

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) with which to measure the gravity field of a planet from orbit. An SGG instrument is under development with the NASA 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 two orders of magnitude better than the electrostatic gravity gradiometer that was used on the ESA's GOCE mission. The SGG operates at the superconducting temperature lower than 6 K. This study developed a cryogenic thermal system to maintain the SGG at the design temperature in 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 the deep space. The support structure uses carbon fiber reinforced plastic, which has low thermal conductivity at cryogenic temperature and very high stress. 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 turbo-Brayton cooler.

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-variations in the gravity field tells us about how a portion of the planet's mass is redistributed as the Martian polar caps form and dissipates seasonally.

There are three ways to measure a planet's gravity field using 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 (e.g., Lemoine *et al.*, 2001; Mazarico *et al.*, 2014). 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) (Tapley *et al.*, 2004), and the NASA Gravity Recovery and Interior Laboratory (GRAIL) (Asmar *et al.*, 2013) 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 was 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 lithosphere (Zuber *et al.*, 2013). The GRAIL data had a precision of 0.05 – 0.07 $\mu\text{m/s}$ (Asmar *et al.*, 2013).

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 obtain (Floberghagen *et al.*, 2011). 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 as a supplement to the EGG measurement. The EGG was about 100 times more accurate than any gravity measurement instrument in space.

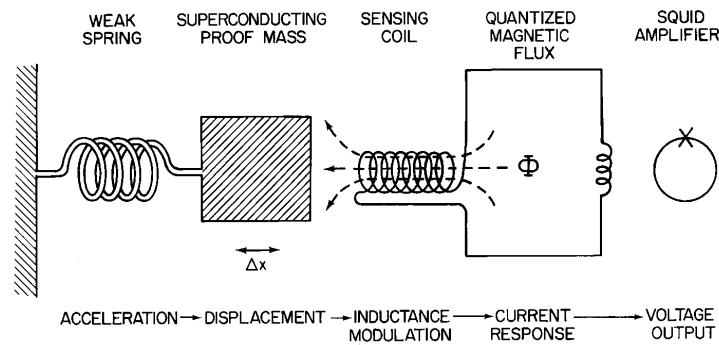
SUPERCONDUCTING GRAVITY GRADIOMETER

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,

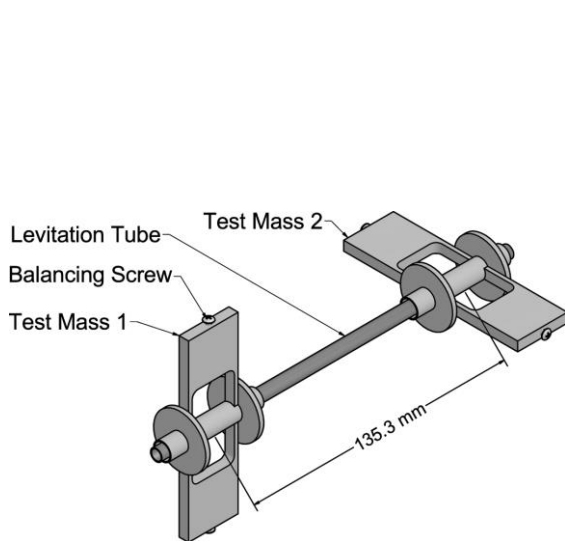
whereas for the long-wavelength time-variable field, sensitivity better than $10^{-5} \text{ E/Hz}^{1/2}$ is expected. Thus, a single spacecraft and mission can accomplish two separate goals for mapping the gravity field of Mars. The SGG instrument is under development at the University of Maryland under 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 resolution (Griggs *et al.*, 2015). Figure 1 shows the configuration of the SGG instrument.

The advantage of using an SGG is that with a single spacecraft flying at about 200-225 km altitude, it will be able to at least double the resolution of the static gravity field over that determined by using the standard method of Doppler tracking of orbiting spacecraft (e.g., Genova *et al.*, 2016). In addition, the Mars time-variable field can be mapped on a monthly basis with a resolution of $\sim 1500 \text{ km}$, 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 resolvable (Genova *et al.*, 2016).

