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Technology Development for Modular Gravitational Reference Sensor (MGRS)

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Abstract

Gravitational wave detection is one of the most compelling problems in physical sciences today [1-11]. Laser Interferometric Space Antenna (LISA) [2-4], Big Bang Observatory (BBO) [5] and Deci-hertz Gravitational Wave Observatory (DECIGO) [6] are highly sensitive space-borne gravitational wave detectors requiring unprecedented precision. At the heart of the LISA like spacecraft is the Gravitational Reference Sensor (GRS), which houses a proof mass (PM), providing a reference at the end point of the distance measurement.

Much progress has been achieved in LISA and its pilot studies [7-9], and LISA Technology Package (LTP) in various aspects such as disturbance reduction, interferometry, data analysis, and more. However, there is need in studying GRS architecture, which could significantly simplify LISA, but more importantly future missions beyond LISA, such as BBO and DECIGO, and thereby enhancing the sensitivity, reliability and lowering the cost.

Until recently, the baseline design for LISA GRS had been direct illumination of the PM as published in 1998 [3-4]. Beginning in 2003, we have revisited the GRS design with the goals of simplifying the design, reducing cross talk, and moving towards true drag free performance. We proposed the Modular GRS architecture (MGRS) in 2004 [11]. Since then, the LISA and BBO baseline designs have changed substantially. The BBO has moved to a single PM. In the new LISA baseline, the laser beam from the remote spacecraft no longer directly illuminates the PM, but instead measures the separation between remote GRS housings. As such, the MGRS architecture has been adopted partially in LISA and BBO.

MGRS [11, 12] represents the next generation of technology for space gravitational wave detection and an array of precision experiments in space. We have been making substantial progress in recent years. It is increasingly recognized that the Modular Gravitational Reference Sensor (MGRS) will achieve better performance, as concluded in join research with European collaborators [24]. We believe now is the right time to increase the support level for MGRS R&D and accelerate technical implementation of this important innovation.

Technology Development for Modular Gravitational Reference Sensor (MGRS)

1. Introduction

Gravitational wave detection is one of the most compelling problems in physical sciences today [1, 2]. Laser Interferometric Space Antenna (LISA) [3, 4] and Big Bang Observatory (BBO) [5], Deci-hertz Gravitational Wave Observatory (DECIGO) [6] are highly sensitive space-borne gravitational wave detectors requiring unprecedented precision. At the heart of the LISA and BBO spacecraft is the Gravitational Reference Sensor (GRS), which houses a proof mass (PM), providing a reference at the end point of the distance measurement.

Much progress has been achieved in LISA and its pilot studies, and LISA Technology Package (LTP) in various aspects such as disturbance reduction, interferometry, data analysis, and more. However, there is urgency in studying GRS architecture, which could significantly simplify LISA, but more importantly future LISA versions, such as BBO and DECIGO, and thereby enhancing the sensitivity, reliability and lowering the cost.

Until recently, the baseline design for LISA GRS had been direct illumination of the PM as published in 1998 [3, 4]. Beginning in 2003, we have revisited the GRS design with the goals of simplifying the design, reducing cross talk, and moving towards true drag free performance. We proposed the Modular GRS architecture (MGRS, or stand-alone GRS) in 2004 [11]. The MGRS 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 providing positioning reference for external use. 2) Only one PM is used. 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 that reduces the disturbances.

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MGRS represents the next generation of technology for space gravitational wave detection and an array of precision experiments in space. We have been making substantial progress in recent years. It is increasingly recognized that the Modular Gravitational Reference Sensor (MGRS) will achieve better performance, as concluded in join research with European collaborators. We believe now is the right time to increase the support level for MGRS R&D and accelerate technical implementation of this important innovation.

In the course of MGRS R&D, one of our important achievements is the education of next generation of space scientist and engineers. The MGRS program has graduated or nearly graduated total six Ph.D’s, three Masters, and two Engineers, in the disciplines Aeronautics and Astronautics (AA), Applied Physics (AP), and Electrical Engineering (EE). It is rare to see these many students graduated with advanced degrees from a single research program only in several years.

