Extreme Environment Electronics

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Extreme Environment Electronics in NASA’s Heliophysics Vision

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3

3.1 Introduction

Heliophysics seeks to understand the variability of the sun, the response of the planets in our solar system, and the impacts of the variability and response on human society. “Helio” is taken from the personification of the sun in Greek mythology. Thus, heliosphere is the area of space including the planets that are influenced by the sun—and that area is our solar system.

3.1.1 The Sun

At the center of our solar system is the sun, our star. This star is the dominant, time-varying source of energy, plasma, and energetic particles in our solar system. Energetic particles are protons with very high energies. The plasma is comprised of high-energy electrons and protons. The energy from the sun (which is typically studied in the extreme ultraviolet wavelength range), or solar wind, can be compared to the heat radiated at the edge of a bonfire. The closer a body is to the energy source, the greater the energy incident upon the body. The edge of our solar system is coincident with the end of the effects from the solar wind.

The sun behaves as a magnetic dipole with strong magnetic field lines. During a minimum in solar activity, the magnetic field lines are aligned. High solar activity occurs when the sun’s dipole is in the process of changing polarity, and the associated field lines invert relative to their starting points (see Figure 3.1). Since similar field lines repel each other, tangled magnetic field lines result in high solar activity. During times of high solar activity, there are releases of energy and/or mass, called solar flares and corona mass ejections (CMEs), respectively (see Figures 3.2 and 3.3). The flares and CMEs spurt energy and matter into the heliosphere, and these eruptions have directionality. Streamers from the flares and CMEs may loop back into the sun, and when the loops return to the sun’s surface, it is called magnetic reconnection.

Solar physicists study the sun in three areas: (1) the interior of the sun called helioseismology, (2) the surface of the sun where activity is manifested as sunspots, and (3) the outer halo of the sun called the corona. Sunspots are small areas that are cooler than the remainder of the sun’s surface.

3.1.2 The Earth and Other Planets with Magnetic Cores

If the flares and CMEs are directed toward the Earth, the electric and magnetic fields in the ionosphere and thermosphere of the Earth can be increased or “charged up,” because the Earth’s magnetic core and associated magnetic field lines attract the sun’s electric and magnetic fields. When electrons and particles (i.e., high-energy protons) enter at the Earth’s poles, they become trapped and build up in medium Earth orbit, bouncing from the top of a donut in high northern latitudes to top of the same donut in high southern latitudes. The populations and distribution of these trapped electrons and ions become important when designing and operating Earth-orbiting spacecraft. Figure 3.4 depicts the areas around the Earth where particles and electrons can get trapped during high solar activity. There are two areas surrounded by light shading that are the Van Allen radiation belts. The inner belt is at one to two Earth radii, and the outer belt is at two to six Earth radii. Figure 3.5 depicts the radiation processes that can be observed in and near the radiation belts with in situ observations. Creation and variation of radiation populations result from a complicated interplay of these processes.
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Heliophysics seeks to understand the coupling not only between the sun and the Earth but also between the sun and other planets such as Mars. It is fortunate that both Earth and Mars have magnetic cores, so heliophysics can understand the coupling of the sun with any magnetic planet in our solar system by focusing on the relatively close-in processes between the sun and Earth. Heliophysics science in its entirety investigates processes taking place throughout the solar interior and atmosphere: the evolution and cyclic activity of the sun; the origin and propagation of the solar wind and magnetic field from the sun to the heliopause (the boundary between the solar wind and the interstellar medium); the acceleration and transport of energetic particles in the heliosphere; and the interface of solar influence with the interstellar medium.

Scientists who study the physics of the interaction of the Earth and the sun are called geospace scientists. The geospace

**FIGURE 3.1** (See color insert.) Magnetic variations in solar activity during a solar cycle in two wavelengths: (a) first wavelength and (b) second wavelength. The bright pictures in the foreground were taken at solar maximum, and the dimmer pictures in the background were taken at solar minimum. The time period to transition from solar maximum, through solar minimum, and reach solar maximum again is 11 ± 2 years.

