MESSENGER Heritage: High-temperature Technologies for Inner Solar System Spacecraft

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Spacecraft missions to the inner solar system require specialized thermal protection and designs to withstand the intense heat associated with proximity to the Sun. The MESSENGER (MErcury Surface, Space ENvironment, Geochemistry, and Ranging) spacecraft, designed, built, and tested by The Johns Hopkins University Applied Physics Laboratory, was launched on August 2, 2004, on a mission to orbit the planet Mercury for one year. High-temperature technology and specialized thermal designs were developed for MESSENGER's telecommunications, power, guidance and control, and thermal control subsystems. MESSENGER milestones in these as areas may be applicable to such future missions as Solar Sentinels, Solar Orbiter, and BepiColombo.

I. INTRODUCTION

The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission will characterize Mercury in detail by observing the planet from orbit for one Earth year. Although it had long been desired to supplement the initial flybys with an orbital mission, early studies had deemed this infeasible, or at least prohibitively expensive, due to mass and thermal constraints. MESSENGER utilizes a new trajectory first discovered by analysts at the Jet Propulsion Laboratory (JPL) [1,2], and later refined by analysts at the Johns Hopkins University Applied Physics Laboratory (APL), to achieve orbit with an overall spacecraft launch mass of 1107 kg (including propellant). Flybys of Earth, Venus, and Mercury itself are interspersed with five large deterministic deep-space maneuvers (DSMs) that target the spacecraft for Mercury orbit insertion (MOI) in 2011.

The high temperatures to be encountered at Mercury were a key engineering challenge in the spacecraft design. Protection from this environment is accomplished with a large sunshade, which shields the spacecraft components from direct exposure to the Sun and allows them to operate at conditions typical of other interplanetary spacecraft. The geometry of the orbit about Mercury was also chosen to limit the worst-case exposure conditions. The solar panels are necessarily exposed to the Sun throughout the mission and were specially designed to handle the temperatures and solar input flux expected at 0.3 AU [3].

MESSENGER is collaboration between the Carnegie Institution of Washington (CIW) and APL and was selected as the seventh Discovery mission with formal project start in January 2000. The spacecraft engineering and science instrument design evolved over the 3-year period from January 2000 to the spring of 2003. Assembly and integration, and testing of the spacecraft began in February 2003 and continued nearly to launch in August 2004. Flight operations are now supported from the mission operations center at APL with communications through NASA's Deep Space Network (DSN) antennas. Mission updates can be found at the project web site http://messenger.jhuapl.edu.

II. MESSENGER SPACECRAFT THERMAL DESIGN OVERVIEW

The thermal design of the MESSENGER spacecraft relies upon a ceramic-cloth sunshade to protect the vehicle from the intense solar environment encountered when inside the orbit of Venus. Creating a benign thermal environment behind the sunshade allowed for the use of essentially standard electronics, components, and thermal blanketing materials. Non-standard thermal designs were required for the solar arrays, sunshade, digital Sun sensors, and the phased-array antennas (Fig. 1). These components have been designed to operate at Mercury perihelion

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(when Mercury is closest to the Sun) and also during orbits that cross Mercury's surface at local noon. When at perihelion, the sunshade, the solar arrays, the sunshade-mounted digital Sun sensors, and the sunshade-mounted antenna suite will experience as much as eleven times the solar flux near Earth and the sunshade temperature will rise to over 300°C. For some orbits around Mercury, the spacecraft will be between the Sun and the illuminated planet for approximately 30 minutes. During this interval the sunshade will protect the spacecraft from direct solar illumination, but the back of the spacecraft will be exposed to the hot Mercury surface. Components such as the battery and star trackers are positioned such that the spacecraft body blocks a substantial portion of the planet view, minimizing direct radiation from the planet surface. Planet-viewing instruments such as the Mercury Dual Imaging System (MDIS) required a specialized thermal design to allow full operation during this hot transient period. Diode heat pipes were employed in both the spacecraft and imager thermal designs to protect attached components when radiator surfaces are exposed to thermal emission from Mercury. The diode heat pipes effectively stop conducting when the radiator surface becomes hot and return to conduction when the radiator surface cools, restoring normal thermal control. Analysis of the orbiting environment as a function of orbit geometry and planet position was integrated into the mission design and has helped to phase the orbit plane relative to the solar distance, minimizing planet infrared heating of the spacecraft and thus minimizing required mass [4].

