MESSENGER Spacecraft Charging Analysis†

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Abstract

The MESSENGER spacecraft will orbit Mercury for one year beginning 6 April, 2009. It will experience solar illumination ranging from 4.5 to 10.4 times the value at 1 AU, as well as an intense solar wind and the Hermean magnetospheric environment. Factors such as high photoemission, highly conductive OSRs and coverslips, and the insulating Nextel™ that blankets the spacecraft present unique charging problems. The analysis shows that in the solar wind, the spacecraft will charge about ten volts negative and the dark, insulating surfaces will charge several tens of volts negative. Normally, in the Hermean magnetosphere the entire spacecraft will attain positive potentials.

Introduction

MESSENGER (MErcury Surface, Space ENvironment, GEochemistry and Ranging)[1] is a mission that will orbit our sun's innermost planet for one Earth year. Encountering intense solar illumination and solar wind while exploring Mercury's unique magnetospheric environment, MESSENGER presents some unique potential control problems. These problems are exacerbated by the need for thermal control, and the wide range of temperatures expected on spacecraft surfaces.

In this paper we give a brief description of the Hermean environment and of the MESSENGER mission. Then we proceed to discuss the MESSENGER model used for Nascap-2K spacecraft charging calculations, along with our estimates of the material properties. Finally, we show simulation results, and discuss how the problems and solutions differ from those of typical geosynchronous orbit spacecraft.

Hermean Environment

Mercury[2,3] has a highly eccentric orbit, with perihelion at 0.31 AU and aphelion at 0.47 AU. Thus, the solar intensity and solar wind density vary from 4.5 to 10.4 times their 1 AU values. The Hermean year is 88 Earth days, while the rotational period is 59 Earth days, leading to the strange consequence that a Mercury solar day lasts two Mercury years.

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The interplanetary environment in the vicinity of Mercury's orbit was observed by the Helios missions during 1974-80[4,5]. All of the major parameters had broad distributions, but were consistent with what would be expected by scaling the 1 AU values. For example, the solar wind density was measured to average 60 cm^{-3} with a standard deviation of 44 cm^{-3}.

The only spacecraft to have a close encounter with Mercury was Mariner 10[5,6], which came within 707 km of the surface on 29 March 1974, and within 327 km on 16 March 1975. Magnetometer measurements gave clear indications of the spacecraft's crossing the bow shock and magnetopause. The total time spent in Mercury's magnetosphere was less than one hour. Nonetheless, from these measurements researchers have estimated the subsolar distances for the magnetopause and bow shock (about 1.5 and 1.9 R_M respectively) and Mercury's magnetic moment (about 2.4×10^{18} Am^2).

Mercury's magnetic dipole is much smaller than Earth's (about 8×10^{22} Am^2), even when scaled by the cube of the planetary radius. The small dipole moment, together with the increased solar wind pressure, makes the Hermean magnetosphere much smaller than Earth's. If we try to scale the structure of Earth's plasma environment to Mercury, we find that such features as the ionosphere and the radiation belts simply cannot exist, as they would be interior to the planet .

Mariner 10[6] detected energetic electrons and found evidence for substorms in Mercury's magnetosphere. Unfortunately, the electron detector had an upper limit of 690 eV. Most scans showed the peak electron energy well below this value, but at least a few scans measured the electron energy peak near or above the instrument's limit. So, the question of whether substorms are occasionally severe enough to produce charging environments similar to those in geosynchronous orbit remains open.

MESSENGER Mission

MESSENGER[1] is scheduled for launch in March 2004. After two Venus flybys in 2004 and 2006, the spacecraft will reach Mercury in July 2007, executing two flybys one during 2007 and one in 2008. Mercury orbit insertion is scheduled for 6 April 2009, and the spacecraft will orbit Mercury for one Earth year (two Hermean solar days, or four Hermean years). The orbit is highly elliptical, with periapsis of 124-502 km near the northern polar zone and apoapsis of about 15,000 km. Over the course of each Hermean year the orbit evolves from noon-midnight with dark-side periapsis to noon-midnight with sun-side periapsis and back, with intervening dawn-dusk configurations, so that the full variety of Hermean conditions can be observed.

