

Design of Superconducting Gravity Gradiometer Cryogenic System for Mars Mission

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ABSTRACT

Measurement of a planet's gravity field provides fundamental information about the planet's mass properties. The static gravity field reveals information about the internal structure of the planet, including crustal density variations that provide information on the planet's geological history and evolution. The time variations of gravity result from the movement of mass inside the planet, on the surface, and in the atmosphere. NASA is interested in a Superconducting Gravity Gradiometer (SGG) which will measure the gravity field of a planet from orbit. An SGG instrument is under development with the NASA Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO) program, which will be able to resolve the Mars static gravity field to degree 200 in spherical harmonics, and the time-varying field on a monthly basis to degree 20 from a 255 x 320 km orbit. The SGG has a precision of two orders of magnitude better than the electrostatic gravity gradiometer that was used on the European Space Agency (ESA) Gravity field and steady-state Ocean Circulation Explorer (GOCE) mission. The SGG operates at the superconducting temperature lower than 6 K. The study presented in this paper designed a cryogenic thermal system to maintain the SGG at the design temperature in the above-mentioned Mars orbit. The system includes fixed radiation shields, a low thermal conductivity support structure, and a two-stage cryocooler. The fixed radiation shields use double aluminized polyimide to emit heat from the warm spacecraft into deep space. The support structure uses carbon fiber reinforced plastic, which has low thermal conductivity and very high strength at cryogenic temperature. The low vibration cryocooler has two stages, of which the high temperature stage operates at 65 K and the low temperature stage works at 6 K, and the heat rejection radiator works at 300 K. The study also designed a second option with a 4 K adiabatic demagnetization refrigerator (ADR) and two-stage 10 K cryocooler.

PLANETARY GRAVITY MAPPING MISSIONS

A planet's gravity field reflects the distribution of mass in its interior and across its surface. Thus a study of a planet's gravity field provides insights into the interior structure of the planet, allows

us to elucidate the thickness of its crust, and provides a means to better understand the geophysical processes that produced many features visible in the surface geology. A planet's gravity field also bears the imprint of the transport of mass across the surface and within the planet. In the case of Mars, the study of time-variation in the gravity field tells us about how a portion of the planet's mass is redistributed as the Martian polar caps form and dissipate seasonally.

There are three ways to measure a planet's gravity field using the spacecraft. The traditional method uses Doppler tracking of planetary orbiters via NASA's Deep Space Network (DSN), measuring changes in the spacecraft velocity as it flies over mass anomalies, such as mass concentrations or mass deficits^{1,2}. The spacecraft is tracked at X band (~8 GHz) with a typical precision of 0.1 mm/s.

The second method uses satellite-to-satellite tracking of two spacecraft that follow each other in the same orbit by measuring the change in range between the two spacecraft as they orbit the planet. With these data, it is possible to estimate the characteristics of the gravity field underneath the spacecraft and how it changes. The U.S./German Gravity Recovery and Climate Experiment (GRACE)³, and the NASA Gravity Recovery and Interior Laboratory (GRAIL)⁴ spacecraft used highly accurate microwave ranging systems to measure the change in range between two identical spacecraft flying in a low polar orbit of the Earth and the Moon, respectively. Data from GRACE were used to construct a detailed map of the Earth's gravity anomalies so that scientists were able to detect changes in the distribution of water and ice across the planet, estimate changes in ocean bottom pressure, and detect changes in the gravity field due to other geophysical processes. The main objective of GRAIL was to understand the internal structure of the Moon and map the lunar crust and lithosphere⁵. The GRAIL data had a precision of 0.05 – 0.07 $\mu\text{m/s}^4$.