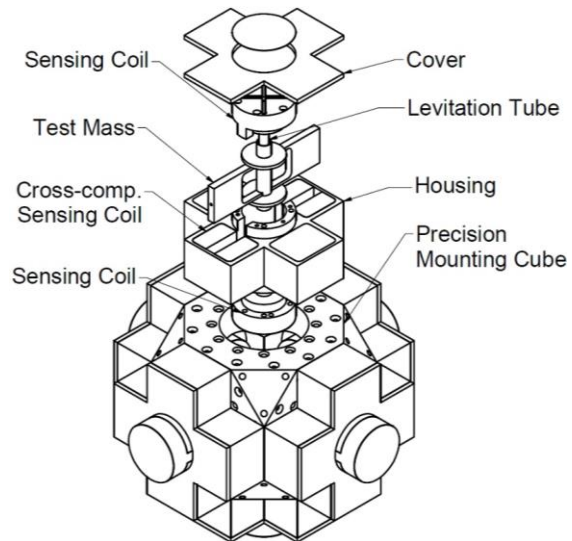
This paper focuses on a preliminary design of a cryogenic system which can maintain the SGG instrument at the required temperature in Mars orbit. The orbit design, environment and spacecraft configuration are also considered prior to the thermal study. Finally, design options, mass and power budgets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



(a) Principle of superconducting accelerometer



(b) Two test masses levitated around a tube



(c) Six test masses form a tensor gradiometer

Figure 1. SGG instrument.

INSTRUMENT REQUIREMENT

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 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} m/s²/Hz^{1/2}, and angular acceleration shall be less than 10^{-5} rad/s²/Hz^{1/2} during the operation. The instrument measures at frequencies below 10 Hz.
5. The operating orbit shall be sun-synchronous, face-on to 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) (DiPirro *et al.*, 2012) astronomy mission as the basis for the thermal design for the SGG (Kogut *et al.*, 2014). 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 and 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

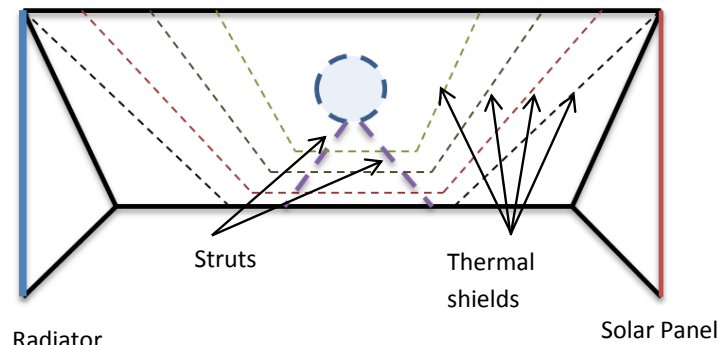


Figure 2. SGG spacecraft cross-section.

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 light weight carbon fiber material and thermally isolated from the spacecraft. It can be used as 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 optimization (C&R Technologies, 2013). Thermal desktop uses a finite difference method to discretize surfaces into surface elements. 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, wirings, struts, radiation shields, and radiator, as shown in Figure 3. Parametric studies were performed with different spacecraft configurations, struts sizes and materials, as well as heat interception points, at which locations the cryocooler removes heat at higher temperature. It was found that thermal conduction through the wiring and struts is much higher than thermal radiation. The materials, number of wires, and conductive heat loads are listed in Table . More analysis has been done to remove more heat by conduction.

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 multilayer insulation (MLI) to reduce radiation from space and thermal shields.