2. **MGRS concept**

Figure 1 shows a schematic overview of the MGRS architecture [11]. The laser light from the remote spacecraft is heterodyned external to the MGRS housing and does not illuminate the proof mass (PM) directly. The internal distance measurement is relayed to an external reference via the housing wall. The LISA fleet is intended to fly drag-free, requiring the PMs be shielded inside the housing to reduce disturbances such as solar wind and magnetic fields. The spacecraft follows the movement of the PM in a pure gravitational field. The optical bench and GRS housing are mounted on the spacecraft, which has relative motion to the PM, due to disturbances and micro thruster noise. Two independent measurements are needed among three targets, namely the PM, the incoming laser beam, and the position of the housing. In the MGRS, measurements are naturally made from the PM to the housing wall, and from the housing wall to the incoming laser phase front. This measurement sequence achieves the shortest possible optical path length. Multiple optical sensors are used in MGRS for precise readout of proof mass center relative to the housing. We have developed concept of two layer sensing and control. Interferometric optical sensing enables for high precision picometer level science measurement. Differential optical shadow sensing provides larger dynamic range (~1 mm), and adequate precision (~1 nm) for drag-free control.

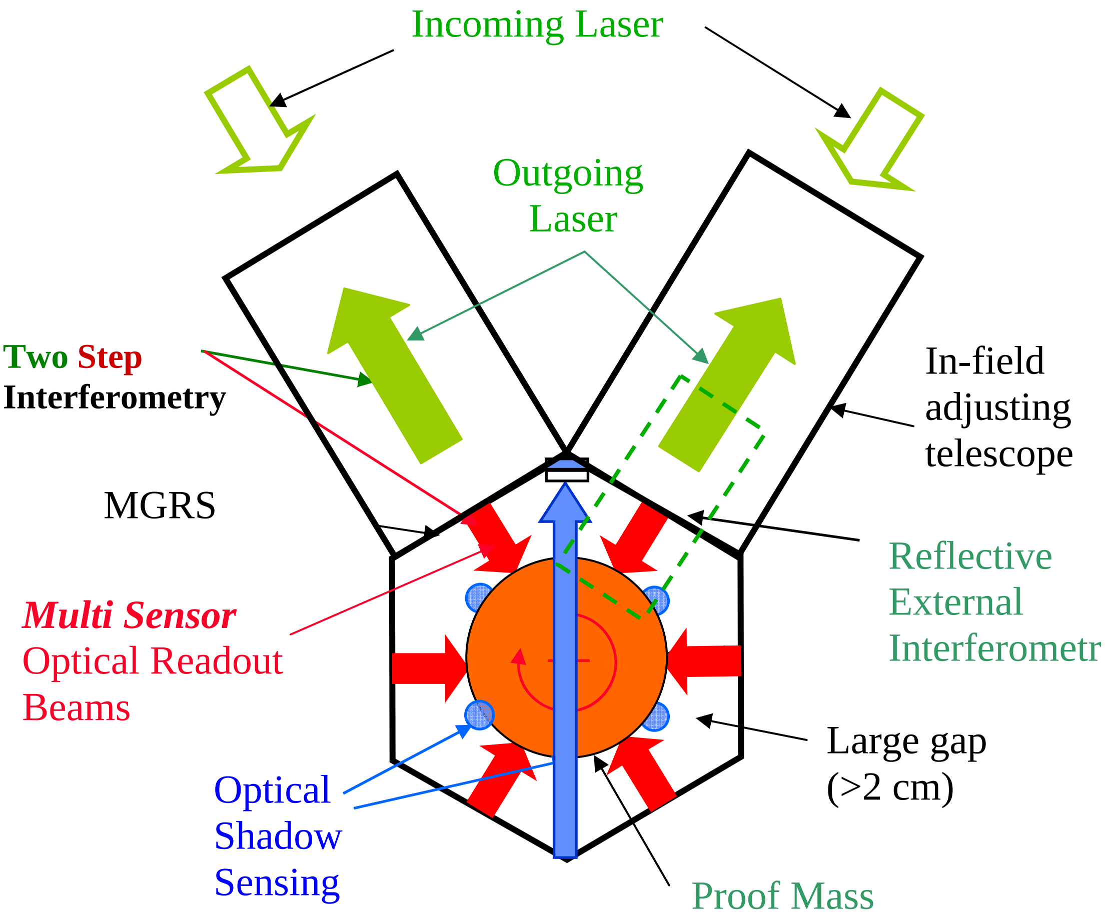

Figure 1. Modular Gravitational Reference Sensor (MGRS)

3. MGRS Technologies

3. 1 System Technologies

3.1.1 *Sphere and cube GRS overview (Collaboration with EADS Astrium)* Collaborating with EADS Astrium, we have conducted a high level review [12] of the state of the art of the LISA GRS. We also started a trade study of GRS configurations with cubic proof masses or with a single spherical proof mass (MGRS). The results show that the performance of the cubic proof mass configurations is adequate for the LPF baseline requirement. Further, the MGRS with a spherical proof mass holds promise as a future GRS, because of its simpler structure and higher performance at low frequencies.

