (DFLF) Mode
  - Applies in Science Mode, as well

Acceleration Goal

- ***DRS control shall strive to meet the goal of maintaining the residual accelerations along the measurement axes of both test masses to better than $30(1+f/(3\ mHz)^2)\ fm/s^2\ /\sqrt{Hz}$ in the measurement band.***
  - Not an explicit requirement since meeting it would depend on the performance of the LTP sensor, which is not part of the DRS experiment.
  - Flowed down to the control system (DCS) as requirements

DCS Requirements

- ***The DCS shall maintain the spacecraft position with respect to the test masses, along the sensitive axis (axis connecting the test masses, X-axis), to better than 10 nm/$\sqrt{\text{Hz}}$ in the measurement bandwidth (MBW). The measurement bandwidth covers the frequency range of 1 mHz to 30 mHz.***

- ***The DCS shall maintain the spacecraft position with respect to the either test mass, along the transverse axis (in the optical plane, Y-axis), to better than $30(1+f/(3\text{ mHz})^2)$ nm/$\sqrt{\text{Hz}}$ in the MBW.***

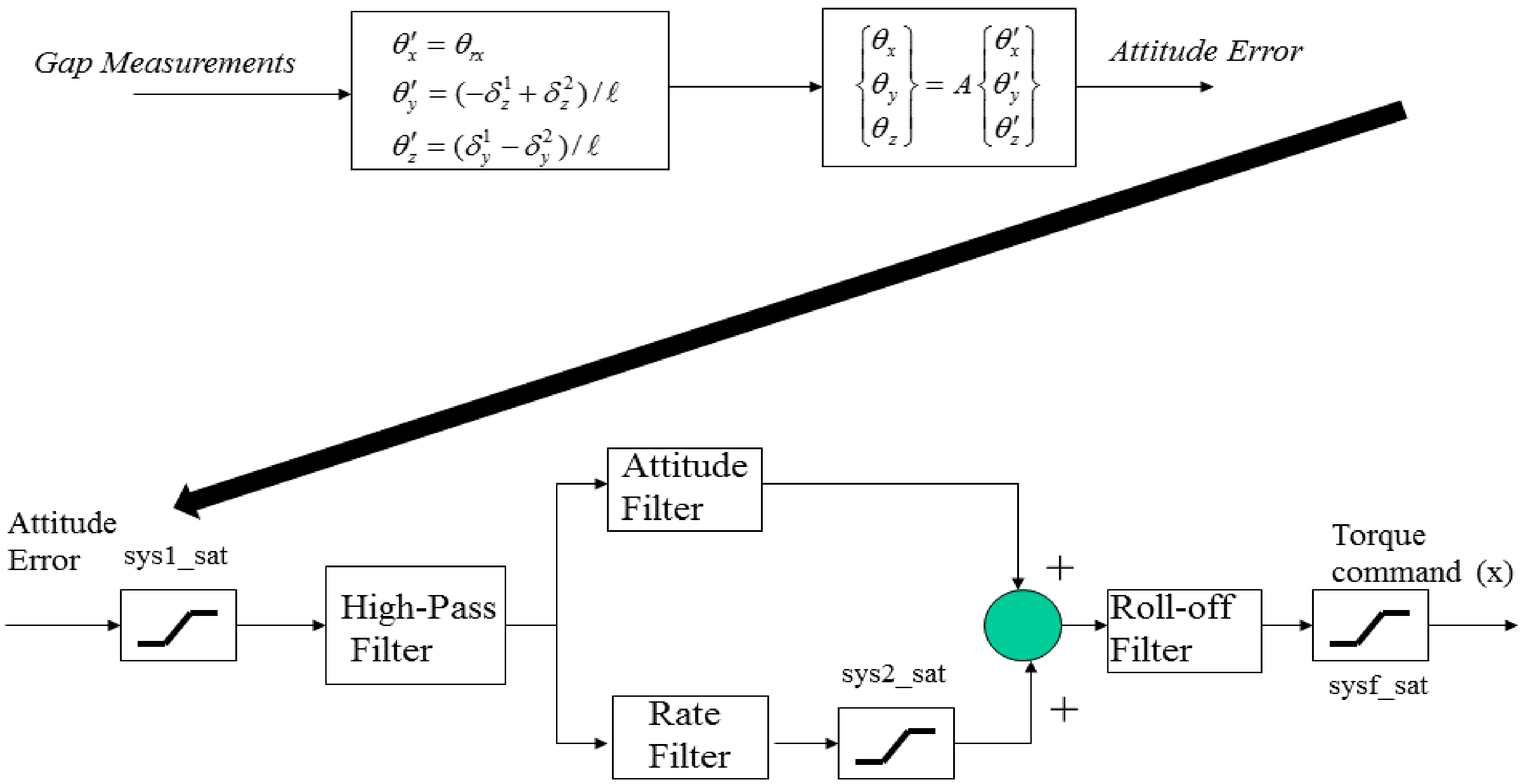
- ***The DCS shall maintain the spacecraft position with respect to the either test mass, along the Z-axis, to better than $60(1+f/(3\text{ mHz})^2)$ nm/$\sqrt{\text{Hz}}$ in the MBW.***

