Progress in Developing the Modular Gravitational Reference Sensor

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Abstract. Modular Gravitational Reference Sensor (modular GRS) was proposed by the Stanford Team in 2004. In a modular GRS, the laser beam from the remote the sensor does not illuminate the proof mass directly. The internal measurement from the housing to proof mass is separated from the external interferometry. A double-sided grating further simplifies the structure and may better preserve the measurement precision. We review the recent progress in developing the modular GRS at Stanford. We are developing optical sensors with picometer resolution, capable of operating with a large gap for high precision readout. We have conducted an initial experiment incorporating RF heterodyne detection and thus lowered the optical power compared with direct detection. We have demonstrated sub-nanoradian sensitivity of a grating angular sensor. We have successfully demonstrated fabrication of localized grating patterns on dielectric and gold surfaces. We have made critical progress in optical measurement of the mass center (MC) position of a spherical proof mass to a precision of a few micrometers. We are studying a method to experimentally determine the self-gravitational attraction via measurement of the moments of inertia. We have further demonstrated over 2700 hours of operation of a UV LED under typical AC charge management conditions. We are modeling the electrostatic field surrounding gapped housing wall, cubic and spherical proof masses. We have studied surface potential of metallic proof masses using a Kelvin probe and UV photoelectric current.

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INTRODUCTION

The Laser Interferometric Space Antenna (LISA) [1-5] and the Big Bang Observatory (BBO) are highly sensitive space-borne gravitational wave observatories requiring unprecedented precision. At the heart of the LISA and BBO spacecraft is the Gravitational Reference Sensor (GRS), in which a proof mass (PM) provides a reference at the end point of a distance measurement. A modular GRS [6-8] was proposed to simplify the GRS structure, enhance GRS performance and reduce the cost of the LISA mission.

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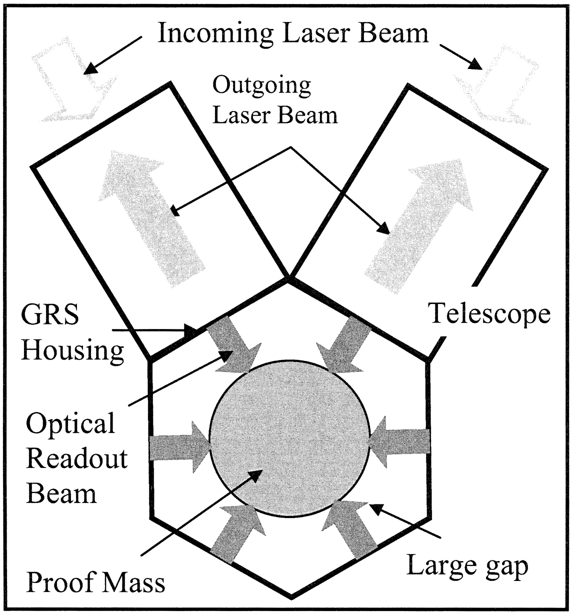

FIGURE 1: The concept of the modular GRS. The external laser beam does not illuminate the proof mass. The GRS is a modular unit, where the internal distance measurement is made from proof mass to housing inside the GRS. The precision measurement is relayed directly to the external surface through the housing wall.

Figure 1 shows the conceptual design of Modular GRS [6-8]. This is a multi-layer proposal containing several key suggestions: 1) The laser beam from the remote spacecraft does not directly illuminate the PM, but illuminates the GRS housing surface. Therefore, the GRS is now a module that provides a position reference for external use. 2) Only one PM is used in a true drag-free spacecraft. The GRS measures PM center of mass position. 3) Multiple internal optical sensors are used to measure the gap between the proof mass and the housing. Optical sensing allows a large gap which reduces disturbances [9]. In the all-reflective version of the modular GRS, measurements are naturally made from the PM to the housing wall and from the housing wall to the incoming laser phase front. This sequence incurs the shortest possible optical path, reducing fluctuations caused by thermal and mechanical instabilities. The modular GRS architecture should improve LISA performance in the low frequency regime by reducing disturbances.