3.1.2 *Sphere and cube trade-off studies: Noise tree (Collaboration with EADS Astrium)* [24] Stanford and EADS Astrium collaboratively studied the acceleration noise trees for the MGRS, and compared the results with the cubic GRS. The results show that the noise from environmental disturbances for the MGRS and cubic GRS are 8.5×10^{-16} m/s^2 and 10.5×10^{-16}m/s^2, respectively, and the stiffness induced noises are 0.4×10^{-16} m/s^2, and 2.8×10^{-16} m/s^2, respectively. Based on these first estimates, the spherical MGRS has ~28% lower total acceleration noise as a result of its large gap, full optical sensing, and no electrostatic actuation. The MGRS further enables simpler drag-free control.

3.1.3 *Two-layer sensing and control* We have devised a two-layer optical sensing scheme, in which the science measurement is accomplished via picometer precision interferometric sensors, and the drag-free control signal is mainly obtained via large dynamic range shadow sensors. There is a substantial overlap region between the two sensing layers.

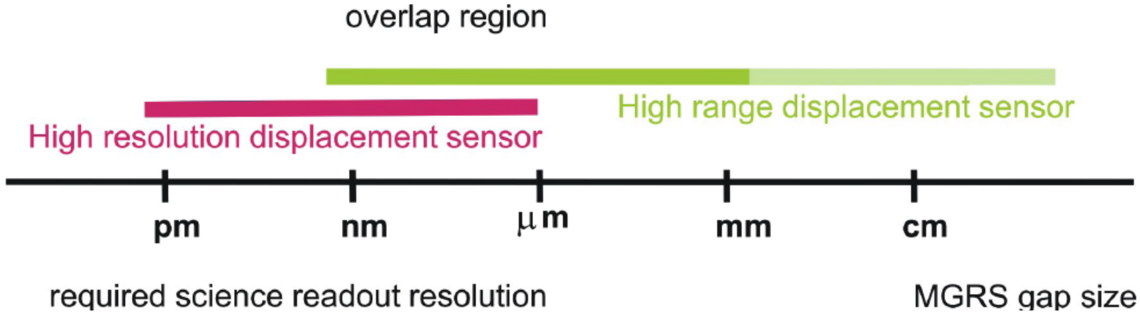

Figure 2. The two-layer sensing and control scheme. High precision laser interferometric sensors provide the science signal. High dynamic range optical shadow sensors provide the drag-free control signal. The two layers overlap in 0.1 nm-1 μm region.

3.1.4 *Mass center determination using multiple optical sensors* We have undertaken an extensive set of analytical [22] and numerical [33] analysis to test the determination of the mass center position of a spinning sphere using a set of optical displacement sensors. The simulation demonstrates that we can accurately separate the proof-mass surface figure (~ 300 nm RMS) from its mass center motion (~ 30 nm RMS) using a numerical fit to the spin frequency and its harmonics. The simulation includes realistic system parameters such as sensor noise and residual drag-free error. The mass center displacement precision is better than 3 pm/Hz$^{1/2}$. This firmly establishes that a set of optical displacement sensors can offer high precision and high system reliability.

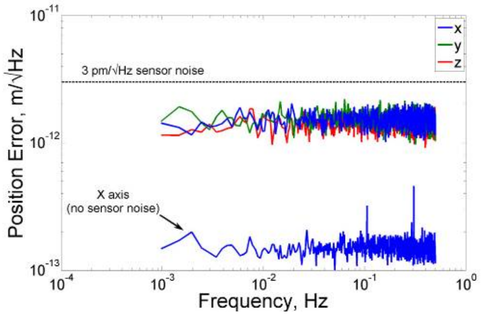

Figure 3: Simulation showing picometer determination of the mass center position, using multiple sensors. Head on sensors achieve even lower noise level (lower trace).

