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Single-event upset in geostationary transfer orbit during solar-activity maximum period measured by the Tsubasa satellite

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Abstract

This paper reports single-event upset (SEU) occurrence related to the space radiation environment in geostationary transfer orbit during solar-activity maximum period measured by the Tsubasa satellite. Most SEUs are measured in the inner radiation belt, indicating that they are mainly caused by trapped protons. Thus, the spatial distribution and the temporal variation of the SEU count correlate well with those of trapped protons. The peak SEU rate appears around $L = 1.4$. The transition point from SEUs caused by trapped protons to those caused by galactic cosmic rays is around $L = 2.6$. During the experiment period, increased SEU count was sometimes detected due to solar and geomagnetic events outside the inner radiation belt.

Keywords: Space radiation environment; Single-event upset; Geostationary transfer orbit

1. Introduction

A single-event upset (SEU) is a type of spacecraft anomalies that is caused by a single high-energy particle in semiconductor electronic devices (e.g., Robinson, 1989). Recently, SEUs are not considered to lead to serious situations in spacecraft system because a SEU is a bit upset in CPUs and/or memories that induces software errors, and can be restored by automatic correction, software re-upload, or power reset. However, SEUs still require attention in both the development and the operation phase of spacecraft since high-energy particles often increase rapidly due to solar and geomagnetic events, or a single high-energy particle often causes multiple-bit upsets (e.g., Swift, 2000). In these cases, simultaneous SEUs may lead to serious situations in spacecraft system.

Thus, it is still important to monitor SEUs over wide areas in the geomagnetosphere in order to understand the characteristics of SEU occurrence and its relation to the space radiation environment. A few experiments have been conducted over wide areas in the geomagnetosphere such as in geostationary transfer orbit (GTO) (Violet and Frederickson, 1993). The Tsubasa satellite was specifically developed for researching the effects of the space radiation environment on spacecraft system, and was operated in GTO during solar-activity maximum period. This paper reports SEU occurrence related to the space radiation environment measured by the Tsubasa satellite.

2. Measurement

The objective of the Tsubasa satellite (Mission Demonstration Test Satellite-1: MDS-1) developed by the Japan Aerospace Exploration Agency (JAXA) is to verify the functions of commercial parts and the new technologies of bus-system components in space. The Tsubasa satellite was launched into GTO, where on board experiments were conducted in the more severe radiation environment of GTO rather than in geostationary orbit (GEO) or low earth orbit (LEO). The Tsubasa satellite had been operated from February 2002 until September 2003, corresponding

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Table 1
The major characteristics of the Tsubasa satellite

Launch date	4 February 2002
Experiment period	12 February 2002 to 24 September 2003
Dimension	1.2 × 1.2 × 1.5 m
Weight	480 kg
Orbit perigee	500 km
Orbit apogee	36,000 km
Orbit inclination	28.5°
Orbit period	10 h 35 min
Attitude control	Spin stabilized 5 rpm

to solar-activity maximum period. In this paper, the data set obtained from March 2002 to May 2003 is used in analyses because, during this period, the operation and the data collection were stable. Table 1 lists the major characteristics of the Tsubasa satellite.

The Space Environment Data Acquisition Equipment (SEDA) is on board the Tsubasa satellite to observe the space radiation environment and to measure the spacecraft anomalies due to them (Koshiishi et al., 2002). The Standard Dose Monitor (SDOM) of the SEDA observes protons with energy range of 0.9–210 MeV in 12 bins in every 8 s (Green et al., 2004). The Heavy Ion Telescope (HIT) of the SEDA observes heavy ions (helium–iron) with energy range of 18–179 MeV/nucleon (Matsumoto et al., 2005).

The Single-event Upset Monitor (SUM) of the SEDA measures SEUs in the test samples of two commercial 64-Mbit DRAMs in every 128 s. The SUM writes a test data into all address of the test samples, waits for 64 s, reads the contents from all address, and compares the contents with the test data. The SUM conducts the same procedure again in next 64 s. If the SUM finds the difference between the contents and the test data in the first 64 s, and does not find the difference at the same address in the second 64 s, the difference is classified to a SEU. Otherwise, if the SUM finds the difference in both successive 64 s, the difference is regarded to be owing to hardware errors. The hex-byte data of “55” and “AA” are used as a test data one after another.

3. Analysis and discussion

The most effective energy range to cause SEUs in the devices depends on the effective shield thickness of the spacecraft body and the materials around the devices. The proton data obtained by the SDOM is compared with the SEU data obtained by the SUM, indicating that the spatial distribution of protons with energy range exceeding several tens MeV is consistent well with that of the SEU count. This result suggests that the equivalent aluminum shield thickness around the test samples of the SUM is about 1 cm (e.g., Holmes-Siedle and Adams, 1993).