**FIGURE 3.2** (See color insert.) Picture of a coronal mass ejection/solar flare.

**FIGURE 3.3** (See color insert.) Components of a solar flare.

**FIGURE 3.4** (See color insert.) Areas around the Earth, the Van Allen radiation belts, where particles and electrons can get trapped during high solar activity.

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discipline is often further divided into the study of the interaction of the Earth’s radiation belts with the remainder of the atmosphere including magnetic reconnection, and the study of the ionosphere–thermosphere.

3.1.3 Space Weather

The changes in solar activity are called space weather. The consequences of space weather are called space weather effects. These effects include

- Enhanced electromagnetic activity that can affect radio transmissions
- Aurora
- Enhanced levels of charged particles in the Van Allen–trapped radiation belts
- Enhanced radiation dose to spacecraft and aircraft crew members that fly over the poles
- Disruption in power transmission in the higher latitudes
- Single event effects in electronics, particularly in spacecraft and aircraft flying over the poles

3.2 Electronics Technology in Heliophysics Missions

Heliophysics missions are prioritized and selected for development based upon the overall heliophysics science priorities. Science investigations, which include instruments, are selected through a competitive process. The final mission destination and prime operating lifetime are driven by the science that is selected for the mission. The spacecraft attributes and orbital mechanics needed to get to the destination are defined by the selected science. Science missions typically have destinations near the sun, at Lagrange points between the sun and Earth, or near the Earth. Figure 3.6 depicts operating heliophysics missions. Understanding the magnetic and electric fields around the sun and Earth is an important area of research, so typically heliophysics spacecraft is magnetically and electrically clean in the vicinity of the science instruments. In some cases, accommodation of this cleanliness necessitates placing instruments...
on deployable booms. The radiation exposure or shielding on a boom may be significantly different than if the instrument was mounted inside the spacecraft, and this must be considered when electronic devices are being selected for missions with booms. In addition, the scientists require “better” data than was available from previous missions, so each mission (and hence the electronics) typically is more complex than previous missions (Figure 3.6).

3.2.1 Electronics Technology for Solar Missions

Instruments on missions that study solar science typically want to image the full disk of the sun and/or measure the particles as well as the electric and magnetic fields of the sun at a cadence coincident or better than the time period for events on the sun. Two missions can serve as examples of the electronics considerations needed in heliophysics solar missions. They are Solar Dynamics Observatory (SDO), which launched in 2010, and ESA’s Solar Orbiter mission.

The SDO mission is in Geosynchronous Earth orbit (GEO). Its instruments collect science data at 120 MB/s and downlink it through 2 Ka band antennas. Full science mission success required that twenty-four 72 day time periods of data are collected during its 5 year prime mission lifetime. In order to collect data for these extended time periods with low error rates, it was very important that the instruments operate during high solar activity. The electronics challenges for this mission were:

- Being able to manufacture 2 K × 2 K charge-coupled detectors (CCD) and stitch them together into 4 K × 4 K detectors
- Ensuring that the electronic devices responsible for clearing the detectors and transferring the data for downlink had their timing synchronized (since this was the first time that these much data were being collected and downlinked using Ka band communications)
- Maintaining the data integrity and very low error rate through transmission from the spacecraft to the ground antennas and then to the scientists at locations away from the antennas
- Operating in the high-radiation GEO location which introduced possibilities for frictional electrostatic discharge and deep dielectric discharge
- Ensuring operation during periods of high solar activity

Some mitigation of the discharging was introduced by using conductive external spacecraft surfaces to bleed off excess charge and checking/rechecking that the surfaces and structure were adequately bonded together. For the spacecraft power system, parts have very little protection in the vicinity of the solar arrays, so care was needed in parts selection for the power system applications. Often Heliophysics missions use electronics in ways that are not the ways they are routinely used on Earth; that is, registers that are not routinely addressed in ground applications may be used in space applications, and the space applications may then introduce problems with parts and devices that had not been identified in the past. The market for radiation-hardened parts is limited, so it was necessary not only to procure the parts but also to verify that they operated as expected. In more than one case, the advertised and actual operating voltages did not coincide. Finally, workmanship of both parts and boards became a significant issue and required diligent inspections to meet the specifications.