MESSENGER instrumentation includes a magnetometer (MAG) to map out the detailed structure and dynamics of Mercury's magnetic field, and an Energetic Particle and Plasma Spectrometer (EPPS) to measure the composition, spatial distribution, energy, and time-variability of charged particles within and surrounding Mercury's magnetosphere. Other instruments include the Mercury Dual Imaging System (MDIS), Gamma-Ray and Neutron Spectrometer (GRNS), Mercury Laser Altimeter (MLA), Mercury Atmospheric and Surface Composition Spectrometer (MASCS), X-ray Spectrometer (XRS), and Radio Science (RS). Details of the MESSENGER mission may be found at http://sd-www.jhuapl.edu/ MESSENGER/details.html.

Nascap-2K Model for MESSENGER

Nascap-2K is a program supported by Air Force Research Laboratory (AFRL) and NASA's SEE (Space Environment Effects) Program to update the NASCAP/GEO spacecraft charging code. The NASCAP/GEO technology will be updated both to modern computers, programming languages, mathematical algorithms and software practices, and to encompass a broader range of space environments, both natural and spacecraft-induced. Nascap-2K is described in more detail elsewhere in this conference. In this work we used the Nascap-2K Object Definition Toolkit and the BEM (Boundary Element Method) charging module.

Figures 1 and 2 show the Nascap-2K model of the MESSENGER spacecraft. The prominent and unusual curved feature is the sunshade, which shields the entire spacecraft body from the intense direct sunlight. The sun-facing surface of the sunshade is made of Nextel™ AF-10 fabric[7], which not only can withstand extreme temperatures, but also has excellent thermal properties that limit the spacecraft's temperature to below 140 C. Most of the remaining spacecraft surfaces are also covered with Nextel™ AF-10, the exceptions being the solar array (see below) and the sides of the spacecraft facing the solar array (covered with OSRs). The model distinguishes between the sun-facing Nextel™ (HotNextel) and the fabric covering surfaces behind the sunshade (Nextel). The magnetometer boom will be wrapped with either Kapton or Nextel™ insulator.

The solar array is designed to operate at a maximum temperature of 130 C. Two measures are taken to limit the temperature to this value: (1) Two-thirds of the solar array surface is covered with OSRs in order to limit absorption of incident sunlight, and (2) the array can be rotated away from the sun-facing direction by about 38° (at aphelion) to about 70° (at perihelion) to reduce the incident solar energy. At this temperature, the conductivity of the glass material is about 10^{-10} $(\Omega\text{-m})^{-1}$. This is sufficiently conductive to limit differential charging and to conduct significant plasma current to the underlying ground. For example, sixty volts across a coverslip produces a current of 4×10^{-5} Am^{-2}, which is comparable to photoemission current, and considerably higher than incident plasma current. As a result of these studies, the project has dropped a requirement for ITO coating of the OSRs and coverslips.

The remaining third of the solar array surface model is covered with solar cell coverslips. The strings run in the inboard-to-outboard direction of the panel, and are represented in the model by five bias levels. The coverslips and OSRs are assumed to be made of the same material, with the exception that the coverslip thickness is 150 microns, whereas the OSR thickness is baselined at 100 microns. The coverslips, array OSRs, and radiator OSRs (on the side of the spacecraft body) are assigned different material names, so that different conductivity values may be assigned.

The backs of the solar arrays are baselined as uncoated kapton. At this writing, AZ93 paint is being considered as an alternative material. The sides of the spacecraft body facing the arrays are covered with OSR radiators. Most of the remaining surfaces are coated with Nextel™ fabric, exceptions being the magnetometer boom (insulator-wrapped carbon composite), the adapter ring (anodized aluminum), and the engine nozzle (Columbium).

