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DYNAMIC CONTROL SYSTEM PERFORMANCE DURING COMMISSIONING OF THE SPACE TECHNOLOGY 7 – DISTURBANCE REDUCTION SYSTEM EXPERIMENT ON LISA PATHFINDER

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The Space Technology-7 Disturbance Reduction System (DRS) launched aboard the European Space Agency's LISA Pathfinder spacecraft on December 3, 2015, after more than a decade in development. DRS consists of three primary components: an Integrated Avionics Unit (IAU), Colloidal MicroNewton Thrusters, and Dynamic Control System (DCS) algorithms implemented on the IAU. During the portions of the mission in which the DRS was under control, the DCS was responsible for controlling the spacecraft and the free-floating test masses that were part of the LISA Test Package. The commissioning period was originally divided into two periods: before propulsion separation and after propulsion separation. A recommissioning period was added after an anomaly occurred in the thruster system. The paper will describe the activities used to commission DRS, present results from the commissioning of the DCS and the recommissioning activities performed after the thruster anomaly.

INTRODUCTION

The Space Technology-7 (ST-7) Disturbance Reduction System (DRS) is an experiment package aboard the European Space Agency (ESA) LISA Pathfinder (LPF) spacecraft. LPF launched from Kourou, French Guiana, on a Vega launch vehicle on December 3, 2015, at 04:15 UTC. DRS is a project managed by the Jet Propulsion Laboratory (JPL) which consists of three primary components: Integrated Avionics Unit (IAU) developed by JPL, Colloidal MicroNewton Thrusters (CMNTs) developed by Busek, and Dynamic Control System (DCS) algorithms and flight software developed at the NASA Goddard Space Flight Center. The CMNTs were designed to nominally provide thrust levels from 5–30 μNewtons at a precision of 0.1 μNewtons. The IAU hosts the flight software, both the DCS and the JPL-developed command and data handling software, as well as interfacing with both the CMNT electronics and the LISA Pathfinder spacecraft. During the portions of the mission where DRS is in control, the DCS is responsible for

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the attitude and position control of the spacecraft and the two test masses inside the LISA Technology Package (LTP) developed by European institutes and industry for ESA.

The DRS mission consists of a commissioning period and an experiment period. The commissioning period is twenty days divided into two periods for commissioning of the overall system: one for thruster checkout and one for experiment checkout. Following commissioning, the experiment period was planned to last ninety days, though this period was spread over four or five months to include regular stationkeeping maneuvers and a few weeks where control was handed back so that the LPF science team could run further experiments. Thruster checkout occurred during the transfer to the L1 Earth-Sun Lagrange point while the propulsion module was still attached. The thruster checkout period lasted ten days and the primary objective was to verify that the thrusters worked and could act as a backup to the cold gas thrusters used by the LPF, if needed. The thruster checkout period exercised both the CMNT and the IAU. The instrument checkout period covered another ten days and occurred approximately six months after thruster checkout, at the completion of the LTP portion of the nominal LPF mission. The DRS instrument checkout period tested the activities that would be needed for the ninety-day experiment period.

This paper will discuss the chronology of the ST7-DRS commissioning, both the thruster checkout period and the instrument checkout period. Additionally, this paper will briefly discuss a thruster anomaly that occurred right after the nominal completion of DRS commissioning. The results of the investigation of this anomaly, the strategy for operating the experiment afterwards, and the testing and recommissioning of the DRS will all be discussed. High level results of the activities will also be discussed in this paper as well as other troubleshooting activities that had to be performed during the original commissioning or recommissioning periods, such as determining the changes needed to support problematic mode transitions between higher level modes.

LISA PATHFINDER AND ST7-DRS OVERVIEW

LPF consisted of two main modules: the propulsion module and the science module. The propulsion module was used to put the LPF on its transfer trajectory from a low Earth parking orbit to the mission orbit around the L1 Earth-Sun Lagrange point. The propulsion module was jettisoned on January 22, 2016, after carrying the spacecraft to the L1 point. The science module carried the LTP, cold gas thrusters, and the DRS experiment; all technologies being demonstrated for future missions. The LTP is the heart of the mission and consists of the inertial sensors, two electrostatically suspended test masses, with capacitive sensing and actuation, and an Optical Measurement System (OMS). An image of LPF with the science module and propulsion module separated are show in Figure 1.

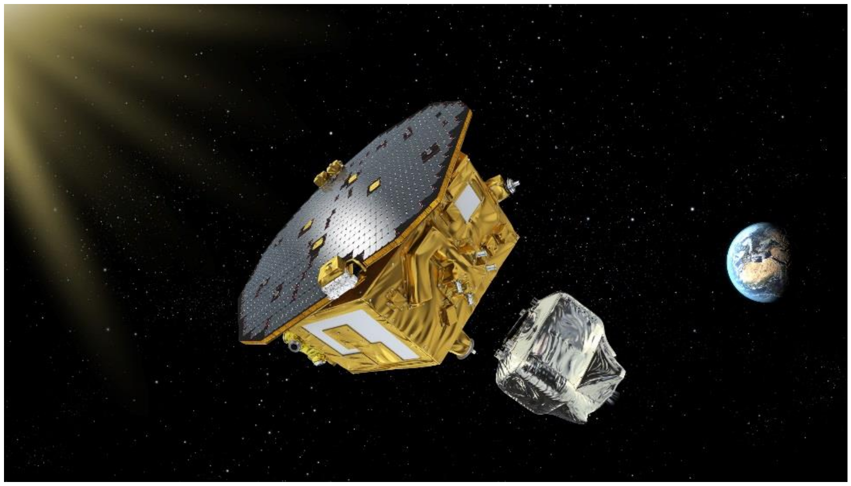

Figure 1. LISA Pathfinder Post-Propulsion Module Separation (ESA/C. Carreau)

The NASA contribution to the LPF was ST-7 DRS experiment. DRS consisted of the IAU and two clusters of CMNTs. The IAU performed two major software functions: Command and Data Handling (C&DH) and the DCS. The C&DH was responsible for DRS Mission Mode configuration by commanding the DCS into the correct control modes (Spacecraft, Reference Test Mass (RTM), and Non-Reference Test Mass (NTM)) and commanding the LTP inertial sensors into the correct sensing/actuation modes. The DRS Mission Modes are shown in Figure 2.