- ***The DCS shall maintain the relative attitude of the either test mass with respect to its housing, about any axis, to better than $500(1+f/(3\text{ mHz})^2)$ nrad/$\sqrt{\text{Hz}}$ in the MBW.***

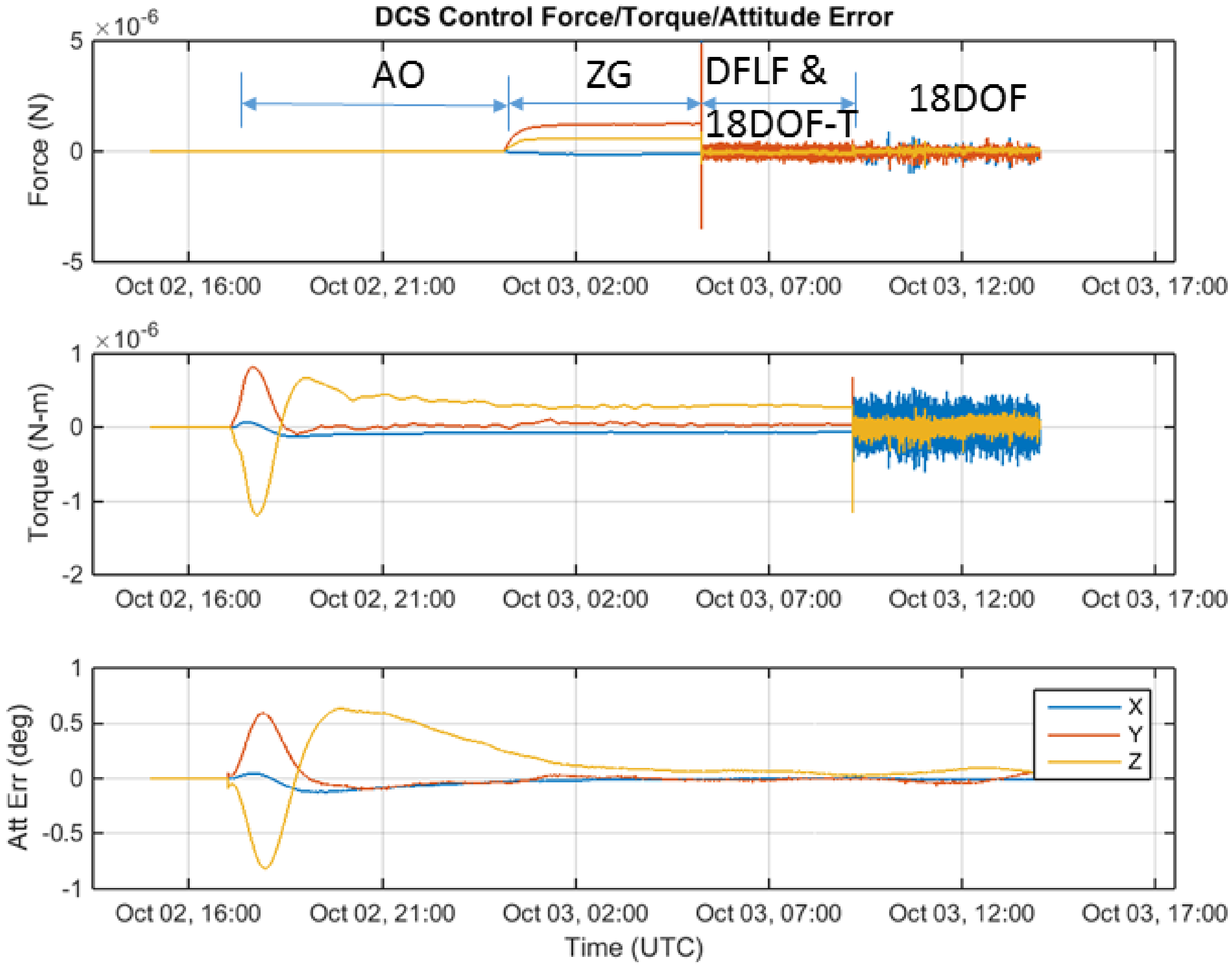
Science (18-DOF) Mode

- Mostly based on classical control design single-input/single-output (SISO) loop shaping techniques
- No suspension control of the reference test mass in translation: fully drag-free
- The spacecraft drag-free control ensures that the spacecraft follows the reference test mass (RTM) in 4 degrees of freedom (DOF) and the non-reference test mass (NTM) in 2 DOFs within the DRS band (1 mHz-30 mHz).
- Low frequency (below band) suspension control of the NTM in translation: no control in the DRS band Suspension control of RTM and NTM attitudes below band
- The spacecraft Torque control is designed to:
  - Properly orient the spacecraft in the low frequency band using the star tracker data
  - Center the spacecraft about the non-reference test mass in the transverse directions in the measurement band
  - Follow the reference test mass about the roll axis (measurement axis) in the measurement band