The third method to map a planetary gravity field is with a gravity gradiometer. A gravity gradiometer measures gravity changes across a short baseline. Gradiometers are used in terrestrial (airborne) gravity surveys, because the differential measurement means spurious accelerations are removed. Launched in 2009, the European Space Agency (ESA) Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) mission included a highly accurate gradiometer to map the Earth's gravity field. GOCE used an electrostatic gravity gradiometer (EGG), which had a precision of $10^{-3} \text{ E/Hz}^{1/2}$, where 1 E (Eötvös) is a unit of 10^{-9} s^{-2} , which represents a unit of acceleration divided by distance that is used to describe gravity gradients. The GOCE data have been used in combination with a mean ocean surface defined from 20 years of ocean radar altimetry to compute the mean dynamic ocean topography, serving studies of the Earth's ocean circulation and transport. The data have also been used in studies of the Earth's lithosphere and mantle, as well as to map the gravity field of the Earth, where previously surface gravity measurements were hard to obtain⁶. The EGG measured the gravity gradients in three directions with a set of six three-axis accelerometers mounted in a diamond configuration. The on-board GPS receiver was also used as satellite-to-satellite tracking to supplement the EGG measurement. The EGG was about 100 times more accurate than any gravity measurement instrument in space.

SUPERCONDUCTING GRAVITY GRADIOMETER

NASA has been interested in Superconducting Gravity Gradiometer (SGG) since the 1980s. Unlike an EGG, an SGG uses a set of six two-axis accelerometers, and the SGG also uses a Superconducting Quantum Interference Device (SQUID) to measure extremely weak magnetic fields. Superconducting circuits offer high stability and sensitivity. Since levitation and sensing coils replace mechanical springs, the restoring force can be tuned to adjust the sensitivity of the instrument. The instrument can be tuned to provide sensitivity to either the short-wavelength gravity field (measuring the gravity expression of surface features at high resolution), or to provide sensitivity to the variations in the long-wavelength gravity field that are due to the effects of mass transport. For the high resolution field, a sensitivity of $10^{-4} \text{ E/Hz}^{1/2}$ is envisaged, whereas for the long-wavelength time-variable field, sensitivity better than $10^{-5} \text{ E/Hz}^{1/2}$ is expected. Thus, a single spacecraft and mission can accomplish two separate goals for mapping the gravity field of Mars. The SGG instrument is under development at the University of Maryland under a three-year NASA program to develop a prototype instrument that can be used on a mission to map the gravity field of Mars at high resolution⁷. Figure 1 shows the configuration of the SGG instrument.

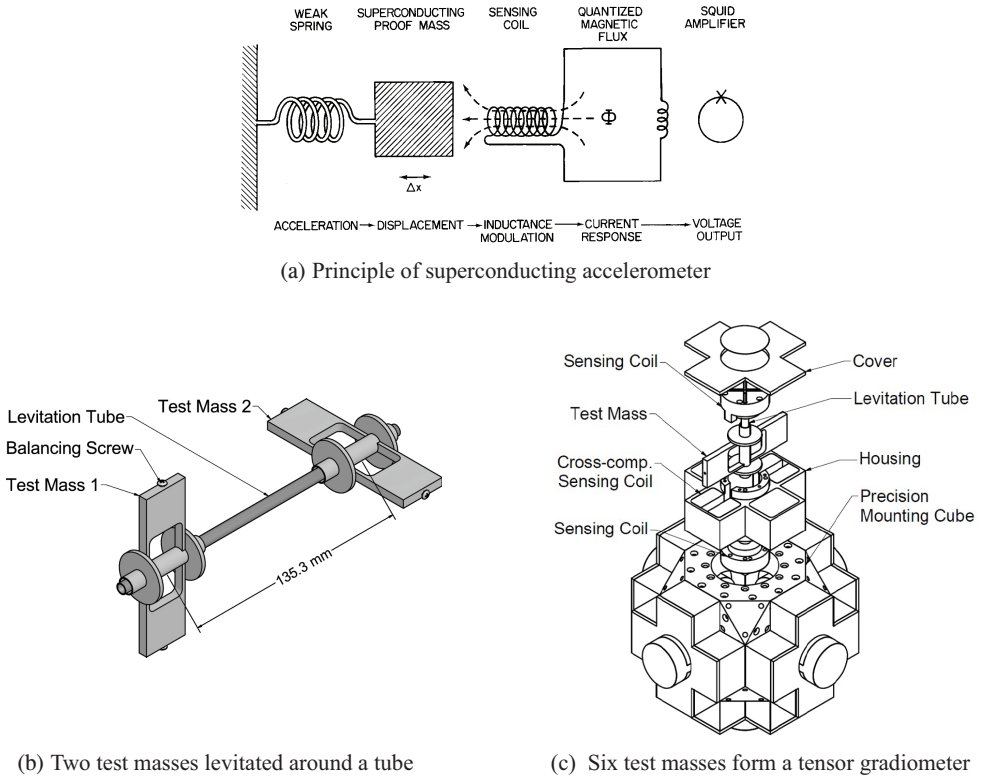


Figure 1. SGG instrument.

