2-1-5 Space Radiation Effect on Satellites

AKIOKA Maki

Solar activity and space environment is considered as fundamental and important factors for space system design and operation. Space and solar radiation is widely known as a cause of malfunction of electronics, surface charging and discharging, and deterioration of materials of space systems. Therefore, empirical model of solar activity and radiation is inevitable tools for reliability design of the systems. Observational data and information may be useful for operation. In this article, influence of space environment to space systems are briefly reviewed.

Keywords
Space environments, Space system, Satellite

1 Introduction

Solar activity and space environmental changes stemming from it are said to exercise various influences on human activities. Since the hazards posed by such phenomena can also adversely affect the service life of artificial satellites, caution must always be taken in proceeding with space development. Electronics parts used in artificial satellites should basically be those having confirmed reliability and validation from various perspectives for space purposes, and resistance to energetic particles is a vital point regarding whether any equipment in question can be used for space purposes. Therefore, when considering whether to use a part or component for a satellite, it is common practice to consider things while paying attention to information about the performance and functions of parts, along with their history of implementation in space equipment and information about their resistance to energetic particles. When any part lacking information about resistance to energetic particles is to be newly adopted, an aboveground testing device (accelerator or irradiator) should be used to irradiate an assumed amount of energetic particles expected to be imposed during the part's design service life, with a task being conducted to ensure that the equipment functions normally. This entails huge costs and labor, but is considered a mandatory task in order to ensure satellite reliability. When devising a final satellite system design, one should assume a quantity of space energetic particles applied to the artificial satellite and proceed prudently, while checking based on model calculations or using a similar means to determine whether each part of the satellite can withstand the space energetic particles. If sufficient reliability cannot be ensured, one must consider changing parts and adding measures to increase reliability (such as adopting standby redundancy and the majority principle).

For the purpose of this paper, "energetic particles" refer to charged particles and electromagnetic waves having high energy stemming from solar flares and other space environments, and covers high-energy ions and electrons, gamma rays, and X-rays. These high-energy particles and electromagnetic waves cause various interactions due to their high energy. Figure 1, for example, shows images taken of the sun's external atmosphere by using a corona graph mounted on the *SOHO* spacecraft launched by the European Space Agency (ESA). This telescope is spe-

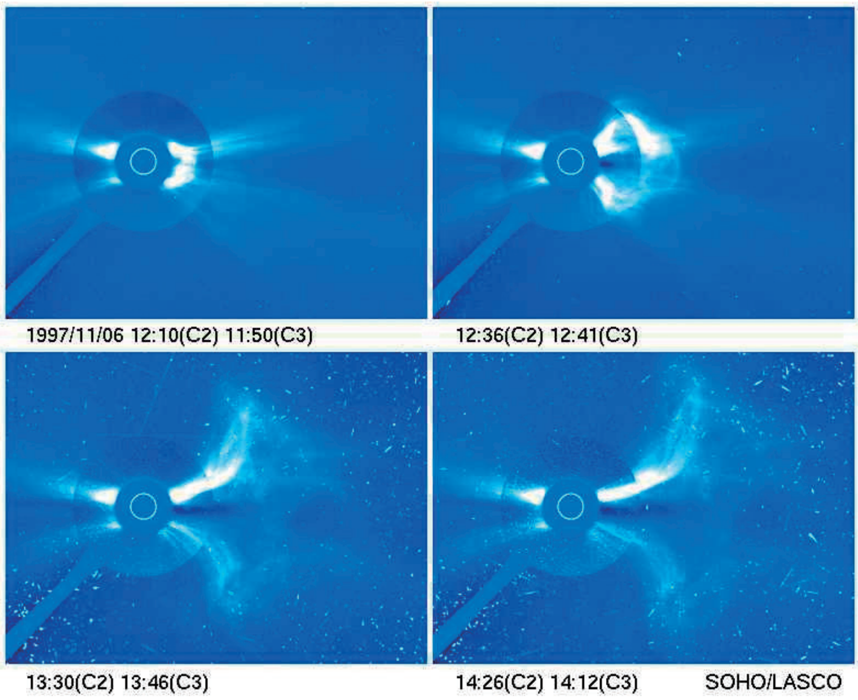

Fig.1 *Traces of CME observed and solar energetic particles that entered the CCD surface as observed by the SOHO spacecraft*

cially designed to enable the observation of lean gases around the sun by artificially hiding the sun proper. The series of images produced are likely to show white spots spread all over the bottom two images. These white spots indicate the noise generated when high-energy particles accompanying a solar flare enter the CCD on the imaging plane of the corona graph. The high-energy plasma particles accelerated and released together with coronal mass ejection (CME; a phenomenon whereby solar corona gases erupt) as shown in these four images generate a high level of noise in the CCD, thereby deteriorating the quality of observation considerably. The CCD functions as a detector by reading electrons generated by the photoelectric effect caused by light striking a semiconductor. Energetic particles entering and passing through the CCD surface will charge the CCD — a condition that is read and detected as a false signal. In strong events, the entire surface may become stark white, generating noise that makes almost everything invisible.