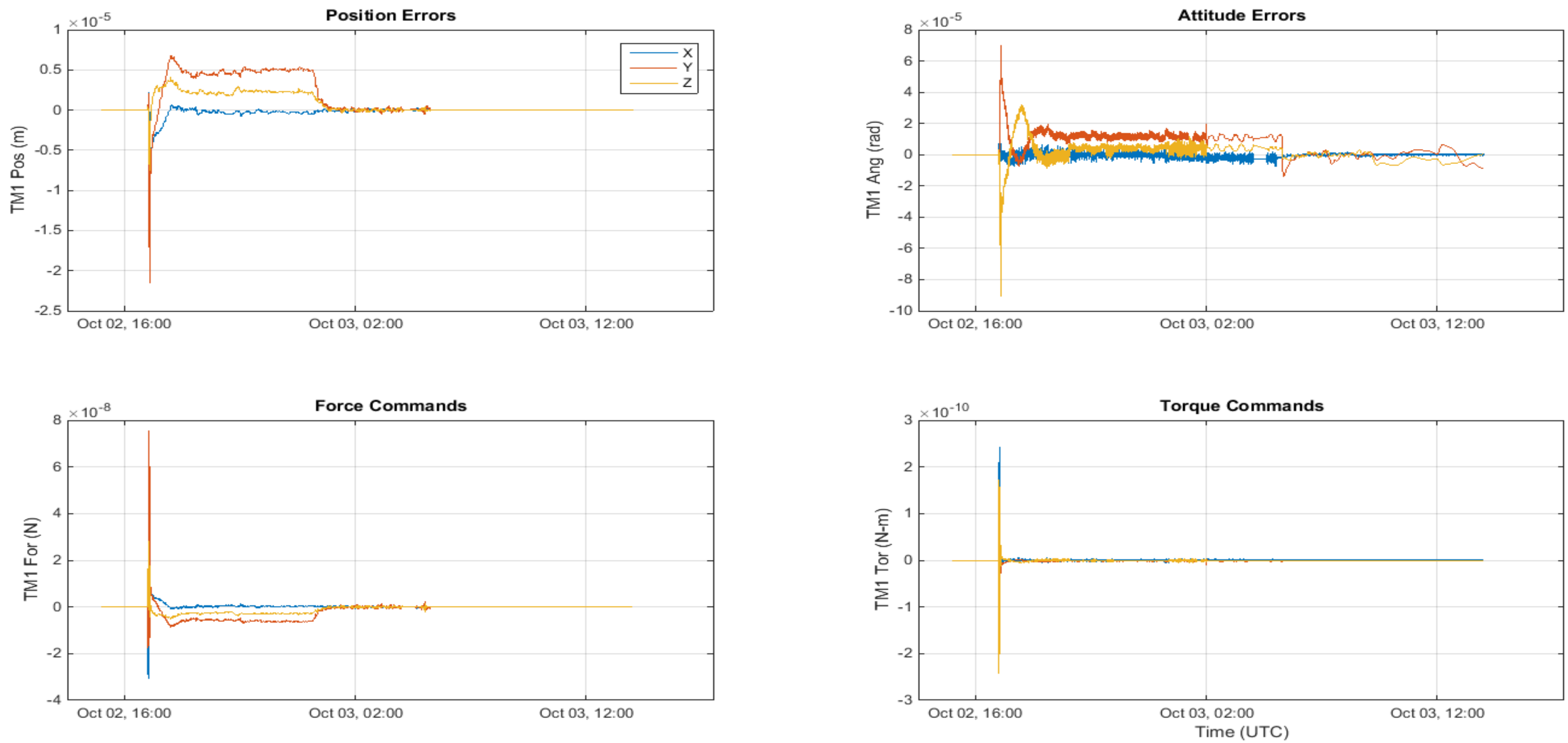
Complementary Attitude Control



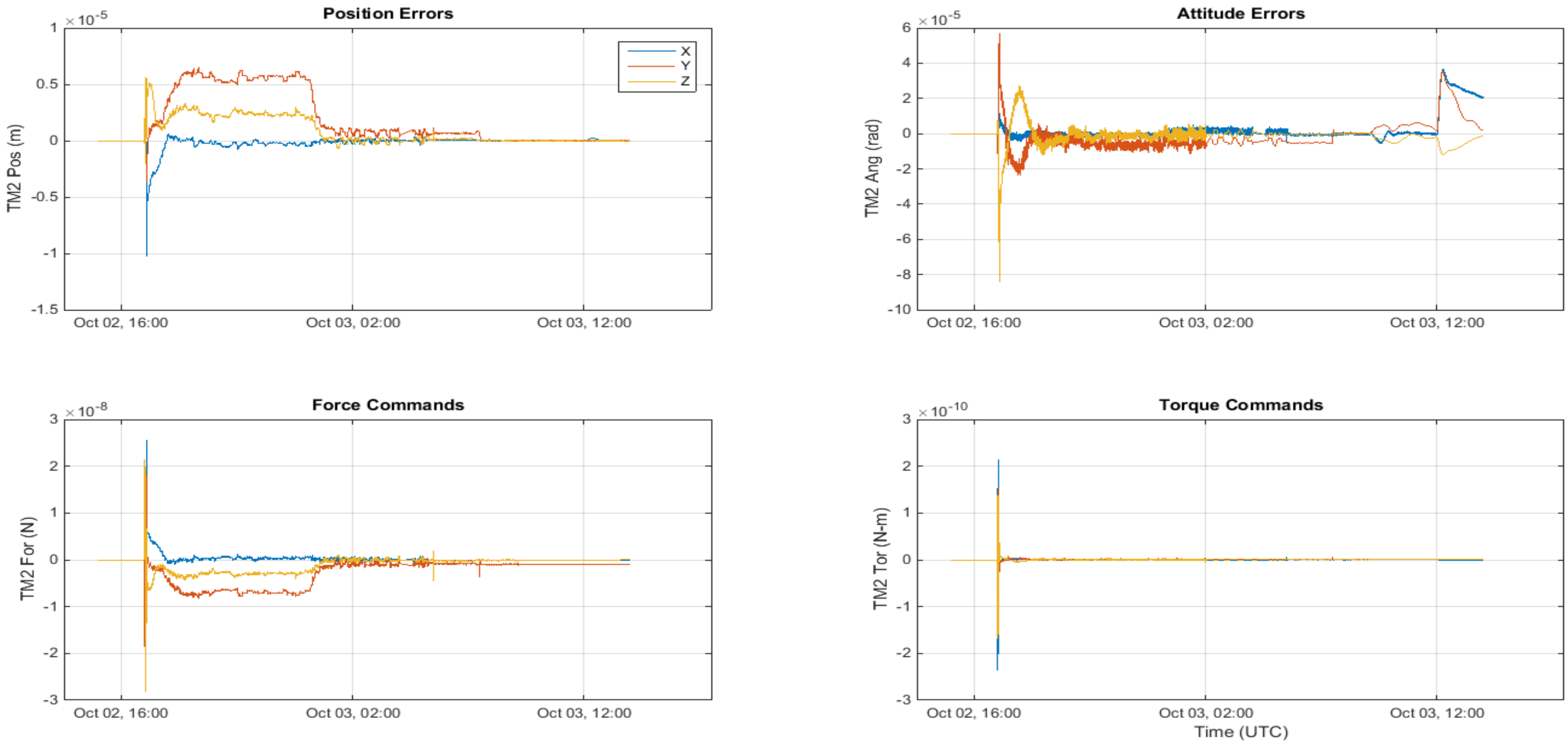
Mode Transitions



Test Mass Transitions: TM1



Test Mass Transitions: TM2

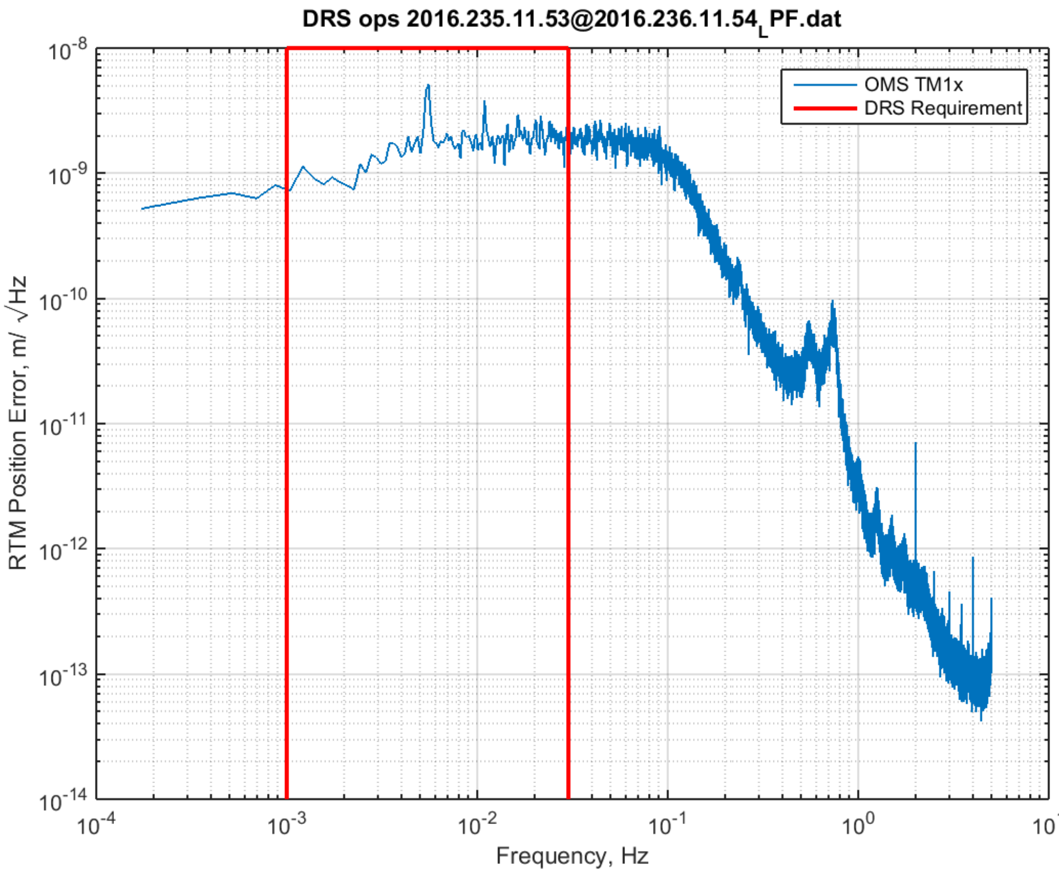


Measurement Feedback Strategy

- DRS baseline used capacitive sensing for test mass position and attitude control.
- However, the baseline was only used during the first week of operations.
- Due to significantly superior performance of the interferometric sensing, Mixed optical measurement system (OMS) and capacitive sensing used from 2nd week onward.
- The reference for the X-position control of the NTM was changed from the housing to the RTM: the OMS’ differential X-position signal was used directly in the control loop.

