GRATTIS: THE GRAVITATIONAL REFERENCE ADVANCED TECHNOLOGY TEST IN SPACE

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ABSTRACT

The Gravitational Reference Advanced Technology Test In Space (GRATTIS) mission will demonstrate the end-to-end functionality and sensitivity performance of the Simplified Gravitational Reference Sensor (S-GRS), an ultra-precise inertial sensor for future Earth geodesy missions. These sensors are used to measure or compensate for all non-gravitational accelerations of the host spacecraft so that they can be removed in the data analysis to recover spacecraft motion due to Earth's gravity field, the main science observable. The S-GRS concept is a simplified version of the flight-proven LISA Pathfinder GRS. It consists of a free-falling cubic test mass inside an electrode housing that senses the position and orientation of the test mass and electrostatically applies forces and torques to it to keep it centered at a nanometer-level. The improved performance of the S-GRS is enabled by removing the small grounding wire used in the GRACE accelerometers, which limits its performance, and replacing it with a UV LED-based charge management system, increasing the mass of the sensor's TM, and increasing the gap between the TM and its electrode housing. GRATTIS will fly two identical S-GRS mounted next to one another at the center of mass of a 160 kg ESPA-class commercial microsatellite with a planned launch in 2027. The six-axis acceleration measurement capability of the S-GRS allows precision measurement of the spacecraft drag-induced translational acceleration, as well as the residual angular acceleration of the nominally inertially-pointed bus. By combining the outputs of each sensor and with the known relative position of the two TMs, we can recover the acceleration sensitivity (noise floor) of the S-GRS.

1 INTRODUCTION

The GRACE (2002-2017) and GRACE-FO (2018-present) missions have provided a 22-year climate data record of Earth system mass change. The utility of the data are incredibly diverse for addressing both scientific hypothesis and serving societal applications. Contributions include quantifying the rate of ice sheet and glacier ablation globally, identifying and quantifying areas of unsustainable groundwater withdrawal due primarily to heavy irrigation, quantifying global and regional sea level changes and ocean heat content (when combined with satellite altimetry), monitoring drought severity through operational assimilation in the U.S. Drought Monitor, and assessment of geohazards, including mapping mass redistributions due to large earthquakes [1].

The sensitivity of low-low satellite-to-satellite tracking missions depends on the orbital characteristics of the mission (altitude, inclination, number of satellite pairs, etc.), the precision of the onboard measurement system (inter-satellite ranging system, accelerometer, attitude and orbit determination), as well as temporal aliasing associated with Earth's dynamic gravity field (Figure 1a) [2]. Two ways have been identified to reduce the impact of temporal aliasing error: (a) sample more frequently via more satellites pairs (example implementation shown in Figure 1(b) [2]), and (b) process the data in an 'along-the-orbital track' approach rather than accumulating observations over a finite number of days which is traditionally done.

Assuming that the impact of temporal aliasing error can be reduced via one of the above two solutions, the precision of the accelerometer becomes important. We find that the precision of the GRACE-FO electrostatic accelerometers (ACC) are insufficient for a multi-pair implementation (Figure 1(b); green dashed curve) at lower altitudes (350 km), and dominate over all other error terms. The S-GRS offers a technological pathway to improve the measurement of non-gravitational accelerations (Figure 1(b)) to an acceptable level for such constellation-type implementations. Furthermore, and perhaps even more importantly, the S-GRS offers a technological solution to measuring non-gravitational forces at a level that is on par with the precision of the laser ranging interferometer (LRI) that was successfully demonstrated on GRACE-FO (Figure 1(a), 1(b) blue and red-dashed curves match) [3]. Such a match in performance between the accelerometer and the inter-satellite ranging instrument has potential to allow for full exploitation of the data in future 'along-the-orbital track' data analysis, as discussed in [4].

The current accelerometers used in GRACE and GRACE-FO have a limiting sensitivity of $\sim 10^{-10}$ m/s^{2}Hz$^{1/2}$ around 1 mHz. The S-GRS is estimated to be at least 10 times more sensitive than the GRACE accelerometers and more than 500 times more sensitive if operated on a drag-compensated platform [2]. The S-GRS concept consists of a free-falling cubic test mass (TM) inside an electrode housing (EH) that senses the position and orientation of the test mass and electrostatically applies forces and torques to it to keep it centered at a nanometer-level. The applied forces and torques required to do so are also used to precisely determine the non-gravitational forces acting on the host spacecraft, as well as the spacecraft's angular acceleration. The full functionality and acceleration noise sensitivity of the S-GRS can only be measured in space. This is because the electrostatic actuation system is only capable of producing micronewton-level forces, which means that it is incapable of suspending the 0.5 kg Tungsten (W) test mass in a 1 g environment. The improved performance of the S-GRS is enabled by removing the small grounding wire used in the GRACE accelerometers, which limits its performance, and replacing it with a UV

