Plan for Compensation of Self-Gravity on ST-7/DRS

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Abstract

The Space Technology 7 (ST-7) payload, flying on the Laser Interferometer Space Antenna (LISA) Pathfinder (LPF) mission, will demonstrate drag-free control of a test mass with acceleration disturbances below $3x10^{-14}$ m/s^2/√Hz. Low frequency acceleration noise introduced by the electrostatic force needed to counter static mass distribution imbalance is expected to be a significant contributor to the acceleration noise budget. For this reason, the self-gravity (due to mass imbalance) is minimized by adding trim mass to bring the total differential acceleration between the two test masses due to self-gravity below $5x10^{-10}$ m/s^2 in any axis and the DC acceleration gradient due to self-gravity below $4x10^{-8}$ m/s^2/m in any axis of either test mass. A plan has been established to develop the distribution and placement of the compensation masses. Compensation for the self-gravity effects on the two test masses is handled in a two step process. A nominal compensation mass is defined and incorporated early and is located very near the test masses. The final trimming for self-gravity occurs after the integration on the spacecraft with small mass added externally to the test mass vacuum enclosures. The plan identifies three preliminary points in the hardware maturity where the trimming to the as-built configuration can take place: (1) during build-up of the sensor vacuum enclosure, (2) prior to delivery of the integrated ST-7 to Europe, and (3) prior to environmental testing of the integrated LPF system. The sensitivity of the self-gravity to knowledge errors in the actual mass distribution is taken into account in the determination of final trimming opportunities and mounting locations.

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1. Introduction

The Space Technology-7 (ST-7) Disturbance Reduction System (DRS) payload will demonstrate drag-free control of a test mass with acceleration disturbances below $3x10^{-14}$ m/s^2/√Hz. Low frequency acceleration noise introduced by the electrostatic force needed to counter static mass distribution imbalance is expected to be a significant contributor to the acceleration noise budget. For this reason, the self-gravity (due to mass imbalance) is minimized by adding trim mass to bring the total differential acceleration between the two test masses due to self-gravity below $5x10^{-10}$ m/s^2 in any axis and the DC acceleration gradient due to self-gravity below $4x10^{-8}$ m/s^2/m in any axis of either test mass.

A plan has been established to compensate for the self-gravity effects on the two test masses via a two-step process. A nominal compensation mass is defined and incorporated early and is located internal to the Gravitational Reference Sensor (GRS) chassis lids, very near the test masses. These are referred to as Internal Trim Masses (ITMs). The final trimming for self-gravity occurs late in the integration flow with small mass added externally to the test mass vacuum enclosures, on the chassis lids. These are External Trim Masses (ETMs). The plan identifies three preliminary points in the hardware maturity where the trimming to the as-built configuration can take place: (1) during build-up of the GRS vacuum enclosure, (2) prior to delivery of the integrated ST-7 to Europe, and (3) prior to environmental testing of the integrated Laser Interferometer Space Antenna (LISA) Pathfinder (LPF) system. The sensitivity of the self-gravity to knowledge errors in the actual mass distribution is taken into account in the determination of final trimming opportunities and mounting locations.

Section 2 provides an overview of the compensation plan including the contributors to the acceleration noise, a description of the trim masses and overall flow of activities. In section 3, uncertainties in the mass and Center of Mass (CoM) locations are described. Finally, the verification of self-gravity compensation is discussed in section 4.

2. Overview of the Compensation Plan

2.1 Contributors to the acceleration noise budget

The acceleration experienced at the test masses as a result of the uneven mass distribution of surrounding hardware with respect to the test masses decreases with the square of the distance ($1/R^2$) and increases linearly with the mass of the distant object. While there are numerous small components in close proximity to the test masses, there are also several large hardware elements at distances of approximately 0.5m, such as the LISA Test Package (LTP), the thrusters assemblies, and spacecraft module (SCM) electronics boxes.