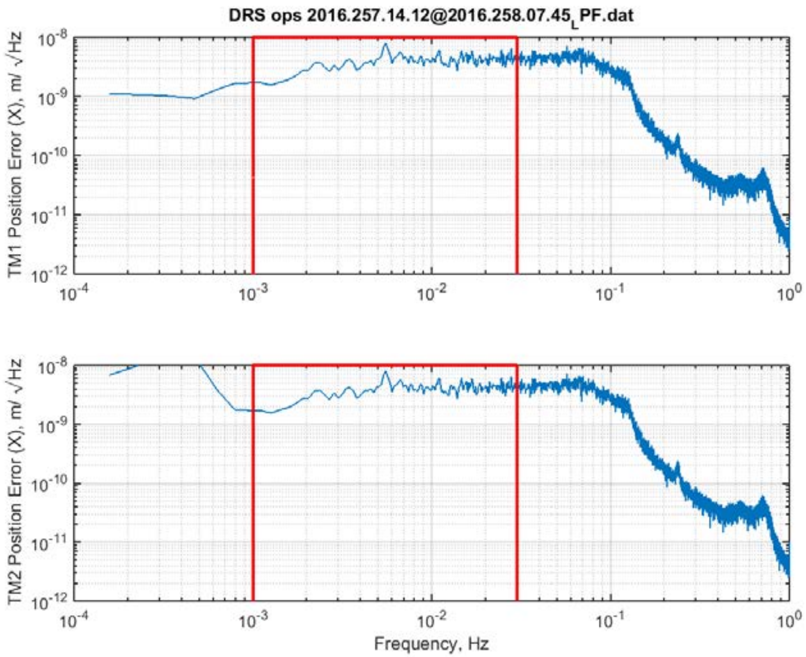
	X- Axis	Y- Axis	Z- Axis
RTM Position	OMS 1x	CAP 1y	CAP 1z
RTM Attitude	CAP 1roll	OMS 1tip	OMS 1tilt
NTM Position	OMS2x-OMS1x	CAP 2y	CAP 2z
NTM Attitude	CAP 2roll	OMS 2tip	OMS 2tilt

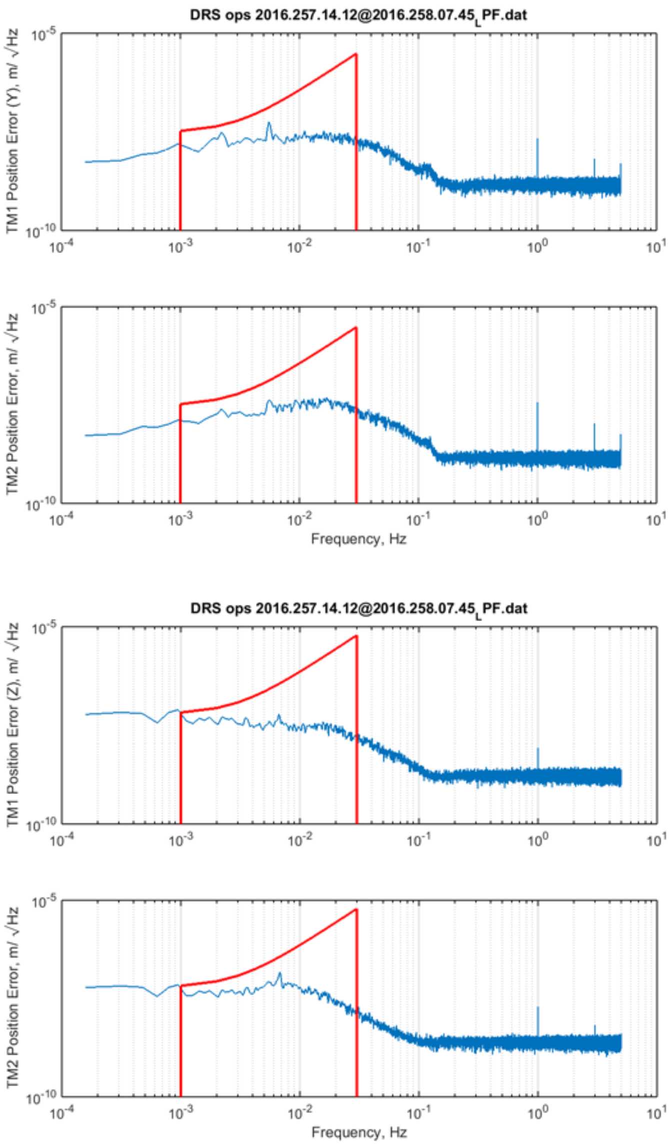
Drag-Free Requirement



- DFLF mode run on August 22, 2016, 16.5 hrs starting at 11:53 UTC
- OMS in the loop