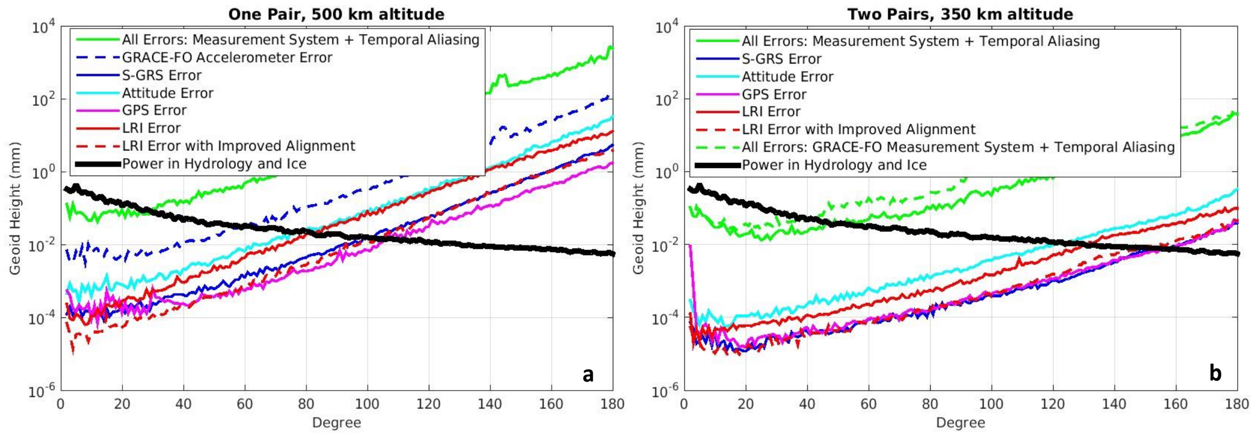

Figure 1. Error budget (a) for a single pair of non-drag-compensated satellites in 500 km polar orbit and (b) for two pairs (one polar, one 70°) at 350 km with drag-compensation (flight direction only). [Note: deg. 2-180 → spatial scales of 20,000-111 km]. In both cases the S-GRS provides sensitivity equivalent to the LRI with improved alignment, easily achieved on a future mission [2].

LED-based charge management system, increasing the mass of the sensor's TM, and increasing the gap between the TM and its electrode housing.

GRATTIS will fly two identical S-GRS mounted next to one another near the center of mass of a 160 kg ESPA-class commercial microsatellite. An artist's depiction of the GRATIS spacecraft in Earth's gravity field is shown in Figure 2. The six-axis acceleration measurement capability of the S-GRS allows precision measurement of the spacecraft drag-induced linear acceleration, as well as the residual angular acceleration of the nominally inertially-pointed bus. By combining the outputs of each sensor and with the known relative position of the two TMs, we can recover the acceleration sensitivity (noise floor) of the S-GRS. The minimum mission success criteria for GRATTIS is to demonstrate an S-GRS acceleration noise of $\leq 10^{-10}$ m/s^{2}Hz$^{1/2}$ between 1-10 mHz, the primary accelerometer requirement for GRACE-FO and GRACE-C, the next mission in the GRACE series. Our mission goal is to demonstrate acceleration noise performance of $\leq 10^{-11}$ m/s^{2}Hz$^{1/2}$.

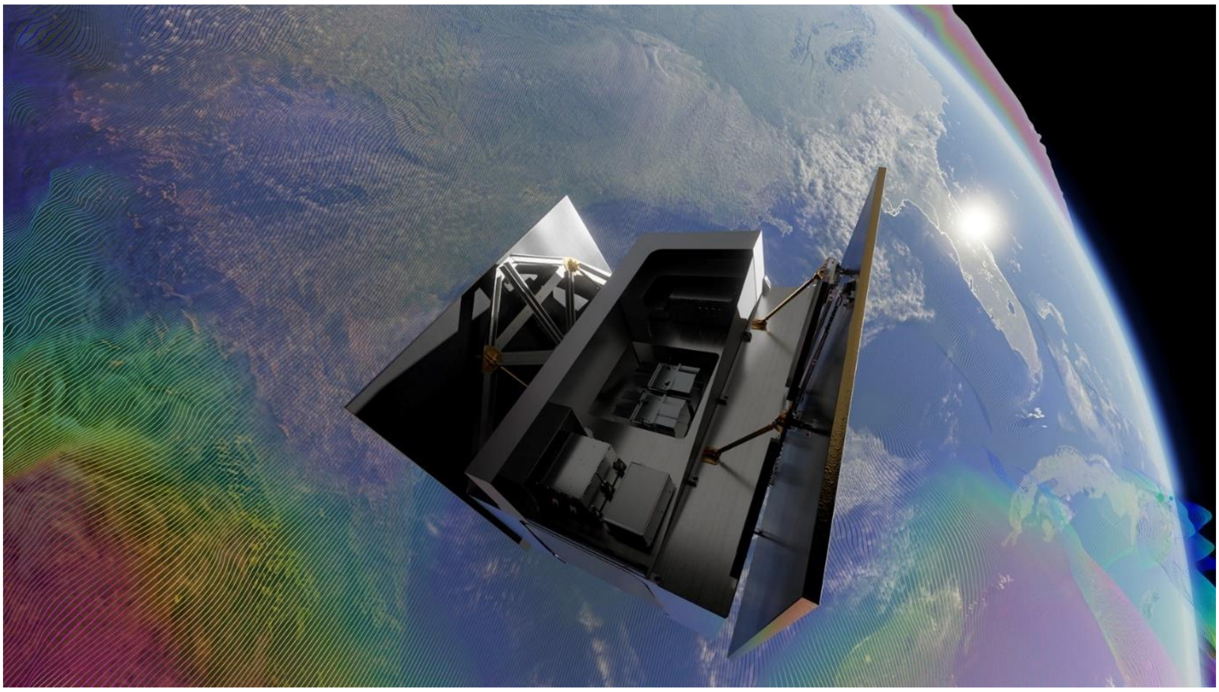

Figure 2. Rendering of the GRATTIS spacecraft in Earth orbit showing the Earth's geoid, the ultimate science goal for this technology demonstration mission

The GRATTIS science team is led by the University of Florida (UF) and includes relevant experts from Texas A&M University, Embry-Riddle Aeronautical University, and CrossTrac Engineering. The S-GRS mechanical sensor heads are provided by BAE Systems, Space & Mission Systems, while the S-GRS electronics units are provided by Fibertek, Inc. CrossTrac Engineering provides the S-GRS software and program management.

The S-GRS is currently in the Technology Readiness Level (TRL) 6 phase supported by the NASA Earth Science Technology Office. The S-GRS mechanical sensor head is expected to reach TRL 6 by the end of 2024 and the electronics units by mid-2025. The flight development phase is planned to begin in 2025. The UF-led team will integrate the flight payload into a single thermal/mechanical enclosure and perform ground testing to the extent possible. Apex Space will provide the Aries microsatellite bus, spacecraft-payload integration, and launch services via a SpaceX F9 Transporter mission planned for early 2027. Apex will perform on-orbit bus commissioning, then they will hand over GRATTIS mission operations to the UF-led science team while continuing to provide support.