Solar energetic particles do not generally affect humans and aboveground systems, except the passengers aboard aircraft and other limited cases, and people probably need not be overly concerned about such particles. Outer space, however, always entails issues regarding the environment of space energetic particles. As such, being careful about the space environment is one process that cannot be avoided to ensure reliability in outer space systems, and the advancement of electronics equipment mounted in recent years raises concerns about such systems being easily affected. The effects of the space environment on satellites entail various mechanisms and are difficult to describe in a uniform manner. In this paper, the author briefly describes the main effects of solar energetic particles and plasma.

2 Energetic particles around the Sun and the Earth

Outer space is filled with high-energy energetic particles stemming from the electromagnetic interactions of plasma in the sun, interplanetary space, planetary magnetosphere and other regions, and from supernova explosions and other phenomena occurring outside the solar system. In addition to those generated and accelerated as the result of a solar flare (also known as solar cosmic rays, solar high-energy particles, or otherwise), other particles accelerated and captured in particular regions in the earth's magnetosphere (otherwise known as the Van Allen Belt or radiation belt), and resulting from supernova explosions and other phenomena occurring in outer space beyond the solar system are called solar flare particles, captured particles, and galactic cosmic rays, respectively. These cannot be considered physically exact classifications, but these terms are often used on a practical level for satellite design. These classifications are thus used here. (Note that many researchers specializing in the sun and space environments feel particularly awkward about the term "solar flare particles.")

Solar flare particles are generated and accelerated by a solar flare and CME that accompanies it. Regarding the generation and acceleration mechanisms, previous observations and theoretic studies have proposed various hypotheses. Still, this can be considered an issue with much remaining to be elucidated. Roughly divided, two major concepts have been discussed: one that holds that particles are accelerated in the solar atmosphere where a solar flare is generated, and one that holds that generation and acceleration are due to particle acceleration in shock waves (interplanetary shocks) generated by CME that accompanies a solar flare. In recent years, a hybrid model intended to describe observation by combining both concepts has been the subject of active discussions. The author personally believes that the issue of solar flare particles is not a matter of selecting either concept, but that it is important to comprehensively combine various factors as in a hybrid model, and discuss the issue including the propagation process up through regions close to the earth.

So-called captured particles are thus named given their existence in a state where these particles are captured in the earth's magnetosphere. Two processes (the generation and acceleration mechanisms) have been conceived up to the time when the particles are captured. One process is considered to be the result of particles entering the earth's magnetic field from outer space, including those from solar flares. The other involves acceleration due to a turbulence phenomenon such as an auroral storm or MHD waves in the earth's magnetosphere. The generation and acceleration mechanisms require further study, even though the subject of much wider discussion than solar flare particles.

Galactic cosmic rays are high-energy particles entering from outside the solar system, and supernova explosions are considered one source of those particles. Considering that these particles include some having extremely high energy and entail a high percentage of heavy particles, the action of each particle is strong but the total quantity of particles is small.

Normally, when considering the effects of energetic particles on a space system, we often discuss and evaluate the issues as divided into the three categories stated above. A standard engineering model is available for evaluating energetic particles. It can be used to perform mechanical calculations, but appropriate design also requires an understanding of the origin and characteristics of such particles. For that reason, a collection of knowledge and experience concerning the space environment necessary for satellite design has been established as a standard for all of Europe (ECSS standard).

3 Malfunction of semiconductor devices due to energetic particles

Artificial satellites use computers, memory, gate arrays, and other semiconductor integrated circuits for various uses. No artificial satellite can therefore function without semiconductor devices. However, highly integrated semiconductor devices malfunction due to the entry of energetic particles, and this can be considered an issue that always accompanies satellite development. For example, the position control system of a satellite uses data from position sensors as input, processes that data onboard by using its dedicated computer, and properly operates the actuator for position control (such as the reaction wheel and momentum wheel), thereby maintaining position. As it were, a system subjected to closed-loop control by using a system consisting of semiconductor devices (including sensors) can be considered the satellite's position control system. Various problems occur when the positioning of a satellite cannot be correctly controlled, such as cases of insufficient communications or the difficulty in properly conducting an observation mission. Moreover, if the solar cell paddles can no longer be oriented toward the sun, the power generated will decline, resulting in a fatal situation for the satellite.