The MESSENGER spacecraft and the associated Sun-illuminated component testing presented a challenging set of problems from both the technical perspective and that of and cost and schedule. It was decided early in development that the system-level thermal vacuum test would be done at the NASA Goddard Space flight Center (GSFC) in a non-solar simulator environment. Specialized solar simulation testing of engineering model solar arrays, Digital Sun Sensor (DSS) heads, radio frequency (RF) antennas, and the sunshade were performed at the NASA Glenn Research Center (GRC) Tank 6 thermal-vacuum chamber. Originally designed to simulate near-Earth solar conditions for the Solar Dynamic Power Experiment, the original test setup was modified to produce an 11-Sun equivalent solar environment over approximately 1.5 m^2. This illuminated area proved large enough to test the various solar array designs, DSSH configurations, sunshade design, and antenna components simultaneously (Fig. 2) while keeping the ratio of testing cost to components tested small.

Much emphasis has been placed on the extreme heat and high temperatures associated with a spacecraft orbiting Mercury. Near the beginning of the mission, the spacecraft required heaters to make up for the maximum solar and planet heating. In order to reduce heater power consumption and increase solar array power margin, the MESSENGER design allowed the spacecraft to be flipped so that the sunshade pointed anti-sunward and the backside of the spacecraft was illuminated by the Sun. MESSENGER flew in this reversed orientation during intervals between launch and June 2006, and on the basis of measurements made during flight the heater power difference using this technique averaged approximately 200 W. Since launch, the MESSENGER thermal control system has operated without many issues. The hardware illustrated in Fig. 1 will be discussed further in the remainder of this paper.

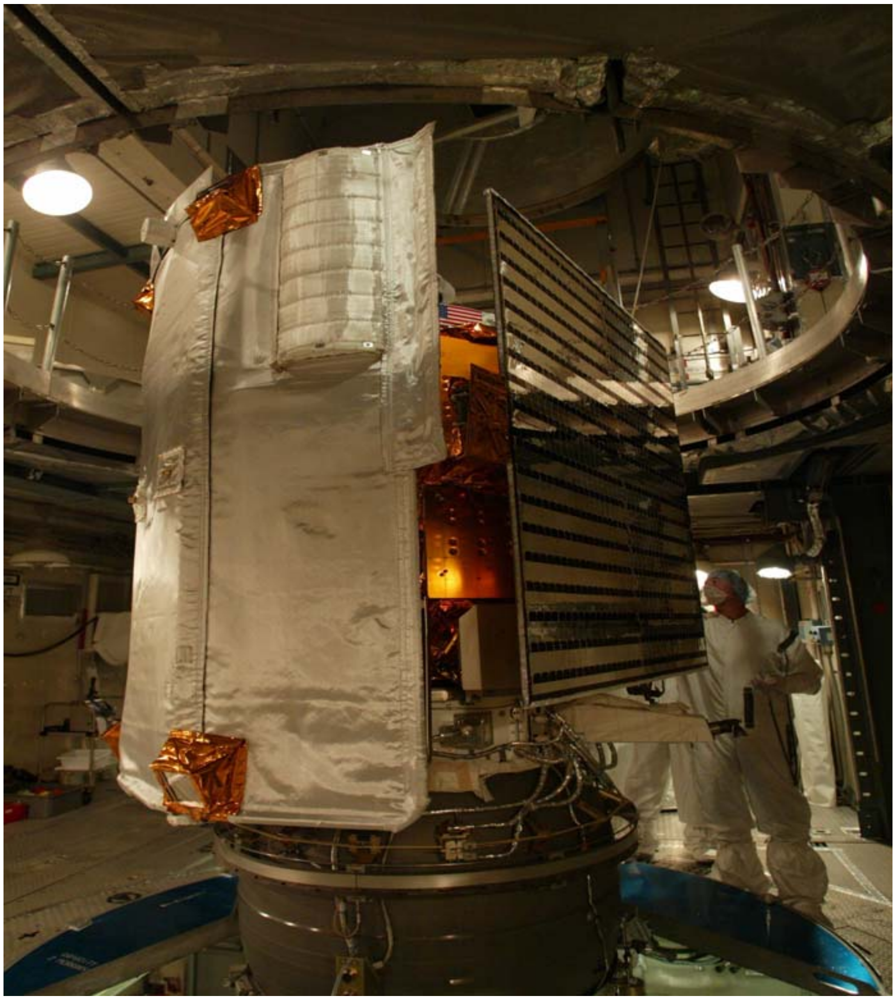

Figure 1. The MESSENGER spacecraft prior to launch.
Illustrated are one of two solar arrays, the sunshade, two of the four shade-mounted digital sun sensors, and the forward-facing phased-array antenna assembly (mounted on the sunshade).