3.2 Optical Displacement Sensing [17, 18]

We have completed construction of a new test platform and vacuum chamber for the interferometric optical displacement sensor, consisting of a 900 line/mm grating, and a mirror surface simulating the proof mass. The cavity length is set at ~ 2 cm, resembling the gap size. The displacement signal is read out using a Pound-Drever-Hall RF modulation scheme. Preliminary testing in air on the new platform shows a noise level of 3~5 pm/√Hz at 1 Hz. The test platform will move into a vacuum chamber for improved performance.

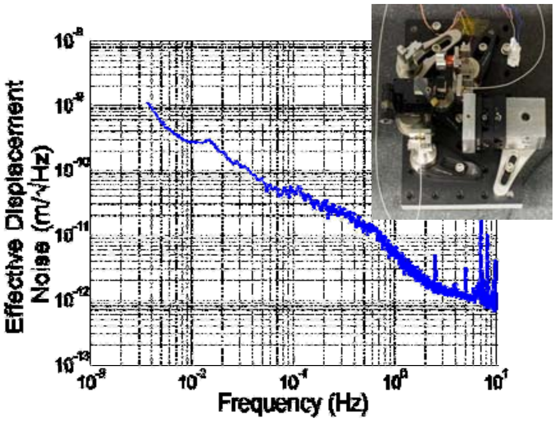

Figure 4. Preliminary results of the optical displacement sensor.

3.3 Differential Optical Shadow Sensing [17, 18, 29]

The Differential Optical Shadow Sensor (DOSS) scheme, shown in Figure 4, cancels laser intensity noise, while doubling the proof mass displacement signal. We have designed and constructed an optical shadow sensing test platform, on which the proof mass can be displaced with nanometer precision using a PZT driven flexure structure. We reduced the noise effects of electronics, electromagnetic interference, air flow and temperature, and achieved ~ 2 nm/Hz$^{1/2}$ at 2 Hz. The dynamic range is 1-3 mm, limited by the photodetector diameter. Our experience shows that optical shadow sensing is more robust than the interferometric sensors thanks to lower requirements in optical alignment.

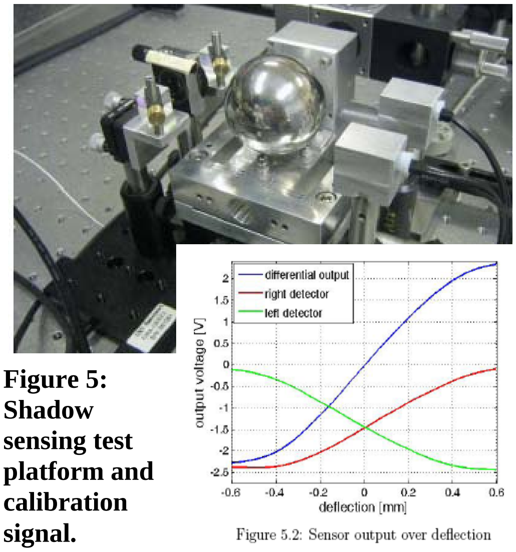

Figure 5.2: Sensor output over deflection

Figure 5: Shadow sensing test platform and calibration signal.

3.4 Air Bearing Supported Platform and Multi Sensor Optical Sensing [41, 49]

We have acquired an air bearing which can float a heavy metal spherical proof mass. With a simple operation of connecting gas line to a compressed air bottle, we have floated a stainless steel sphere of 2 inch diameter. The stainless sphere can be manipulated to spin smoothly. The spin rate is variable. The air bearing is mounted on a flexure based 3-dim stage, which can be driven in 3 translational degrees of freedom using PZT actuators. We are building multiple optical sensors around this test platform. The initial plan is to build four optical shadow sensors in a tetrahedron configuration, which can monitor the movement of the spherical proof mass in 3-dim translational compounding with spinning.