2 THE SIMPLIFIED GRAVITATIOANL REFERENCE SENSOR

The S-GRS design follows that of the flight-proven LISA Pathfinder (LPF) Gravitational Reference Sensor (GRS) that represents the current state of the art. LISA Pathfinder, launched in 2015, exceeded acceleration noise requirements by 10×. TM acceleration noise amplitude spectral density (ASD) caused by residual spurious forces acting on the TM is the primary performance metric for these instruments, as well as the GRACE-FO ACC. LPF demonstrated an acceleration noise below 3×10^{-15} m/s^{2}Hz$^{1/2}$ between 0.4 mHz and 20 mHz, the same frequency band that is important for Earth geodesy [5]. This represents a factor of ~10^4 improvement over GRACE and GRACE-FO and ~10^3 over GOCE. It is important to note however, that LPF operated drag-free in deep space, rather than in the low Earth orbit environment of the GRACE and GOCE missions.

The S-GRS is a scaled-down version of the LPF GRS, with reduced mass and complexity, and with optimized performance for future geodesy missions [2]. Shown in Figure 3, the S-GRS consists of a 0.5 kg W TM inside a molybdenum EH. The housing holds 12 gold-coated electrodes to differentially sense the position and orientation of the cube via capacitive sensing and to control it using electrostatic actuation. Six “injection electrodes” are driven with a 100 kHz AC voltage to frequency-shift the readout to high frequency. The gap between the TM and EH is 0.5 mm and is a trade-off between reducing noise sources, e.g. from uncontrolled potentials on the electrodes, and providing sufficient actuation on the TM when the S-GRS is operated as an accelerometer. A Caging Mechanism (CM) uses a pair of mechanical fingers to secure the TM during launch. During science operations, the TM charge is controlled by a charge management system (CMS) based on UV photoemission. The CMS eliminates the need for the grounding wire used in the GRACE ACC that limits performance and causes challenges during integration. Key features of the design that improve sensitivity are with respect to the GRACE-FO ACC are:

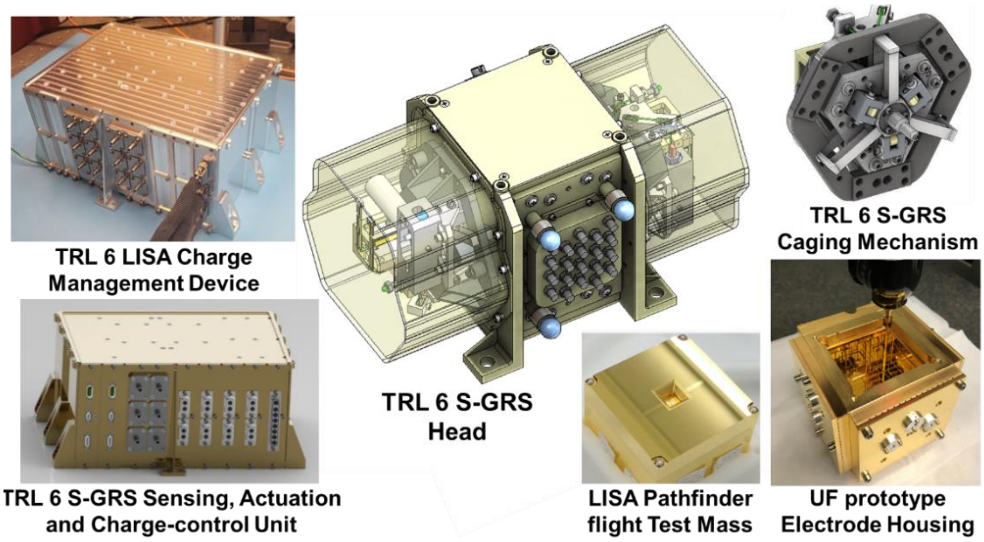

Figure 3. The Simplified Gravitational Reference Sensor and associated components, some based on LISA technology

- The test mass grounding wire used in previous accelerometers is removed and TM charge is instead controlled via non-contact UV photoemission as in LPF. The grounding wire is one significant source of acceleration noise in current electrostatic accelerometers.
- Removing this grounding wire allows us to increase the TM-to-EH housing gap from ~100 µm to 0.5 mm, as well as the TM mass from ~100 g to >500 g. Acceleration noise performance scales linearly with TM mass and, to first order, with the gap size between the TM and EH.
- Careful control of the environment surrounding the TM, including venting to space to reduce residual pressure, and shielding against Earth’s magnetic field and thermal fluctuations.
- Design for the possibility operating the S-GRS on a drag-compensated platform to further reduce acceleration noise, while simultaneously maintaining orbit altitude.

The instrument consists of an S-GRS Head and two electronics units, the Sensing, Actuation, and Charge-control Unit (SACU) and the Power and Caging Unit (PCU). Here, we briefly describe each of these elements.

2.1 S-GRE Head

The S-GRS Head is the mechanical sensor component that comprises the Test Mass, Electrode Housing, Caging Mechanism, and structural enclosure. The S-GRS uses a 30 mm cubic W test mass with a mass of 520 g. This results in the target acceleration noise performance described in Section 3, while keeping mass and volume of the sensor to a minimum. The TM is a perfect cube, coated in gold, except for two indented features on opposite sides, where the CM grabbing fingers constrain the TM during launch.

The EH is a scaled-down version of the LISA-like EH prototype previously fabricated by the UF team, shown in Figure 3 [6]. The inner dimension of the cubic EH is 31 mm creating a 0.5 mm gap between the TM and EH, and its wall thickness is ~10 mm. The Electrode Housing is fabricated from gold-coated molybdenum with sapphire electrode spacers. Molybdenum is chosen for its low magnetic properties, machinability, and high thermal conductivity, which reduces thermal gradients across the sensor. Sapphire is chosen because its coefficient of thermal expansion is nearly the same as that of molybdenum.

