

# THE SPACE TECHNOLOGY-7 DISTURBANCE REDUCTION SYSTEM

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## ABSTRACT

The Space Technology 7 Disturbance Reduction System (DRS) is an in-space technology demonstration designed to validate technologies that are required for future missions such as the Laser Interferometer Space Antenna (LISA) and the Micro-Arcsecond X-ray Imaging Mission (MAXIM). The primary sensors that will be used by DRS are two Gravitational Reference Sensors (GRSs) being developed by Stanford University. DRS will control the spacecraft so that it flies about one of the freely-floating Gravitational Reference Sensor test masses, keeping it centered within its housing. The other GRS serves as a cross-reference for the first as well as being used as a reference for the spacecraft's attitude control. Colloidal MicroNewton Thrusters being developed by the Busek Co. will be used to control the spacecraft's position and attitude using a six degree-of-freedom Dynamic Control System being developed by Goddard Space Flight Center. A laser interferometer being built by the Jet Propulsion Laboratory will be used to help validate the results of the experiment. The DRS will be launched in 2008 on the European Space Agency (ESA) LISA Pathfinder spacecraft along with a similar ESA experiment, the LISA Test Package.

## 1. INTRODUCTION AND OVERVIEW

The Space Technology 7 (ST7) mission is a Disturbance Reduction System (DRS) flight validation experiment within NASA's New Millennium Program [1]. New Millennium Program missions are intended to validate advanced technologies that have not flown in space in order to reduce the risk of their infusion into future NASA science missions. DRS incorporates two new technologies: a highly sensitive Gravitational Reference Sensor (GRS) to measure the position and attitude of a spacecraft with respect to an internal free-floating test mass, and a set of Colloidal MicroNewton Thrusters (CMNT) to provide low-noise control of the spacecraft for drag-free flight. The DRS is scheduled to fly on the European Space Agency's (ESA) LISA Pathfinder (LPF) spacecraft in 2008, (LISA Pathfinder is an ESA mission funded by the ESA member states and NASA) and will operate in an orbit about the Earth-Sun L<sub>1</sub> point. The DRS is designed to maintain the spacecraft's position, with respect to the GRS free-floating test mass, to less than 10 nm/ $\sqrt{\text{Hz}}$ , over DRS's science band, a frequency range from 1 to 30 mHz. This requirement will help ensure that the residual accelerations on the GRS test masses (beyond gravitational acceleration)

will be below  $3 \times 10^{-14} [1 + (f/3 \text{ mHz})^2] \text{ m/s}^2/\sqrt{\text{Hz}}$ , the DRS goal. The DRS instrument package consists of two Gravitational Reference Sensors, two sets of four Colloidal MicroNewton Thrusters each for position and attitude control, a pair of interferometers to measure the distance of each test mass with respect to the spacecraft in the direction of the separation between the test masses, and associated electronics. Additionally, DRS will receive star tracker attitude quaternions from the LISA Pathfinder spacecraft. Fig. 1 shows a schematic of the elements of the DRS.

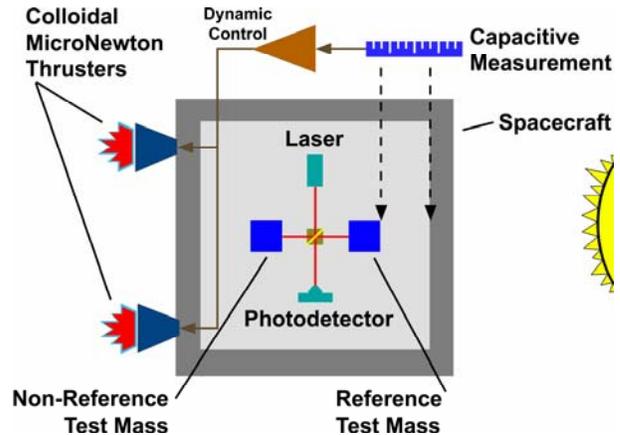


Fig. 1 DRS Schematic

The drag-free goal is to use small thrusters to fly a spacecraft about a test mass such that the test mass follows a purely gravitational trajectory, unaffected by the spacecraft or any external disturbances. The performance measure for a gravitational reference sensor is the residual acceleration in the frequency band of interest (dictated by the mission). These residual accelerations come from sources such as time varying temperatures, residual gas pressure, magnetic forces acting on the test mass, internal gravity between the test mass and the spacecraft, and cross-talk from the GRS electrostatic suspension control.