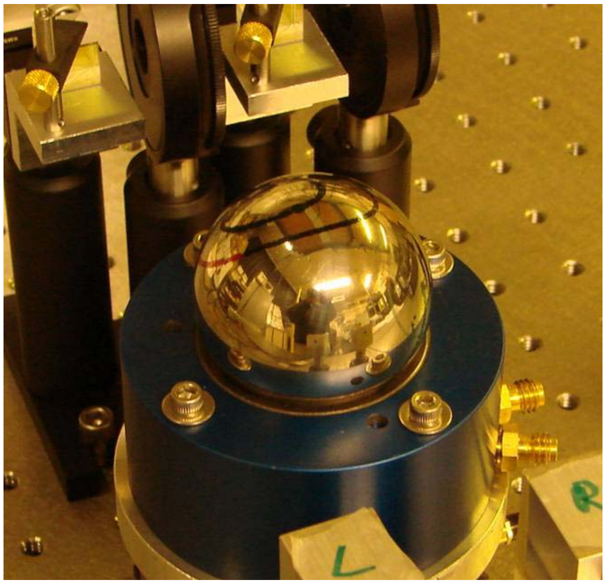

Figure 6: Shadow sensing test platform and calibration signal

3.5 Grating Angular Sensing [17, 18, 31]

We have improved the grating angular sensor by lowering noise and expanding the dynamic range. We have also constructed a vacuum enclosure for the entire grating angular sensor assembly. The photodetector and amplifier circuits now can receive higher laser power without saturation. With a mere working distance of 6 cm, and with an input laser power of 14 mW, we have observed an angular sensitivity of ~ 0.2 nrad/Hz$^{1/2}$ using the symmetric grating angular sensor. At low frequencies, we have achieved 1-2 nrad/Hz$^{1/2}$ at 1 Hz. The angular sensor will be applicable for both MGRS and space telescope steering. (JPL DRDF program)

3.6 Laser Frequency Stabilization Using a Grating Angular Sensor [17, 19]

The typical scheme for laser frequency stabilization utilizes a resonant optical cavity. Ambiguity in absolute frequency may occur due to periodicity in the cavity spectra. Grating angular sensor can be used as a non-resonant, robust laser frequency stabilizer. The grating angular sensor takes advantage of grating angular magnification and beam projection compression, thus exhibiting a high angular sensitivity of 0.1 nrad/Hz$^{1/2}$. The laser frequency deviation to produce such a small angle is ~ 300 kHz. Frequency stability at this level is sufficient for many practical applications, such as the absolute frequency indicator for LISA. The grating stabilizer will have a simpler structure and easier mechanical alignment.

3.7 Diffractive Optics [28, 30, 42, 46]

We have expanded our diffractive optics work to characterize some LLNL gratings that may have applications in external interferometry, which requires high diffraction efficiency. We constructed grating cavities with extensive work in improving alignment, mechanical stability, interferometric calibrating the PZT actuation, and mode matching. Our highest observed finesse so far was 1002 ± 2.5, or a grating diffraction efficiency of 99.577 ± 0.002%.

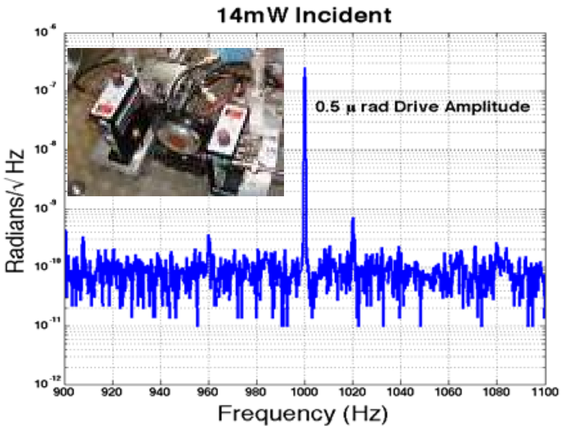

Figure 6. Measurement results from the grating angular sensor. The noise floor was below 2×10^{-10} rad/Hz$^{1/2}$. Inset: Grating angular sensor in vacuum chamber.