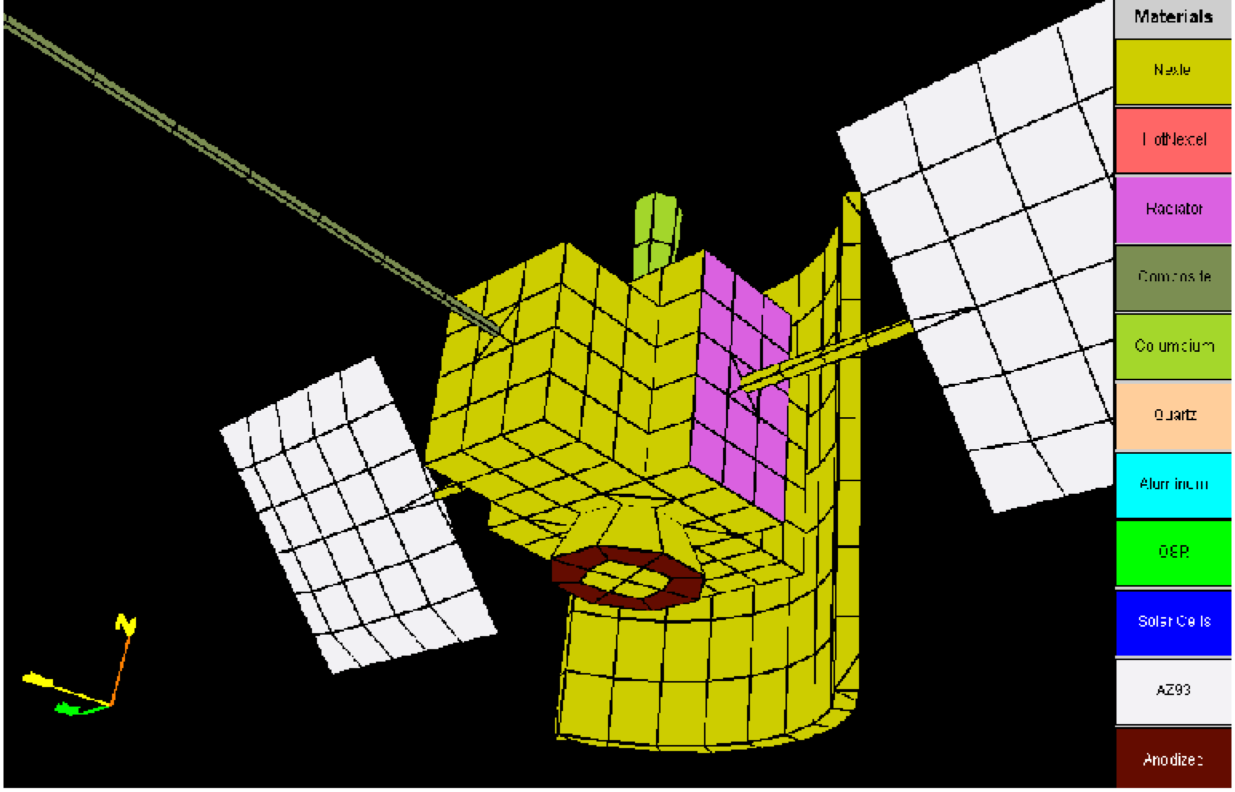

Figure 1. View of MESSENGER model, showing solar arrays and sunshade.