III. SUNSHADE DESIGN

MESSENGER has a low-risk passive thermal control design that is dominated by the sunshade. The sunshade is constructed using commercially available ceramic cloth combined with multi-layer aluminized kapton. Calculations based upon solar simulation testing predict that the sunshade will be heated to a maximum temperature of 325°C when at Mercury perihelion.

The sunshade structure performs two functions: (1) support for the high-temperature multi-layer insulation (MLI) blanket that protects and insulates the core spacecraft from direct solar radiation when inside of 0.95 AU and (2) support for active components consisting of four Digital Sun Sensors, one of the phased-array and three low-gain antenna assemblies, an X-ray solar monitor, and two thrusters, shown in Fig. 2. These components, except for the phased-array antenna, are "off-the-shelf" technologies that were modified by the specialized cost-effective thermal designs. The sunshade MLI is constructed from a combination of inherently temperature-tolerant materials. White in appearance, Nextel 312-AF 10 was chosen as the outer skin for the sunshade because of its superior thermal, mechanical, and optical properties. The technical issue with the Nextel material is that it is a woven fabric that allows light transmission between the different layers, increasing the effective alpha of the outer layer. The solution to this problem was to have the Nextel metalized with aluminum. This process was performed by the Dunmore Corporation of Newtown, Pennsylvania, using their Beta Cloth metalizing procedure. Since the least temperature tolerant material used in the sunshade is the kapton with a maximum allowable temperature of approximately

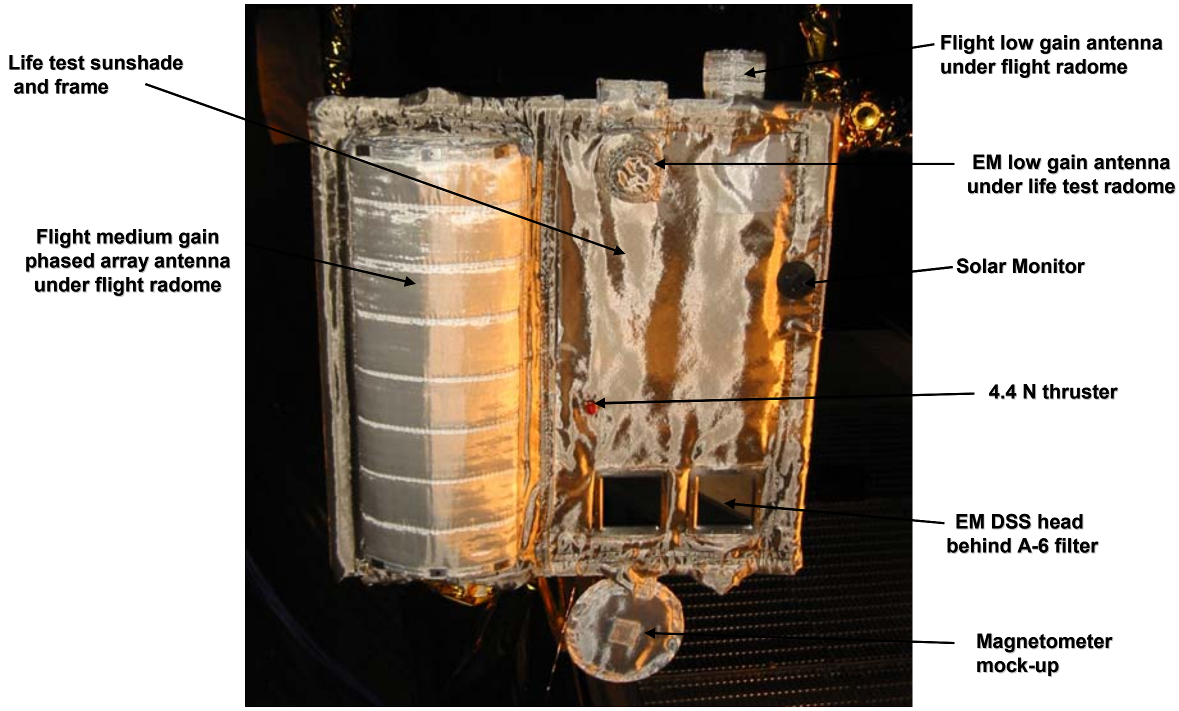

Figure 2. The MESSENGER qualification sunshade after the final 11-Sun test at GRC. Highlighted are the flight phased-array antenna and the engineering model DSS with flight filter.