The first drag-free mission, known as TRIAD-1, was flown in 1973 [2]. Fig. 2 shows the residual acceleration performance of TRIAD and the operational mission GRACE, the required performance of future missions EX-5 and LISA, as well as the baseline and minimum performance expected from DRS. The DRS goal at the time of its inception was to demonstrate a level of residual acceleration more than four orders of magnitude lower than previously demonstrated in space

(now closer to three orders of magnitude with the launch of GRACE) [3].

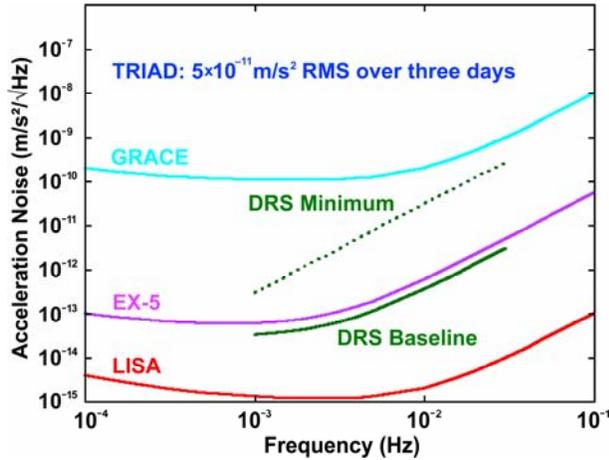


Fig. 2 DRS Performance Requirement

The purpose of this paper is to give an overview of the DRS mission, discussing the four major components. First, the two new technologies will be discussed, the Gravitational Reference Sensors and the Colloidal MicroNewton Thrusters. Then the Dynamic Control System (DCS) being designed to provide six degrees of freedom control to DRS will be explained, followed by a discussion of the laser interferometers used to provide experiment validation.

## 2. GRAVITATIONAL REFERENCE SENSORS

The Gravitational Reference Sensors are being developed by Stanford University [4]. Fig. 3 shows a cutaway view of the GRS assembly, which holds both GRSs. Each of the two GRSs will consist of a 4 cm Au/Pt cube, a ceramic housing with gold plated electrodes, a titanium vacuum enclosure, a pneumatic caging mechanism, an ultraviolet charge (UV) control system, and electrostatic suspension electronics. The position of the test mass is determined by measuring the capacitance between the test mass and 14 electrodes. These electrodes are also used to apply electrostatic forces on the test mass for the control of certain degrees of freedom, depending on what GRS control mode is being used. The main performance requirements of the GRS are to sense the position of the test mass with an accuracy of  $3\text{nm}/\sqrt{\text{Hz}}$  and to reduce test mass residual acceleration to no greater than  $3 \times 10^{-14} [1 + (f/3 \text{ mHz})^2] \text{ m/s}^2/\sqrt{\text{Hz}}$ , both within the science band of 1–30 mHz.

Two sensors are being flown to allow the spacecraft to be flown drag-free with respect to one test mass (the Reference Test Mass or RTM) while using the second (the Non-Reference Test Mass or NTM) for validation. The measurements of these two test masses during drag-free flight along with interferometer measurements of their relative position will provide the validation of the technology.

The GRS has eight electrostatic control modes. Three of these, Standby, Damping, and Interferometer Calibration, are used for initial handover or for special calibrations, and are not used by any of the DCS spacecraft control modes. In GRS Accelerometer mode, the test mass is held centered in its housing electrostatically and the applied forces are output as a measure of spacecraft acceleration. The Drag Free and Suspended modes are used to support drag-free operation of the spacecraft and correspond to the GRS control applied to the RTM and NTM, respectively. Both modes control the orientation of the test masses with respect to their housings and output gap measurements of the test mass position with respect to its housing in all three axes. Suspended mode also provides translational control of the NTM at frequencies below the science band. The last two modes provide the same functionality as Drag Free and Suspended, but use the interferometer translational measurement along the axis connecting the two test masses (called the sensitive axis) in place of the electrostatic measurement.