The advantage of using an SGG is that a single spacecraft, flying at an altitude of about 200-225 km, will be able to double the resolution of the static gravity field at the least over that determined by using the standard method of Doppler tracking for an orbiting spacecraft⁸. In addition, the Mars time-variable field can be mapped on a monthly basis with a resolution of ~1500 km, whereas today with Doppler tracking, only the variations in the zonal spherical harmonic coefficients of the Mars gravity field, C_{20} and C_{30} , are resolvable⁸.

This paper focuses on a preliminary design of a cryogenic system which can maintain the SGG instrument at the required temperature in Mars orbit. The orbit design, environment, and spacecraft configuration are also considered prior to the thermal study. Finally, design options, mass, and power budgets are provided for future mission design activities.

INSTRUMENT REQUIREMENTS

The SGG instrument, as shown in Figure 1, is about 20 cm in each direction and has a mass of ~10 kg. The driving requirements for this design are listed below.

1. The SGG operates with the highest efficiency at ≤ 4 K, and it operates with reduced accuracy at any temperature below 8 K.
2. In general, it takes 6-8 months for the spacecraft to travel from Earth to Mars, and another 5-6 months for insertion into the low-altitude mapping orbit using aerobraking. For example, this was the experience of the Mars Reconnaissance Orbiter (MRO).
3. The SGG should be precisely located at the center of gravity of the whole spacecraft.
4. The SGG instrument is sensitive to vibration. Linear acceleration from the spacecraft shall be less than $10^{-6} \text{ m/s}^2/\text{Hz}^{1/2}$, and angular acceleration shall be less than $10^{-8} \text{ rad/s}^2/\text{Hz}^{1/2}$ during the operation. The instrument measures at frequencies below 10 Hz.

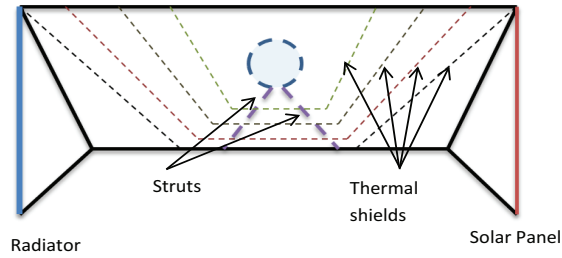


Figure 2. SGG spacecraft cross-section.

5. The operating orbit shall be sun-synchronous, facing the sun to minimize thermal variations, and the mean altitude is assumed to be 200 km.
6. The mass of spacecraft shall be less than 500 kg, and the power shall be less than 300 W.

SPACECRAFT CONFIGURATION

We used the thermal shield design for the Primordial Inflation Explorer (PIXIE)⁹ astronomy mission as the basis for the SGG¹⁰ thermal design. The SGG instrument and thermal shields are embedded inside the spacecraft to satisfy requirement 3. The subsystems of the spacecraft will be positioned to meet this requirement.

The cross section of the spacecraft is narrow in the flight direction to minimize the drag force, as shown in Figure 2. Although the Mars atmosphere is more tenuous than that of Earth, it can still exert a drag force on the orbiting spacecraft. Orbits lower than 200 km degrade quickly, especially near the Mars perihelion, when the upper atmosphere density increases due to the melting of the Mars ice caps just prior to the southern hemisphere summer. The shape of the cross section is designed to accommodate the shape of radiation shields, which will be discussed in the following section. All the shields face deep space away from the sun, since the spacecraft is assumed to be in a near dawn-dusk orbit.