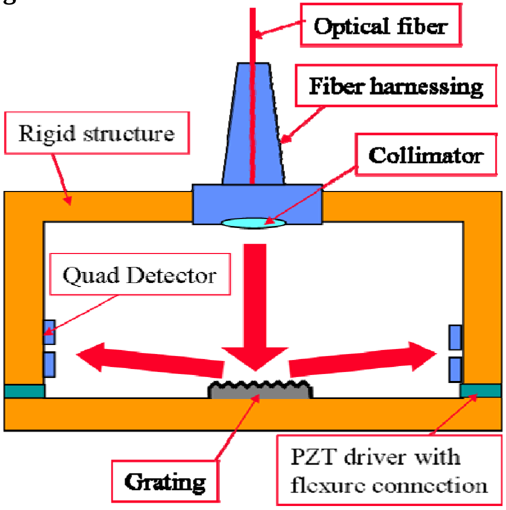

Figure 7. Structure of the grating laser frequency stabilizer

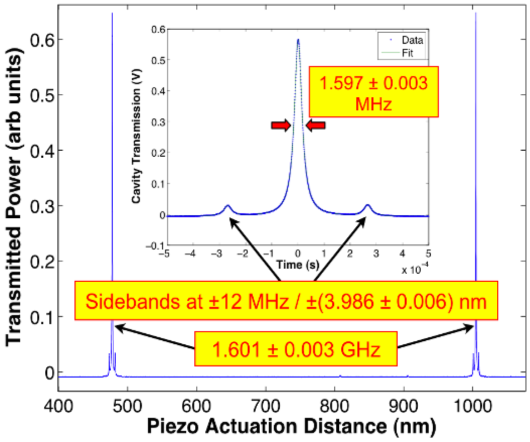

Figure 7. Grating cavity transmission versus cavity scan. Finesse of 1002 is demonstrated, representing diffraction efficiency of 99.577%. Inset: Blow up of the resonance portion.

3.8 Center of Mass Measurement [17, 18, 32]

A new approach for measuring the mass center location of a spherical proof mass has been demonstrated to 150 nm precision. Knowledge of the mass center of a drag-free test mass is critical for calibrating the cross-coupling between rotational and translational degrees of freedom, and for inferring density inhomogeneities in the test mass material. Improvements in precision have come from the damping of mechanical vibrations due to the sphere rolling, careful isolation of the electronics to remove systematics caused by magnetic field fluctuations, shielding from air convection currents, and improving the detectors and data acquisition system design.

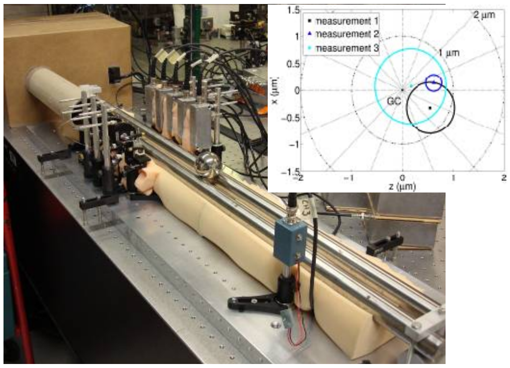

Figure 8. Mass center measurement apparatus, with improved vibration isolation and electronic noise reduction. Inset: Measurement of the mass center. Standard deviation < 150 nm.

3.9 Moment of Inertia and Self Gravity Attraction [26]

The five-wire torsion pendulum apparatus for moment of inertia measurements has been improved. A new version was designed and fabricated using SolidWorks CAD modeling software and a CNC milling machine. The improved design has a better mass balance and better tension distribution, resulting in reduced translational motion. In addition, a quad photo-detector was added to the grating angular sensor for higher sensitivity. The pendulum now can operate with higher spectral purity or signal to noise ratio. The amplitude spectral density plot shows a clean peak at the natural frequency around 3 Hz with error sources due to translation shifted above the measurement band.

Figure 9: Measurement sphere on torsion pendulum platform.

3.10 UV LED Charge Management System [13][14][16][17][33]

We have continued UV LED power and spectral lifetime tests. The UV LED has now been operated more than 20,000 hours without significant power drop. The spectral shift is measured to be ~ 1 nm towards shorter wavelengths, which actually enhances photoelectric effects. These results are shown in Fig. 11. Another power stability test in a vacuum chamber and now has been running close to 10,000 hours without seeing appreciable power change.

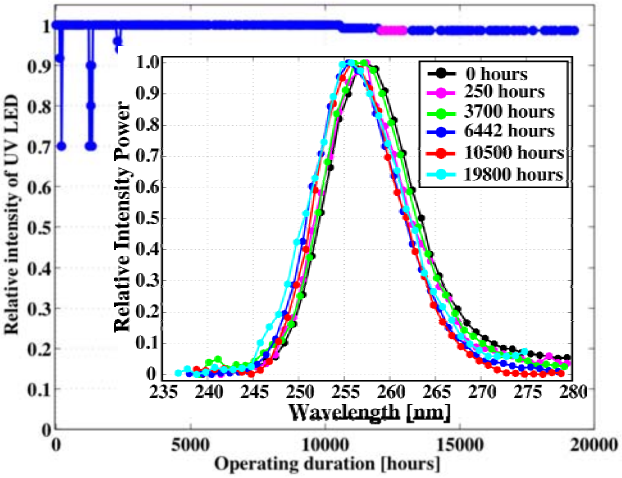

Figure 10. UV LED power and spectral stability.