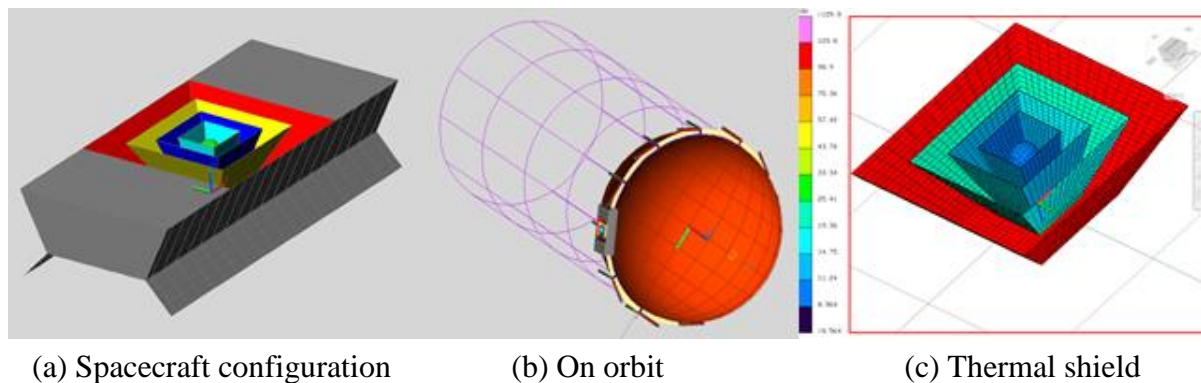


Figure 3. SGG spacecraft.

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 1. Wiring material and heat load.

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 be at 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 done by NASA GSFC (DiPirro *et al.*, 2007). 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 due to the 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 to 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 layer shields are listed in Table 2.

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

Table 2 Temperature of the shields (thermal model results)

Struts

The hexapod struts use carbon fiber reinforced plastics (CFRP). CFRP is used for JWST MIRI instrument, which is at 7 K (Makowski *et al.*, 2010). 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.

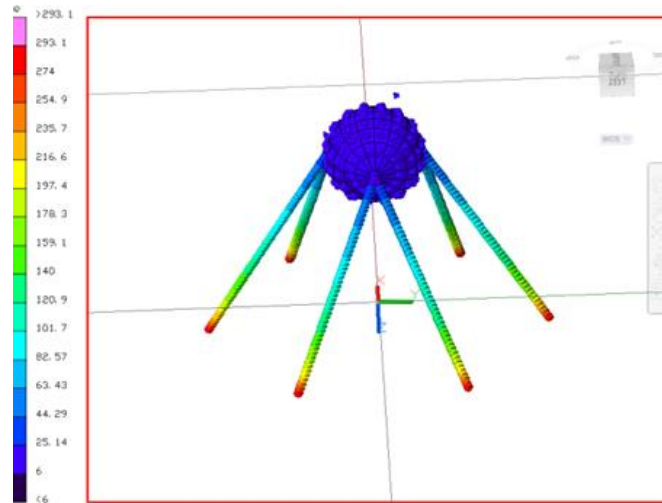


Figure 4. Temperature of the SGG support structure (K).

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 cause change of the spacecraft center of gravity, which does not meet requirement three. 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 cooler (Nellis *et al.* 1998) for space applications. This type of cooler was used to replace NICMOS dewar for the Hubble Space Telescope (HST) (Swift *et al.*, 2004). The NICMOS cooler operated at 65 K, and