The solar panels have been sized to generate 300 W of power at Mars. A radiator is attached to the opposite side of the solar panel. The radiator removes the heat generated by the electronics and cryocooler at close to room temperature, 300 K. The bottom of the spacecraft, which faces Mars, uses high thermal conductivity material to transfer the heat from solar panel to the radiator. The top of the spacecraft will be made of lightweight carbon fiber material, and thermally isolated from the spacecraft. The carbon fiber material can be used as a higher temperature radiator to further reduce the parasitic heat to the instrument.

CRYOGENIC THERMAL SYSTEM

The objective of the cryogenic thermal system is to maintain the instrument at operating temperatures. In this study, we studied both 6 K and 4 K cryogenic system options for the instrument. The cryogenic system includes thermal shields, low thermal conductivity support structure (struts) and cryocooler(s).

Thermal model

Thermal Desktop® was used to perform a thermal analysis for the cryogenic thermal system design and optimization¹¹. Thermal Desktop® discretizes the surfaces into surface elements in preparation for the use of a finite difference method. RADCAD, which is one of the add-on programs, uses the Monte Carlo method to calculate the thermal radiation between surface elements. Thermal conduction between elements is calculated using SINDA. The thermal analysis calculates the radiation and the conduction heat load on the instrument. The thermal model includes the spacecraft body, solar panels, radiator, wiring, struts, radiation shields, and radiator, as shown in Figure 3.

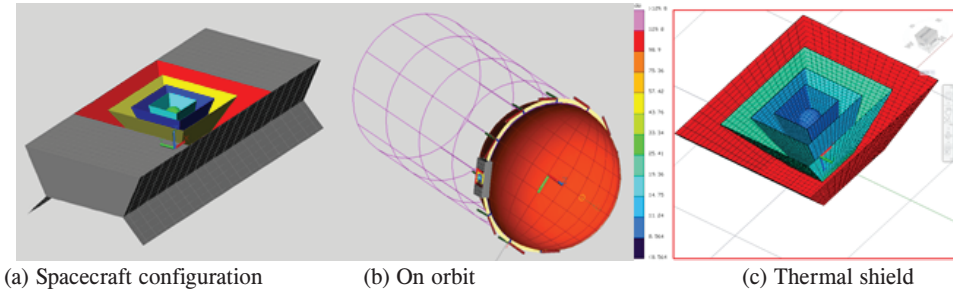


Figure 3. SGG spacecraft.

Parametric studies were performed with different spacecraft configurations, strut sizes and materials, and heat interception points, at which locations the cryocooler removes heat. It was found that the heat transfer by thermal conduction through the wiring and struts is much higher than the heat transfer by radiation. The materials, number of wires, and conductive heat loads are listed in Table 1. More analysis has been done on how to minimize the radiation heat load.

Instrument shield

The instrument, as shown in Figure 1, has a large surface area. A spherical aluminum shield, as shown in Figure 3, is used to reduce the surface area and thermal radiation from the environment. The shield can also protect the instrument from environmental hazards throughout all phases of the mission. The shield is actively cooled by the cryogenic thermal system. The aluminum shield conducts heat, and it creates a uniform temperature boundary for the instrument. The instrument shield is covered by 40 layer multi-layer insulation (MLI) to reduce exposure to radiation from space and thermal shields.

Thermal shielding

There are four layers of thermal shields, which protect the instrument from solar radiation, Mars infrared (IR) radiation, as well the spacecraft IR radiation. All shields face deep space, which is assumed to have a temperature of 7 K. Each layer of the shields, as shown in Figure 3, has four sides to accommodate the spacecraft configuration. It can be modified to six sides or circular in future studies. The shields are constructed by using double aluminized Kapton (DAK). Lab tests of the radiation properties and shield design were performed by NASA GSFC¹². The angle to the vertical of layer one is 45°, and reduced 5° for each layer to 30° for shield four. Layer one is mounted on the spacecraft and MLI is used to further reduce the heat loads from the spacecraft bus (assumed to be at room temperature) and IR radiation from Mars. Layer two, three and four are mounted on the hexapod struts. The shields will be launched as shown in the design, and use T10 to stabilize all edges. Additional T10 support tubes can be used locally, if any area of the shields cannot withstand the launch load after a detailed stress analysis. The thickness of the DAK is about 25 microns. Therefore, the thermal conduction can be neglected, and thermal radiation dominates the shield design. The sides of layer two facing deep space are painted black, which is used as a radiator to remove heat at 150 K from struts. Thermal Desktop® is used to predict the thermal performance of the shields. The temperatures of the different layers of shields are listed in Table 2.