<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>

Figure 2. Dynamic Control System Mode Transition Diagram

DRS Mission Modes

There are six DRS Mission Modes managed by the IAU: Standby, Attitude Control, Zero-G, Drag-Free Low Force, 18-DOF (Degree of Freedom) Transitional, and 18-DOF Mode. Standby mode is for use when the IAU is powered on but no actuation commands should be generated by the control system. Attitude Control (AC) Mode is used for the transition from LPF control to DRS Control. In this mode, the DRS nulls spacecraft attitude errors and rates while keeping the test masses centered in their housing. The Zero-G (ZG) Mode is designed to use the thrusters to minimize the electrostatic forces being applied to the reference test mass, attempting to effectively cancel out secular disturbance forces on the spacecraft, such as those from solar radiation pressure. The Drag Free Low Force (DFLF) Mode is the first time where there are no electrostatic forces being commanded on the reference test mass and the reference test mass is in its high resolution measurement mode. In the DFLF Mode, the spacecraft is being flown drag-free about the reference test mass in all translational axes. 18-DOF Transitional (18DOFT) is a transitional mode to get to 18-DOF (18DOF mode) control of the spacecraft and two test masses. Each of these DRS Mission Modes consists of a spacecraft control mode, a test mass control mode for each test mass, and a test mass force mode.

Spacecraft Control Modes

There are five control modes used for spacecraft control: Standby, Attitude-Only, Accelerometer, Drag Free 1, and Science Mode. Standby mode is used when the C&DH software needs to run without any actuation commands from the control system, i.e. thruster checkout activities. Attitude-Only Mode is used during the transition from LPF to DRS control using star tracker measurements only. Accelerometer Mode incorporates electrostatic data from the reference test mass to null the acceleration on the spacecraft at low frequency, primarily from solar radiation pressure. Drag Free 1 substitutes the acceleration data with position data from the reference test mass to null position errors (from the reference test mass to its housing). The final spacecraft control mode is Science mode and the controller now incorporates position data from both test masses.

Test Mass Control Modes

There are six control modes available for test mass control: DFS Standby, DFS Accelerometer, DFS Drag Free 1, DFS Drag Free 2, Suspended Drag Free 1, and Suspended Drag Free 2. DFS Standby is the same as the spacecraft standby mode, no actuation commands being sent to the LTP. DFS Accelerometer Mode is designed to use larger bandwidth electrostatic forces and torques to keep the test mass centered in the housing. DFS Drag Free 1 and DFS Drag Free 2 are designed to maintain the attitude of the RTM by applying torques at low frequencies. Suspended Drag Free 1 and Suspended Drag Free 2 are similar to the DFS Drag Free modes with the addition of translational correction of the non-reference test mass position, mainly below the measurement frequency band.

Test Mass Force Modes

There are two test mass force/measurement modes available: Wide-Range/High Force and High-Resolution/Low Force. As the names imply, the wide-range/high force mode provides additional actuation authority with reduced resolution in the measurements. Another feature of the Wide-Range mode is that forces and torque commands are applied in alternating control cycles. High-Resolution/Low force mode provided higher resolution measurements and lower actuation authority. In the High-Resolution/Low Force Mode, force and torque commands are applied in the same control cycle.

For more detailed information about the overall design of the DRS experiment and hardware, as well as the design, analysis, and testing of the DCS algorithms, see our previous publications. References 1 and 2 both contain a very good summary of the overall mission and descriptions of the hardware, particularly the IAU and CMNTs. References 3 through 6 describe in much more depth the details of the DCS.

DCS CONTROL DESIGN CHANGES PRIOR TO LAUNCH

The DCS control design was completed in 2006, the DCS flight software was delivered in early 2007, and the DRS technology package was delivered to LISA Pathfinder in 2008. The next major changes in the DCS algorithms and flight software were in 2015, a little over a year before launch. These changes were motivated by issues with tests in the LPF Real-Time Test Bed (RTB) at Stevenage, UK, in 2012 and 2014, and by finalization of the spacecraft and test mass geometry, mass, and functional properties. The issues in the RTB testing were, for the most part, attributed to the behavior of the test masses in the Accelerometer Mode (DRS Mission Modes Attitude Control and Zero-G). Unmodeled and undefined nonlinearities in the test mass dynamics, such as actuation to sensing cross-talk, delays, a previously undefined commutation scheme between translational and rotational degrees of freedom, and nonstationary dynamics, warranted a considerable softening of the test mass control loops in the Accelerometer Mode. Furthermore, the integral actions in the control loops were also removed to render the controllers passive in the bandwidth of interest, and thereby more robust to nonlinearities and unmodeled dynamics. Finally, the controller gains, parameters, and tables were updated for all control modes once the final updates on mass, geometry, and functional properties were received from the LPF team. However, no design changes or optimizations, other than noted above, were considered or incorporated.

The updated DCS algorithms and flight software were successfully tested on the RTB in July 2015, allowing the DRS to be certified for flight operations. In addition to the DCS changes, the DRS flight software was modified to optionally allow for the processing and inclusion of the test mass optical sensing signals in the control loops. The OMS uses interferometers to accurately measure the X-axis translation, and tip and tilt (Y and Z axis rotations) of the test masses. The OMS signals are orders of magnitude less noisy than capacitive sensing.

THRUSTER CHECKOUT

The DRS thruster checkout period occurred during the transit to L1 Earth-Sun Lagrange Point. The goal of this phase was to verify that the DRS thrusters are a viable backup to the cold gas thrusters prior to separation of the propulsion module. The checkout period was allocated ten days and activities were scheduled for seven days with three days of contingency. The actual checkout period occurred from January 2–10, 2016. Some of the activities executed during this period were a thruster impedance test, thruster bubble and dissipation test, and thruster functional test.

As stated previously, the goal of this checkout period was to verify that the DRS thrusters could act as a backup to the cold-gas system during separation of the propulsion module. Therefore, the tests during this period were geared to verify the aliveness and functionality of the thrusters. The thruster impedance test was used to verify there were no electrical shorts in the thruster system. The thruster bubble and dissipation test was used for estimating the severity of any bubbles in the propellant line and to remove them. After successful dissipation of the bubbles, a functional test of each thruster was performed to gauge the performance of the thruster.

All success criteria defined for the thruster checkout periods were met. During the thruster commissioning period, it was discovered that the response time for thruster 1 was slower than the other thrusters but still within requirements.

INSTRUMENT CHECKOUT/EXPERIMENT PHASE COMMISSIONING

The DRS instrument checkout/experiment phase commissioning occurred between June 27, 2016, and July 7, 2016. The intent of this phase was to validate the command sequences needed during the experiment phase and to begin testing the DCS control modes.