Test Mass Acceleration: Drag-Free Requirements





- ASDs generated from the flight data on DOY 257 (14:12 UTC) to DOY 258 (07:45 UTC)
- Science Mode, with OMS in the loop

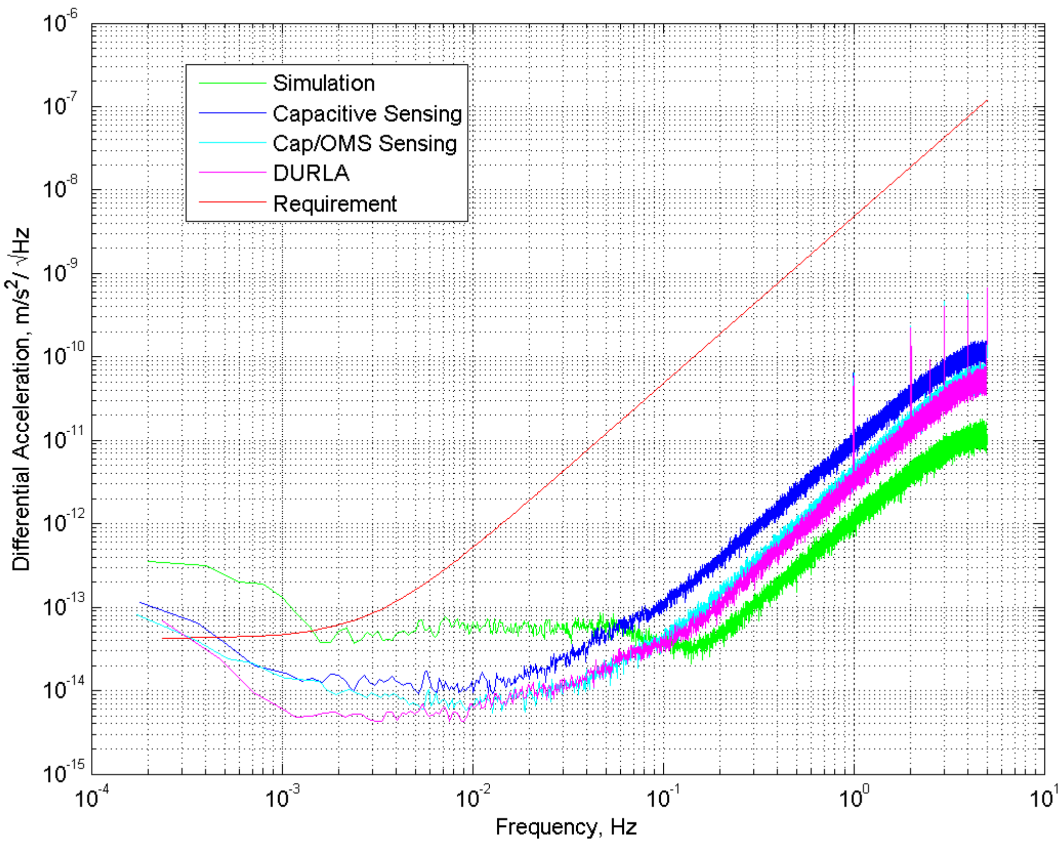
Test Mass Acceleration

- Capacitive or OMS sensing does not provide a direct measurement of test mass motions (accelerations)
- The differential motion provides a reasonable basis for estimating the average test mass acceleration
  - Double differentiate the differential OMS signal
  - Include corrections for electrostatic force commands along the sensitive axis, with adjustments for calibrated gain
- Starting from week 5, the test mass actuation authority was reduced (with margin) to decrease the suspension noise of the test masses. These levels are referred to as the DRS Ultra Ridiculously-Low Actuation (DURLA).

Nominal and DURLA Actuation Limits (Forces in pN, and Torques in pNm)