Table 1. Wiring material and heat load.

Material	Number of wires	Diameter (AWG)	Heat load		
			6 K only (mW)	68 K (mW)	6 K (mW)
Manganin	144	36	8.0	463.0	0.7
Phosphor bronze (PhBr)	50	36	53.7	193.0	5.1
	23	28			
	10	22			
Stainless steel	576	36	22.1	70.0	7.7

Table 2. Temperature of the shields (thermal model results)

Shields	Temperature (K)
Shield 4 (outer layer)	171
Shield 3	70
Shield 2	28
Shield 1 (inner layer)	10

Struts

The hexapod struts use carbon fiber reinforced plastics (CFRP). CFRP is used on the JWST MIRI instrument, which is at 7 K¹³. It has higher yield strength and modulus of elasticity than the other support materials used for cryogenic system design, but has low thermal conductivity at cryogenic temperature, which significantly reduces the thermal conduction to the low temperature instrument. The thickness, length and the angle between pod symmetry, as shown in Figure 4, are designed based on a simple stress analysis. The minimum natural frequency of the struts is higher than 100 Hz, and the safety factor is greater than two for a launch load of 10 g.

Active cooling

There are a couple of ways of maintaining the instrument operating temperature. A helium cryostat can be used for cooling the SGG. However, the Mars mission lasts significantly longer than an Earth mission, because of the distance to Mars and the time needed for orbit insertion. Helium venting will also affect of the spacecraft center of gravity, which fails to meet requirement 3. The other way to cool the instrument is to use cryocoolers. Most of the mechanical cryocoolers generate vibration, which cannot meet requirement four.

Low-frequency vibration creates noise to the instrument, which causes errors in the measurement. Turbo-Brayton cooler is considered to be a vibration-free cooler¹⁴ for space applications. This type of cooler was used to replace NICMOS dewar for the Hubble Space Telescope (HST)¹⁵. The NICMOS cooler operated at 70 K, and provided continuous cooling of 7 W to HST. Low temperature turbo-Brayton coolers can provide hundreds of ~0.1 W of cooling at 6 K¹⁶. A schematic of the Brayton cycle cooler is shown in Figure 5. The compressors and turboalternators operate at hundreds of thousand rpm; therefore, the vibrations generated by these components are at the frequency of thousands of hertz, which is much higher than the frequency band of the SGG instrument. Flow turbulence in the working fluid (low pressure helium gas) can cause pressure fluctuations at frequencies below 10 Hz, which can also cause mechanical vibrations in the transfer tubes between components. The most recent study¹⁷ shows that the mechanical vibrations in the transfer tubes can be managed to satisfy the SGG vibration requirement.

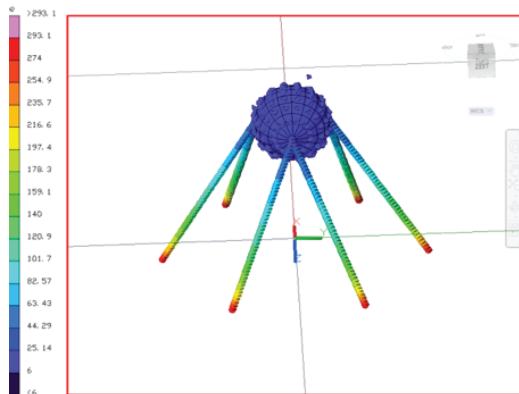


Figure 4. Temperature of the SGG support structure (K).