3.11 UV LED Radiation Hardness Test [33]

We have conducted large dose radiation hardness tests using an accelerator source for 63 MeV protons. For proton fluence from 10^{10} to 10^{12} protons/cm^2, there was no significant power drop for UV LED light output at 255 nm wavelength. The UV emission spectrum also remains the same. This level of radiation test exceeded 100 years of radiation dose in the deep space LISA orbit. Therefore, we have demonstrated the extreme radiation hardness of UV LED. The combination of the successful tests in power lifetime, spectral stability, and radiation hardness has proven that the UV LED is far superior to mercury lamps in reliability. Thus a UV LED based AC charge management system developed at Stanford should be the first choice for LISA and other high precision space flights requiring charge control.

Our UV LED work has received interest from LISA community and beyond. We have received request of information and collaboration from NASA Ames Research Center, NASA EXIS program, NASA Goddard Space Flight Center, and DECIGO.

3.12 Thermal Control [13] [34]

We are developing combined passive and active thermal control system with the goal of achieving sub microkelvin temperature stability and uniformity over a bench size volume. For the active control, we have developed a model predictive control (MPC) scheme. For the passive control, we are designing a new thermal enclosure with multilayer structure with alternative conducting and insulating layers which insures the temperature uniformity and eases the burden on the active control. The upgraded thermal enclosure will be an important test facility for MGRS development. The experimental results show that stability of the new system is as low as 2 mK/Hz$^{1/2}$ at 1 mHz. Uniformity improvement is expected to be even more significant.

3.13 Small Satellite Series for MGRS

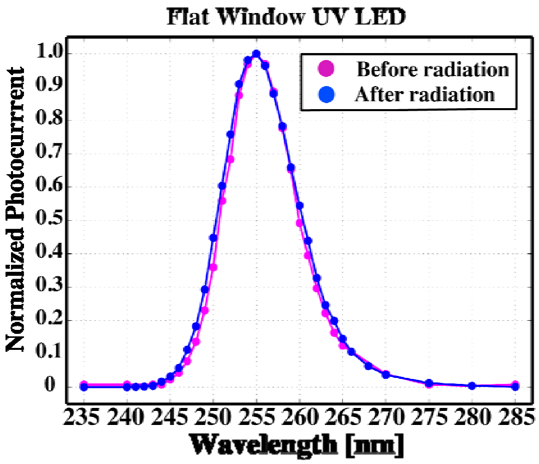

Figure 11. Proton irradiation results: No spectral shift was observed after irradiating protons on the ball lens /flat window UV LEDs

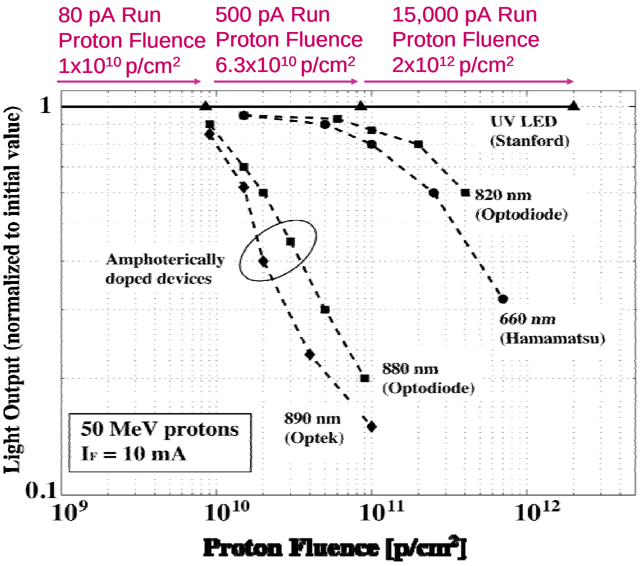

Figure 11. UV LED radiation hardness test. UV LED output power vs. proton fluence. (Note: Data points other than UV LED are from Johnston et al. IEEE Trans. Nucl. Sci. p.2500 vol. 47 (2000).)

Figure 12. Newly constructed multi-layer thermal chamber.

