

Exploring the Moon and Mars Using an Orbiting Superconducting Gravity Gradiometer*

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Abstract. Gravity measurement is fundamental to understanding the interior structure, dynamics, and evolution of planets. High-resolution gravity maps will also help locating natural resources, including subsurface water, and underground cavities for astronaut habitation on the Moon and Mars. Detecting the second spatial derivative of the potential, a gravity gradiometer mission tends to give the highest spatial resolution and has the advantage of requiring only a single satellite. We discuss gravity missions to the Moon and Mars using an orbiting Superconducting Gravity Gradiometer and discuss the instrument and spacecraft control requirements.

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1. Introduction

Detailed knowledge of gravity is essential to understand the interior structure, dynamics, and evolution of planets. High-resolution gravity maps for the Moon and Mars will also help locating subsurface water, natural resources, and underground cavities for astronaut habitation.

Lunar Prospector provided a complete coverage of the lunar *near* side to degree and order of 75 (Konopliv *et al* 1998). SELENE, scheduled for 2005 launch, will map the entire Moon by differential VLBI radio sources and a relay satellite (Sasaki *et al* 2003). Data on the surface and subsurface structure will be obtained by terrain camera, laser altimeter, and lunar radar sounder. Mars Global Surveyor tracking data yielded a global gravity map of Mars to degree and order 80 (Smith *et al* 1999). Higher resolution will be required to locate natural resources.

There are three instrumentation options for obtaining high-resolution gravity maps: (1) a single satellite with a high-altitude relay satellite (SELENE-type), (2) satellite-to-satellite Doppler tracking (GRACE-type) (Tapley *et al* 2004), and (3) a single satellite carrying a gravity gradiometer (GOCE-type) (Rebhan *et al* 2000). By detecting the second derivatives of the potential, the gradiometer mission tends to give the highest spatial resolution. The gravity gradiometer mission also has the advantage of requiring only one satellite, minimizing the mission cost.

2. Orbit and instrument requirements

To obtain the highest gravity and spatial resolution, the altitude must be minimized. On Mars, a low-altitude gravity survey could be performed in principle by using a balloon-borne gravity gradiometer. Although the sensitivity requirement will be modest due to the low altitude, the balloon-borne survey will be an extremely slow process and will only permit very limited local surveys. A balloon experiment is not feasible on the Moon, where there is no atmosphere. Therefore, gravity survey from an orbiting spacecraft is the only means available on the Moon and a preferred means on Mars. On Mars, the satellite altitude must be kept at $h \geq 100$ km due to

its atmosphere. On the other hand, a short-duration lunar gravity mission could be conducted at an altitude $h \leq 25$ km, limited only by the Moon's shape and the influence of the Earth's gravity.

Even at such a low altitude, detecting an underground cavity from the orbit is extremely challenging. For example, an underground cavity of size $(50 \text{ m})^3$ produces a gradient signal:

$$\Gamma = \frac{GM}{h^3} = \frac{(6.67 \times 10^{-11})(2.7 \times 10^3)(50^3)}{(2.5 \times 10^4)^3} = 1.4 \times 10^{-6} \text{ E}, \quad (1)$$

at $h = 25$ km, where $1 \text{ E} \equiv 10^{-9} \text{ s}^{-2}$. It may be possible to reduce h to 10 km over a limited area by using a slightly elliptical orbit. The signal then increases to $\Gamma \approx 1.8 \times 10^{-4} \text{ E}$. With the orbital speed of 1.6 km/s, it takes $t \approx 6$ s to traverse 10 km. The required measurement bandwidth, $\Delta f \approx 1/t \approx 0.16$ s, then leads to a gradiometer sensitivity requirement:

$$S_{\Gamma}^{1/2}(f) \leq \frac{\Gamma}{\sqrt{\Delta f}} = \frac{1.8 \times 10^{-4}}{\sqrt{0.16}} = 4.5 \times 10^{-4} \text{ E Hz}^{-1/2}, \quad 0.1 \text{ Hz} \leq f \leq 0.2 \text{ Hz}. \quad (2)$$

To be able to identify the signal, the background gravity feature must also be known to this level.

3. Superconducting Gravity Gradiometer

To meet the demanding sensitivity requirement of $10^{-4} \text{ E Hz}^{-1/2}$, a superconducting gravity gradiometer (SGG) operating at $T \leq 4$ K is required. A three-axis SGG has been developed at the University of Maryland with Code-Y support for Earth orbit application (see Figure 1). The intrinsic noise of this instrument was $4 \times 10^{-3} \text{ E Hz}^{-1/2}$, limited by the relatively stiff mechanical suspension used (Moody and Paik 2002). One could vastly improve the sensitivity of the SGG by employing magnetically levitated test masses.