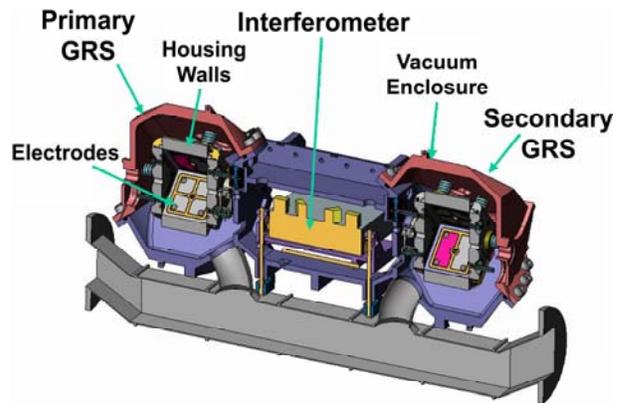


Fig. 3 The Gravitational Reference Sensor

Controlling both the test masses and the spacecraft about them is a very difficult, highly coupled problem. While providing the primary sensor information to the DCS, the GRS must also control the two test masses as described above. A Simulink-based GRS Performance Model was developed to simulate the performance of the GRS (see Fig. 4) and as a basis for control design.

By integrating the design requirements, analyses, and experimental data of the various subsystems with a dynamic simulation of the sensor, the overall performance of the instrument can be predicted and control laws designed. The performance model has these three key subsystems: a force model that converts position and commanded force into an actual test mass force, including external noise sources, a measurement model that converts actual test mass position into measured position and includes measurement noise, and a control system model that emulates the data acquisition system and control laws implemented in flight software.

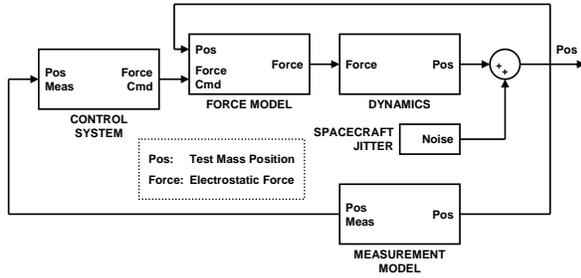


Fig. 4 GRS Performance Model

The most difficult GRS electrostatic control mode to design is the Suspended mode. This control law is used in the sensitive direction of the NTM and must serve sometimes contradictory aims.

First, it must control the test mass position, which is naturally unstable due to the negative spring constant associated with the electrostatic force between the test mass and any electrode. The GRS model has the following transfer function relating test mass position to the force applied to the test mass:

$$G_p(s) = \frac{X(s)}{F(s)} = \frac{1/m}{s^2 - k/m}, k < 0$$

$m$  is the mass of the test mass and  $k$  is the spring constant acting between the test mass and the housing. Given the values of  $m$  and  $k$ , the GRS has an unstable pole on the real axis at a frequency of 1 mrad/sec. To stabilize this system, the controller must provide phase lead at some frequency above 1 mrad/sec. This implies that the controller has significant gain at frequencies higher than 1 mrad/sec. A simple lead-lag network is used for this purpose.

Controller gain is constrained by a second requirement. Force noise produced by sensor noise is amplified by the controller gain and must be small in the measurement band: below  $5 \times 10^{-14} \text{ m/s}^2/\sqrt{\text{Hz}}$  at 1 mHz. In fact, the control law must attenuate its gain by a factor of six between the cross-over at 2 mrad/sec and the start of the measurement band at 6.3 mrad/sec. A third-order Type II Chebyshev low-pass filter is used for this purpose. However, care must be taken to maintain phase margin at cross-over as any low-pass filter will have negative phase where it has gain less than one. This phase loss has an impact on the transient response of the test mass, the source of a third requirement on the controller. The phase margin must be sufficient so that the transient response to an initial offset in test mass position damps out in less than 30 minutes. Finally, the controller uses integral control to reject the steady acceleration disturbance acting on the test mass, expected to be  $10^{-9} \text{ m/s}^2$ . The three parts of the controller (integral, lead-lag, and low-pass filter) are implemented in a digital form with a sample frequency of 10 Hz.