Thruster Checkout

The beginning of the instrument commissioning phase began on June 27, 2016, and started with testing of the thrusters post propulsion module separation. The first set of activities were the same as used during thruster commissioning. Sequences were updated on the IAU, thruster impedances were verified, bubble and dissipation tests performed, and thruster functional tests performed. In addition to the tests performed during thruster commissioning, thruster calibration tests were performed to verify the response of the thrusters due to voltage steps and impacts on various thruster control parameter settings.

Results of the thruster checkout period were overall positive. During the checkout, it was determined that thruster 1 had a slower response to thruster commands and a lower maximum thrust than the other thrusters due to bubbles in the propellant. Its performance, however, was acceptable for proceeding with the rest of commissioning. Overall, the information gained through the thruster tests were used to calibrate the thrusters prior to using them for active control of the spacecraft. Thruster checkout and calibration activities were completed on July 1, 2016.

Handover/Handback Test – DRS Attitude Control Mode

July 4, 2016, was the day that DRS first controlled the LISA Pathfinder spacecraft. The primary activities for the day were to allow ESA to test their calibration of the CMNTs by commanding them from the LTP, and then to test the handover and handback sequence between LISA Pathfinder and DRS. Many hours had been spent on this sequence in ground testing using both the testbed at JPL and the RTB in Stevenage, UK.

The command to hand over control to DRS was issued at 08:32 UTC. DRS stayed in control of the spacecraft until 10:21 UTC when the command was issued to hand back control to LISA Pathfinder. The control for approximately two hours was long enough for the team to see that the attitude errors started to turn around and were approaching zero. The attitude error and commanded torque is shown in Figure 3. Recalling that the thrusters produce thrust between 5-30 µNewtons, the controller took eleven minutes before the commands reached their peaks due to initial transients and 100 minutes before the attitude errors reached their peaks and began to decrease.

The handback to LPF control was uneventful and the next handover to DRS control occurred at 12:25 UTC. The second handover was also uneventful and DRS remained in control of the spacecraft overnight. At acquisition of signal the following morning, DRS was still successfully controlling the spacecraft, so no issues cropped up overnight, and the DRS software Mode Complete flag was set, marking another DCS milestone. The last activity performed in AC Mode prior to transitioning to ZG Mode was to update the DCS Thruster Bias table to set the CMNT bias levels to counteract more of the Solar Radiation Pressure (SRP) Force. The thruster biases were originally set to counteract half of the estimates SRP and provide a large thruster range for the attitude control during handover. Based on the performance of the two handover sequences and amount of fuel needed in the cold gas system for station-keeping due to the large offset, it was decided to update the biases to fight more of the SRP Force.

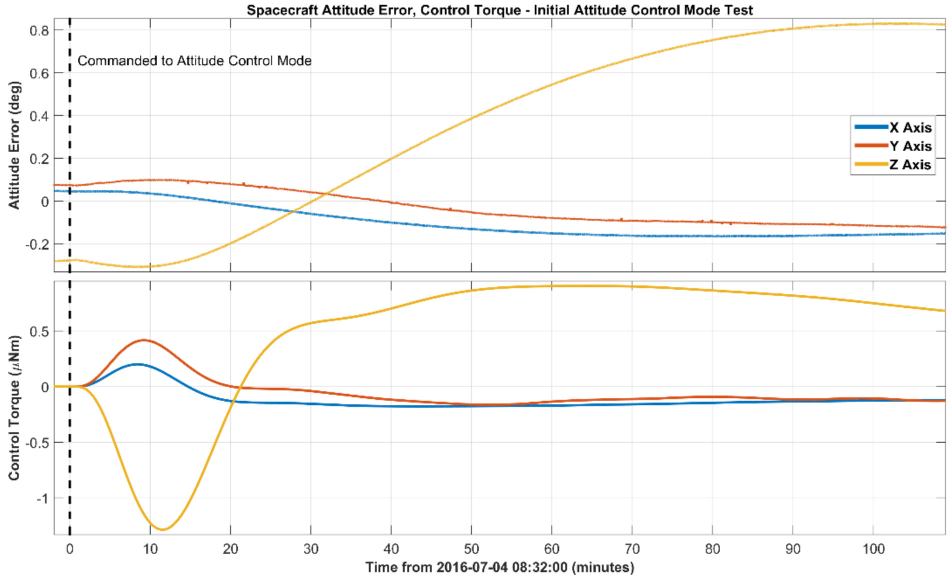

Figure 3. Spacecraft Attitude and Control Torque for Initial DCS Control Test

Zero-G Mode Test

The ZG Mode is the next DRS Mission Mode after handover into AC Mode. In this mode, spacecraft position is actively controlled via CMNT commands to null out low frequency spacecraft disturbances, primarily SRP force. The DCS force control uses the electrostatic signal from the reference test mass as a measure of spacecraft acceleration (for all runs shown in this paper, test mass 1 is used as the reference test mass). This mode was first tested on July 5 at 8:00 UTC. The spacecraft attitude error, torque, and force commands are shown in Figure 4. This figure shows that the spacecraft attitude continues to converge, with no impact from the transition into ZG. This is expected, as the same attitude controller operates from the previous mode. A slight action in the force commands to offset residual accelerations can be seen. The CMNT thruster commands are shown in Figure 5; the commands at transition and thereafter are benign. At approximately 8:47 UTC, a sine wave signal injection with Thruster 7 is performed. This was done to verify this functionality for future experiments, and the injection test was successful. Figure 6 shows the reference test mass position, attitude, force and torque commands. Again, the behavior is benign, and as expected, the test mass position errors and forces were all driven towards null in this mode. The behavior of the non-reference test mass (not shown) was similar.