The CM must secure the TM against launch loads and gently release it once in orbit. The design is such that upon release, the TM has a low enough velocity (<10 μm/s) relative to the spacecraft so that the S-GRS control system can electrostatically capture it. However, LPF demonstrated that even when the release velocity exceeds this level and the TM gently touches the EH wall, the control system is still able to electrostatically capture the TM. To achieve a low relative velocity, the design minimizes both adhesion to the TM gold surface and the mechanical preloads just prior to release [7]. The S-GRS caging mechanism designed reduces the three-stage LISA system to a simpler two-stage system (see Figure 4). Both stages drive opposing hard gold alloy Grabbing Fingers (GF) that engage the TM at the indents. The GF are mounted on a flexure system to maintain alignment. The first stage uses a radial clamp driven by a standard aerospace launch lock actuator to generate a kN-level preload, while the second stage utilizes a commercial vacuum-compatible piezo-walker motor. After the one-time first stage launch-lock is released, the second stage retracts the GF until the TM is held with a <1 N preload by spring-loaded release tips. The spring stiffness is designed to break the gold adhesion between TM and the GF. The final release tips are fabricated from a hard, non-stick silicon nitride material to avoid adhesion with the TM. Damping is added so that the TM motion is minimized upon final retraction and release.

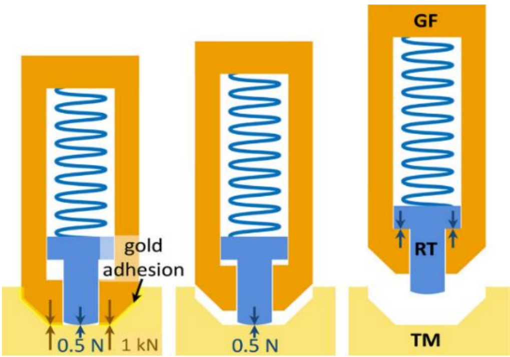

Figure 4. CM release concept: Launch-lock actuator provides kN preload (left) via the grabbing fingers. After launch-lock release, the GF retracts (center) and the 0.5 N preload applied by the springs break gold adhesion. Finally, RTs damp TM motion until fully retracted (left)

The titanium sensor head enclosure, seen in Figure 3, serves as the structural exterior of the S-GRS Head and provides a clean, isolated environment for the EH and TM. A port on the bottom is connected to a vent pipe that allows for venting to space. A filter mounted in the pipe prevents contaminants from entering the enclosure during integration and test. The filter and venting system provided were also used for the GRACE-FO optical cavities [8].

A 70 mm cubic mu-metal shield, 1 mm think surrounds the EH and is mounted to the structural enclosure. Prior acceleration noise modeling showed that an attenuation factor of at least 10 of the Earth's magnetic field is needed to meet performance goals.

2.2 Sensing, Actuation, and Charge-control Unit

The SACU performs the following:

- Generate (digitally) the test mass injection bias to frequency shift the capacitive readout from low frequency to the injection frequency (100 kHz)
- Perform the six degree-of-freedom position readout of the test mass by differencing opposing pairs of sensing/actuation electrodes via analog electronics, and demodulating the differenced signals at the injection frequency via digital electronics
- Generate actuation voltages (digitally) and apply them to the sensing/actuation electrodes at audio frequencies to control the position and orientation of the test mass
- Drive the analog current source for the UV LEDs to discharge the test mass
- Contain software for (a) feedback control of the TM, (b) commanding of the CMS, (c) commanding of the CM, and (d) telecommand and telemetry interface with the spacecraft.

The SACU architecture consists of a chassis containing a backplane and electronics cards. The TM capacitive sensing design has undergone multiple iterations at UF [2, 6]. The design is mature with sensing performance at 500 pm/Hz$^{1/2}$ above 1 mHz, exceeding the S-GRS requirement. The actuation electronics generate the low-noise voltages on the EH used to produce forces and torques on the TM to keep it centered within the EH. The design of the actuation electronics is critical because TM actuation noise is expected to dominate the overall noise performance of the S-GRS when operated as an accelerometer like in the GRATTIS mission.

The charge management electronics is the most mature due to NASA's LISA technology development. The LISA Charge Management Device (CMD), shown in Figure 3, serves as the baseline design for the S-GRS SACU. The CMS utilizes newer UV LEDs that both resolve technical issues related to the Hg-lamp system used by LISA Pathfinder and reduce volume, mass, and power. The S-GRS will utilize an advanced continuous charge control scheme, where a low level (nW) of UV light is pulsed with low duty cycle synchronously with the applied 100 kHz injection electric field [9]. Photoelectron flow between the TM and EH will anti-align with the injection field. Proper selection of the phase of the UV light pulses with respect to the field results in a net flow of photoelectrons that produces a stable TM equilibrium charge near zero.

The SACU Controller Card, also based on the LISA CMD, uses an FPGA for high-speed digital signal processing functions and a microprocessor for TM control logic and all other higher level processing.

2.3 Power and Caging Unit (PCU)

The second electronics assembly, the PCU, houses a Power Card and a Caging Actuation Card (CAC). The Power Card uses 28 V spacecraft power to generate the 5 V and ±15 V lines needed by the SACU. The CAC design is based on the commercial high voltage caging actuator driver. The PCU is separated from the SACU because it is a potential source EMI for the performance-driving SACU.

2.4 Control Software

The S-GRS control software handles all the higher-level functions including (a) feedback algorithms for TM control, (b) TM charge management, (c) caging and release, (d) mode switching and safe modes, and (e) spacecraft interfacing and telemetry handling.

The S-GRS can be operated in two primary modes: drag-compensation and accelerometer mode. In accelerometer mode, all control algorithms are embedded within the S-GRS so that it may be treated as a black box that provides spacecraft acceleration estimates. This is the mode in which the S-GRS will operate for GRATTIS. The commanded TM force and torque needed to keep it centered is used to estimate the spacecraft six-axis acceleration. No propulsion is required.

Drag-compensation is a spacecraft-level control loop that uses data from the S-GRS to command micronewton thrusters to minimize TM actuation forces. In this mode external forces on the spacecraft are directly cancelled by a propulsion system, minimizing the applied TM forces and therefore acceleration noise. This higher-performing mode is a possibility for future Earth geodesy missions.

