

**TUNABLE SUPERCONDUCTING GRAVITY GRADIOMETER FOR MARS CLIMATE, ATMOSPHERE, AND GRAVITY FIELD INVESTIGATION** C. E. Griggs<sup>1</sup>, H. J. Paik<sup>1</sup>, M. V. Moody<sup>1</sup>, S.-C. Han<sup>2,3</sup>, D. D. Rowlands<sup>3</sup>, F. G. Lemoine<sup>3</sup>, P. J. Shirron<sup>4</sup>, X. Li<sup>4</sup>, <sup>1</sup>Department of Physics, University of Maryland, College Park, MD 20742, USA, <sup>2</sup>Faculty of Engineering and Built Environment, University of Newcastle, Callaghan, NSW 2300, Australia, <sup>3</sup>Planetary Geodynamics Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA, <sup>4</sup>Cryogenics and Fluids Branch, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.

**Introduction:** We are developing a compact tensor superconducting gravity gradiometer (SGG) for obtaining gravimetric measurements from planetary orbits. A new and innovative design gives a potential sensitivity of  $\sim 10^{-4}$  E Hz<sup>-1/2</sup> ( $1 \text{ E} \equiv 10^{-9} \text{ s}^{-2}$ ) in the measurement band up to 0.1 Hz (suitable for short wavelength static gravity) and of  $\sim 10^{-5}$  E Hz<sup>-1/2</sup> in the frequency band less than 1 mHz (for long wavelength time-variable gravity) from the same device with a baseline just over 10 cm. The measurement band and sensitivity can be optimally tuned in-flight during the mission by changing resonance frequencies, which allows measurements of both static and time-variable gravity fields from the same mission.

Significant advances in the technologies needed for space-based cryogenic instruments have been made in the last decade. In particular, the use of cryocoolers will alleviate the previously severe constraint on mission lifetime imposed by the use of liquid helium, enabling mission durations in the 5 – 10 year range.

The original SGG, fully developed in the 1990's, had *mechanically suspended* test masses, which limited the sensitivity at 1 mHz to  $\sim 10^{-2}$  E Hz<sup>-1/2</sup> with a baseline nearly 20 cm [1]. *Magnetic levitation* gives a number of advantages. The resulting magnetic spring is much more compliant and gives two degrees of freedom to each test mass. Hence a tensor gradiometer can be constructed with only six test masses, and the  $10^{-4}$  -  $10^{-5}$  E Hz<sup>-1/2</sup> sensitivity can be achieved with a device miniaturized by an order of magnitude in volume and mass from the existing device.

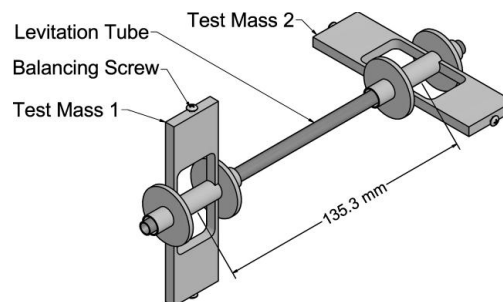
Even with the static measurement mode of  $10^{-3}$  E Hz<sup>-1/2</sup> sensitivity up to 0.1 Hz, the present resolution of the global gravity field from decades of Doppler tracking data ( $l \sim 110$  for Mars, where  $l$  is the maximum degree of gravity coefficients) could be substantially improved by using SGG data ( $l \sim 220$ ) from a single spacecraft only within 100 days. It would be similar with or even better than the expected resolution ( $l \sim 180$ ) using satellite-to-satellite tracking (SST) from two co-orbiting spacecrafts. With the time-variable mode of  $\sim 10^{-5}$  E Hz<sup>-1/2</sup> up to 1 mHz, the SGG should also enable mapping the regional scale ( $\sim 400$  km) of time-variable gravity variations due to seasonal mass transport of CO<sub>2</sub>, dust, and water cycle every month.

The development of a *single-axis* SGG with levitated test masses started in 2012 with support from NASA's Earth Science Division. Without provision to

measure linear and angular accelerations in the other two axes, the common-mode rejection ratio (CMRR) in this device will be limited to  $10^5$ . Under the present PICASSO program, we will expand this instrument to *three axes* and apply *residual balance* to improve the CMRR by a factor of  $10^3$  to  $10^8$ , with a goal to advance the TRL from 3 to 4.

**Principle of Gravity Gradiometry:** The second spatial derivatives of the gravitational potential  $\varphi(x_i, t)$  form a gravity gradient tensor  $\Gamma_{ij}$ .  $\Gamma_{ij}$  is symmetric and its trace is proportional to the local mass density  $\rho$  due to the inverse-square law. An *in-line*-component gradiometer can be constructed by differencing signals between two *linear* accelerometers whose sensitive axes are aligned along their line of sight. Likewise, a *cross*-component gradiometer can be constructed by differencing signals between two concentric *angular* accelerometers whose moment arms are orthogonal to each other. [2,3,4,5]

**Magnetic Levitation and Tensor SGG:** Figure 1 is a perspective view of two Nb test masses levitated by a current along a single horizontal Nb tube. Each test mass has two wings  $180^\circ$  apart, which provide a moment arm about the tube axis ( $x$ ). A balancing screw is provided at the end of each wing to adjust the center of mass position and bring it to the rotation axis. The current flowing along the tube provides stiff suspension in the radial directions ( $y$  and  $z$ ), but leaves the test masses to move freely along the axis and rotate freely about the same axis. By sensing the differential *linear* and *angular* acceleration of the two masses, one can measure an *in-line* ( $\Gamma_{xx}$ ) and a *cross*-component gradient ( $\Gamma_{yz}$ ) simultaneously.