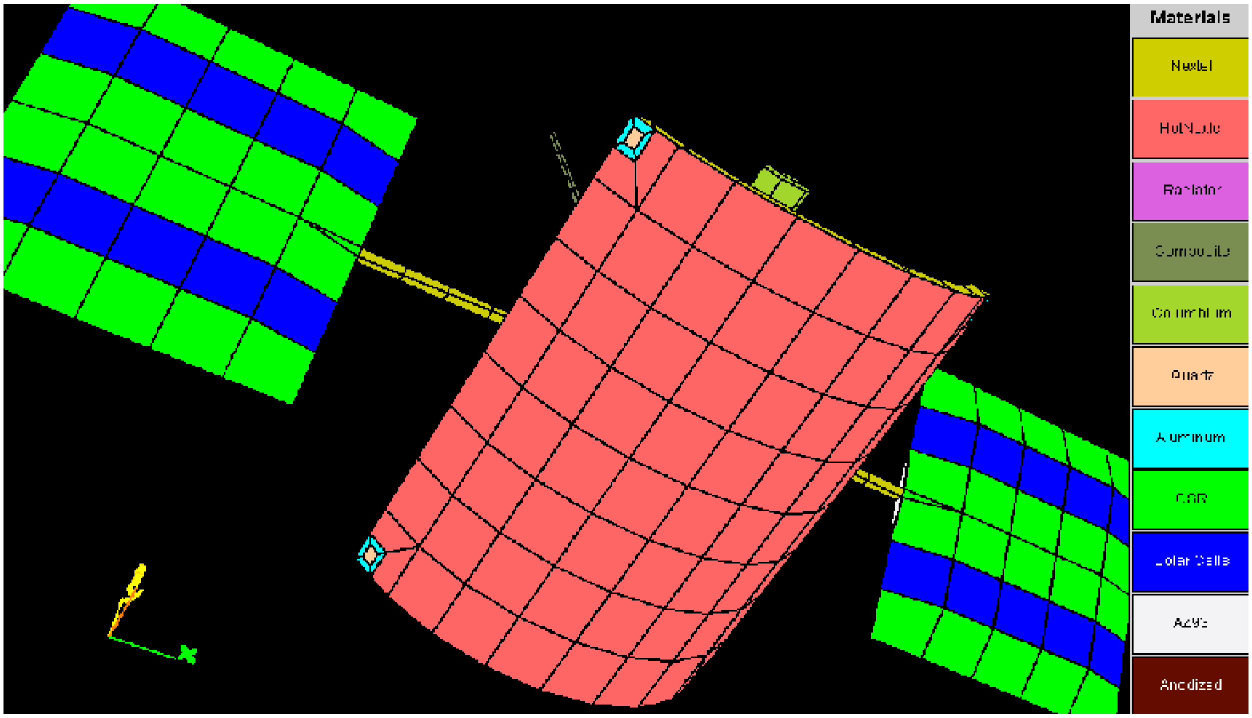

Figure 2: View of MESSENGER model showing magnetometer boom, radiator OSRs, and anodized adapter ring.

At present, the science instrumentation has not been explicitly included in the model. The EPPS is located on the rear side panel (around the corner from the magnetometer boom, looking past one of the solar panels), and the MAG is on the end of the long boom. Most of the other instruments are located inside the adapter ring on the lower deck (opposite the nozzle).

Charging Simulation Results

Charging simulations to date have focussed on the year when MESSENGER is in orbit around Mercury. Apart from brief eclipse periods, the spacecraft is exposed to intense solar illumination (4.5 to 10.4 times its 1 AU value). A majority of its orbital time is outside the magnetosphere in the solar wind plasma, and some time is spent in the less dense plasma of the Hermean magnetosphere.

In these simulations we have taken the sun intensity multiplier as either 5.0 (with the arrays rotated 45°) or 10.0 (with the arrays rotated 65°), and the solar wind plasma density as either 30 or 100 cm^{-3}. Most of the runs took the electron temperature as 20 eV, with a few runs at 10 eV. The ions were modeled as an 800 eV beam from the sun, and the same shadowing factors were used for ions as for sunlight.

Needless to say, we lack any secondary emission data for Nextel™ fabric. The chemical composition of Nextel™ is 62.5% Al_2O_3, 24.5% SiO_2, and 13% B_2O_3. Initially we used glass-like parameters (δ_{max}=2.4, E_{max}=400 eV), and later switched to values[8] for alumina (δ_{max}=6.4, E_{max}=650 eV). The results showed little sensitivity to this switch, as both sets of parameters lead to charging for the assumed solar wind electron energy spectrum.

Because we expect some surfaces to charge more than a few volts positive, the integrated photoemission spectrum is needed to determine the effective photoemission coefficient vs. surface voltage (or electrostatic potential barrier). Figure 3 shows the spectrum used, which is based on data [9] from the WIND spacecraft, provided courtesy of the STEREO [10,11] program. The spectrum is similar to a double Maxwellian with the two temperatures of 2 eV (as is customarily used for geosynchronous charging) and 10 eV (characterizing the higher-energy emitted electrons).