3 S-GRS PERFORMANCE MODELING

Our GRS noise models account for roughly 30 different noise sources that are relevant at levels below 10^{-10} m/s^{2}Hz$^{1/2}$ [10]. This model is based on both UF torsion pendulum experiments [6] and flight experiments performed on LPF [5]. On a non-drag-compensated spacecraft at an orbit altitude of 500 km (like GRACE-FO) the performance is expected to be 5×10^{-12} m/s^{2}Hz$^{1/2}$ from 1-10 mHz (see Figure 5). This model assumed a spacecraft environment based on GRACE-FO flight data. In Figure 5, the acceleration noise goal is shown by the black curve, while individual contributions are shown in various colors. Note that the dominant acceleration noise contribution is due to actuation. Also shown in Figure 5 are the sensing noise curves for the LRI and S-GRS capacitive readout, doubly differentiated to convert them to acceleration noise. From Figure 5, we see that if the S-GRS were implemented on a GRACE-like mission we could expect the performance to be 10× better than the GRACE-FO ACC depending on the required maximum acceleration range, since actuation noise scales with maximum required acceleration. If the sensor were operated on a drag-compensated platform, its performance would improve by an additional factor of 70 or to below 10^{-13} m/s^{2}Hz$^{1/2}$ around 1 mHz.

The force noise of our UF torsion pendulum equipped with a prototype GRS following the geometry for LISA and without actuation applied is also shown in Figure 5. The measured performance at 1 mHz is 3×10^{-13} N/Hz$^{1/2}$. It is important to note that torsion pendula are only sensitive to TM surface forces in one degree of freedom. They are not sensitive to TM bulk material forces such as gravitational or magnetic. Nevertheless, if we scale this measured performance by the S-GRS TM surface area (30×30 mm^2) relative that of LISA (46×46 mm^2) and inversely by the S-GRS gap size (0.5 mm) relative that of LISA (4 mm), for the 0.5 kg S-GRS TM, the acceleration noise would be 2×10^{-12} m/s^{2}Hz$^{1/2}$. This is comparable to the estimated performance of the S-GRS, neglecting actuation noise.

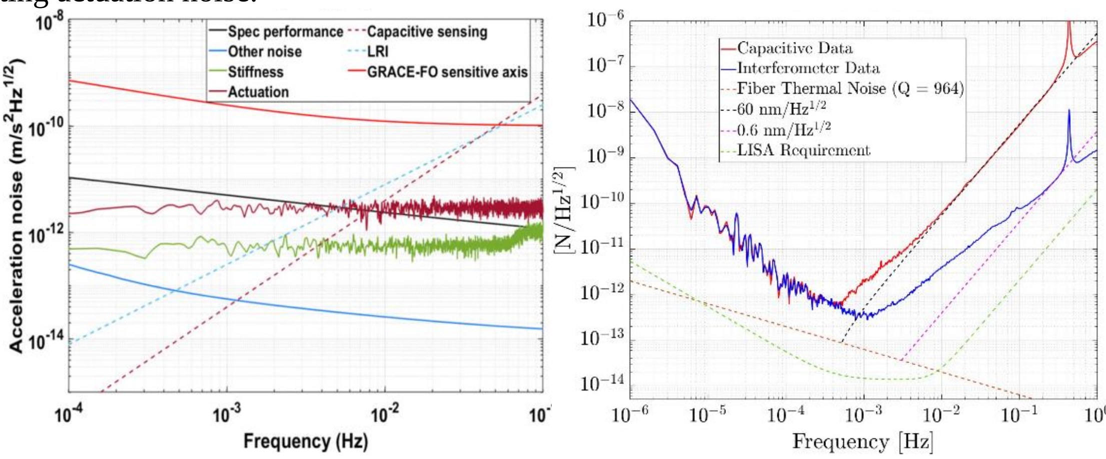

Figure 5. S-GRS acceleration noise estimate for a 500 km orbit (left) [2] and measured force noise of the GRS prototype integrated into the UF torsion pendulum (right) [6]

4 GRATTIS MISSION ARCHITECTURE

4.1 Measurement Principle

The translational acceleration measured by each S-GRS is:

$$\vec{a}_i = \vec{a}_{S/C} + \vec{\alpha}_{S/C} \times \vec{r}_i + \vec{\omega}_{S/C} \times \vec{\omega}_{S/C} \times \vec{r}_i + \vec{n}_i \tag{1}$$

where $\vec{a}_{S/C}$ is the spacecraft (S/C) acceleration due to atmospheric drag, $\vec{\alpha}_{S/C} \times \vec{r}_i$ is the Euler acceleration due to the angular acceleration of the spacecraft and the position offset of the i^{th} TM relative to the spacecraft center of mass, $\vec{\omega}_{S/C} \times \vec{\omega}_{S/C} \times \vec{r}_i$ is the centripetal acceleration due to the angular velocity of the spacecraft and the TM offset, and $\vec{n}_i$ is the noise due to spurious forces on the TM and readout noise. Here, i = 1, 2 for the two S-GRS. The primary goal of the GRATTIS mission is to determine the spectrum of $\vec{n}_i$. Due to the magnitude $\|\vec{r}_i\|$ = 7 cm and the residual angular acceleration of the Apex Aries bus, the Euler and centripetal accelerations are significant.

Assuming perfect alignment (or calibration) of the two S-GRS and that the noise of each S-GRS have the same stochastic spectra (that of $\vec{n}_i$), the measured differential acceleration is:

$$\vec{a}_1 - \vec{a}_2 = \vec{\alpha}_{S/C} \times (\vec{r}_1 - \vec{r}_2) + \vec{\omega}_{S/C} \times \vec{\omega}_{S/C} \times (\vec{r}_1 - \vec{r}_2) + \sqrt{2}\vec{n} \tag{2}$$

The Euler acceleration is orthogonal to $\vec{r}_1 - \vec{r}_2$. Along this direction, the differential acceleration ideally only contains the centripetal acceleration and the noise.