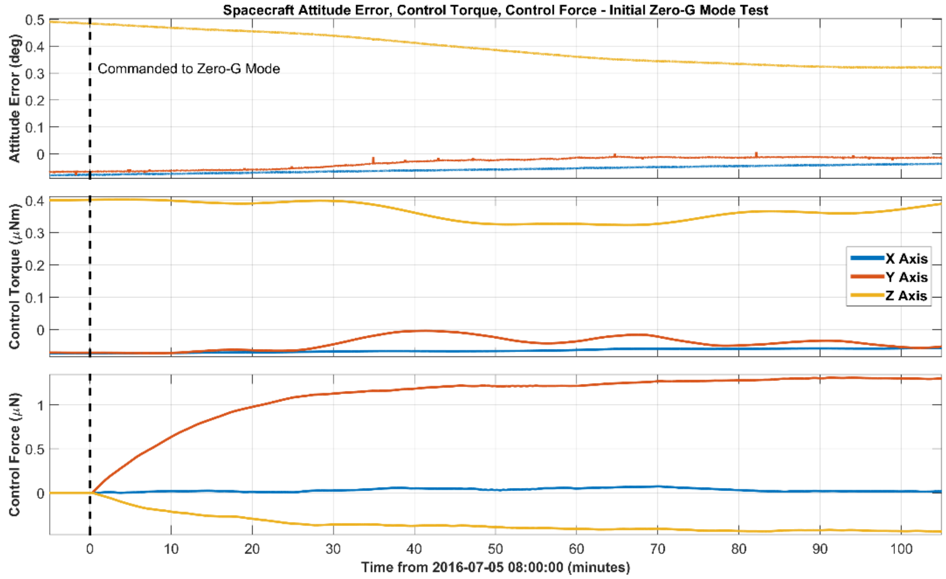

Figure 4. Spacecraft Attitude Error, Torque and Force Commands

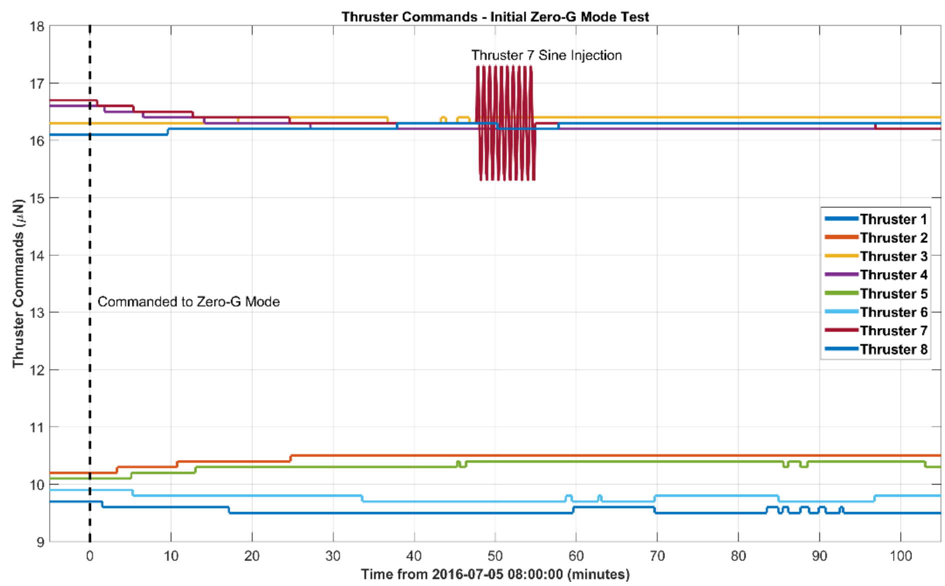

Figure 5. Colloidal MicroNewton Thruster Commands

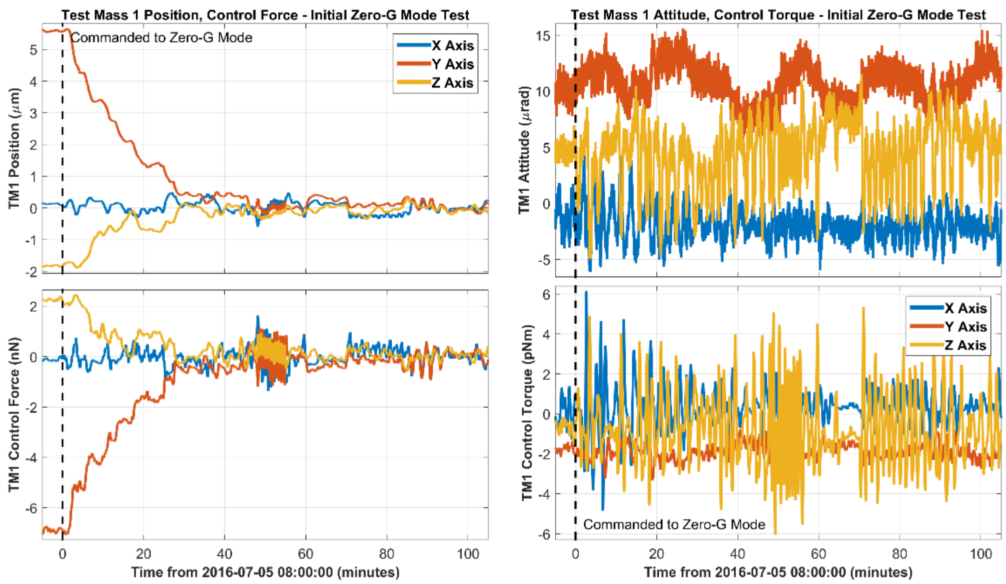

Figure 6. Test Mass 1 Position and Attitude Errors, Force and Torque Commands

Drag-Free Low Force Mode Test

On July 5 at 11:07 UTC, transition into the DFLF Mode was attempted. This is the first mode in which drag-free motion of the reference test mass is established. The electrostatic force commands for the reference test mass are nulled, and the DCS spacecraft position control commands the thrusters to follow the test mass along the three translational degrees of freedom. This transition can be seen in Figure 7 and the corresponding CMNT commands shown in Figure 8. As shown in the figures, the transition was not stable. DCS force commands grew to large, unsustainable levels, while the thrust commands oscillated between minimum and maximum values. The transition was aborted at 11:12 UTC by commanding the spacecraft back into ZG. The behavior at transition into DFLF was attributed to the initialization transients of a rate filter in the drag-free controller, which uses the sensed test mass position errors. The drag-free controller has a considerably large bandwidth compared to the attitude controller in order to meet the drag-free requirements below 30 mHz. Analytical simulations and simulations on the real-time testbeds at NASA and ESA had confirmed the existence of transients at this mode transition. However, while the transients resulted in a period of saturated thrust commands, they had never resulted in a failure to transition into the mode. The likely cause of deviation from past behavior has to do with the thruster response. Several thrusters, particularly Thruster 1, were suffering from slow and limited response due to bubbles in the line. This exacerbated the dynamics to the point of instability.