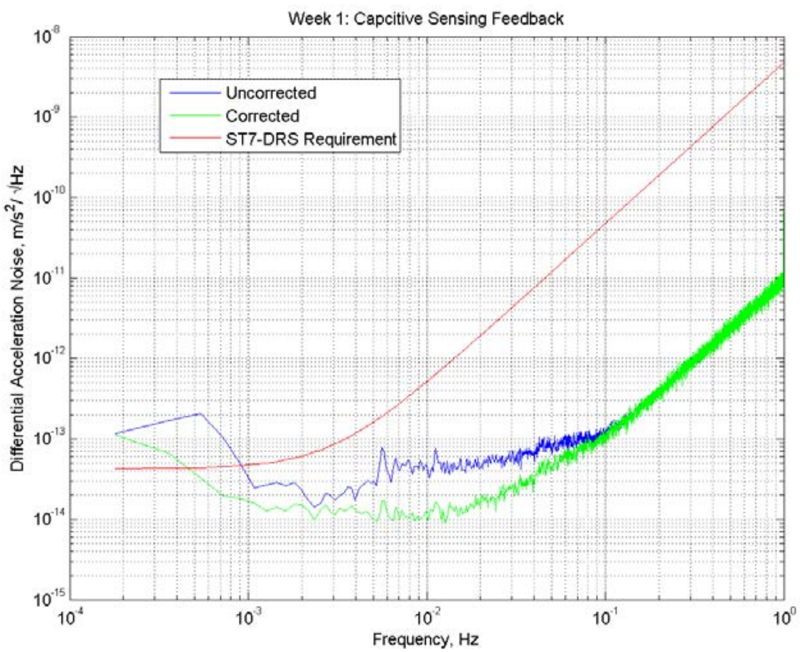
DOF	X1-Force	Y1-Force	Z1-Force	X1-Torque	Y1-Torque	Z1-Torque
Nominal	0	0	0	16.4	13.3	10.4
DURLA	0	0	0	4	4	1.5
DOF	X2-Force	Y2-Force	Z2-Force	X2-Torque	Y2-Torque	Z2-Torque
Nominal	2200	3670	5826	16.4	13.3	10.4
DURLA	100	2000	500	4	4	1

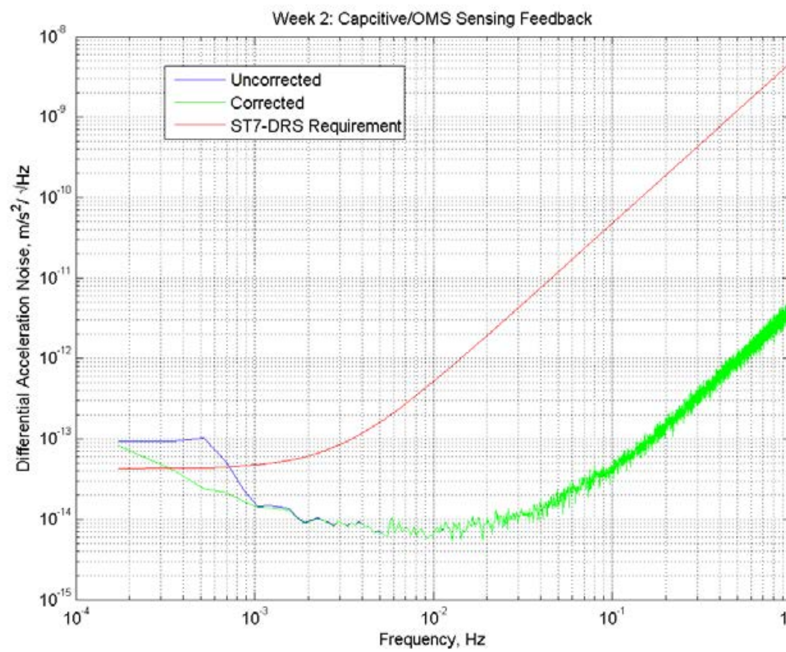
Acceleration Noise Requirement



- Correction for electrostatic force commands (x2) only
- Further corrections for centrifugal accelerations, cross-talk, and others are possible

Commanded Force Correction





- Higher noise and cross-talk from capacitive only feedback (left)
- Very low authority controller used in x2 control to reduce the need for a correction, as seen by the OMS in the loop results from week 2 (right)

Acknowledgements

- The Hammers Company
- Busek Co.
- Airbus Defense and Space in Stevenage, UK
- European Space Operations Centre in Darmstadt, Germany
- LISA Pathfinder Spacecraft and Science Team

Concluding Remarks

- DRS launched aboard LISA Pathfinder on December 3, 2015, and started nominal mission on August 14, 2016.
- DRS Modes and Mode Transitions successfully verified.
- All Drag-Free requirements and acceleration goal were met with margin.
- The noise performance, in general, was better than expected mainly due to the LTP and the micro-Newton thrusters performing better than their requirements.
- Nominal operations was cut a bit short with a failure of thruster#4 on October 27, 2016.

Questions?