To determine the spectrum of $\vec{n}$ we will calculate and subtract the centripetal and residual Euler accelerations from the measured differential acceleration. It is important to note that from Eq. (2), we only need the relative position ($\vec{r}_1 - \vec{r}_2$) and relative orientation of the two TMs and not their positions $\vec{r}_1$, $\vec{r}_2$ relative to the S/C center of mass nor their orientations relative to the S/C axes.

The GRATTIS payload will be integrated in the UF Precision Space Systems Lab (PSSL) clean room and thermal-vacuum (TVAC) facility, where we also house our precision coordinate-measuring machine (CMM). Our Brown & Sharpe CMM (used to measure our EH prototype in Figure 3) has been calibrated and certified by the manufacturer to have an accuracy of ≤10 µm. Once the two S-GRS Heads are mounted on the enclosure baseplate, this CMM will measure the relative position and orientation of the two S-GRSs to at least 10 µm and 100 µrad. These measurements will be facilitated by the precision metrology spheres on the exterior of the sensor head that are mounted on the EH frame (also shown in Figure 3).

In addition to measuring translational acceleration, each S-GRS also provides precision angular acceleration measurements. At 1 mHz, the performance is limited by actuation to counter drag and S/C torques. The Apex Aries bus is expected to experience a 10^{-5} rad/s^2 average acceleration over orbital time scales. The actuation noise to counter this will be 4×10^{-11} rad/s^{2}Hz$^{1/2}$. This angular acceleration noise level can be directly verified in orbit by comparing the two S-GRS since both experience the same angular acceleration. This angular acceleration measurement provides an indirect estimate of translational acceleration noise of the S-GRS because of the known electrode geometry. The relative angular measurements can also be used to improve the estimate of the relative orientation of the two S-GRS.

Figure 6 describes the expected differential acceleration noise measurement sensitivity along the axis connecting the two TMs, accounting for the noise from both sensors and the expected uncertainty in the relative positions and orientations of the two S-GRS TMs based only on ground measurements. The differential sensitivity of the payload is 2×10^{-11} m/s^{2}Hz$^{1/2}$ over 1-10 mHz or below, meeting requirements and providing excellent signal-to-noise compared with the GRACE-FO measured drag acceleration (also shown). The expected raw and corrected Euler accelerations are also shown in Figure 6. The error in the corrected Euler acceleration assumes that knowledge of the relative position and orientation of the S-GRSs are off by 10 µm and 100 µrad in all three axes. At 1 mHz, the correction is consistent with the sensitivity of the S-GRS and at 10 mHz the correction is 5× worse than the S-GRS sensitivity. Further calibrations on-orbit involving dithering the spacecraft attitude and measuring the response of the S-GRSs could improve the Euler correction as was done on both GOCE [11] and LISA Pathfinder [5].

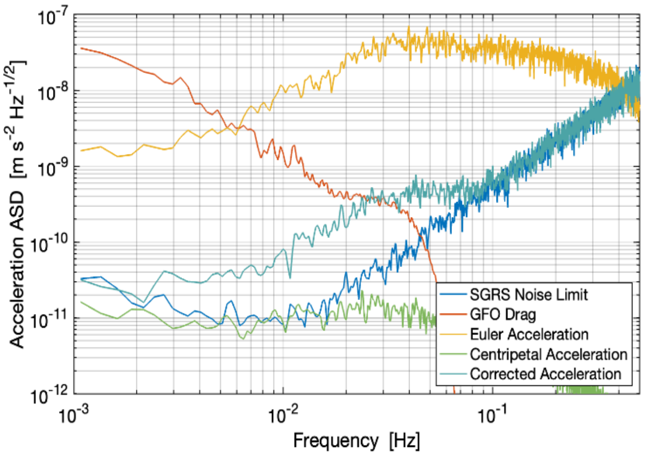

Figure 6. S-GRS sensitivity (blue) compared with the GRACE-FO measured drag (red), estimated GRATTIS Euler (yellow) and centripetal (green) accelerations and the level at which the Euler acceleration can be estimated (teal).

4.2 Spacecraft Environment

The performance of S-GRS is directly tied to the attitude, temperature, electromagnetic, and gravitational environment provided by the spacecraft. To accommodate a range of spacecraft possibilities in the future, our performance model assumes a spacecraft environment described in Table 1, which is orders of magnitude less strict that those for LISA. The primary environmental mitigation steps taken in the S-GRS design are to include a small mu-metal magnetic shield surrounding the EH and the mechanical/thermal enclosure itself with venting to space. The temperature stability of the S-GRS is an important driver for its noise performance. Our noise models assume a temperature stability of 1 K/Hz$^{1/2}$. The temperature stability of the Aries bus payload mounting plate is shown in Figure 7 both with and without active control. From this figure we see that if the GRATTIS payload enclosure provides thermal attenuation factor of 10, the temperature stability requirements of the S-GRS payload will be satisfied.

Table 1. Spacecraft environmental requirements

Quantity, variable	Value
Angular acceleration	5 µrad/Hz$^{1/2}$
Magnetic field at the TM	100 µT
Magnetic field fluctuation at the TM	2 µT/Hz$^{1/2}$
Magnetic field gradient at the TM	20 µT/m
Mag field gradient fluctuation at TM	0.5 µT/m Hz$^{1/2}$
Mean temperature at the TM	293 K
Temperature difference across EH	5 mK/Hz$^{1/2}$ (1 mHz)
Temperature fluctuations near TM	1 K/Hz$^{1/2}$ (1 mHz)
Pressure around the TM	10 µPa