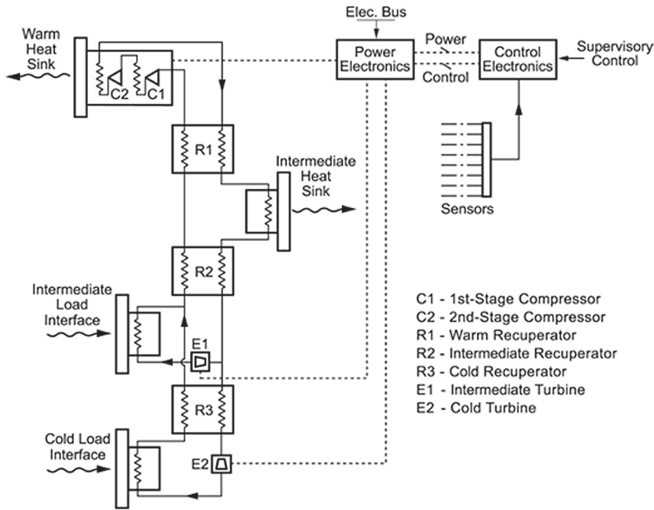


Figure 5. Reverse Brayton cycle cooler.

An adiabatic demagnetization refrigerator (ADR) can cool an instrument to superconducting temperature without vibration. ADR uses a material's magnetocaloric effect, in which a temperature change in the material is caused by exposing the material to a changing magnetic field, to remove heat with an adiabatic thermal boundary condition. ADR works more efficiently than mechanical coolers at temperatures below 10 K. NASA GSFC conducted a study of 10 K ADR¹⁸, which uses a 10 K heat sink to cool the instrument to 4 K. Figure 6 shows an example of a 4 K ADR¹⁹.

In this study, two options for cryocoolers are considered. One option is to use a two-stage turbo-Brayton cryocooler to cool the instrument to 6 K. The higher temperature stage removes conductive heat from struts at 68 K, and the lower temperature stage maintains the SGG instrument at 6 K. The second design is to use a two-stage 10 K Brayton cycle cooler with a 68 K upper stage and an ADR to maintain the instrument at 4 K with a 10 K heat sink.

The higher temperature stage at 68 K intercepts heat on struts at a cooling point. The location of the cooling point was calculated using the 1-D thermal conduction equation, and then verified using the Thermal Desktop® model. The 68 K cooler also removes heat from wiring to reduce thermal

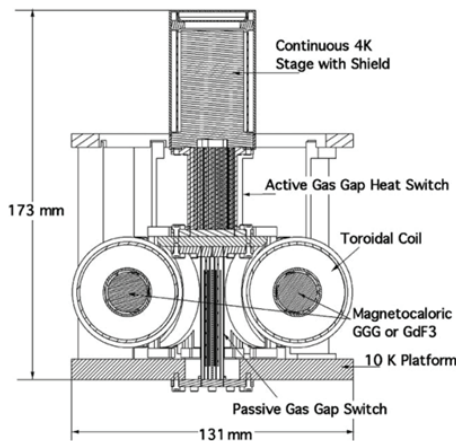


Figure 6. 10 K to 4 K ADR

Table 3. Comparison of 6 K and 4 K cryocoolers.

	Option 1		Option 2	
Instrument temperature	6 K		4 K	
Cooler(s)	Reversed Brayton 68 K/6 K two-stage cryocooler		Reversed Brayton 68 K/10 K two-stage cryocooler with ADR from 10 K to 4 K	
Cooling load	68 K	1500 mW	68 K	2888 mW
	6 K	100 mW	10 K	115 mW
Power	120 W		4 K	10 mW
			68 K	193 W
			10 K	50 W
6 K	4 K			
Mass	26 kg		36 kg	

conduction through the wiring. Specifications of Brayton cycle cryocoolers and ADR for options one and two are listed in Table 3. The cooling loads are estimated based on the thermal analysis. A margin of 100% is applied to both options.

SUMMARY

This paper presents a preliminary thermal design of the cryogenic thermal system for an SGG Mars mission. The system includes thermal shields, a low thermal conductivity support structure, and cryocoolers. The design also defines the size of the thermal shields and the size of struts. Two options were given for the active cooling. One uses a 6 K/68 K two-stage Brayton cycle cryocooler, and another uses a 10 K to 4 K ADR and 10 K/68 K two-stage Brayton cycle cryocooler.

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