Fig. 1 illustrates the L–t diagram of the proton flux with energy range of 21–43 MeV obtained by the SDOM. Trapped protons in this energy range are observed mostly in the L-shell below $L = 2$. Precipitations of protons were also observed especially on 21 April 2002 and 24 August 2002, which were due to solar flares (see Solar-Geophysical Data) and halo-type coronal mass ejections (see SOHO LASCO CME CATALOG) occurring on the same days. Fig. 2 depicts the magnetic-local-time (MLT) distribution of the proton flux. In the inner radiation belt, trapped protons distribute almost uniformly against MLT. An asymmetry that appears in peak-flux range is mostly due to the relation between the orbit of the Tsubasa satellite and

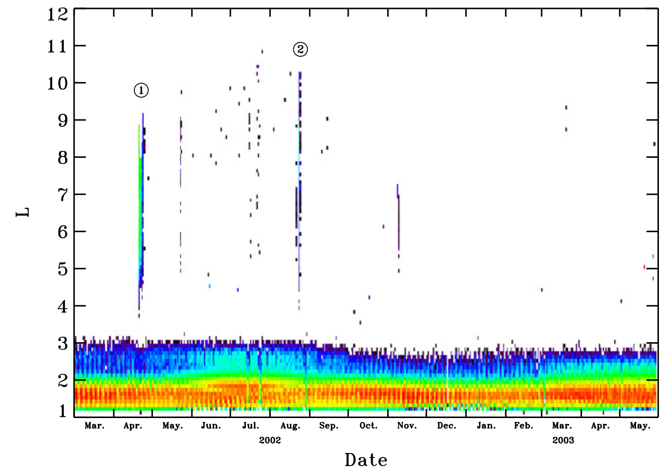

Fig. 1. The L–t diagram of the proton flux with energy range of 21–43 MeV from March 2002 to May 2003. Precipitations of protons observed on 21 April 2002 and 24 August 2002 due to solar flares and halo-type coronal mass ejections are marked with “1” and “2”, respectively.

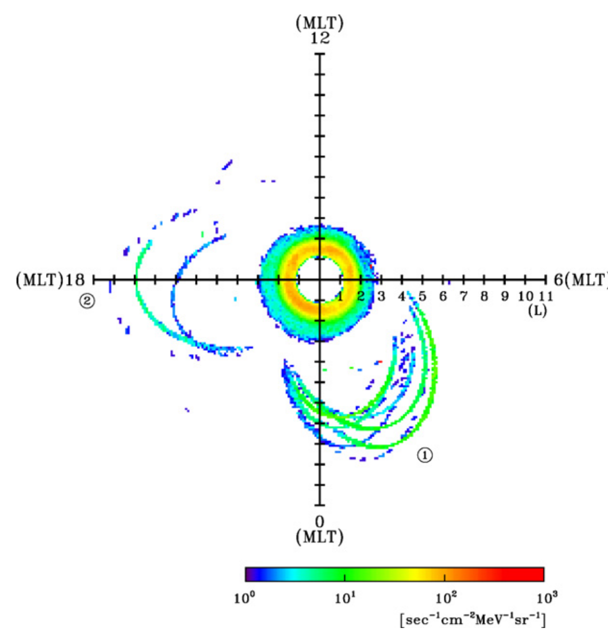

Fig. 2. The magnetic-local-time (MLT) distribution of the proton flux with energy range of 21–43 MeV from March 2002 to May 2003. Each value is the largest flux at each location during the above period. Enhanced flux between 0 h and 6 h (MLT) and around 18 h (MLT) corresponding to precipitations of protons observed on 21 April 2002 and 24 August 2002 are marked with “1” and “2”, respectively.

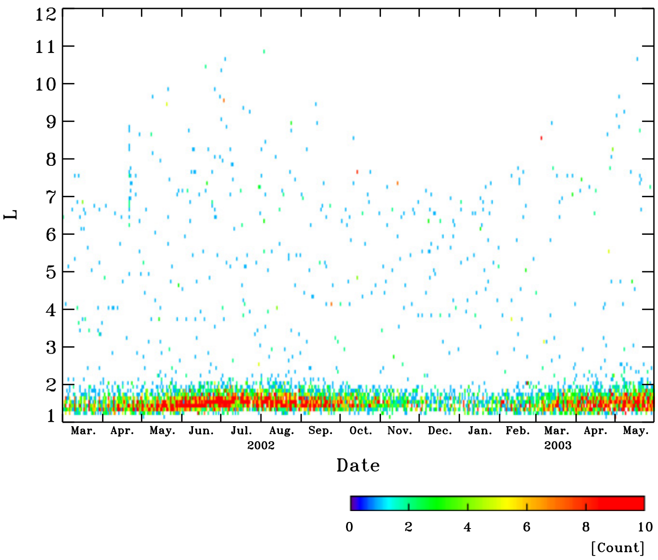

Fig. 3. The L–t diagram of the single-event upset (SEU) count detected in two 64-Mbit DRAMs from March 2002 to May 2003.