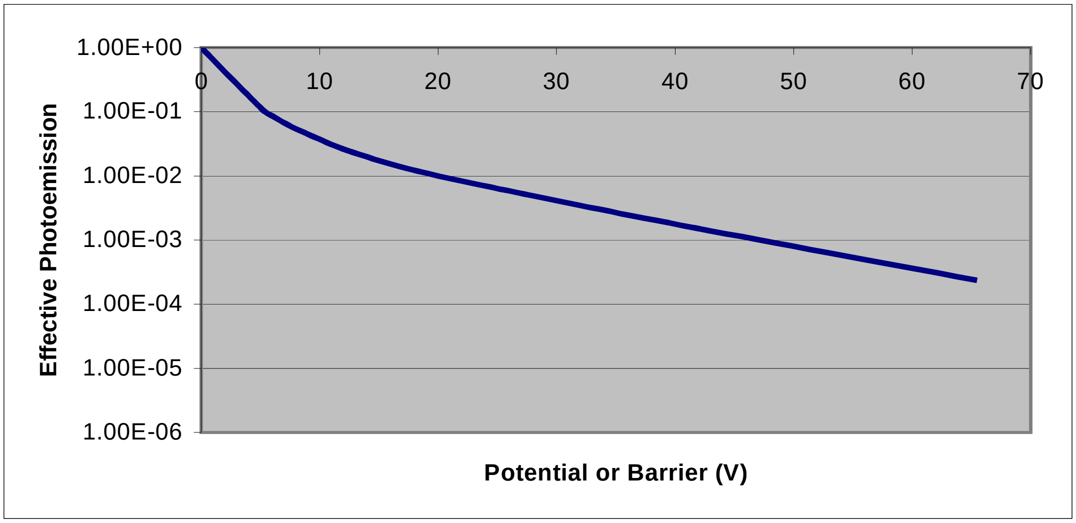

Figure 3: Photoelectron spectrum (effective photoemission coefficient) used in calculations. The initial (low energy, steep) part of the curve has a temperature of 2 eV, while the high energy (less steep) part has a temperature of about 10 eV.

Table 1 shows results from calculations for various conditions and configurations. Except as noted in the ensuing discussion, the sunshade was grounded, the solar array voltage was 60 V, the conductivity of the coverslips and the array OSRs was 10^{-10} $(\Omega\text{-m})^{-1}$, the conductivity of the radiator OSRs was 10^{-13} $(\Omega\text{-m})^{-1}$, and the conductivity of the Nextel™ blankets was 3×10^{13} $(\Omega\text{-m})^{-1}$.

Shown in the table are:

1. A code indicating the case number;
2. The plasma environment, specified by the plasma density and (for solar wind cases) the electron temperature, or (for magnetosphere cases) the plasma temperature; the Hermean environment for Cases MSW 58-64 is specified in Table 2.
3. The sun intensity (5 or 10 times the 1 AU value), indicating also the angle of the solar arrays;
4. The backing material for the solar arrays (either insulating Kapton or conductive AZ93 paint);
5. The calculated ground potential;
6. The range of Nextel™ potentials, with the maximum normally at the center of the sunshade and the minimum on the spacecraft body;
7. The mean potential of the radiator OSRs on the side of the body; and
8. The peak potential on the array surface, i.e., the surface potential of the coverslip over the 60 volt solar cells.

Runs MSW53-MSW57 are in the solar wind at high-normal density (100 cm^{-3}) and typical electron temperature (20 eV). In this environment the spacecraft ground potential is about ten volts negative, the insulating Nextel™ and the radiator OSRs are many tens of volts negative, and the solar array surface peaks at twenty volts positive. Using the standard Nascap parameters for secondary emission of Kapton, the Kapton is non-charging in a 20 eV electron environment (first crossover at about 30 eV). Therefore, the Kapton backing for the solar panels goes negative only far enough to match the potential field of the Nextel™ and radiator OSRs (about 20 to 30 volts negative). By contrast, if the arrays are backed with AZ93 paint (considered conducting) the spacecraft ground charges a few volts more negative, driven by plasma electrons incident on the paint. There is no obvious difference between charging at the perihelion and aphelion configurations. An additional run with lower (10 eV) electron temperature shows that the ground potential and negative insulator potential scale roughly with the temperature, while the potentials of sunlit surfaces are governed by other considerations.