400°C, three layers of the aluminized Nextel make up the Sun facing side of the sunshade. The first layer is single-sided aluminized Nextel with the non-metalized side facing the Sun. This allows the low-absorption, high-emissivity thermo-optical properties of the Nextel fabric to reflect and readily radiate away thermal energy introduced by the Sun. Behind the first layer of Nextel are two more layers of Nextel that are aluminized on both sides followed by 15 layers of embossed kapton followed by a single closeout layer of one side aluminized Nextel with the bare side facing out. This layout configuration was derived from numerous solar simulation tests in an attempt to optimize the temperature at the first layer of aluminized kapton without adding additional weight to the overall sunshade assembly. The sunshade materials were sewn together using high temperature fiberglass thread. Stainless-steel Velcro was used to attach securely the three main sections to each other and to the sunshade titanium frame.

IV. SOLAR ARRAY DESIGN AND TESTING

Covered with a blend of Second Surface Mirrors (SSMs) and solar cells, the MESSENGER solar array consists of two deployed single-panel wings [5]. Each wing contains eighteen strings of 3 cm by 4 cm triple junction cells, manufactured by the EMCORE Corporation, with a minimum efficiency of 28%. To protect the solar array materials from the expected worst-case thermal environment, each string of cells uses two equal-area strings of SSMs, equating to a 33% packing factor. The mirrors were manufactured by Pilkington and use 0.15-mm CMX glass as the substrate. The cells and mirrors were applied in alternate parallel rows, allowing for heat spreading across the face and through the back of each panel. Aggregately, each panel will reflect approximately 60% of the incident solar energy. The cell and mirror lay-down process and all solar panel electrical fabrication was carried out by Northrop Grumman Space Technology (NGST).

Each panel, 1.54 m wide and 1.75 m long, utilizes high thermal conductivity RS-3/K13C2U composite face sheets with an aluminum honeycomb core. Applied Aerospace Structures Corporation (AASC) was selected over four other composite structure suppliers to provide all the substrates used during solar array qualification testing and flight panel substrate fabrication [6]. For heat conduction reasons the face sheets have a minimum thickness of 0.6-mm with local stiffeners in high-stress regions. To demonstrate the survivability and validate the thermal analysis, qualification panels successfully completed a series of high-temperature tests including infrared heater and high--intensity illuminated high-temperature tests in vacuum at the Tank 6 facility at GRC. Four major U.S. cell lay-down manufacturers using EMCORE solar cells and Pilkington mirrors fabricated qualification test solar panels using

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Figure 3. A MESSENGER solar array prior to integration.
Illustrated here are the descrete strings of second-surface mirrors and solar cells

ASCS supplied substrates. All of the qualification panels went head-to-head during the qualification program and were tested in vacuum over a temperature range from -130°C to 270°C at APL. Upon successful test passage at APL they were then tested at GRC using the Tank-6 facility where they were subjected to 11-Sun intensity illumination. The panels were also life cycled successfully over the range from -130°C to 150°C in a nitrogen environment at the Aerospace Corporation in Los Angeles. The rate of change in temperature was 80 to 100°C/minute to simulate the thermal shocks expected at Mercury eclipse exit. Upon completion of the qualification test program the flight panels were cycled in vacuum over the -140°C to 240°C maximum operational temperature range. The flight panels were not exposed to temperatures over the substrate materials' glassing temperatures, above 240°C, due to concerns over possible weakening of the substrate mechanical strength required for launch.