The computer mounted onboard a satellite is equipped with vast amounts of memory. Memory functions correctly when, in addition to what is called data, computer programs, parameters, and other facilities used to control memory execution are properly maintained and updated. However, charged high-energy energetic particles entering that area will adversely affect the charge status of semiconductor devices. In other words, as high-energy particles enter, the materials and interactions of such devices will undergo a certain percentage of charge coming from outside (Fig. 2). This will entail a sudden memory error and cause various malfunctions in the satellite system, such as computer hang-up. Moreover, a charge generated will cause continuity in parts that should be insulated and may result in a phenomenon where current continues to flow (latch-up). If burning occurs due to this continuous flow of current, permanent breakdown may result. Therefore, devices that do not readily cause latch-up should be selected. Moreover, in power MOSFET devices, burnout (i.e., burning due to energization caused by the generation of charged particles) and gate rupture phenomena as disorders stemming from energetic particles may also occur.

Changes in properties due to the ongoing effects of energetic particles over long years are sometimes collectively referred to as the "total ionizing dose effects." Typical examples would be the deteriorating characteristics of CMOS devices and the deterioration of solar cell paddles. Figure 3 [1] shows some irradiation results of gamma-rays generated by a cobalt-60 source on a high-performance CPU

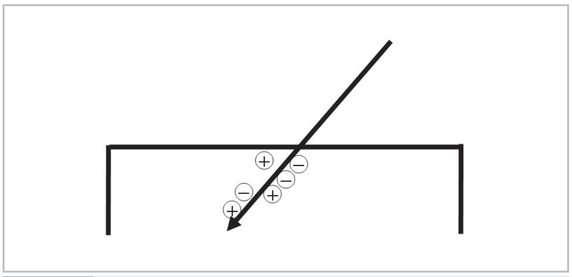

Fig.2 *Charges in a semiconductor device due to the entry of high-energy particles*

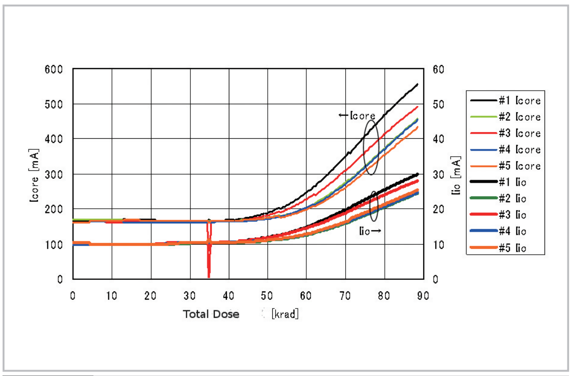

Fig.3 *Example of a test of irradiating energetic particles on a CPU*

With a rise in the amount of energetic particles irradiated on the CPU, current consumption rises.

used for civic purposes. The x-axis represents the total amount of irradiation (equivalent to irradiation time), while the y-axis represents the current flowing through the CPU. As the amount of irradiation rises, the amount of current also rises. Learning the amount of irradiation upon reaching the rated maximum current of a device allows us to obtain a guide for determining the total amount of irradiation that the device can withstand.

This test was conducted to consider the possible use of the civic CPU as a data processor mounted on a satellite. CPUs intended for use in space are normally extremely expensive and often fail to be approved for space purposes unless endorsed by flight data results. This entails structural problems where the latest devices cannot be easily applied to outer space. In other words, in case of a sufficient flight history, the CPUs concerned are likely to be obsolete. Semiconductor devices that undergo rapid advances encounter serious problems. Despite those concerns, if a high-performance civic device is to be used, then one must judge whether to use it by conducting tests to check its resistance to energetic particles, such as a cobalt-60 irradiation test and heavy particle rays irradiation test as shown in Fig. 4.

To examine the resistance of a certain CPU device to energetic particles, the author once conducted a test where a comparatively low-energy proton ray of about 10 MeV was irradiated. At that time, under normal conditions, a cable is extended to another room where the measuring system and data collection system are arranged. However, a PC was brought to a location only a short distance away from the irradiation line for data collection, and the author had a difficult time taking measurements because the PC hung up many times. Although the value 10 MeV is a region with relatively low energy, the author has experienced the occurrence of hang-up with a certain probability, and consequently felt the undesired effects of energetic particles.

4 Electric charging of satellites and deterioration of members by energetic particles

The outer space surrounding an artificial satellite is filled with plasma. Due partly to the action of electrons (Fig. 5) generated by the photoelectric effect of sunlight, the surface of the satellite is in a state ready to be electrically charged (surface electric charging). Moreover, comparatively high-energy particles in the radiation belt pass through the surface of the satellite to reach its deepest areas. These particles then apply an electric charge to the components and harnesses within the satellite, and may be discharged for some kind of charge, thereby posing a hazard to the satellite. To prevent such things from occurring, various ingenious ideas are adopted in the electrical