The modular GRS only uses a single PM instead of two. In principle, science measurement of a gravitational wave needs only one PM per spacecraft. The disturbances to the single proof mass are lower than the two-mass system by at least a factor of $\sqrt{2}$, which is a significant improvement, especially in the low frequency region where acceleration noise dominates. But more importantly, the single PM eliminates the constraint forces required in a multiple proof mass system. Cross coupling of these constraint forces along the sensitive axes is a signification source of acceleration noise. Elimination of these constraint forces would likely reduce the disturbances by more than $\sqrt{2}$. A single spherical proof mass is preferred due to reduced control complexity and cross coupling [10,11].

The modular GRS uses multiple optical sensors. We propose using 18 optical sensors for a true drag-free implementation in all three displacement degrees of freedom. This array of sensors is highly redundant and provides pico-meter level signals to the flight computer for improved drag-free performance.

PROGRESS IN DEVELOPMENT OF MODULAR GRS

Since the conception of the modular GRS, the Stanford team has made substantial progress in further research and development [6-8,10-30]. As a result of the comprehensive study on modular GRS architecture, we have a clear perspective on the system configuration and have implemented an integrated program for modular GRS development.

We have been developing the critical component technologies for the modular GRS. This technology development effort has significant overlap with the LISA baseline design. The grating beam splitter based all-reflective optical configuration can achieve higher performance while reducing complexity. Therefore we are investigating several aspects of grating interferometry: optical displacement, angular sensing, grating design and fabrication, and external interferometry. A true drag free modular GRS calls for a spherical proof mass. Therefore we are investigating the high precision measurement of mass center and moment of inertia of spherical proof masses. A charge management system is indispensable in GRS operation and disturbance reduction. We have demonstrated UV LED based AC charge management and are currently investigating UV LED stability. We have been conducting electromagnetic modeling of realistic spherical and cubic proof masses. We are planning to study surface effects using a surface electron emission technique and a Kelvin probe. We are researching active thermal control to achieve highly stable temperatures at low frequencies. Figure 2 illustrates how our efforts fit into the system concept of the modular GRS. Table 1 itemizes our research efforts and relevant references.

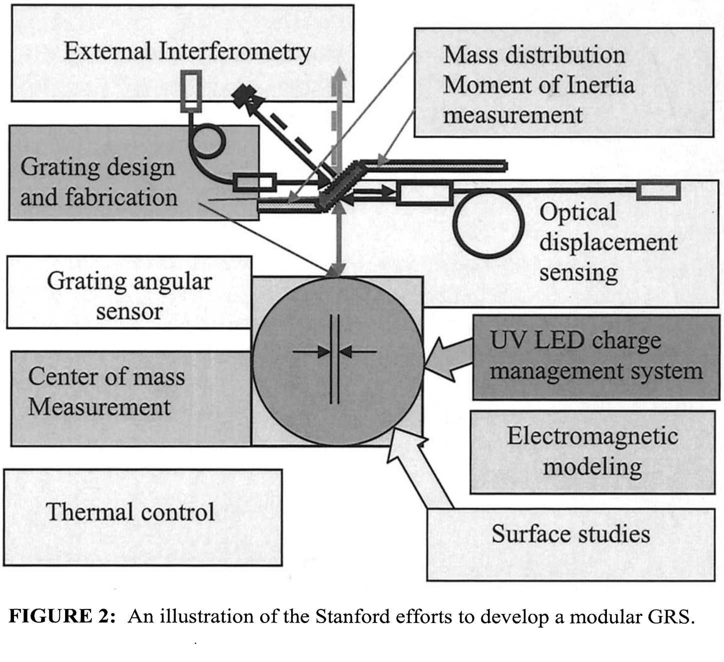

FIGURE 2: An illustration of the Stanford efforts to develop a modular GRS.