The initial design of the GRS Suspended mode was sufficient to control the NTM in the DCS Science Mode, but because it is highly coupled into the spacecraft control it was difficult to design the Science Mode to meet all of its requirements. This problem was solved by introducing a feedforward force command from the spacecraft controller to the NTM when in Science Mode; this will be discussed in the Dynamic Control System section below.

### 3. COLLOIDAL MICRONEWTON THRUSTERS

The Colloidal MicroNewton Thruster system is being developed by the Busek Co. [5]. Fig. 5 shows the electro-mechanical system for each CMNT cluster of four thrusters. This diagram shows the main elements of the CMNT system: the thrusters, the bellows that hold the colloidal propellant, the valve ( $\mu\text{V}$ ), power electronics (PPU), heater for each thruster, the digital control electronics (DCIU), and the cathode that emits electrons to keep the spacecraft electrically neutral.

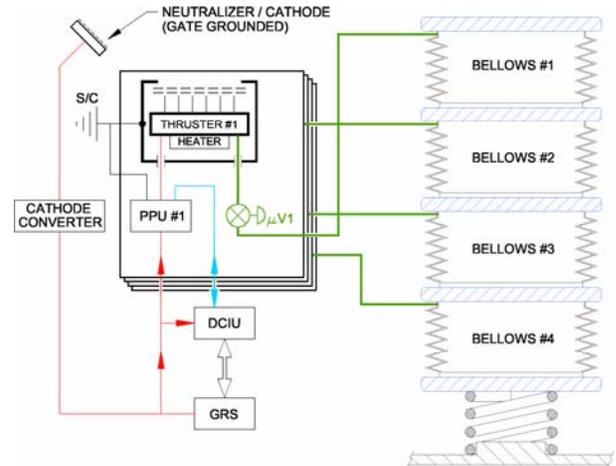


Fig. 5 CMNT Electro-Mechanical System

Each DRS colloidal thruster consists of a set of emitters and electrodes that generate thrust by ejecting and electrostatically accelerating nanometer-sized, positively-charged propellant droplets (colloids) (Fig. 6). The emitters are held at a positive variable voltage by a beam voltage source typically operating at 6kV. The extractor electrode located near the emitters is supplied by a variable voltage, nominally ranging between 1.5kV to 2.5kV below the emitter voltage. The extractor electrode asserts an electrostatic force on the fluid to form the so-called Taylor cone at the tip of each emitter. The cone tip transits into a cylindrical jet, some tens of nanometers in diameter, which ultimately breaks into a fine spray.

After passing through the extractor, the spray is further accelerated as it flows through an accelerator electrode, which is held at a lower potential than the extractor electrode and negative with respect to the neutralizer cathode to prevent neutralizer electrons from flowing back into the thruster.

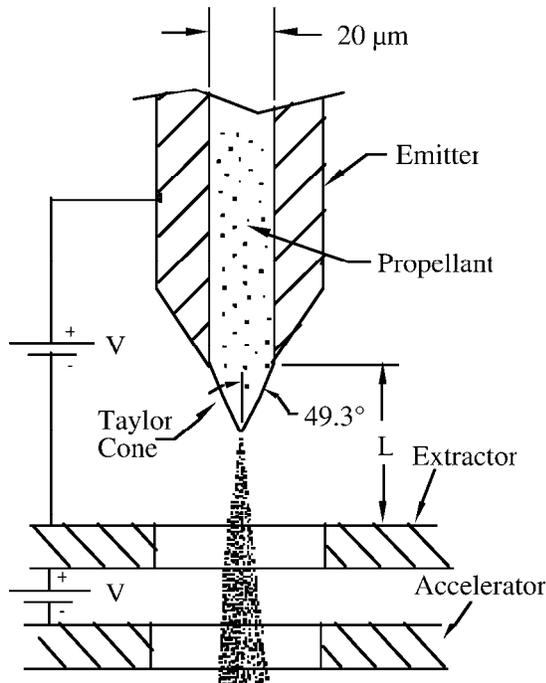


Fig. 6 Colloidal Thruster Schematic

Very precise thrust control is achieved by a combination of valve flow rate control for slow adjustment and beam and extractor voltage control for faster adjustment. Fig. 7 shows an example of the precision valve control, showing spray current steps of 1 nA each (each step corresponding to approximately 0.001  $\mu\text{N}$  of thrust). These parameters are controlled using an algorithm encoded into the CMNT microcontroller firmware that processes externally computed thrust commands into the appropriate voltage and spray current settings. The CMNT microcontroller can also be commanded directly with current and voltage through override commands; this gives DRS the capability to update the CMNT control algorithm in flight through software running in the spacecraft main computer.