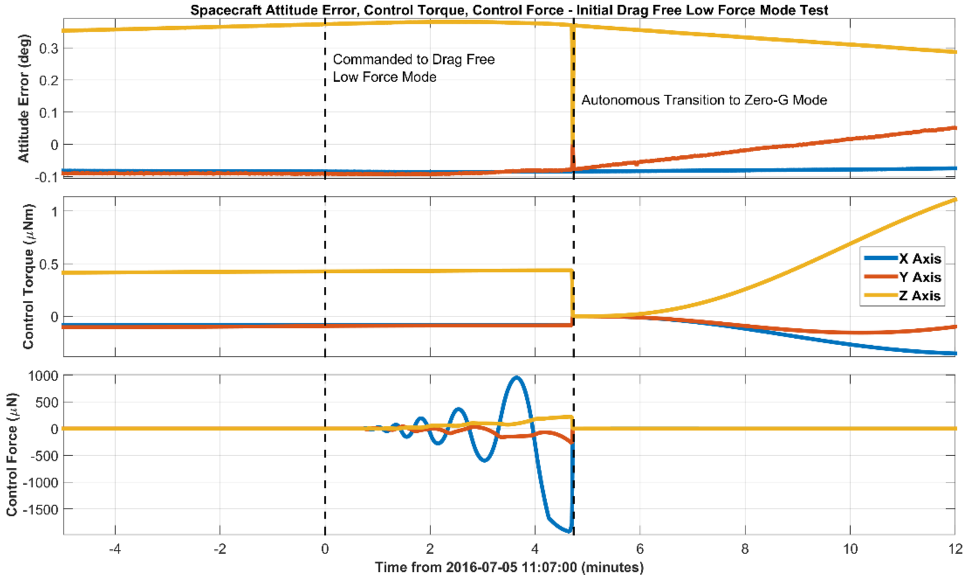

Figure 7. Spacecraft Attitude Error, Torque and Force Commands

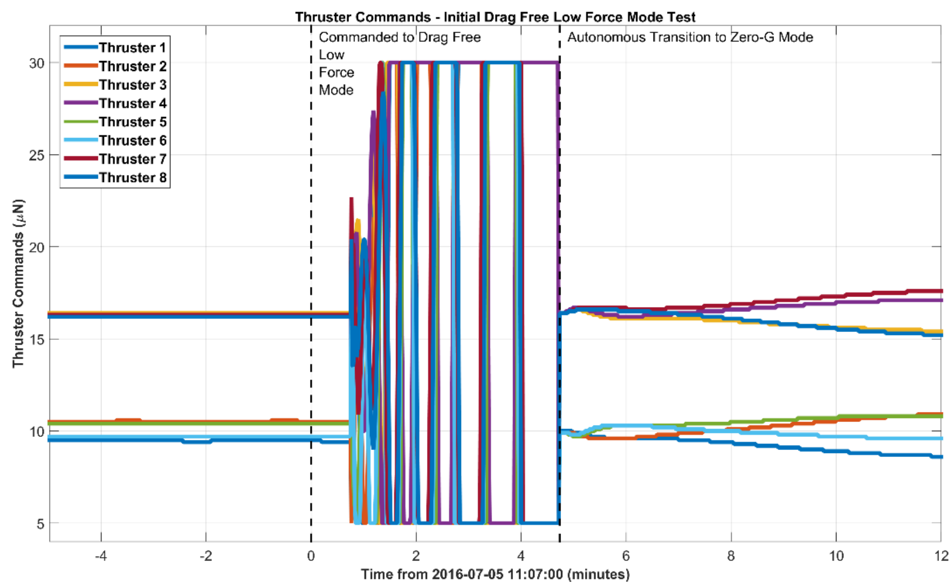

Figure 8. Colloidal MicroNewton Thruster Commands

A two-pronged approach to reduce the DCS command variations at the transition was considered and implemented at the next signal acquisition on July 6. First, the reference test mass force mode was switched from High Force to Low Force while in Zero-G Mode, prior to transition into the DFLF. Capacitive sensing in Low Force is considerably less noisy than sensing in the High Force mode. On July 6 at 5:30 UTC, the reference test mass was commanded into Low Force Mode and then at 5:50 UTC the control system was commanded into DFLF. The transition to DFLF was successful and the spacecraft was left in that mode for three hours. Although the DCS force and thruster commands at the transition into DFLF were considerably reduced and the transition was successfully, the variations were too high given the slow response of Thruster 1.

Hence, in addition to an earlier transition into Low Force on the reference test mass, the DFLF control system was also changed via table update to limit spacecraft force commands to 5 µN per axis. The limits would serve to further cap the variations in the thrust commands, thereby reducing dynamic demand on Thruster 1. After this change was made, another test of DFLF was begun at 11:00 UTC. The transition was successful (see Figure 9), with substantially reduced thruster demand (Figure 10). Note that upon transition into DFLF, control force commands to the reference test mass go to zero, as shown in Figure 11. The spacecraft successfully remained in mode for the remainder of the pass and was left in DFLF overnight.