TABLE 1. R&D Areas in Developing Modular GRS

No.	Area	Approach & Activity	Result	Reference
1	GRS Architecture	a) Configuration b) Telescope c) External interferometery	a) Modular GRS b) Multi-element telescope c) Simplified interferometry	[6-8] [6,13] [6]
2	System technologies	a) Control implication b) Noise tree	Modular GRS reduces control complexity and cross talk	[6-8]
3	Optical displacement Sensing	Fiber fed grating cavity with RF modulated input	10 pm/ $Hz^{1/2}$ @ 1kHz for 2 cm long cavity	[14]
4	Optical angular sensing	Grating angle magnification enhanced angular sensor	1 nrad/ $Hz^{1/2}$ @ 1kHz Robustness	[15,16]
5	Diffractive optics elements	a) e-beam lithography b) Ion beam writing c) Transfer imprint	Gratings fabricated on dielectric substrate and gold coating	[17]
6	Mass center measurement for proof mass	Velocity modulation with differential optical shadow sensing	2 μm precision of MC location relative to geometric center	[18,19]
7	Moment of inertia measurement for proof mass	Rotational pendulum with grating angular sensor. Data useful for self gravity attraction calculation	10^{-4} precision determination of oscillation period over 900 seconds	[20-22]
8	UV LED charge management system	a) AC charge management b) UV LED lifetime tests c) UV LED charge management system	a) 10 kHz AC charge management b) UV LED lifetime exceeds 2700 hours c) In design process	[23,24]
9	Electrostatics	Electrostatics modeling for cubic and spherical proof mass GRS	Potential maps for cubic and spherical proof masses surrounded by a housing	[25]
10	Surface studies	a) Kelvin probe b) UV photoelectron emission	Proof mass and coating surface potential measurement	[26]
11	Thermal control	Active thermal control at low frequencies	Temperature stability 1 mK @ 1 mHz	[27]
12	Electronics	Low noise electronics for forcing and sensing	Capacitive sensing 3 nm/$Hz^{-1/2}$ @ 1 mHz	[28,29]

The technologies being developed for the modular GRS are equally useful to LISA conventional configurations. The resonant optical displacement sensing can be directly applied to GRS optical sensing. The grating angular sensor can be used in point ahead angle sensing and control. The UV LED has recently been incorporated into the LISA baseline design. The high precision mass center and moment of inertia measurements are critical in understanding kinetic cross coupling and self gravity. The results of EM modeling, surface studies and thermal control are required for any LISA design. In the following sections, we will present an overview of areas three to nine in Table 1. Many of these areas had specific posters presented at the LISA 6 Symposium and more details can be found in the individual articles in this journal.

Modular GRS Component Technologies

Optical Displacement Sensing Using a Grating Cavity [6,14]

Optical sensing offers a high-resolution method of sensing across a large gap while maintaining low disturbances. The sensing element is a low-finesse Fabry-Perot cavity formed between a Littrow-mounted diffraction grating and the surface of the proof-mass. The sensor reached 10 pm/Hz1/2 sensitivity with 120 μW of optical power, as shown in Fig. 3. Further improvements should drop the required optical power to 10 μW.

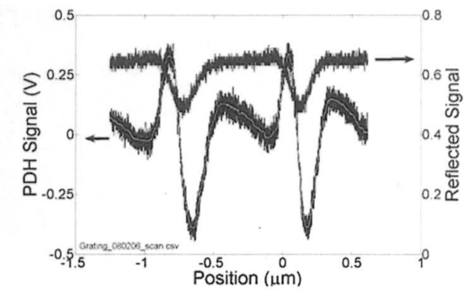

Figure 3. Scan of the interferometer across several cavity resonances. The Pound-Drever-Hall signal shows a steep slope as the cavity sweeps through resonance.

Optical Angular Sensor Using Grating Magnification [15,16]

High precision angular sensing is needed in proof mass orientation, telescope steering, and point-ahead-angle control. We have proposed the use of grating diffraction orders as angular sensing signal beams, taking advantage of grating angular magnification. We have demonstrated an angular sensitivity better than 1 nrad/$\text{Hz}^{1/2}$ with a 6 cm working distance, as shown in Figure 4.

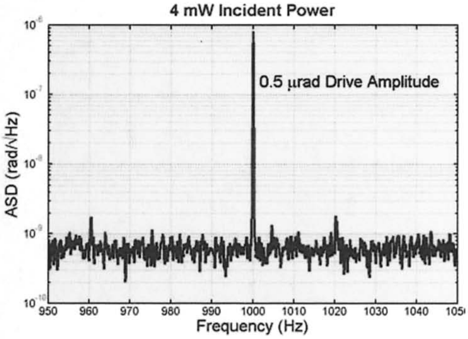

Figure 4. Spectrum of the combined output of the quad detectors at the two sides of the grating angular sensor. The equivalent angular rotation amplitude was 0.5 μrad. The noise floor is below 1 nrad/$\text{Hz}^{1/2}$.