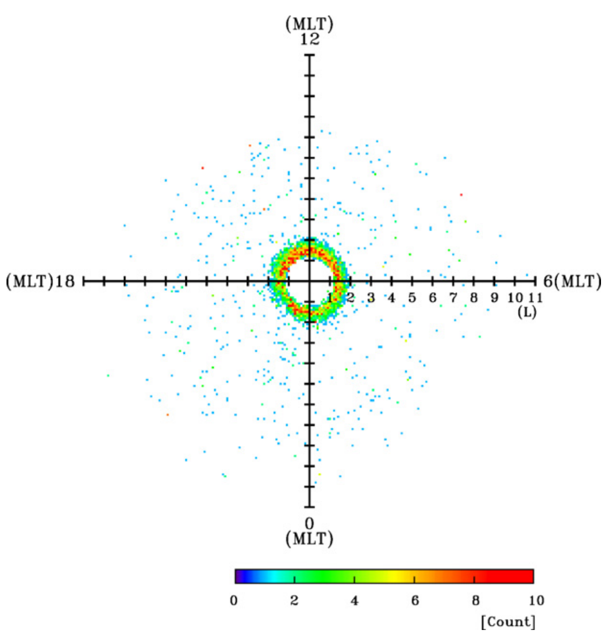

Fig. 4. The magnetic-local-time (MLT) distribution of the single-event upset (SEU) count detected in two 64-Mbit DRAMs from March 2002 to May 2003. Each value is the largest count at each location during the above period.

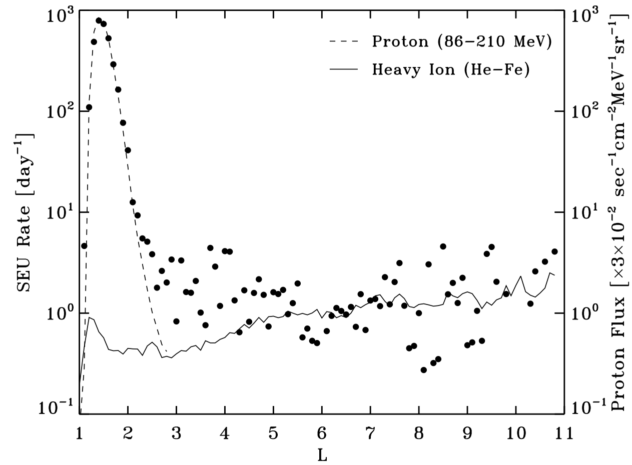

Fig. 5. The single-event upset (SEU) rate as a function of L in 0.1 step detected in two 64-Mbit DRAMs averaged from March 2002 to May 2003. The proton flux with energy range of 86–210 MeV and the heavy ion count (helium–iron) averaged through the above period are also plotted.

the spatial distribution of trapped protons in the inner radiation belt, which is seen as a seasonal effect in Fig. 1. Outside the inner radiation belt, two groups of enhanced proton flux were obtained along the orbit of the Tsubasa satellite, which corresponded to precipitations of protons in Fig. 1. In these cases, the proton radiation environment becomes severe for a few orbit periods in GTO even outside the inner radiation belt.

The L–t diagram of the SEU count obtained by the SUM is illustrated in Fig. 3. Most SEUs are measured in the L-shell below $L = 2$, indicating that they are mainly caused by trapped protons. The temporal variation of the SEU count correlates well with that of trapped protons in Fig. 1. SEUs measured outside the inner radiation belt are mainly caused by galactic cosmic rays (GCRs). The SEU count outside the inner radiation belt is almost constant with time, except for increased SEU count associated with solar and geomagnetic events especially on 21 April 2002, since the flux of GCRs is considered to be almost constant during such a short experiment period as compared with an 11-year solar cycle period. The MLT distribution of the SEU count is depicted in Fig. 4. While the MLT distribution outside the inner radiation belt is almost uniform, the MLT distribution in the inner radiation belt shows an asymmetry in peak-count range, which follows the asymmetry of the proton flux seen in Fig. 2.

Fig. 5 plots the SEU rate as a function of L in 0.1 step obtained by the SUM overlaid with the proton flux with energy range of 86–210 MeV obtained by the SDOM and the heavy ion count (helium–iron) obtained by the HIT averaged through the experiment period. The peak SEU rate appears around $L = 1.4$. The transition point from SEUs caused by trapped protons to those caused by GCRs is around $L = 2.6$. Outside this point, the SEU rate shows a slight increase with L as well as the heavy ion count, which is considered to be due to decrease of geomagnetic cut-off effects. These results are in good agreement with the other measurement and the model calculation (CREME 96) (Bashkirov et al., 1999), though these results depend on the effective shield thickness. A few solar and geomagnetic events raised the SEU count outside the inner radiation belt as shown in Fig. 3, which had little influence on the averaged SEU rate.

4. Summary

The SEDA on board the Tsubasa satellite measured SEUs related to the space radiation environment in GTO during solar-activity maximum period. Most SEUs are measured in the inner radiation belt, indicating that they are mainly caused by trapped protons. Thus, the spatial distribution and the temporal variation of the SEU count correlate well with those of trapped protons. The peak SEU rate appears around $L = 1.4$. The transition point from SEUs caused by trapped protons to those by GCRs is around $L = 2.6$. During the experiment period, increased SEU count was sometimes detected due to solar and geomagnetic events outside the inner radiation belt.

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