SUPERCONDUCTING GRAVITY GRADIOMETER FOR PLANETARY MISSIONS. C. E. Griggs[1], H. J. Paik[1], M. V. Moody[1], D. D. Rowlands[2], F. G. Lemoine[2], X. Li[3], S.-C. Han[4], [1]Department of Physics, University of Maryland, College Park, MD 20742, [2]Planetary Geodynamics Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD 20771, [3]Cryogenics and Fluids Branch, NASA Goddard Space Flight Center, Greenbelt, MD 20771, [4]University of Newcastle, NSW 2308, Australia.

Introduction: We are developing a compact tensor superconducting gravity gradiometer (SGG) for obtaining accurate gravimetric measurements from planetary orbits. A new and innovative design gives a potential sensitivity better than 10^{-4} E Hz$^{-1/2}$ (1 E ≡ 10^{-9} s^{-2}) in the measurement band of 1 mHz to 0.1 Hz for a device with a baseline just over 10 cm.

The SGG requires cooling to ≤ 6 K, and the goal for a space mission is to use a cryocooler to enable mission lifetimes of ≥ 5 years. The most significant issue has been the potential for vibration from the cryocooler to couple into the gradiometer. On this front, there has been a *major breakthrough*. A 10-K turbo-Brayton cryocooler for space application has recently been demonstrated by Creare, LLC [1]. With the only vibration sources being low-mass, precisely balanced, rotors turning at > 1 kHz, and turbulent pressure forces from helium fluid, **the vibrations from the turbo-Brayton cryocooler will *not* affect the SGG performance even without active control or isolation**.

The original SGG, fully developed in the 1990's, had *mechanically suspended* test masses, which limited the sensitivity to ~ 10^{-2} E Hz$^{-1/2}$ with a baseline nearly 20 cm [2]. *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} E Hz$^{-1/2}$ sensitivity can be achieved with a device miniaturized by an order of magnitude in volume and mass.

With 10^{-4} E Hz$^{-1/2}$ sensitivity, **the expected resolution (l ~ 220, where l is the maximum degree of harmonic coefficients) of the gravity field for Mars is better than the expected resolution (l ~ 180) using satellite-to-satellite tracking (SST) from two co-orbiting spacecraft.** The more sensitive measurements from the SGG should also enable mapping the regional scale of seasonal gravity variations due to mass transport of CO_2 every month or every season.

SGG Instrument: Both a diagonal and an off-diagonal-component SGG have been developed at the University of Maryland (UM) [2,3]. Signal differencing by means of stable persistent currents *before* detection is a unique feature of the SGG. **This assures excellent *null stability* of the device, which in turn improves the overall common-mode (CM) rejection. The mechanical stability of materials at cryogenic temperatures guarantees that misalignments are also stable.** These error coefficients can therefore be measured once for all during the initial setup, multiplied by the proper acceleration components, and subtracted from the gradiometer output. By applying this 'residual CM balance' [4], the error coefficients have been reduced to ≤10^{-7} and ≤10^{-9} for the diagnonal and off-diagonal components, respectively.

A simple levitation scheme, which provides stiff suspension for unwanted degrees of freedom while permitting complete compliance along the sensitive axis, has been devised and demonstrated at UM. Figure 1 illustrates the principle of levitation by current induced along a superconducting tube. Inside the levitation tube, each of N-turn wires carries current I_L. This induces a screening current on the tube, NI_L, to flow along the inner surface of the tube and return along the outer surface. **The current density on the outer surface is *uniform*, independent of the current distribution inside the tube. This generates a *cylindrically symmetric* magnetic field,** as shown in Fig. 1(a). A tube-shaped superconducting test mass with a bigger diameter surrounds the levitation tube. When the test mass is concentric with the levitation tube, the field is uniform around the levitation tube and does not exert a net force on the test mass. However, if the test mass is displaced radially, as shown in Fig. 1(b), the field becomes stronger at P and weaker at Q, resulting in a radial restoring force.