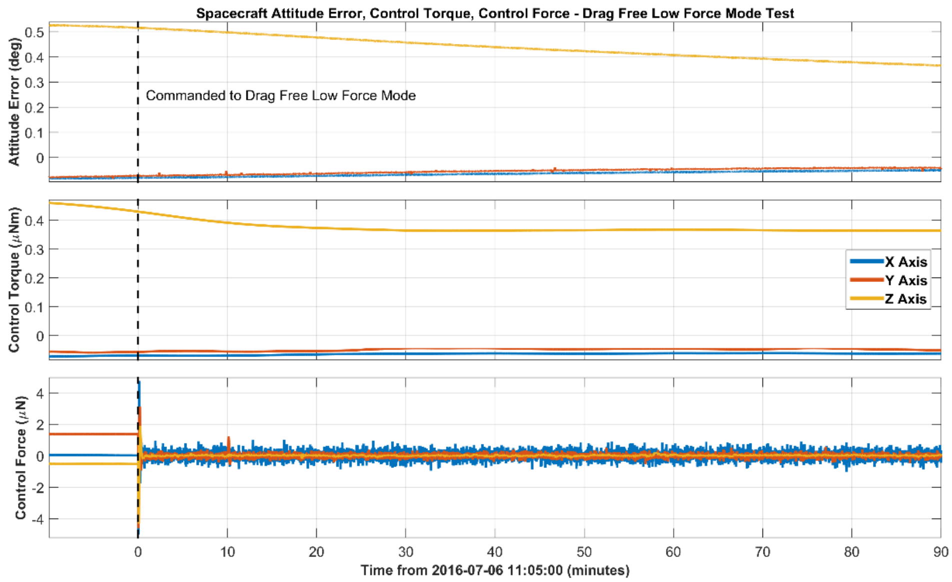

Figure 9. Spacecraft Attitude Error, Torque and Force Commands

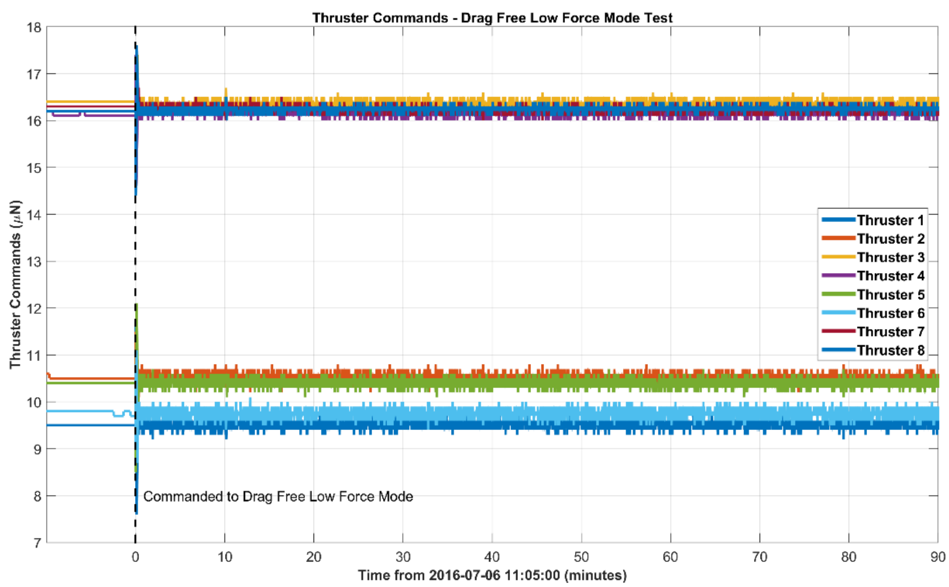

Figure 10. Colloidal MicroNewton Thruster Commands

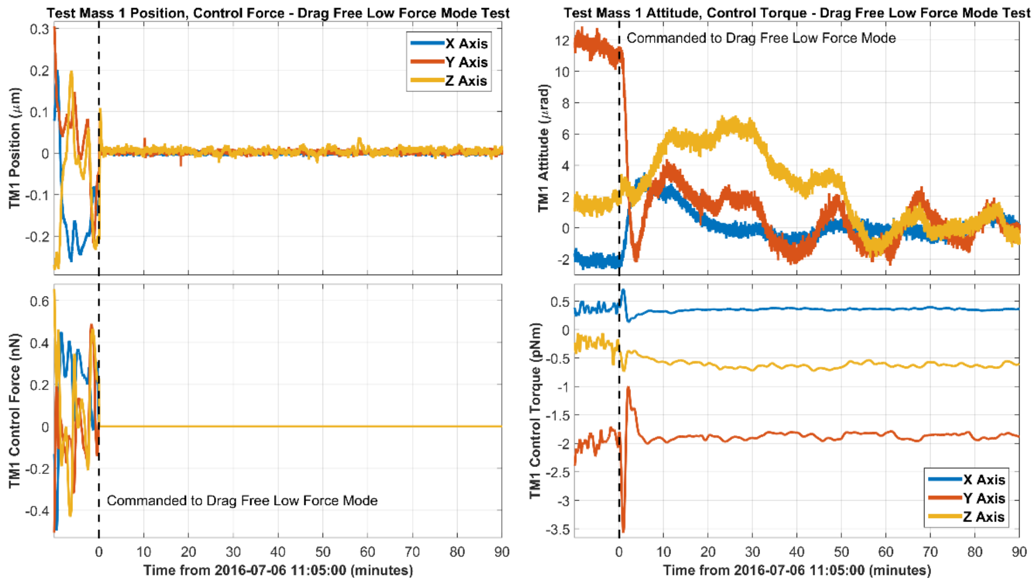

Figure 11. Test Mass 1 Position and Attitude Errors, Force and Torque Commands

Final Commissioning Tests

Tests were run on July 7, 2016, to verify the remaining command sequences needed for the experiment phase of the DRS mission. The activities included test mass signal injection, single thruster open loop test, freeze thruster open loop test, and system level delays. The test mass signal injection activity was used to verify that a sine wave could be injected into the reference test mass position measurement used by the DRS drag-free spacecraft controller. The single thruster open loop test was designed to take one thruster out of the DRS control loop and verify that the DRS was able to maintain control. The third activity was a freeze thruster open loop test, designed to verify that the spacecraft was in a quiet state and could be left to drift for an extended period without handback to LISA Pathfinder. The final activity was to measure the overall system delay from the DCS control system issuing a command and seeing the test mass respond to the command. Unfortunately, the system delay could not be accurately measured due to the low level of actuation force and torque available. Other than the system delay test, all other tests were successful.

This completed all tests that had been put on the commissioning timeline. While the DCS had not yet been commanded into its 18-DOF Transitional or 18-DOF Modes, this activity was planned for the following week. On the final day of commissioning, some additional tests were run that were not initially in the timeline. This included testing the capability of DRS to use OMS measurements within its control loop, as well as confirming the ability to use test mass 2 as the reference test mass. Again, all of these tests were successful.

THRUSTER COMMAND ANOMALY AND RECOMMISSIONING

At the end of the pass on July 8, after a second successful week of commissioning, the spacecraft was left with DRS under control in the ZG Mode. The following week was scheduled to be the first week of nominal operations, but JPL and Goddard personnel planned to continue in-person support at the European Space Operations Centre (ESOC) to support initial testing of the DCS 18-DOF Mode. The last major function of the DCS to be tested at the beginning of the third week was transitioning through the 18-DOF Transitional (18DOFT) Mode into the 18-DOF (18DOF) Mode. In 18DOF, the spacecraft flies drag-free about the reference test mass and simultaneously flies drag-free about the non-reference test mass along the sensitive axis (the axis joining the two test masses) within the frequency range of interest, from 1–30 mHz.

Unfortunately, while out of contact overnight, DRS experienced its first significant anomaly, with an apparent reset of thruster cluster 2, which housed Thrusters 3, 4, 7, and 8. When the cluster dropped out, the output from all four thrusters went to zero and the spacecraft went unstable. After exceeding fault detection limits, the LISA Pathfinder control system took back control from DRS and safed the spacecraft. As a result of this anomaly, the week of July 10 was devoted to diagnosing and troubleshooting the cause of the anomaly. To summarize the extensive anomaly investigation, by the end of the week it was determined that the likely cause of the anomaly was a fault in the Digital Control Interface Unit (CMNT firmware), possibly due to some single event effect, causing the hardware logic that processes thrust commands to reset the cluster whenever it received a thrust command, in the Thrust Command Mode.