Figure 2 is a schematic of the SGG with magnetically levitated test masses. The upper figure shows two levitated test masses along with levitation and sensing coils. The lower figure shows the superconducting differential circuit. Persistent currents I_1 and I_2 stored in the two sensing

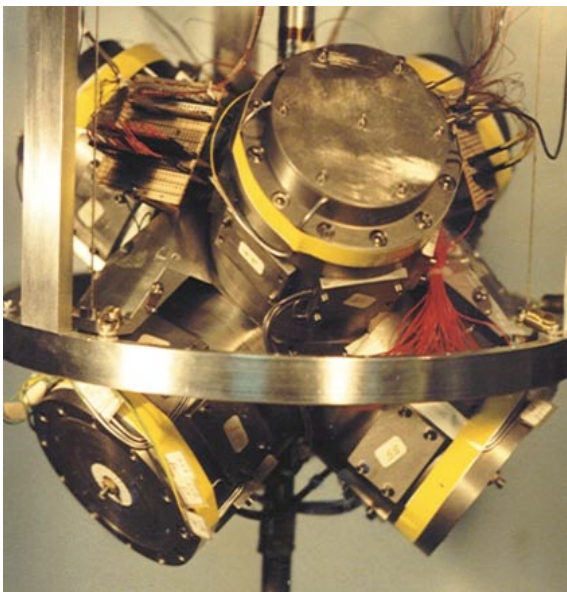


Figure 1. SGG developed for space application.

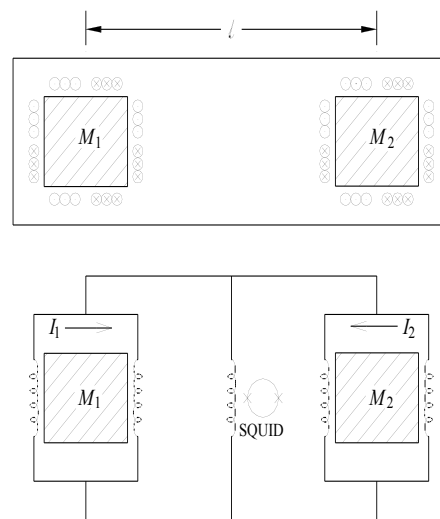


Figure 2. Schematic of SGG with magnetically levitated test masses.

loops provide coupling between the displacement of the test masses and the SQUID. The ratio I_1/I_2 is adjusted to precisely balance out common-mode acceleration at the SQUID output.

The intrinsic gradient noise of an SGG can be shown to be (Chan and Paik, 1987)

$$S_{\Gamma}(f) = \frac{8}{m\ell^2} \left[k_B T \frac{\omega_0}{Q} + \frac{\omega_0^2}{2\beta\eta} E_A(f) \right], \quad (3)$$

where m , $f_0 = \omega_0/2\pi$, and Q are the mass, resonance frequency, and quality factor of the test mass; ℓ is the gradiometer baseline; β , η , and $E_A(f)$ are the transducer energy coupling constant, amplifier coupling efficiency, and SQUID energy resolution; and $f = \omega/2\pi$ is the signal frequency, respectively. With the same parameter values as the mechanically suspended SGG except for f_0 : $m = 1.0$ kg, $\ell = 0.2$ m, $f_0 = 0.2$ Hz, $T = 2$ K, $Q_0 = 10^6$, $2\beta\eta = 0.5$, $E_A(f) = 5 \times 10^{-31}$ J Hz⁻¹ (1 + 0.1 Hz/ f), one finds $S_{\Gamma}^{1/2}(f) = 8 \times 10^{-5}$ E Hz^{-1/2} at 0.01 Hz $\leq f <$ 0.2 Hz.

4. Spacecraft control requirements

For cooling the SGG, a liquid helium cryostat will be the simplest option for a lunar gravity mission since it requires a lifetime of only three to six months. For a Mars gravity mission, a liquid helium cryostat, supported by even a noisy cryocooler, will work. En route to Mars, the cryocooler can be used to conserve liquid helium. During the orbital operation, the cryocooler can be turned off so the instrument can be cooled by the quiet liquid helium cryostat.

To minimize the centrifugal acceleration error, the gradiometer must be in an inertial orientation. On the other hand, to minimize the attitude control and dynamic range requirement, the gradiometer must be in a planet-fixed orientation. Only one axis, the orbit normal, satisfies both of these requirements. Therefore, to obtain the best sensitivity, a single-axis SGG could be carried by a spacecraft in an inertial orientation, with its sensitive axis normal to the orbit plane.

With the SGG's common-mode rejection ratio of 10^7 , the spacecraft linear acceleration must be controlled to 10^{-7} m s⁻² Hz^{-1/2}. The attitude, attitude rate, and attitude acceleration control requirements are 10^{-4} rad, 10^{-7} rad s⁻¹ Hz^{-1/2}, and 10^{-6} rad s⁻² Hz^{-1/2}, respectively. The linear acceleration control requirement could be met without a drag-compensation system. The attitude control requirement, although demanding, could be met by combining star trackers with gyros.

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