The guiding principle in designing the SGG for laboratory test is the capability to levitate the test masses in 1-g. This led to a test mass design using thin "wings" to produce a light mass (m = 0.10 kg). On the ground, a relatively large current (I_L ~ 10 A with N = 120) is required to levitate the test masses against

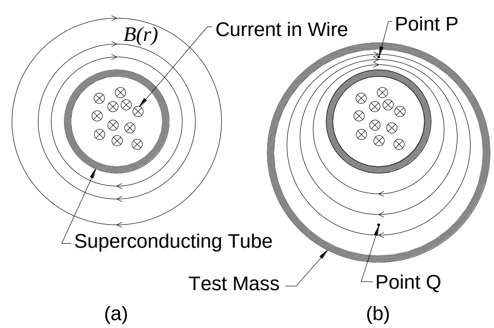

Figure 1. Principle of levitation by current induced on a superconducting tube.

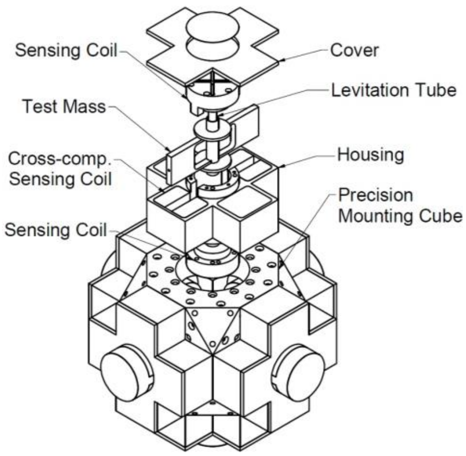

Figure 2. Partially exploded view of the tensor SGG.

Earth's gravity. **In space, the levitation becomes easier and the g-related errors disappear.**

A partially exploded view of the tensor SGG is shown in Fig. 2. The device will measure all six components of the gradient tensor, as well as all six components of the linear and angular accelerations of the platform. The entire SGG assembly weighs 12 kg and fits within a sphere of 22 cm in diameter.

Expected Sensitivity: The intrinsic noise of the diagonal components is better than 2×10^{-4} 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 GOCE gradiometer over a wider bandwidth. **The intrinsic noise at $f \leq 1$ mHz could be improved by a factor of 30 by lowering the resonance frequency f_D to 0.2 mHz. With such frequency tuning, SGG outperforms SST at low degrees, where time-varying signals are, as well as at high degrees yielding a superior spatial resolution.**

***Test Results*:** The first of the three axes of the tensor SGG has been assembled and is undergoing tests. A test mass has been successfully levitated and its dynamics is being investigated. Figure 3 shows the observed resonance frequency squared versus the sensing current squared for the translational mode. The excellent fit to a straight line shows that the acceleration-to-current transfer function is highly linear. The successful levitation proved that the magnetic field from the levitation tube not only *levitates* the mass but indeed provides *stable suspension* in two linear and two angular degrees of freedom, as predicted.

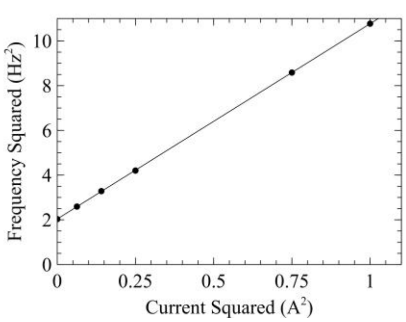

Figure 3. Frequency squared vs. current squared for the translational mode.

SGG Cryogenic System: The turbo-Brayton technology cryocoolers developed by Creare produce lower vibration levels than any of the competing cryocooler technologies. The successful operation of the turbo-Brayton cryocooler on the HST application combined with subsequent component and system developments at Creare to improve system efficiency, reduce weight, and provide cooling to < 10 K make the Creare turbo-Brayton an *ideal enabling technology* for providing the low vibration cooling required for the SGG.

Enabled Planetary Science: The unique high sensitivity of the gravity gradiometer has been demonstrated with the ESA's GOCE mission for the Earth [5]. Those measurements were particularly useful to characterize the lithospheric and (steady-state) oceanic processes at an unprecedented spatial resolution, substantially better than the GRACE mission [6] that exploits SST, while the latter has been addressing large-scale time-variability of the global gravity fields that the former is not capable of observing.

The SGG technology will bring similar advances to the planet's gravity fields. By virtue of inherent sensitivity to high-frequency gravity signals exceeding the spectrum attainable from Doppler tracking and SST, our gradiometer technology will significantly enhance the resolution of the global gravity field. Gradiometer measurements will help the trajectory determination of the spacecraft, and thus will improve the quality of surface height measurements from the laser altimeter.

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