Fortunately, the DRS flight software already had the capability to command the thrusters in what was known as Thrust Diagnostic Mode. In the nominal Thrust Command Mode, commands are sent to each thruster in μN and firmware running within the electronics determines the beam voltage and current settings needed to achieve that thrust. In Thrust Diagnostic Mode, the flight software had the capability to command each thruster directly via the low-level voltage and current commands. While this capability existed within the DRS flight software and had been tested, it had never been run or tested while running under closed-loop control with the DCS control algorithms. Over the next three weeks, engineers at JPL and GSFC made the necessary changes to flight software, simulation testbeds, and operational procedures in order to test the capability to run the DRS mission using Thrust Diagnostic Mode. This was successfully tested on the LPF Real-Time Test Bench during the first week of August, and members of the DRS team returned to ESOC for a week of recommissioning the week of August 8.

The first three days of the recommissioning period passed successfully. On August 8, the DRS was powered on and the thrusters were configured. The next day saw DRS assuming control of the spacecraft for the first time post-anomaly, with a brief handover-handback test, followed by maintaining control in AC and ZG Mode. On August 10, thruster signal injection and open-loop tests were run, followed by commanding the spacecraft into DFLF Mode. Performance in all of these tests, in AC, ZG, and DFLF, was similar to the performance during tests run during the initial commissioning period and shown earlier in the paper.

Finally, on August 11 and 12, DRS control of the spacecraft was successfully transitioned through the 18-DOF Transitional Mode into the 18-DOF Mode. On the first use of 18DOF, a configuration error in the spacecraft parameters resulted in the transition from 18DOFT to 18DOF occurring much more quickly than desired. Nonetheless, performance of 18DOF was nominal. After the initial 18DOF test, the DRS was commanded into ZG and the spacecraft was configured to allow the DCS to use the output of the LPF OMS in place of capacitive measurements for the applicable degrees of freedom (position along the sensitive axis as well as two axes of attitude about this axis) of both test masses. The benefit of the successful execution of this test is that the OMS measurements are much less noisy than the capacitive measurements of test mass position and orientation and would enable better measurements during future tests.

On August 12, the final day of the recommissioning period, a second test of 18DOF was run, this time with the correct amount of time for the 18DOFT to 18DOF transition. This test ran successfully, as shown below. Figure 12 and Figure 13 show the spacecraft attitude, control torques and forces, along with the CMNT thruster commands. Note that the thrust command variations in 18DOF are much greater as a result of the flying the spacecraft drag-free (at least partially) about both test masses. Figure 14 and Figure 15 show the position and attitude, force and torque commands for both test masses. Note that in the control force plot of Figure 15, it appears that the x-axis control force has gone to zero, which is consistent with the spacecraft flying drag-free about the sensitive axes of both test masses. It is not possible to be completely drag-free about both test masses, along the same axis, however. Figure 16 shows the detail of the control force plot, showing the small command force going to test mass 2 well below the DRS measurement band.