The Solar Orbiter mission has a different scenario than SDO. It will be launched out of the Earth’s atmosphere, have a cruise phase that includes Earth and Venus gravity assists to increase the speed of the spacecraft, and then have an operational phase orbiting the sun. Initially it will orbit equatorially and after several orbits, it will use a series of Venus gravity assists to change the orbit from equatorial to increasingly higher heliolatitudes. The distance of closest approach to the sun will be about 62 solar radii. The Observatory’s remote sensing instruments may be taking data during the cruise phase, and both the in situ and remote sensing instruments will collect data during its orbits around the sun. The electronics for this mission will need to be selected so that they are capable of operating both during the cruise phase and during the high temperatures present close to the sun. The NASA imager has a 4 K × 4 K active pixel sensor (APS) detector. This mission will be the first time that an APS detector of this size will be stitched together and flown. The solar cells and associated power electronics will also require attention due to the operational environment and the relative inability to protect them from the heat from the sun and space weather; whether the heat will affect the materials and electronics selections has not been determined but will be addressed prior to exiting from critical design review, where 90% of the drawings are expected to be completed. The imager detector will also need to be mindful of the effect of its field of view due to light reflection by the solar arrays; devices or other means to correct for the absence of a clear field of view may be needed.

The Solar Probe Plus mission will explore the last region of the solar system to be visited by a spacecraft, the sun’s outer atmosphere, or corona as it extends out into space. Solar Probe Plus will repeatedly sample the near-sun environment, revolutionizing our knowledge and understanding of coronal heating and of the origin and evolution of the solar wind and answering critical questions in heliophysics that have been ranked as top priorities for decades. Moreover, by making direct, in situ measurements of the region where some of the most hazardous solar energetic particles are energized, Solar Probe Plus will make a fundamental contribution to our ability to characterize and forecast the radiation environment in which future space explorers will work and live. The Solar Probe Plus spacecraft will fly within 9.5 solar radii of the sun, posing challenges for the design of the electronics. As the spacecraft approaches the sun, its heat shield must withstand temperatures exceeding 2500 F and blasts of intense particle radiation. Estimating the levels of high-energy, penetrating radiation levels to which the spacecraft will be exposed is particularly challenging due to the lack of...
high-energy particle measurements at less than 1 astronomical units (AU) from the Earth. This may require the use of large margins in the predicted levels of total ionizing dose and single event effects rates.

### 3.2.2 Electronics Technology for Geospace Missions

Geospace missions typically address one of two categories: either they are ionosphere/thermosphere (I/T) missions or they are radiation belt missions. The I/T missions address the interactions, drivers, and energy exchange between the layers of the atmosphere and how the sun influences the changes. The radiation belt missions address how and why the belts change as a function of time and solar activity.

The science for these missions requires multipoint measurements, so often missions contain multiple spacecraft that are launched from a single launch vehicle and operated independently. There are several instances where the only difference between the multiple spacecraft is the frequency with which each spacecraft is commanded from the mission operations center. Examples of multi-spacecraft missions are Magnetospheric Multiscale and Radiation Belt Storm Probes.

The geospace mission science measures the magnetic and electric fields, so the spacecraft and instrument electronics need to be magnetically and electrically clean. This is sometimes accomplished by placing instruments at the tips of long booms. The area of space where the geospace missions operate is also a very harsh environment, so even if the spacecraft is single string, selective redundancy is employed to achieve the full science success and operational lifetime. The advice for selecting electronic devices for the solar missions also applies to the geospace missions. That is, electronics may use registers that are not routinely used in applications on the ground, so verification of correct performance is essential. Workmanship problems must also be anticipated, because all the heliospheric missions are one-of-a-kind mission, and the goal of each mission’s science is to advance (or be better than) the last mission.