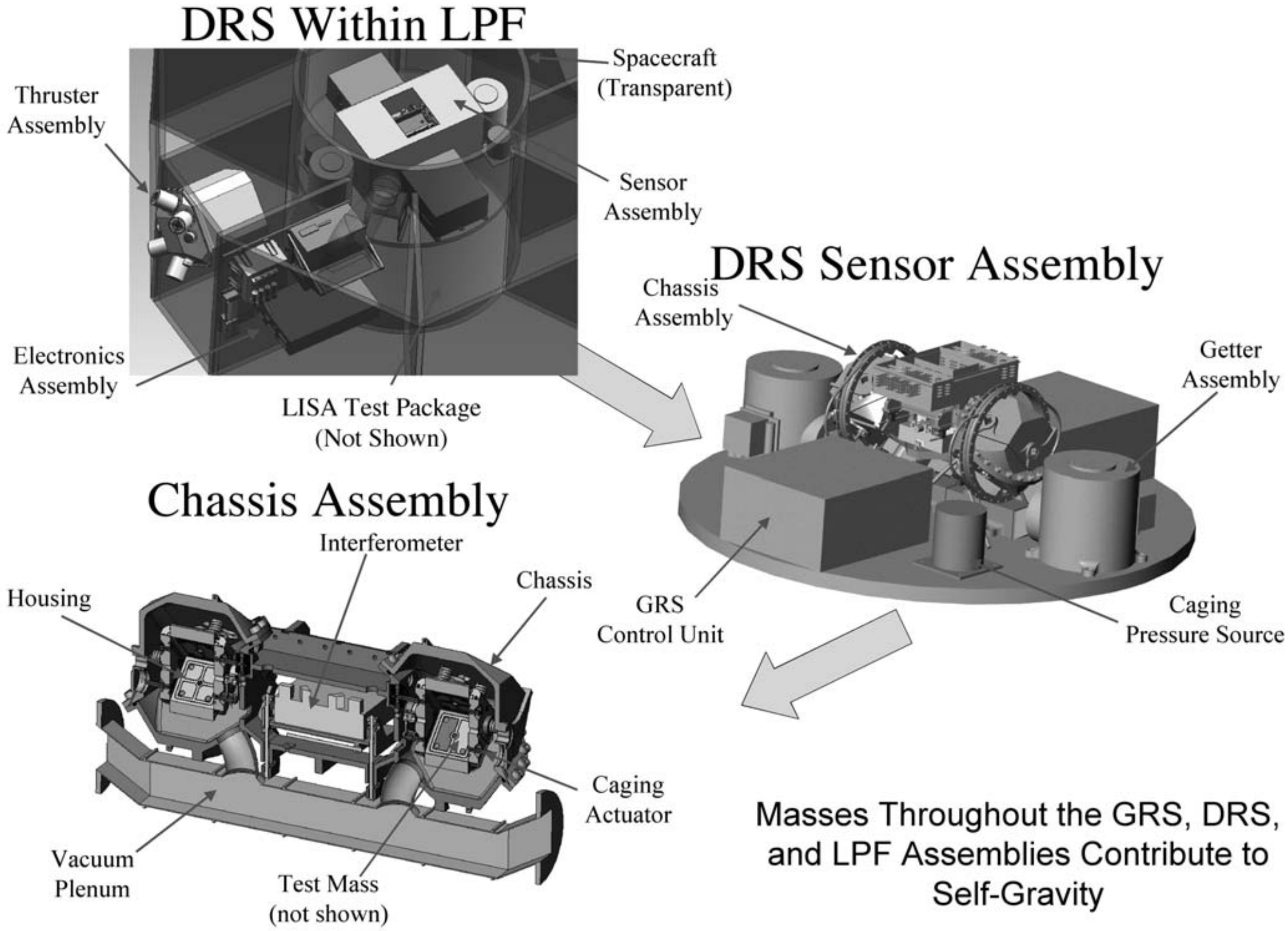

Figure 1. Influences Contributing to Self-Gravity of the DRS. The items within the Chassis Assembly, very near the test masses, are a significant influence on the self-gravity. As one moves away from the test masses, to the overall sensor assembly and elsewhere around the spacecraft and LTP, the distance helps to minimize the effect per unit mass due to the $1/R^2$ relationship of gravity force to distance.

2.2 Description of the trim masses

The trim masses make use of as much available volume internal and external to the GRS chassis as possible. The material selected for the trim masses is an alloy of Tungsten-Copper. This material was selected for four primary reasons:

1. High density: allows more mass to be placed in proximity to the test masses for greatest effect on acceleration field
2. Machinability: allows for tighter tolerances and more freedom in the final shape
3. Coefficient of thermal expansion (CTE): matches very well with the CTE of the titanium chassis lid to which the trim masses are mounted
4. Non-magnetic: does not contribute to the magnetic field-related parameters in the acceleration noise budget

Both the ITMs and ETMs begin as “Blanks.” The Blanks are pre-fabricated to the maximum allowable volume available as defined in the interface control drawing (ICD). Once the final shape is determined, these Blanks are modified and machined into their final shapes. This two-step process is expected to reduce the fabrication time between determination of the final shape and installation of the trim masses, thereby maximizing the time available to directly measure the mass distribution of the flight hardware and complete the self-gravity analysis.