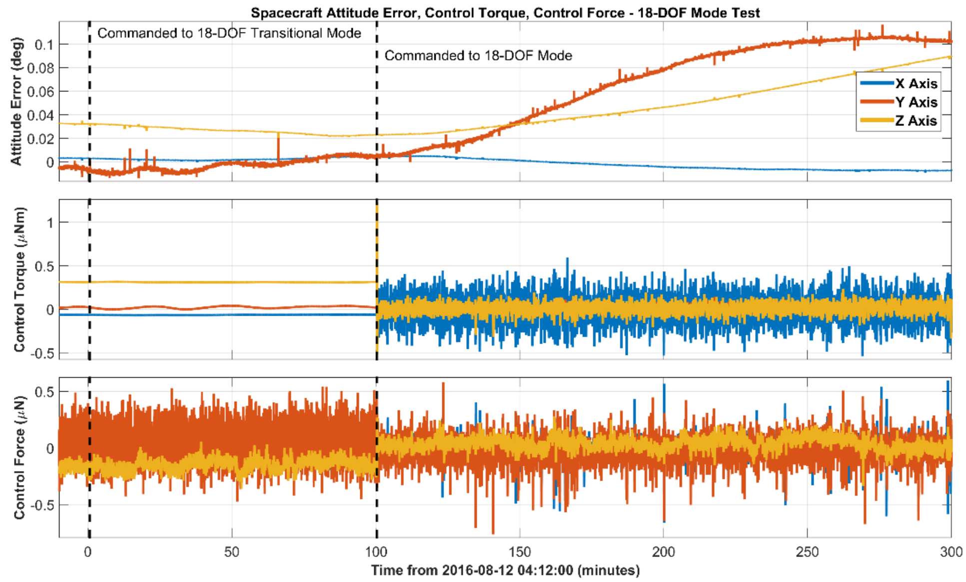

Figure 12. Spacecraft Attitude Error, Torque and Force Commands

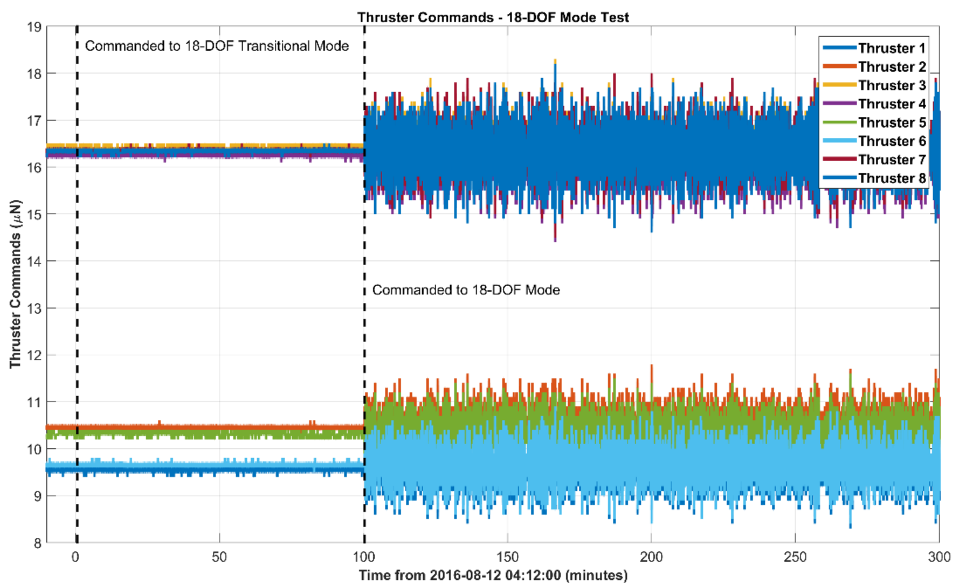

Figure 13. Colloidal MicroNewton Thruster Commands

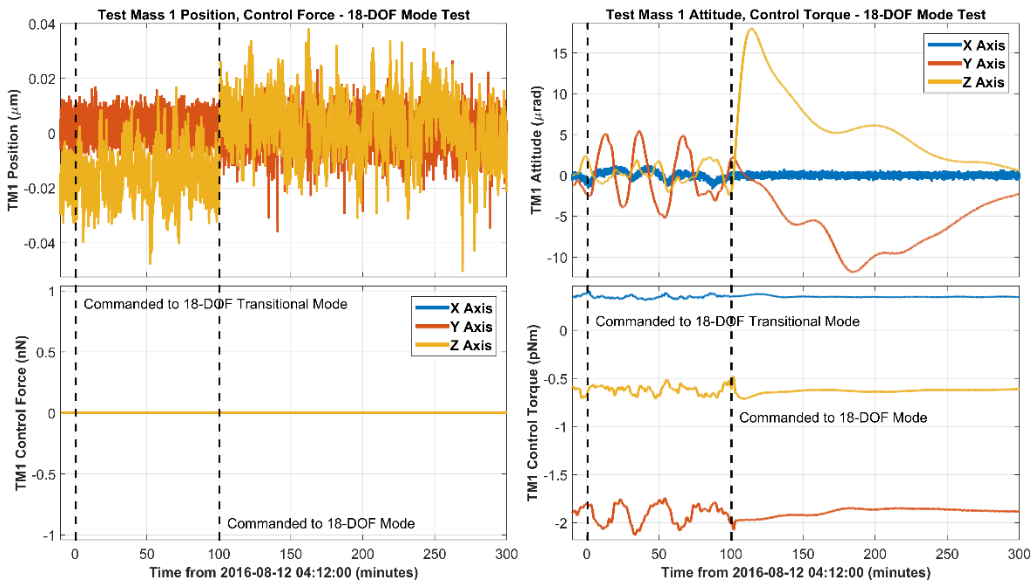

Figure 14. Test Mass 1 Position and Attitude Errors, Force and Torque Commands

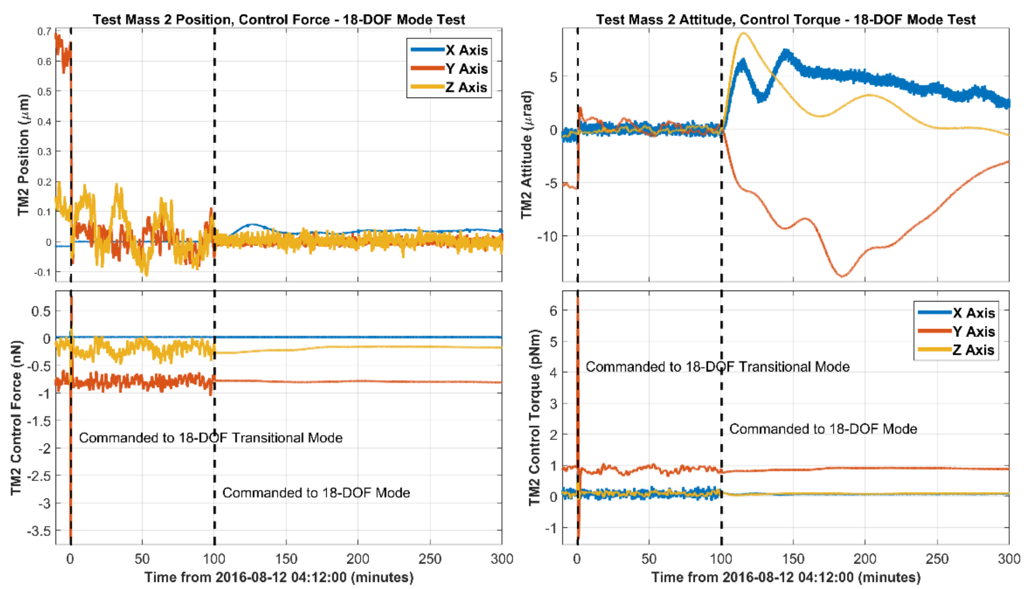

Figure 15. Test Mass 2 Position and Attitude Errors, Force and Torque Commands

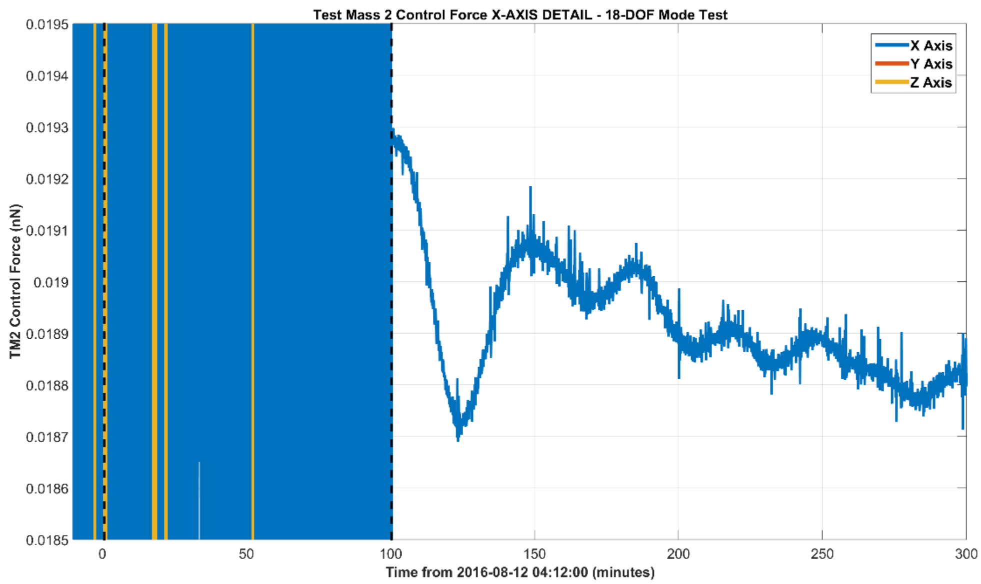

Figure 16. Test Mass 2 X-Axis Force Commands

With the recommissioning tests described above complete, the DRS experiment was ready to commence nominal operations.

CONCLUSION

The ST-7 DRS launched on December 3, 2015 aboard the LISA Pathfinder spacecraft after more than a decade of development. The commissioning of the DRS was divided into two periods, with a recommissioning period added on after a thruster anomaly. All three commissioning periods were highly successful, with all DCS modes and mode transitions verified

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