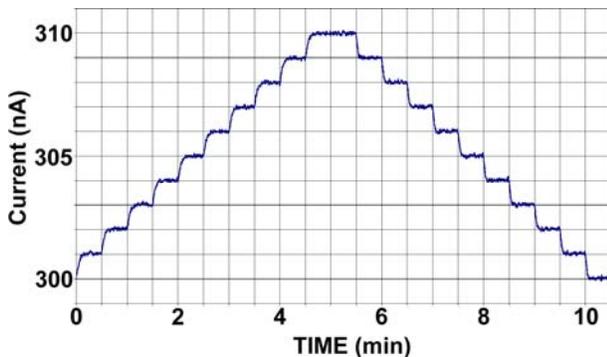


Fig. 7 CMNT Precision Control

Fig. 8 shows one of two identical CMNT clusters to be flown on DRS. Each cluster consists of four thruster systems and a single neutralizer cathode. The initial cluster design was symmetric, with each thruster canted at an elevation angle of  $45^\circ$  from the plane parallel to

the sunline and oriented with azimuth angles of  $\pm 45^\circ$  and  $\pm 135^\circ$  from the sunline.

As the DRS Dynamic Control System was designed, it became clear that this was not the best orientation for the thrusters for two reasons. Because it is not possible to easily turn thrusters on and off, the normal mode of operation is to have all thrusters on at some nominal bias thrust, with attitude and translation control being performed by variations from that bias level. Because the two thrusters facing away from the sun in each cluster need to fight the solar pressure force, they need to be able to exert more force along the sunline than the thrusters facing the sun. Also, because constraints imposed by ESA limited DRS to two thruster clusters, DRS has very weak torque control authority along the axis connecting the two clusters.

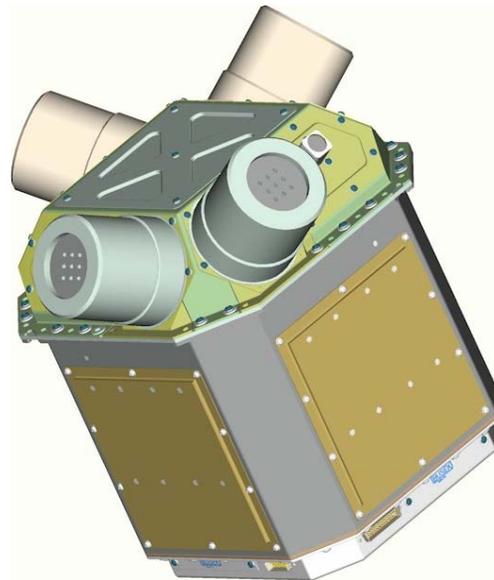


Fig. 8 DRS CMNT Cluster

The final thruster configuration was chosen to increase the torque authority about the weak axis and even out the bias levels of the sun-facing and anti-sun thrusters, while still satisfying contamination requirements. The elevation angle of all thrusters was lowered to  $35^\circ$  while the two sun-facing thrusters of each cluster were spread out to azimuth angles of  $\pm 65^\circ$ .

#### 4. DYNAMIC CONTROL SYSTEM

The Dynamic Control System (DCS), designed by the Goddard Space Flight Center and the Hammers Co., consists of the control algorithms and flight software needed to compute CMNT thrust commands based on GRS and star tracker measurements, and is implemented as five distinct control modes: Attitude-Only (AO), Accelerometer (AC), Initial Drag-Free (DF1), Interim Drag-Free (DF2), and Full Drag-Free/Science Mode (SM). In AO mode, star tracker information is used to control the attitude of the spacecraft; this mode is used for initial handover of control to DRS. AC mode continues to control spacecraft attitude using star tracker

information while using force outputs of one GRS in its Accelerometer electrostatic control mode to attempt to null external forces acting on the spacecraft. AC mode is the first mode in which the spacecraft will fight the solar radiation pressure force acting on the spacecraft in a closed-loop fashion. The test mass within the GRS used for AC mode is the RTM.