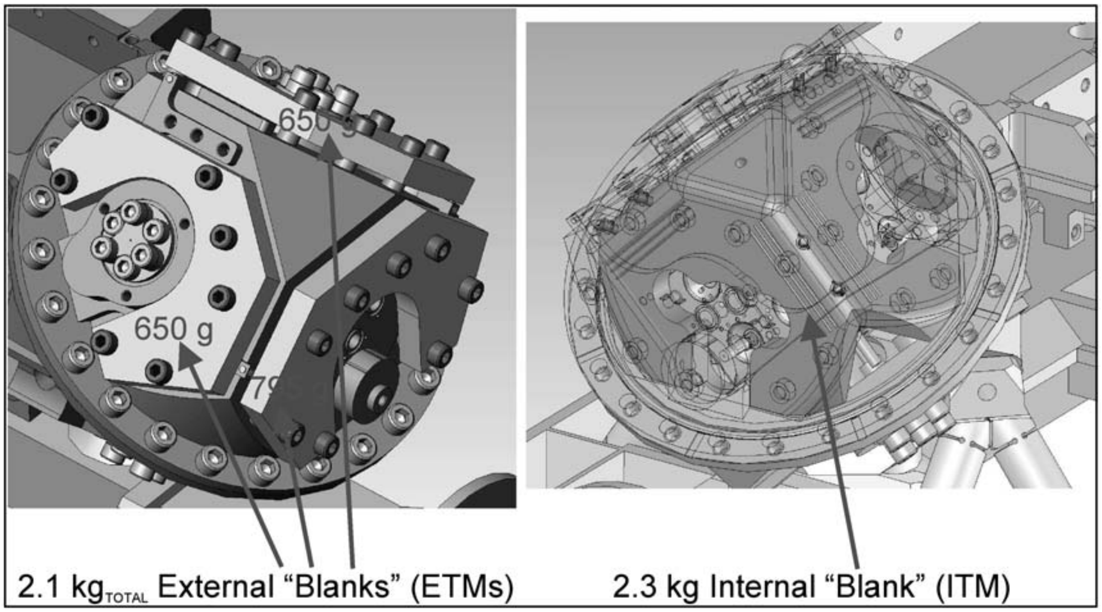

Figure 2. Trim Mass Blanks (full volume prior to machining). The Blanks, mounted both internally and externally to the vacuum chassis, provide a maximized volume to start from for developing the final flight shapes. The blanks represent 4.4 kg of total "capability" per side but it is expected that these blanks will be machined away to a total, per side, of ≤ 1.5 kg.

2.3 Nominal Compensation Using Internal Trim Masses

The location of the ITMs (Figure 2) requires fabrication and installation very early in the DRS development, prior to closeout of the GRS vacuum enclosure. The final configuration of the LPF flight system, particularly of the spacecraft, will not be determined by the time the ITMs are needed. For this reason, the ITMs will be designed to compensate for the hardware contained within the LPF central cylinder. This allows ST-7 to take advantage of the proximity to the test masses by being inside the vacuum enclosure, while still allowing the LPF design to proceed. Final trimming will utilize the ETMs, described in Section 2.5.

The shape chosen for the ITMs begins with the Blank. The shape of the ITM Blank was chosen using hand calculations of the differential acceleration due to DC self-gravity to determine the likely areas where trim mass would be required. Once the likely areas were characterized, the maximum available volume was established. This volume was then refined into the shape of the ITM Blanks by addressing the mounting and virtual leak requirements.

The mounting configuration must be such that there are sufficient holes to attach the final shape of the ITMs, which might be far smaller than the ITM Blank. Also, the ITMs are required to follow design practices consistent with the prevention of virtual leaks (i.e. minimize the potential to trap gases). This requires the use of through-holes wherever possible and features to act as standoffs in order to prevent large surfaces from coming in contact with each other and potentially trapping gases.

The final shapes of the ITMs are determined by using the self-gravity analysis tools to see the effects of variations on the shape of the trim mass via a Monte Carlo analysis. The final shape is then communicated via a modification drawing to the original shape (ITM Blank).

2.4 Final Compensation Using External Trim Masses

As with the ITMs, the shapes defined as ETM Blanks were established to maximize the volume available to the trim masses in regions of the GRS that hand-calculations show to be likely hosts for trimming the differential acceleration and gradients.

The point in the schedule when the flight ETMs are installed is dependent upon the maturity of the DRS, LTP, and SCM gravitational modeling efforts. The DRS is being designed such that the ETMs can be installed very late in the integration flow, as late as just prior to the environmental testing of the integrated LPF flight system. The nominal plan is to install the flight ETMs near the end of DRS integration and test (I&T) at the Jet Propulsion Laboratory (JPL), just prior to DRS environmental testing.