**Figure 1. Two superconducting test masses levitated around a single superconducting tube.**

All components for a full tensor SGG have been manufactured, including machining Nb test masses and

housings. Critical Nb components have been polished in order to maximize Q. In addition, sensing coils and heat switches have been constructed. A levitated SGG with a single translation and a single rotation axis is currently being assembled. A cryostat isolation system has been constructed, and means of applying excitations in six degrees of freedom are complete.

**Tunable Sensitivity:** Figure 2 shows the intrinsic instrument noise spectral density of the *tensor* SGG with the DM resonance frequency  $f_D$  tuned to 20 mHz (solid blue line). The noise level of the diagonal components is better than  $2 \times 10^{-4} \text{ E Hz}^{-1/2}$  in the 0.001 to 0.1 Hz frequency band. This represents two orders of magnitude improvement over the performance of the Gravity and Ocean Circulation Experiment (GOCE) gradiometer over a wider bandwidth [6]. The frequency band and sensitivity is optimized for the high-resolution static gravity recovery. Another attractive feature of our SGG is the tunability of  $f_D$  in flight by changing persistent currents stored. The intrinsic noise at  $f \leq 1 \text{ mHz}$  could be improved by a factor of 30 by lowering  $f_D$  to 0.2 mHz (solid red line) [7]. It will be useful for the analysis of time-variable gravity at the spatial resolution of  $\sim 400 \text{ km}$  every month or so.

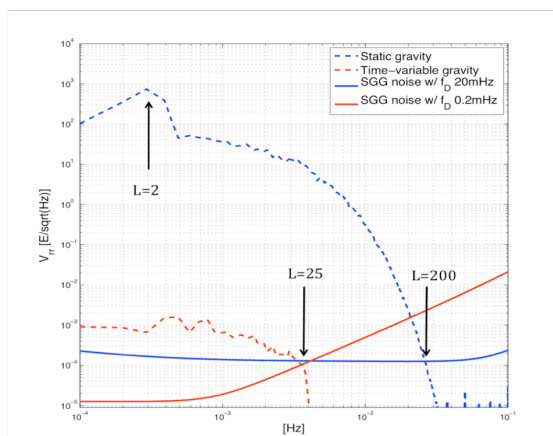


Figure 2. SGG instrument noise spectral density.

**SGG Cryogenic System:** The SGG requires stable cooling to  $\leq 6 \text{ K}$ . For planetary missions, requiring potentially a long cruise phase and extended orbital observations, the cryogenic system will consist of a small, highly efficient dewar and a low temperature mechanical cryocooler. The dewar will structurally contain the instrument, using low thermal conductance supports and internal shields to minimize heat leak from the warm spacecraft environment to the cold instrument. The cryocooler(s) will provide direct cooling of the instrument at  $\leq 6 \text{ K}$ , and the internal shields. Over the past two decades, development efforts for missions such as Planck and Herschel (ESA), Astro-H

(JAXA) and JWST (NASA) have resulted in mature cryocooler technologies that can reach the temperature required for the SGG.

**Mars Static and Time-Variable Gravity Field Recovery:** Figure 3 presents the amplitude of the Mars static gravity field at various spatial scales. Presently, the static field is resolved at the spatial resolution of  $100 \text{ km}$  from the analysis of several decades of Doppler tracking data. Using SGG, it could be improved down to  $50 \text{ km}$  only within a few months. The simulation based on NASA/Ames Mars General Circulation Model shows the time-variable gravity signals are  $\sim 10^4$  times smaller than the static signal over the spatial scale of a few hundreds km or larger. Presently, the Doppler tracking data constrain only the planetary scale ( $\sim 4000 \text{ km}$ ) of time-variable gravity limited to very low degree harmonics such as  $J_2$ . SGG will open new opportunity to understand Mars climate, polar ice cap, and  $\text{CO}_2$ , dust and water cycles at the spatial scale down to  $400 \text{ km}$  by measuring the time-variable gravity fields every month or less.

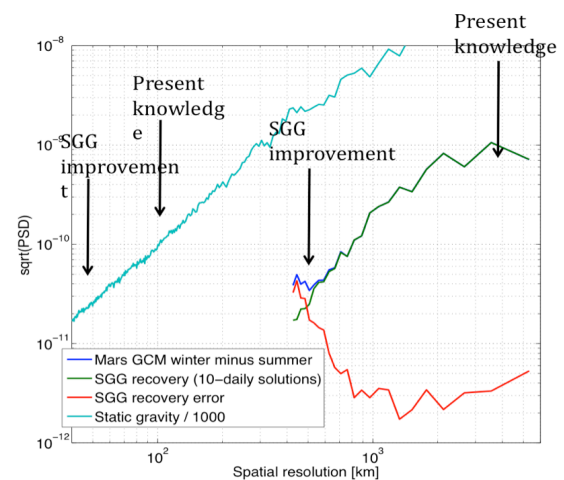


Figure 3. Degree amplitude of the Mars static and time-variable gravity field recovery.

**Acknowledgement:** This work was supported by NASA grants NNX12AK18G and NNX14AI43G.

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