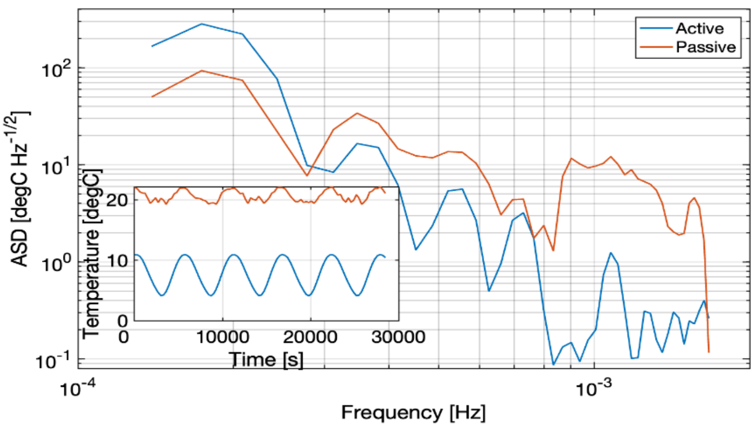

Figure 7. Apex Aries bus payload plate temperature amplitude spectral density

4.3 Payload Accommodation

The GRATTIS payload mass, volume and power consumption can be accommodated by the Apex Aries bus with wide margins. Figure 8 shows the layout of the two S-GRSs integrated with the spacecraft bus. Because of the ESPA mounting ring in the center of the Aries bus, the two S-GRS Heads can be placed very near the spacecraft center of mass. The volume of the two sensor heads allows the two test masses to be placed within 7 cm of the spacecraft center of mass. The sensor heads, as well as the electronics units are mounted within the two-layer thermal/mechanical enclosure, made semitransparent in Figure 8 to shown the two S-GRS inside. We plan to keep the solar arrays stowed as shown in Figure 8 to reduce drag disturbances, made possible by the >100 W power margin.

The orbit average power consumption during the nominal science mode has both S-GRS operating. This power consumption is a factor of 3 below the End Of Life (EOL) capability of the bus. The payload peak power draw is dominated by the TM launch-lock release. During this minutes-long operation, the PCU that drives the launch-lock actuator can consume an additional 50 W of power. This is small compared to the Aries peak-power capability of 4 kW.

4.4 Concept of Operations

Launch is planned for early 2027 on a SpaceX Falcon 9 Transporter flight. The orbit will be a 550 km ± 50 km sun-synchronous orbit similar to the GRACE-FO 500 km polar orbit. The minimum orbit altitude required for GRATTIS is 500 km driven by atmospheric drag levels. GRATTIS payload/spacecraft integration is the responsibility of Apex Space and will occur at their facility in CA, after which Apex will deliver the spacecraft to the SpaceX launch integration facility.

Spacecraft bus commissioning is planned for 30 days after launch and is also the responsibility of Apex Space. After bus commissioning, spacecraft and payload operations will be handed over to the UF-led operations team. The first week of science operations will involve turning on both S-GRS, placing them into standby-mode, and evaluating health and safety data. The single-shot launch-lock mechanisms for each S-GRS test mass will then be released, after which the TMs will be supported by the low-preload GFs. During the second week we will release each TM sequentially from the GFs and bring them under electrostatic suspension in the Wide Range (WR) mode. Once the WR mode has been proven to stably control the TMs over at least a day-long stretch, the S-GRS control system will transition into the High Resolution science mode. Calibration of the S-GRS will take place over the subsequent two weeks. Calibration involves verifying the relative position and orientation of the two S-GRS, needed to compensate for Euler accelerations caused by spacecraft attitude jitter, as well as determining the optimal UV charge control parameters.

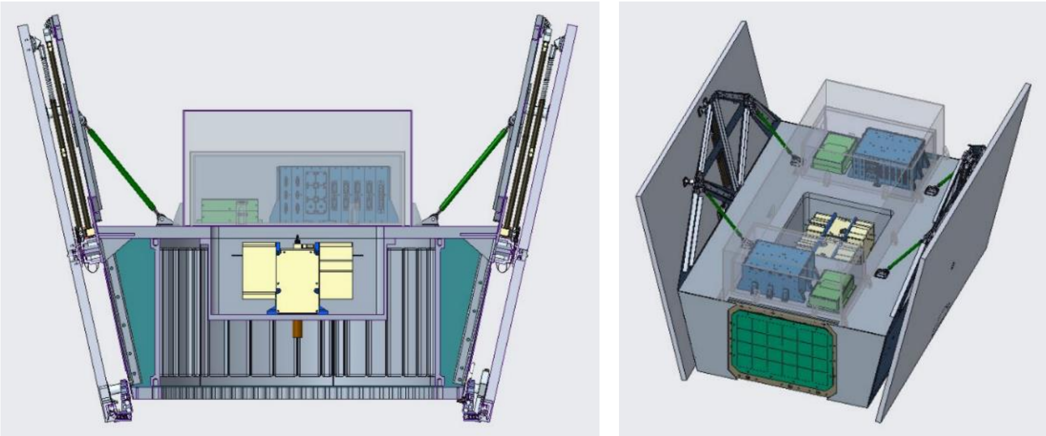

Figure 8. GRATTIS spacecraft and payload with the two-layer payload enclosure made semitransparent: S-GRS Heads are shown in yellow near the S/C center of mass with vent pipes in brown, SACUs are shown in blue, and PCUs are shown in green.

Over the subsequent three months, we will collect at least one-orbit of science data each day from each S-GRS. A single orbit is sufficient to determine the acceleration noise performance of the S-GRS. However, averaging data over multiple orbits will reduce measurement uncertainty and validate the performance of the S-GRS over potentially changing environmental conditions. This three-month period will also allow the operations team to optimize calibration parameters and evaluate and compensate for any systematic effects discovered in the data.

During the final month of operations, assuming we have collected sufficient data to demonstrate the acceleration noise performance of the S-GRS, we will mechanically re-grab the TMs and re-release them to electrostatic control. This grab-and-release process will be repeated many times to determine the reliability of the caging mechanism and electrostatic test mass capture. At the end of the mission the spacecraft solar arrays may be deployed to increase drag and expedite deorbiting.

5 CONCLUSIONS

The GRATTIS technology demonstration mission will validate the functionality and sensitivity of the Simplified Gravitational Reference Sensor in Earth orbit. The S-GRS is a new, ultra-precise inertial sensor designed for future Earth geodesy missions. These sensors are used to measure or compensate for all non-gravitational accelerations of the host spacecraft so that they can be removed in the data analysis to recover spacecraft motion due to Earth's gravity field. Low-low satellite-to-satellite tracking missions like GRACE-FO that utilize nm-level laser ranging interferometers are technologically limited by the acceleration noise performance of their electrostatic accelerometers. The S-GRS is estimated to be at least 10 times more sensitive than the GRACE accelerometers and more than 500 times more sensitive if operated on a drag-compensated platform. Temporal aliasing associated with Earth's dynamic gravity field also limits the gravity recovery capability of missions like GRACE-FO. However, improvements in the modeling of Earth's time-variable gravity and data analysis techniques, as well as the possibility of flying multiple geodesy satellite pairs in the future are likely to mitigate these aliasing effects.