2.5 Self-Gravity Trimming Flow

A flowchart has been developed to highlight the overall phasing and key features of the self-gravity compensation plan.

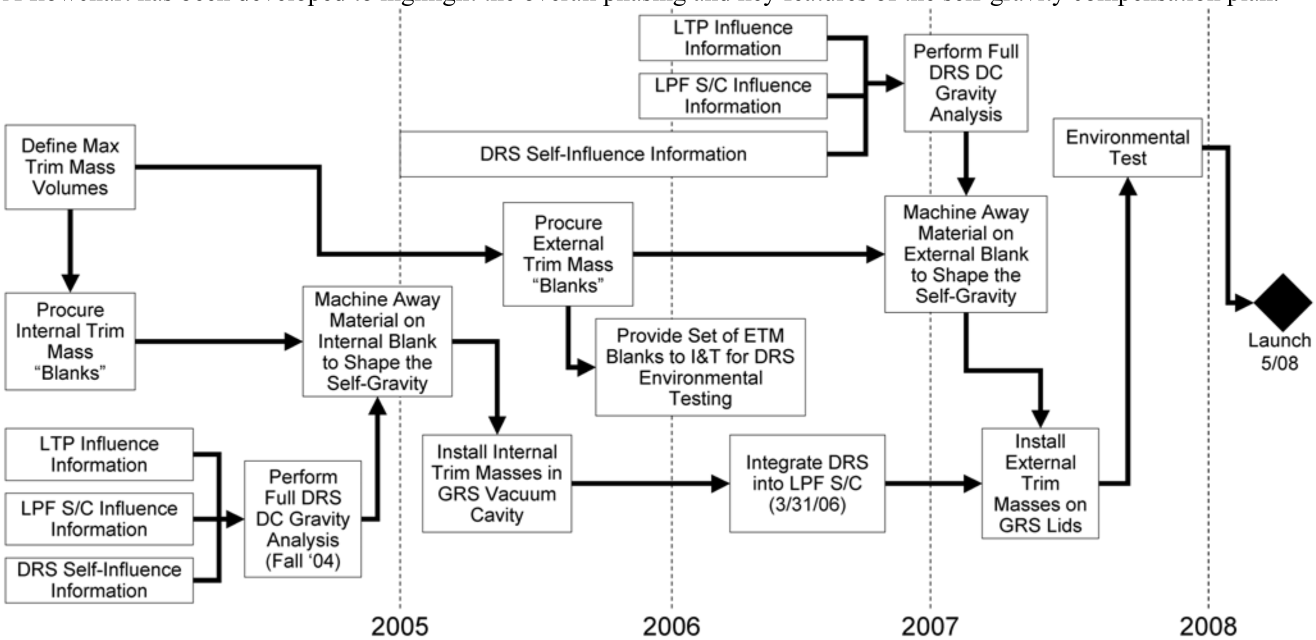

Figure 3. Overall analysis, fabrication, and integration flow for self-gravity compensation. The flow illustrates the early definition of the maximum trim mass volumes and two cycles of influence information gathering (model updates) and associated DC self-gravity analysis. The ITMs are installed into the GRS vacuum cavity in early 2005, with the ETM installation occurring much later, after the DRS has been assembled, tested, and integrated into the spacecraft to ensure the as-built configuration is accounted for properly in the self-gravity compensation.

3. Error Analysis

The relationship between uncertainty in the mass and CoM location of each point mass that is meshed to perform self-gravity analysis has been established and used to identify the mass and CoM location knowledge requirements for each of the DRS components. This relationship reveals a "knee" in the curve of mass or location knowledge error beyond which there is no appreciable reduction in the uncertainty of the computed differential acceleration. The equation for the uncertainty in differential acceleration ($\sigma\Delta a$) as a function of the uncertainty in mass (σ_m) and uncertainty in center of mass location (σ_R) is given in equation (1):

$$\sigma\Delta a = \sqrt{\sigma a_{TM1}^{\;2} + \sigma a_{TM2}^{\;2}} \qquad \text{where} \qquad \sigma a_{TM\_} = \left(\frac{G_o m}{R^2}\right)\sqrt{\left(\frac{\sigma_m}{m}\right)^2 + 4\left(\frac{\sigma_R}{R^2}\right)^2} \tag{1}$$

For a sample case looking at a 75 kg LTP (assumed as a point mass for simplicity in this case), it can be seen from the two plots in Figure 4 that a point is reached for the uncertainties of both location (Sigma R) and mass (Sigma M) beyond which there is no appreciable reduction in the uncertainty of the calculated differential acceleration (Sigma ΔAx).