The next mode, DF1, is the first drag-free mode. In DF1, the RTM is placed in the GRS Drag Free mode, and the spacecraft flies about the RTM. In this mode, star tracker information is still used to provide the information needed for coarse attitude control. The DF2 mode begins to bring the NTM “online”. In DF2, the spacecraft continues to fly drag-free about the RTM, while force outputs from the NTM in GRS accelerometer mode are used to reduce accelerations seen at the NTM. Finally, the SM mode uses position outputs from the RTM in GRS Drag Free mode and the NTM in Suspended mode. It is in this mode that the DRS performance requirements must be met.

Fig. 9 shows the different pieces of the DCS SM controller. The top portion of the controller represents the attitude controller and complementary attitude controller, which use the star tracker information and the RTM and NTM positions, respectively, to generate the  $T_{CMD}$ , the torque commands needed to keep the spacecraft pointed at the Sun, as well as establishing drag-free flight for the NTM in the axes transverse to the sensitive axis. Next, the drag-free controller uses the RTM position and  $T_{CMD}$  to generate the force commands needed for spacecraft translational control. The last component of the SM controller uses the low-frequency component of the attitude control to generate feedforward force commands to be used by the GRS NTM Suspended mode controller. This feedforward command helps to decouple the GRS and DCS control loops and improves their robustness and performance.

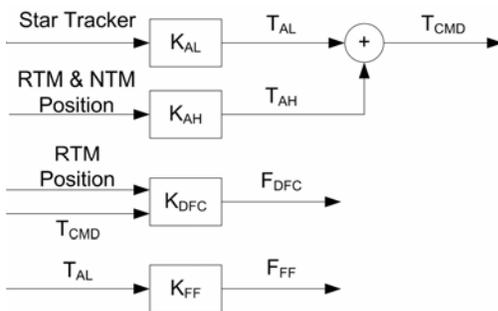


Fig. 9 DCS Science Mode Controller

More details of the design and performance of the DCS controllers can be found in [7–10].

## 5. LASER INTERFEROMETER VALIDATION

The DRS experiment includes a pair of homodyne laser interferometers, being developed by the Jet Propulsion Laboratory, for use in the validation of DRS performance [1]. The interferometer is based on a simple

Michelson interferometer, comparing the distance between the two GRS test masses with the length of a stable reference arm. The reference arm is formed by two mirrors on the optical bench. Fig. 10 shows a diagram of the interferometer.

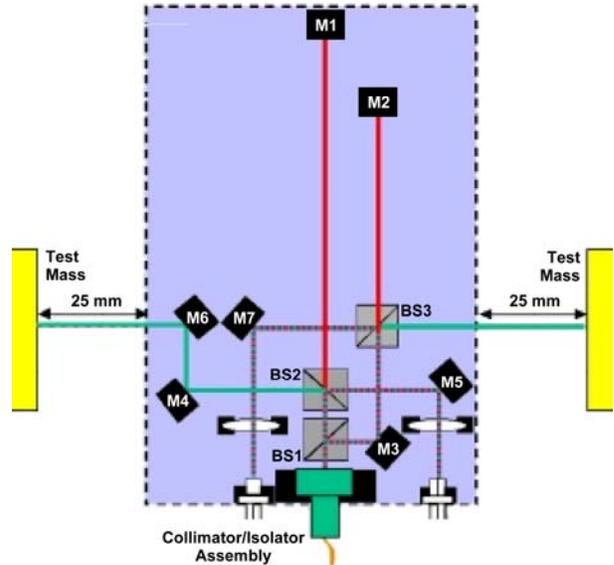


Fig. 10 Schematic of DRS Interferometer

Light from the laser is brought to the optical bench via a fiber. The laser beam is split so that half goes to each of two simple Michelson interferometers which measure the change in distance between each test mass and the optical bench. For each test mass, light from the laser is divided at a beam splitter with half reflected off the test mass and half reflected off a reference mirror. The beams recombine at the beam splitter and are imaged on a quadrant photodiode. A change in the test mass position causes the intensity of the beam on the photodetector to change and is recorded in the GRS computer electronics. This double-Michelson design allows separate readouts for the two test masses. Quadrant detectors are used to measure the angle between the normal to the test mass surface and the laser beam direction. The pointing information is used to adjust the orientation of the test mass by applying voltages to the orientation control electrodes.