Stanford and Ames collaboratively worked on cost effective strategies to accelerate space tests for MGRS. Ames Research Center is now making intensive effort to develop small satellites, including Nanosat measuring 12 cm x 12 cm x 28 cm, weighing ~ 2-5 kg, and Microsat, weighing 10~20 times more. Most key components of MGRS will fit into Nanosat, and a sub-scaled MGRS could fit into a Microsat. We have perceived a series of 7 Nanosats and 1 Microsat to space test the key component technologies of MGRS, and finally a Microsat to space test MGRS system performance. Since Nanosat and Microsat modules are designed for ride-along flight as the secondary payload, the launching costs of MGRS series Nanosat and Microsat will be minimized. We are working towards a realization.

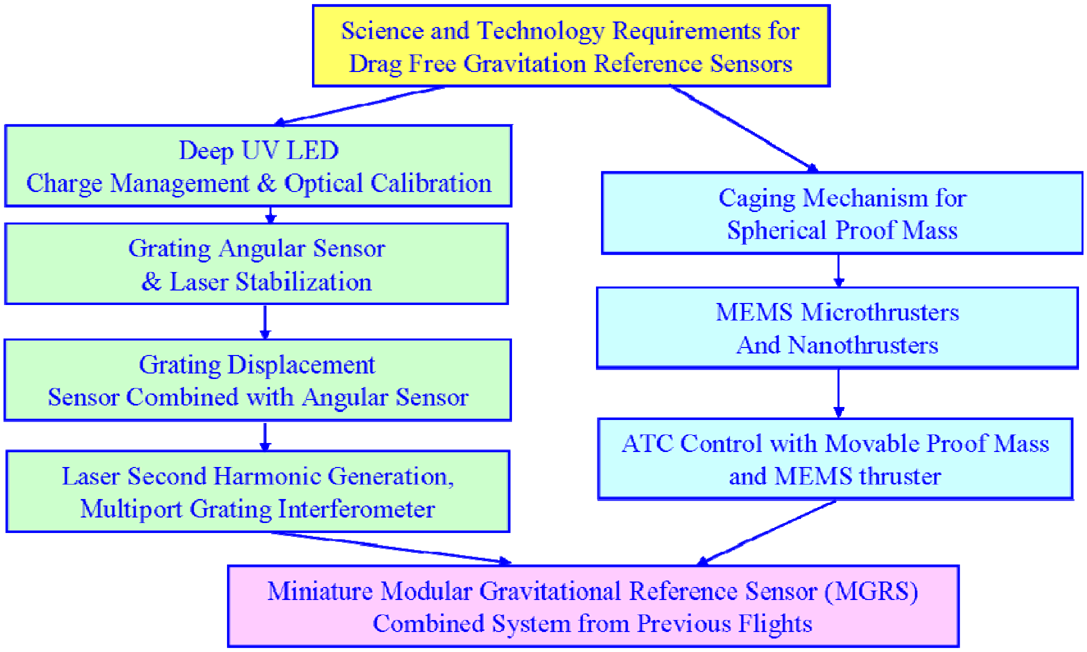

Figure 13. Small satellite series for MGRS. Each Nanosat (green and cyan color) will carry a key subsystem for space test. A Microsat (purple color) will carry the small scale MGRS for system test.

Conclusion

During the first and second year of MGRS funding, the Stanford team made exceptional progress, and exceeded our program goals. We educated the largest graduate student body in LISA related research in the Unite States. Our EPO program success is celebrated at Stanford University. We have proven that we can deliver in all fronts of NASA sponsored research.

Most importantly, we have kept pace of innovation and expanded research beyond the original plan to accelerate MGRS development. We have developed a new array of technologies that were beyond our original work scope.

Our program has attracted collaborations from NASA Ames Research Center, Jet Propulsion Laboratory, EADS Astrium in Europe, and DECIGO in Japan.

We believe that it is now the right time for NASA to increase the funding level to our MGRS program for strengthening the MGRS R&D. With the added support, we will be able to deliver the MGRS that is vital to LISA, GRACE II, BBO, and many defense applications.

MGRS is designed to fully take advantage of space can offer: 3 dim drag free or geodetic reference with minimal constrain and thus highest precision. MGRS is also designed with cost-effectiveness. MGRS will be the core instrumentation for a large class of future NASA missions, spanning from gravitational sciences, earth and planetary survey, and autonomous constellation.

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