On-orbit Performance Analysis on Solar Array Paddle of X-ray Astronomy Satellite "Suzaku"

Takanobu Shimada[*1], Hiroyuki Toyota[1], Akio Kukita[1],
Kazuyuki HIrose[1], Yoshitomo Maeda[1], and Kazuhisa Mitsuda[1]
1 Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA),
3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa 252-5210, Japan
*Email: shimada.takanobu@jaxa.jp
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Abstract

This paper presents the analysis results for the on-orbit performance of a solar array paddle of the X-ray astronomy satellite *Suzaku*. The current generated by the solar array was confirmed to be gradually but continuously decreasing since the middle of 2011. We estimated the degradation of the output to simulate the on-orbit environment according to the JPL prediction method. The analysis results indicated that greater on-orbit degradation of the solar cell occurred compared to the predicted performance degradation under the space environment when *Suzaku* was exposed to the orbit. We determined that the difference in the on-orbit data and analysis results could be attributed to an increase in cell temperature or radiation degradation due to solar flares.

1. Introduction

Suzaku, formerly known as ASTRO-EII, is an X-ray astronomy satellite developed by the Japan Aerospace Exploration Agency (JAXA) and has been successfully making observations since its launch in July 2005. However, the current generated by its solar array was confirmed to be gradually but continuously decreasing since the middle of 2011. Consequently, we estimated the degradation of the solar array output to simulate the on-orbit environment according to the JPL prediction method. The analysis results indicated that on-orbit degradation of the solar cell was greater than that of the predicted performance in a space environment. In this paper, we discuss the on-orbit performance of the solar array paddle for *Suzaku*.

2. Mission Overview and Solar Array Paddle

Suzaku is the fifth Japanese X-ray astronomy satellite and observes a wide variety of X-ray sources; it has a higher energy resolution and higher sensitivity than other previous satellites over a wide range from soft X-rays to gamma rays (0.4–600 keV) [1]. *Suzaku* is an international collaboration between the United States and Japan and was launched on July 10, 2005, by an M-V rocket.

Figure 1 shows a schematic diagram of *Suzaku*. The body consists of eight side panels with solar array paddles and five X-ray telescopes on an extensible optical bench; it has dimensions of approximately 6.5 m × 5.4 m × 1.9 m when deployed in orbit configuration. The total mass of the satellite is approximately 1700 kg; this includes the scientific observation instruments, which have a mass of 950 kg. After launch, the satellite cruised to an approximately circular orbit around Earth with an inclination of 31°, periapsis altitude of 570 km, and orbital period of approximately 96 min. *Suzaku* has continued to observe beyond the mission duration of 3 years.

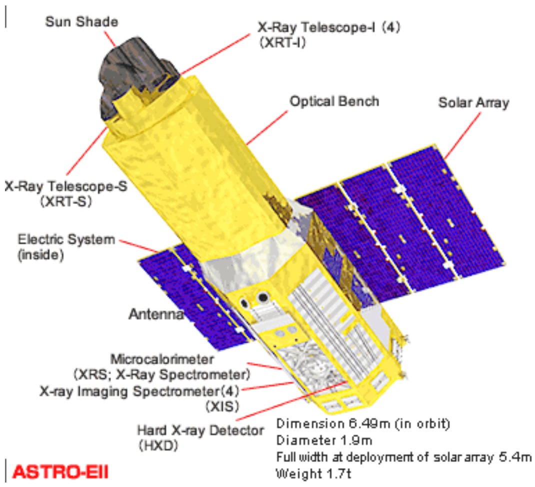

Fig. 1. Schematic drawing of *Suzaku*

Suzaku is equipped with two wings of solar array paddles (SAP) mounted next to each +Y directional side panel. The solar irradiance in the orbit ranges from 0.87 to 1 sun because the sun angle is up to +/-25° perpendicular to the sun normal due to the scientific observation. The estimated temperature of the solar panels reaches up to 73 °C.