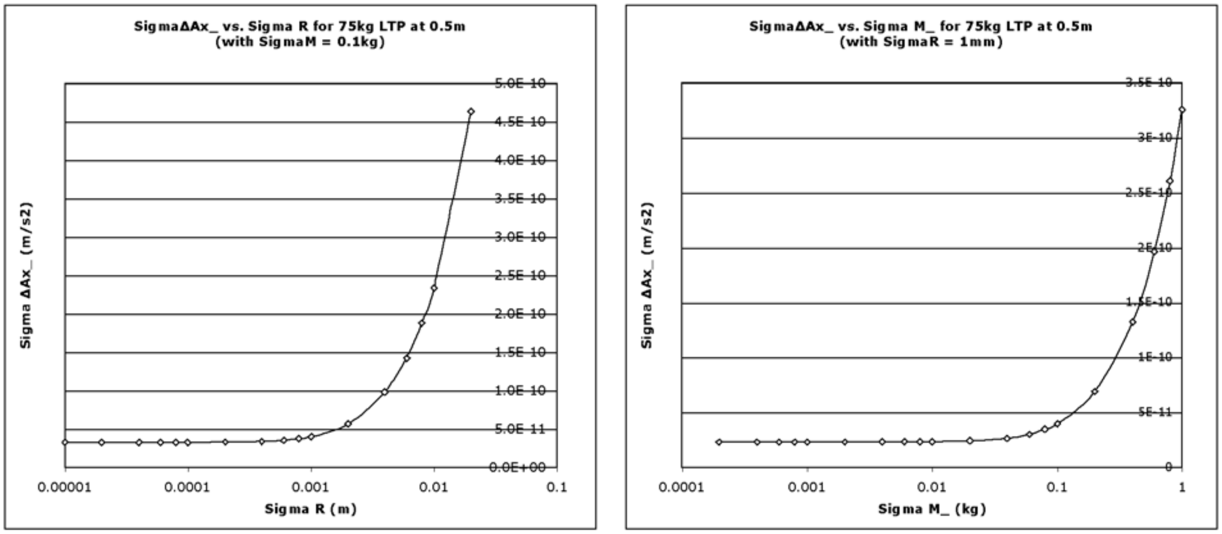

Figure 4. Sample plots from error analysis. The uncertainty in CoM location and the uncertainty in mass both exhibit a "knee" in the curve beyond which there is no significant reduction in the calculated differential acceleration for a reduction in the location or mass uncertainty.

The error analysis used to determine the required mass and location knowledge within the DRS was based on limiting the uncertainty in the calculated acceleration (or differential acceleration) to two orders of magnitude away from the requirement (≤1% of the requirement). Additionally, the establishment of the recommended mesh size (or point mass representation) was developed by calculating the nominal distance from each DRS component to the surface of the closest test mass and then using a ratio developed by Haile [3]. The ratio relates the mesh size to nominal distance from the closest test mass surface and largest dimension of the component in question. The results allowed the project to levy requirements on a per-component basis based on proximity to the test masses and physical configuration. This resulted in some items, such as electronics boards, being treated as point masses and resulting in lower location knowledge error then representing the boards as a mesh due to the ability to directly measure the properties of the item at the board level.

In addition to the analyses performed to date in support of mass and location uncertainty, the effects of deviations in the density of the trim mass material and the final machined shape (machining tolerances) will also be examined. These uncertainties will be examined as part of the determination of the final shape of the ITMs and ETMs using the self-gravity analysis tools.

4. Verification of Self-Gravity Compensation

Compliance to the requirements for differential specific force and specific force gradient cannot be directly verified by test on the ground given the disturbances present relative to the magnitudes being measured. These requirements will be verified by analysis. As such, the focus for verification is on correlating the models and tools to test data wherever practical.

The solid models used as inputs in the self-gravity analysis will be regularly updated and correlated to mass properties data as available. The CoM and mass knowledge requirements on components within ST-7 are quite stringent and the lowest level of direct measurement will be used to correlate the solid models.

The tools used to calculate the differential specific force and specific force gradient are validated largely by running comparison cases that have closed form solutions. In the future, additional validation of the tools may occur by modeling some of the "small forces" testing performed at the University of Washington or the University of Trento. This work is not planned as part of ST-7 but may be carried out under LISA funding using the same self-gravity tools in use for ST-7.

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References

[1] W. Haile, "A Self-Gravity Analysis Tool," unpublished.