Operationally, the solar array temperature is accurately managed during flight by single axis rotations relative to the Sun. As the MESSENGER spacecraft gets closer to the Sun, the solar arrays are rotated to operational angles per predictions made by the power thermal model. The model balances the power output of the solar arrays with operating temperature. Currently five operational and safe-mode solar array tilt angles for solar distance ranging from 1.0 AU to 0.30 AU have been placed into the flight operations database. These angles, optimally balancing temperature and power output, will be uploaded to the spacecraft during predetermined blocks covering associated DSN passes. Three years after launch, on August 1, 2007, the MESSENGER solar arrays were operationally tilted for the first time. Figure 3 shows a MESSENGER flight solar array prior to spacecraft integration.

V. ANTENNA DESIGN AND QUALIFICATION

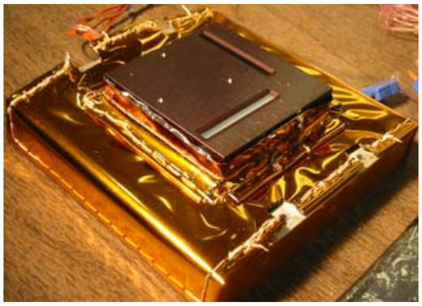
The MESSENGER spacecraft has used the first electronically scanned phased-array antenna for a deep-space telecommunication application. Designed, built and tested [7] by APL, two lightweight phased-array antennas mounted on opposite sides of the spacecraft have provided the high-gain downlink coverage for the mission to date. Constructed completely of aluminum, these antenna assemblies have been tested to thermal extremes between –110° and +325°C. Electronically steerable, these antennas have no moving parts, gimbals, or booms, and do not require risky spacecraft maneuvers to point. Maintained in fixed orientations that are 180° apart, the antennas can be positioned by rotations of the spacecraft around the Sun line to give 360° of coverage in a plane that contains the

Figure 4. Flight phased-array assembly with radome removed. The fanbeam antenna is shown on the right

Earth and spacecraft. Normally operated in four stick mode, each antenna can be cross-strapped to the opposite Solid-State Power Amplifier (SSPA) as to increase the downlink data rate by a factor of four at a cost of twice the

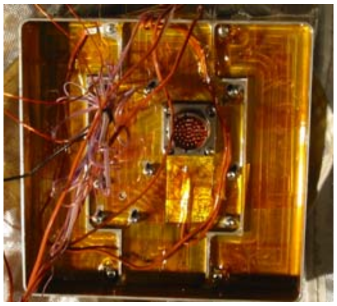
direct current power that is needed to operate four sticks. The design of the MESSENGER phased-array antenna complies with several challenging requirements, such as the wide operating temperature range, one-dimensional electronic scanning, circular polarization, and bandwidth. The wide operating temperature range is driven by the mission geometry. During the early portion of the mission, while the spacecraft is still relatively far from the Sun and heater power is limited, the antennas must operate at temperatures as low as -30°C and survive at temperatures as low as -100°C. In Mercury orbit, the Sun-facing front array is exposed to 11 times the solar radiation intensity as that observed at Earth, while the back array faces deep space. Even with the thermal protection of a radome, the predicted temperature of the front array at Mercury is as high as +300°C. Except for the early months of the mission, the back array temperature is controlled with a heater to approximately +150°C. The high operating temperature of the front array limits the choices of radiating elements and circular polarization options to those that are comprised entirely of metal. The waveguide elements of both phased-array antennas are identical in design.

As described, the characteristics of the phased array antenna mechanical and electrical designs have been matched very well to the thermal requirements dictated by the MESSENGER mission. The all aluminum construction has proven to be robust and predictable as verified during RF testing. The electronic steering complicated the electronics (SSPA) but simplified the operational risks associated with solar proximity, RF system reliability, and flight operations. A key component of the antenna system is the high-temperature radome. Designed in collaboration between the thermal and RF system groups at APL, the radome was fabricated from Mansville Q-Fiber felt and bare Nextel 312-AF 10. The radome was designed to be integral to the antenna assembly and was nearly perfectly matched to the antenna frequency output. Testing at the APL compact antenna range verified that RF loss through the radome was negliable. An exposed MESSENGER-class phased-array antenna with its cavities, gold coatings, and aluminum construction would warp and possibly soften enough to completely distort when at an 11-Sun condition. The radome provides a geometrical and optically favorable thermal environment for the underlying antenna by creating an infrared cavity that is very uniform in temperature and will keep the maximum antenna temperature well below 300°C as demonstrated at GRC when the flight antenna assembly was tested to 11 Suns.