Table 1: Results for MESSENGER charging in the solar wind and in the Hermean magnetosphere. The environment is characterized by an electron temperature in the solar wind or a plasma temperature in the magnetosphere, and a plasma density. The sun intensity is in units of its 1 AU value. Potentials are in volts relative to "plasma ground."

Case	Environment		Sun	Array Back Material	Ground Potential	Nextel™ Potential		Radiator Potential	Coverslip Peak
	eV	m^{-3}				Min	Max		
MSW53	Te=20	1.00E+08	10	Kapton	-10.6	-82	-1	-70.1	21
MSW54	Te=20	1.00E+08	5	Kapton	-10.636	-81.4	-3.5	-69.3	21.45
MSW55	Te=20	1.00E+08	5	AZ93	-13.9	-80.1	-2.2	-67.92	20.08
MSW56	Te=20	1.00E+08	10	AZ93	-14	-82.5	-0.4	-70.1	19.39
MSW57	Te=10	1.00E+08	5	AZ93	-7.7	-47.8	6.5	-39.7	21.2
MSW71	Te=20	3.00E+07	5	Kapton	0.247	-58.6	3	-48	46.35
MSW72	Te=20	3.00E+07	5	AZ93	-3.33	-59.8	3.16	-48.54	43.28
MSW58	T=82	1.00E+07	5	Kapton	9.1	5.8	16.9	1.9	64.3
MSW59	T=82	1.00E+07	5	AZ93	5.5	1.4	16.9	1.8	60.83
MSW60	T=37	3.00E+06	5	Kapton	14.3	1	29.1	7.3	72.6
MSW61	T=37	3.00E+06	5	AZ93	13.9	1	29	7.2	72.19
MSW62	T=1000	3.00E+06	5	Kapton	11.9	4.1	24.8	4.8	70.16
MSW63	T=1000	3.00E+06	5	AZ93	10.8	4	24.5	4.5	69.11
MSW64	T=37	3.00E+06	0	Kapton	1.1	1	1.8	0.9	1
MSW65	T=37	3.00E+06	0	AZ93	1.25	1.8	1.8	0.9	1

Runs MSW71-MSW72 are in the solar wind at low-normal density (30 cm^{-3}). With the lowered electron current, the ground potential remains near zero, the negative charging of insulators is somewhat lessened, and the array surface charging (driven by the array voltage) is greatly increased.

In all of these cases, a substantial (often dominant) contribution to the negative current to ground comes from conduction through the coverslips over the positively biased solar cells. These coverslip surfaces attain potentials above the normal floating potential of the material, and below the sum of the ground potential plus the cell bias. Current conducted through these coverslips represents a small parasitic current through the array circuit, but substantial plasma current to spacecraft ground. The dominant positive current to ground comes from conduction through the array OSRs, which always charge positive (due to solar photoemission) relative to the underlying ground.

For example, in case MSW55, the negative current to ground consists of 22 μA of direct plasma current (mostly on the AZ93 solar array backs), plus 12 μA conducted through the coverslips. This is balanced (approximately) by 36 μA conducted through the array OSR's. In the similar case with Kapton backing on the solar arrays (MSW54), the negative current to ground consists of only 5 μA of direct plasma current plus 15 μA of conducted current, balanced by 20 μA of positive current conducted through the OSR's.

We are also concerned with charging during passage through the Hermean magnetosphere. Mariner 10 measured three sets of plasma sheet environments, Maxwellian approximations to which are shown in Table 2. Of these, environments A and B (at 82 eV and 37 eV) lie above the first crossover of most materials, and environment C (at 1 keV) lies below the second crossover, so that no negative potentials are seen. (See runs MSW58-MSW65.) However, in all these environments electron collection by positive surfaces is rather difficult, so that nearly the full solar array potential appears on the coverslip surfaces. (See Figure 4.) To cause substantial negative spacecraft charging, even in eclipse, requires a Hermean electron temperature exceeding 3 keV.

Table 2. Maxwellian approximations to three representative Hermean magnetospheric environments observed by Mariner 10 and used in Table 1.