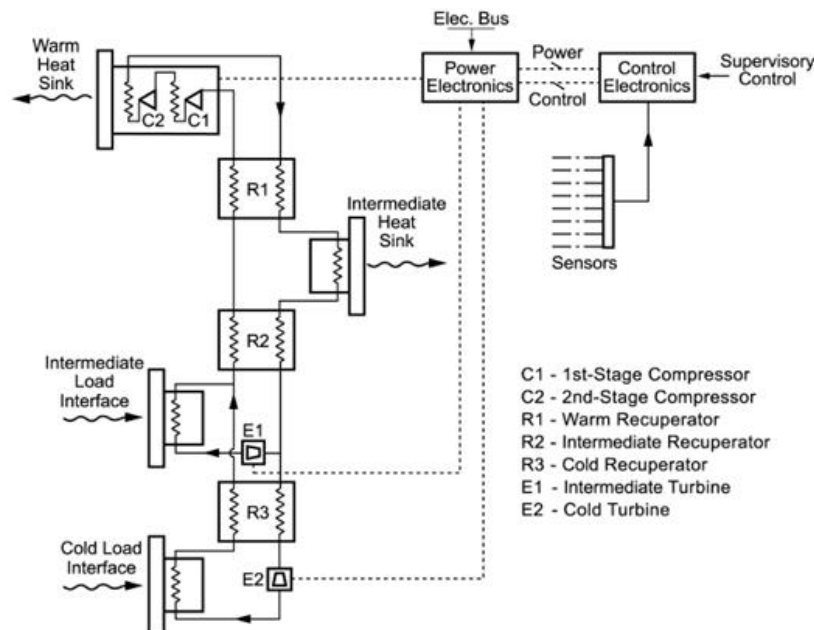


Figure 5. Reversed Brayton cycle cooler.

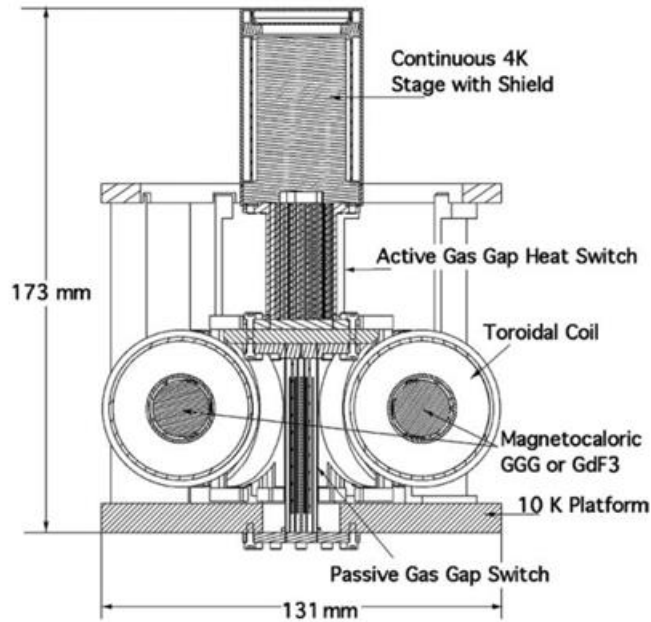


Figure 6. 10 K to 4 K ADR

provided continuous cooling of 5 W to HST. Low temperature turbo-Brayton coolers can provide hundreds of milliwatts of cooling at 6 K (Zagarola *et al.*, 2003). A schematic of 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. Vertex shredding in flow transfer tube can cause vibrations at frequencies below 10 Hz, which also cause vibration in the transfer tube. The most recent study (Cragin *et al.*, 2016) shows that the vertex shredding in the transfer tube can be managed to satisfy the SGG vibration requirement.

An adiabatic demagnetization refrigerator (ADR) can cool an instrument to superconducting temperature without vibration. ADR uses materials' magnetocaloric effect, in which a temperature change of material is caused by exposing material to a changing magnetic field, to remove heat with an adiabatic thermal boundary condition. ADR works more efficiently than mechanical coolers at below 10 K. NASA GSFC conducted study of 10-K ADR (Tuttle *et al.*, 2004), which uses a 10-K heat sink to cool the instrument to 4 K. Figure 6 shows an example of 4-K ADR (DiPirro *et al.*, 2004).

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 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 is used 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 1D thermal conduction equation, and then verified using the Thermal desktop® model. The 68-K cooler also removes heat from wiring to reduce thermal conduction through the wiring. Specifications of Brayton cycle cryocoolers and ADR for option one and two are listed in Table 1. The cooling loads are estimated based on the thermal analysis. The margin of 100% is applied to both options.

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	2000 mW	68 K	2000 mW
	6 K	100 mW	10 K	200 mW
			4 K	10 mW
Power	68 K	160 W	68 K	200 W
	6 K		10 K	
			4 K	
Mass	26 kg		36 kg	

Table 1. Comparison of 6 K and 4 K cryocoolers.

SUMMARY

This paper presents a preliminary thermal design of the cryogenic thermal system for an SGG Mars mission. The system includes thermal shields, low thermal conductivity support structure, and cryocoolers. The design also defined 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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