The S-GRS concept is a simplified and scaled-down version of the LISA Pathfinder GRS. It consists of a free-falling cubic test mass inside an electrode housing that senses the position and orientation of the test mass and electrostatically applies forces and torques to it to keep it centered at a nanometer-level. The applied forces and torques required to do so are also used to precisely determine the non-gravitational forces acting on the host spacecraft, as well as the spacecraft's angular acceleration. The improved performance of the S-GRS is enabled by removing the small grounding wire used in the GRACE accelerometers, which limits its performance, and replacing it with a UV LED-based charge management system, increasing the mass of the sensor's TM, and increasing the gap between the TM and its electrode housing.

GRATTIS will host two identical S-GRS mounted next to one another near the center of mass of a 160 kg ESPA-class commercial microsatellite, operating in a 550 km sun-synchronous Earth orbit. The six-axis acceleration measurement capability of the S-GRS allows precision measurement of the spacecraft drag-induced translational acceleration and residual angular acceleration of the nominally inertially-pointed bus. By combining the outputs of each sensor and with the known relative position of the two TMs, we can recover the acceleration sensitivity (noise floor) of the S-GRS to at least $\leq 10^{-10}$ $m/s^2Hz^{1/2}$ between 1-10 mHz. Our mission goal is to demonstrate acceleration noise performance of $\leq 10^{-11}$ $m/s^2Hz^{1/2}$, depending on the orbit altitude and atmospheric conditions in which GRATTIS operates.

The PI and science team is led by the University of Florida and includes relevant experts from Texas A&M University, Embry-Riddle Aeronautical University, and CrossTrac Engineering. The

S-GRS mechanical sensor heads are provided by BAE Systems, Space & Mission Systems, while the S-GRS electronics units are provided by Fibertek, Inc. CrossTrac Engineering provides the S-GRS software and program management. The UF-led team will integrate the flight payload into a single thermal/mechanical enclosure and perform ground testing to the extent possible. Apex Space will provide the Aries microsatellite bus and launch services via a SpaceX F9 Transporter mission planned for early 2027. Mission operations are expected to span at least six months.

7 ACHNOWLEDGEMENTS

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8 REFERENCES

[1] Tapley, B. D., Watkins, M-M., Flechtner, F., Reigber, C., Bettadpur, S., Rodell, M., Sasgen, I., Famiglietti, J-S., Landerer, F.W., Chambers, D.P., Reager, J.T., Gardner, A.S., Save, H., Ivins, E.R., Swenson, S.C., Boening, C., Dahle, C., Wiese, D.N., Dobslaw, H., Tamisea, M.E., Velicogna I, *Contributions of GRACE to Understanding Climate Change*, Nature Climate Change, Vol. 9, No. 5, 358-369, 2019.

[2] Dávila Álvarez, A., Bevilacqua, R., Hollis, H., Mueller, G., Knudston, A., Patel, U., Sanjuan, J., Spero, R., Ware, B., Wass, P., Wiese, D., Ziemer, J., Conklin, J.W. *A Simplified Gravitational Reference Sensor for Satellite Geodesy*, Journal of Geodesy, Vol. 96, No. 10, 70, 2022.

[3] Abich et al., *In-orbit performance of the GRACE Follow-On Laser Ranging Interferometer,* Phys. Rev. Lett., Vol. 123, No. 3, 031101, 2019.

[4] Spero, R., *Point-mass sensitivity of gravimetric satellites,* Adv. In Space Res., Vol. 67, No. 5, 1656-1664, 2021.

[5] Armano, M., et al., *Beyond the Required LISA Free-Fall Performance: New LISA Pathfinder Results down to 20 μHz,* Phys. Rev. Lett., Vol. 120, No. 6, 061101, 2018.

[6] Apple, S. et al., *Design and performance characterization of a new LISA-like (laser interferometer space antenna-like) gravitational reference sensor and torsion pendulum testbed*, Review of Scientific Instruments, Vol. 94, No. 5, 054502, 2023.

[7] Bortoluzzi, D., Zanoni, C., Conklin, J.W., *Prediction of the LISA-Pathfinder release mechanism in-flight performance,* Advances in Space Research, Vol. 51, No. 7, 1145-1156, 2012.

[8] Thompson, R., Folkner, W.M., deVine, G., Klipstein, W.M., McKenzie, K., Spero, R., Yu, N., Stephens, M., Leitch, J., Pierce, R., *A Flight-Like Optical Reference Cavity for GRACE Follow-on Laser Frequency Stabilization*, IEEE International Frequency Control Symposium, 729-731, ISBN 978-1-61284-110-6, 2011.

[9] Inchauspé, H., Olatunde, T., Apple, S., Parry, S., Letson, B., Mueller, G., Wass, P., Conklin, J.W., *Numerical Modeling and Experimental Demonstration of Pulsed Charge Control for the Space Inertial Sensor used in LISA*, Physical Review D, Vol. 102, No. 4, 042002, 2020.

[10] Gerardi, D., Allen, G., Conklin, J.W., Sun, K-X., DeBra, D., Buchman S., Gath, P., Fichter, W., Byer, R.L., Johann, U., *Invited Article: Advanced drag-free concepts for future space-based interferometers: acceleration noise performance,* Review of Scientific Instruments, Vol. 85, No. 1, 011301, 2014.

[11] Siemes, C., Haagmans, R., Kern, M., Plank G., Floberghagen, R., *Monitoring GOCE gradiometer calibration parameters using accelerometer and star sensor data: methodology and first results,* Journal of Geodesy, Vol. 86, 629-645, 2012.