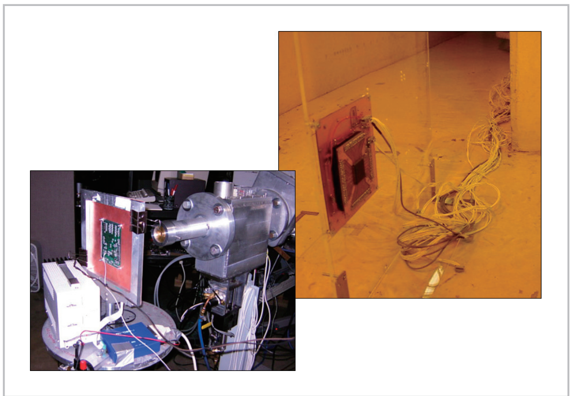

Fig.4 *Status of a test where energetic particles are irradiated on a CPU*

Irradiation of heavy particle rays (left) and irradiation of cobalt-60 (right)

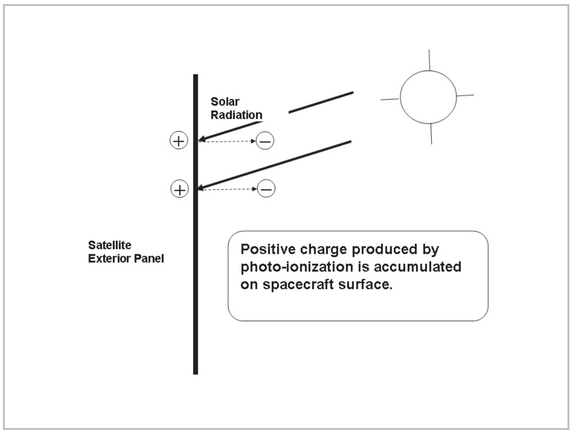

Fig.5 *Electric charging of satellite surfaces due to the photoelectric effect of sunlight*

design of a satellite, but electrical charging and the discharge thereof are probably responsible for more malfunctions occurring.

Energetic particles may change the material characteristics of the members of a satellite. Examples include changes in the refraction index and browning (coloring) of the vitreous materials of optical equipment. As highly energized energetic particles enter, their high momentum may cause certain changes in the atomic structure of the surrounding materials. This is known as displacement damage and, in the case of optical vitreous materials, these particles can cause such physical properties as the refraction index to deteriorate (change). The temperature dependence of the refraction index is one characteristic that cannot be ignored in ensuring the performance of high-precision optical systems. Therefore, the possibility of changes in those systems in outer space over the years must be carefully and properly considered.

Since vitreous materials include lead oxide, such materials are also known to deteriorate in terms of transmittivity due to the irradiation of energetic particles. Figure 6 shows how various materials change as exposed to energetic particles with human intervention. The five samples shown in the figure were exposed to the same level of energetic particles and significant changes in the status of coloring due to the different types of vitreous materials can be seen.

Fig.6 *Changes in transmittivity after an irradiation test with energetic particles due to differences in vitreous materials*

Deterioration and changes in vitreous materials used in optical equipment due to energetic particles may affect ultimate performance. For that reason, they may become a great issue in design particularly for telescopes mounted in satellites whose mission is to observe astral bodies and the earth, along with star trackers (i.e., the bus equipment of satellites), earth sensors, and other optical equipment. As the result of optical design where designs are adopted based on vitreous materials lacking sufficient information about their resistance to energetic particles, a test using energetic particles must be conducted by a specific organization on its own. Quartz is apparently resistant to energetic particles, while flint and other vitreous materials with high refraction indexes tend not to be resistant to energetic particles.

Solar energetic particles and space energetic particles also significantly deteriorate solar cell paddles. Great care is therefore exercised in the design and operation of power supply systems as well. However, an appropriate model must be used to prevent an excessive evaluation of the effects of such particles. Regarding the method of evaluating the deterioration of solar cell paddles due to energetic particles, Japan previously proposed a method based on data obtained from space environmental monitoring equipment mounted on a meteorological satellite, and ISO is now in the process of deliberation to make that method an international design standard [“Methods for Calculation of Solar Cell Degradation due to Energetic Particles (ISO Draft)].

5 Conclusion

As electronics parts become more advanced along with a rising degree of integration, such parts generally decline in resistance to energetic particles. In addition, more devices now operate at low voltages to reduce power consumption, and this raises another concern from the standpoint of resistance to energetic particles. Many FPGAs and other parts having many gates are extremely fragile to energetic particles. In order to realize implementations as advanced as aboveground technologies in outer space, understanding the effects of energetic particles becomes increasingly important. At present, a standard effort is under way to make designs with sufficient likelihood while referring to engineering models. However, in order to enhance the degree of freedom in design and reduce the cost of developing satellites and related equipment, technologies must be developed for flexibly changing the operation status while flexibly referring to observation data about the space environment in real time.

References

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***AKIOKA Maki**, Dr. Sci.*

Senior Researcher, Project Promotion Office, New Generation Network Research Center

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