Grating Fabrication [17]

Since the tip/tilt sensor may eventually require a grating atop the proof mass, we have demonstrated several ways of fabricating gratings on dielectric and Au surfaces: electron-beam lithography, mechanical transfer imprinting, and ion-beam writing. Figure 5 shows a grating fabricated on top of a gold surface using ion beam writing. The grating pattern is clearly visible, with only small irregularities caused mainly by the step size of the ion beam movement.

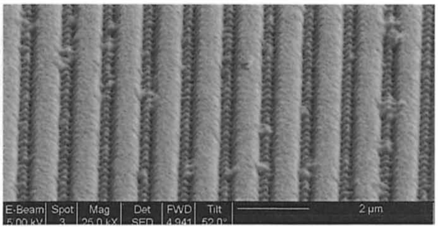

Figure 5: Scanning electron microscope photo of ion beam writing of gratings on a gold surface.

Center of mass determination [18,19]

The trajectory of mass center (MC) in the external gravitational field is the reference for drag-free flight in inertial space. The precise determination of the MC offset from the geometric center (GC) is needed for LISA. We have developed a new method for measuring the MC location, which involves rolling the proof mass and optically detecting the PM velocity modulation generated by the MC offset from the GC. The MC location is recovered by comparing the times that the sphere crosses optical gates with times computed using a mechanics model. Figure 6 shows the results of four different MC measurements. The standard deviation in the MC measurements is 1.5 μm.

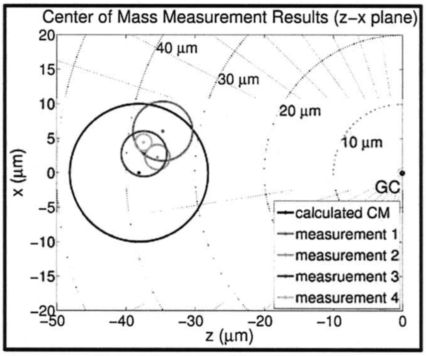

Figure 6. MC location measurement results

Moment of Inertia Measurement [20-22]

Drag-free flight places stringent requirements on the density distribution within satellite. The gravitational self-attraction force on the proof mass can be indirectly measured through a second order expansion, consisting of the measurable quantities of mass, mass center, and moment of inertia [30]. The moment of inertia is measured using a five-wire torsion pendulum, which reduces errors due to translational degrees of freedom [20,21]. The torsion pendulum is integrated with an optical grating angular sensor to provide both a large dynamic range and high resolution sensing [15,16]. The instrument calibration phase indicates the capability of moment of inertia measurements to a relative precision of a few parts in 10^4 .

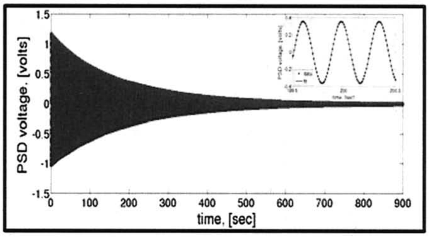

Figure 7. Torsion pendulum oscillation measurement over 15 minutes

UV LED Based AC Charge Management System [23,24]

Deep UV LED charge management systems (CMS) have the advantages of high dynamic range, low disturbance, low power consumption, and light weight. After the demonstration [17] of AC charge management using a UV LED, we have started the space qualification of UV LED CMS. Figure 8 shows 2600-hour operation of a UV LED under AC charge management working conditions. Additional measurements show spectral stability in UV LED emission over an extended period of time.

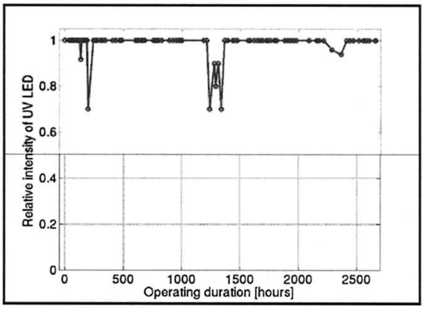

Figure 8. UV LED power stability tests over 2,600 hours. Power dips were due to temperature rise caused by thermal controller error, not by the LED itself.

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