## 6. CONCLUSION

Design and development of all major subsystems of the ST7 Disturbance Reduction System continues as the project works towards a 2006 delivery to the European Space Agency and a 2008 launch. DRS operation and performance has been tested in a high-fidelity simulation developed for the mission, with tests conducted to show the validity of the spacecraft and test mass control modes and to demonstrate the transition strategy into Science Mode (see the RTM position error root power spectral density plot in Fig. 11). Testing results demonstrate that the DRS Dynamic Control System, working in conjunction with the GRSs and CMNT, will meet all mission performance requirements.

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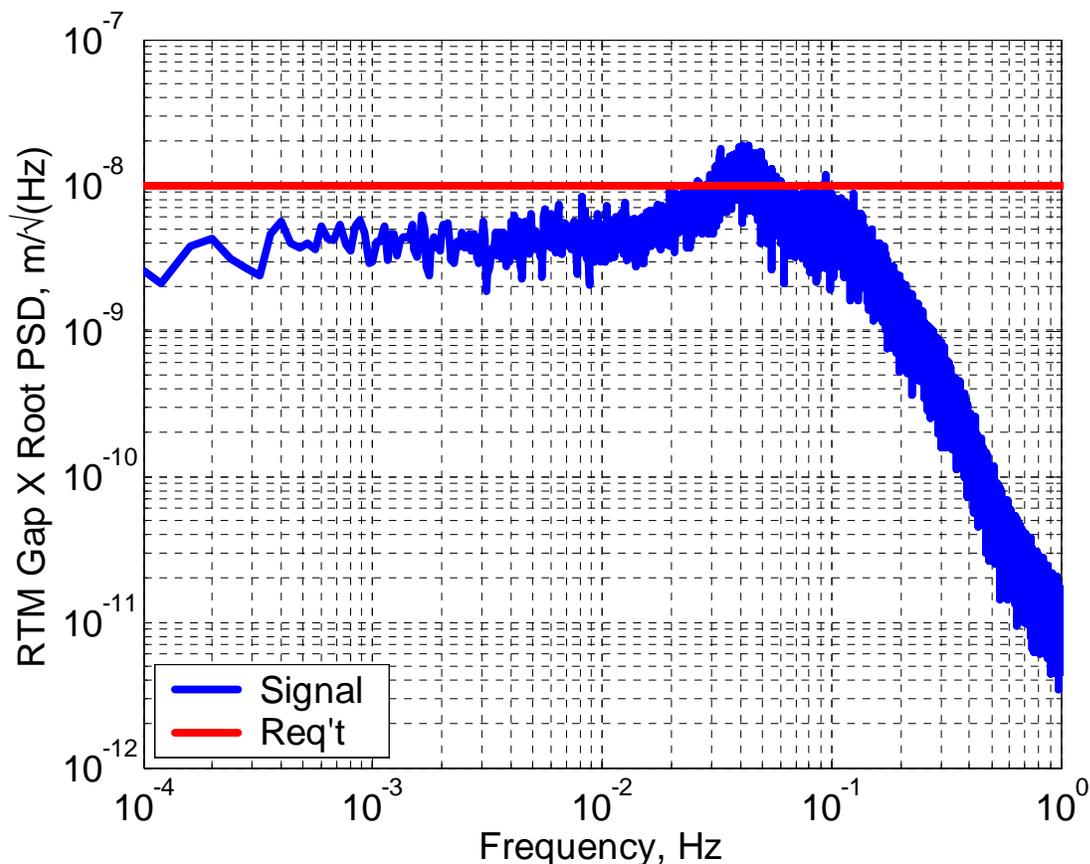


Fig. 11 DCS Science Mode Performance