	A	B	C
n [m^{-3}]	1×10^{7}	3×10^{6}	3×10^{6}
T [eV]	82	37	1000

Conclusions

The intense solar illumination and solar wind at Mercury orbit leads to charging considerations different than those of the more familiar geosynchronous orbit charging. The high temperature of the solar array causes the coverslips and OSRs to be sufficiently conductive to reduce differential charging between the array surface and spacecraft ground. A large fraction of the array potential remains on the coverslip surfaces. Based on this information, the project has elected not to use conductive ITO coating on the coverslips or the array OSRs.

The calculations indicate that in the solar wind spacecraft ground will charge negative to about ten volts, while the insulating spacecraft surfaces (OSR radiators and Nextel™ blankets) will charge several tens of volts negative. By contrast, we expect the entire spacecraft to charge positive in the Hermean magnetosphere, even in eclipse.

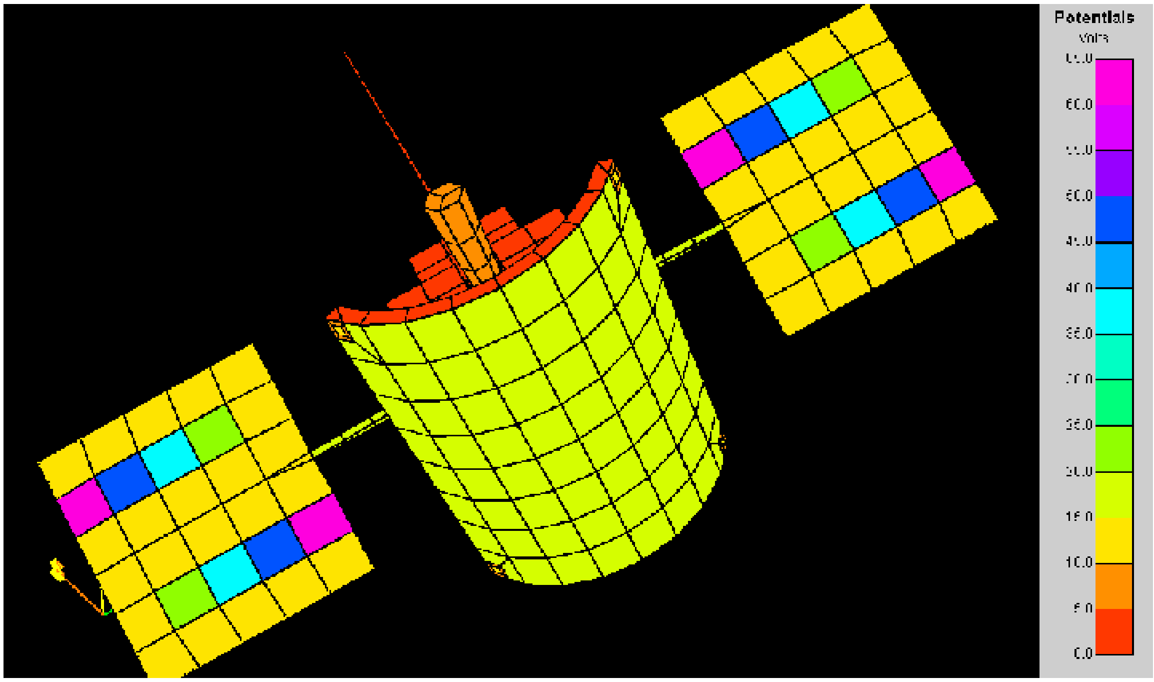

Figure 4. Surface potentials for MESSENGER in the Hermean magnetosphere (case MSW58) showing solar array voltages conducted to coverslip surfaces

Further calculations are needed to assess the impact of the charged insulating surfaces on the EPPS and other science instruments. If these are found to cause a problem, it may be necessary to apply a conductive coating to the radiator OSRs and Nextel™ blankets in the vicinity of the plasma instruments.

To cause conventional spacecraft charging, as seen in Earth's magnetosphere, requires a plasma with electron temperature of at least 3 keV, more than three times hotter than was observed by Mariner 10. Such charging would present a hazard only on exit from eclipse, when the solar arrays are cold. At any other time the high conductivity of the coverslips would maintain a level of differential charging too small to cause solar array arcing.

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