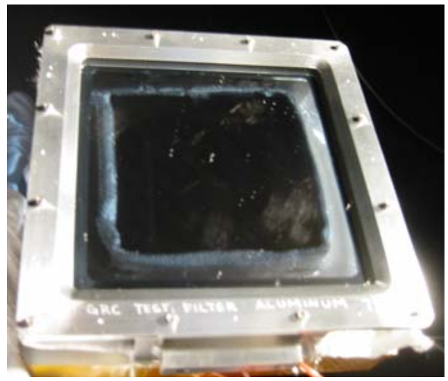


Looking through the ND filter as the DSS would (light source is a 1000w halogen lamp)

EM DSS with multi-layer blanket



EM DSS radiator (opposite Sun)



EM DSS and ND filter assembly

Figure 5. Engineering model DSS during thermal qualification testing.

VI. DIGITAL SUN SENSOR DESIGN

Located on the sunshade along with the phased-array antenna are four DSSs. The MESSENGER spacecraft utilized standard Adcole DSS's and modified the mechanical and thermal designs by using an enlarged housing to better reject heat. Internal to the sensor, high-temperature adhesives similar to those used on MESSENGER solar arrays replaced the lower temperature adhesives used for the more standard applications. A special solar attenuating neutral density filter was placed over each head to reduce the incident solar intensity by one order of magnitude. The filter, essentially a second-surface mirror that transmits 10% of the incident solar energy to the DSS, was manufactured by Melles-Griot and used aluminum as the reflecting metal. The six flight DSSs, four Sun facing and two rear facing, create near hemispherical coverage and are primarily needed in the event of a star tracker reset or a spacecraft safing anomaly.

As with the solar arrays and phased-array antenna, an Engineering Model (EM) DSS was developed by Adcole per APL thermal and mechanical specifications. The EM DSS was qualification tested at GRC as part of the solar simulation qualification test program. During the development of the Neutral Density (ND) filter design two different optical coatings, Inconel and aluminum, each in combination with fused silica glass, were chosen as candidate materials for accurate ultraviolet (UV) light transmission and true neutral-density performance. Solar simulation testing at GRC allowed direct comparisons for each design as a function of its thermal performance. It was apparent that the aluminum ND coating was superior thermally, as the DSS operated approximately 30-40°C cooler with the aluminum ND filter than with the more conventional Inconel ND filter. Both performed nearly the same when compared for UV light transmission and attenuation and DSS electrical performance. Therefore as a direct result of the GRC testing, the aluminum ND filter was chosen for flight. Figure 5 shows the EM DSS hardware in a few configurations during the thermal qualification test program.

VII. MESSENGER AND OTHER INNER SOLAR SYSTEM MISSIONS

As presented in this paper, the MESSENGER spacecraft has demonstrated inner Solar System technologies that can be applicable to other missions that have perihelia between 0.30 (11 Suns) and 0.20 (25 Suns). Current missions that could benefit from MESSNGER design and technology developments include BepiColombo (0.30 AU), Solar Sentinels (~0.25 AU), and Solar Orbiter (~0.22 AU). Although the thermal environments to be experienced by Solar Sentinels and Solar Orbiter are dictated by solar flux only, the thermal developments made during the MESSENGER program may be applicable because MESSENGER must withstand not only direct solar heating but also infrared heating from the planet that is proportional to the solar flux. Each of these future missions will require a solar array system for power generation, an antenna system for RF communications, Sun sensors for guidance and control, and a primary attitude sensor back-up, and for the three-axis-stabilized spacecraft such as the BepiColombo Mercury Planetary Orbiter (MPO) and Solar Orbiter a sunshade will be required. Spinning spacecraft such as the Solar Sentinels and the BepiColombo Mercury Magnetospheric Orbiter (MMO) would experience more benign thermal environments because of the spin attenuation effect on the incident solar flux, so components such as the solar arrays and DSSs would be well within the qualification environments used for MESSENGER.

VIII. SUMMARY

Specialized thermal design and technology developments made during MESSENGER program may be of benefit to any mission that will journey into the inner solar system. Although MESSENGER technologies and designs may not be directly applicable to all missions, the analytical processes and hardware developed are somewhat generic regarding the expected thermal environments when at these solar distances. The development completed during the MESSENGER program may serve as a practical pathfinder for programs resolving issues relative to testing, thermal modeling, and material selection. Why re-invent the wheel?

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