We used high-efficiency silicon (HES) solar cells (Sharp Corp.) with an efficiency of 16.7% at the beginning of life (BOL); these cells qualify as NASDA-QTS-1013. The HES cells used for *Suzaku* are 100 µm thick, and the base material has a resistivity of 2 Ω cm. The solar array has 26 solar cell strings consisting of 132 cells in series and four strings consisting of 131 cells in series. The minimum power requirement at the end of life (EOL) (3 years) was 1530 W. The SAP operating point on the I–V curve was constantly controlled at 51.5 V of the interface voltage during sunshine periods because shunt dissipators were adopted as an unregulated 50 V bus power control method.

3. On-orbit Status

Figure 2 shows the telemetry of status transition for the *Suzaku* electrical power subsystem after launch. The current generated by the SAP (SAP I is indicated in Fig. 2) was calculated from the sum of the input current to power control unit (PCU in I) and the shunt current because the onboard SAP generated current was not directly monitored by telemetry.

Suzaku has been successfully operating since its launch in July 2005. However, SAP I was confirmed to be gradually but continuously decreasing, as shown in Fig. 2, since the middle of 2011. No sudden decline in SAP I due to string open failure was observed by the telemetry data during this time. Consequently, the satellite function of the under voltage controller (UVC) to protect the onboard battery was activated on January 24, 2011. This is the reason for the sharp decline in the battery voltage (BAT V) in Fig. 2; it caused a decrease in the output current of the power control unit (PCU out I) to lower the load power. To accommodate this deterioration in SAP-generated power, *Suzaku* has been limited to operating at a solar incidence angle range from 25° to 20°, and the battery charging voltage level has been raised.

The telemetry of SAP I and SAP temperature (SAP T) periodically shows a seasonal change—i.e., a slight increase in winter and a slight decrease in summer—due to the change in solar intensity caused by the Earth's orbit around the Sun. Shorter-term variations seen in these telemetries are assumed to be changes in the sun incidence angle to the solar array.

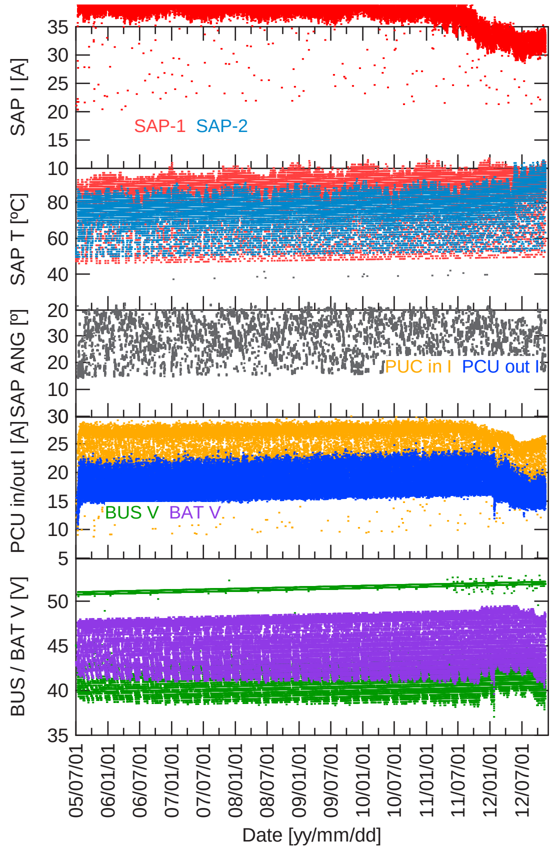

Fig. 2. Telemetry of on-board status for the *Suzaku* electrical power subsystem since the launch

The temperature of SAP-1 is around 10 °C higher than that of SAP-2 because the onboard temperature sensor is on the non-cell side of the inner panel, close to the satellite body, of SAP-1 while it is on the outer panel of SAP-2. Although the increase in temperature of SAP-2 has been observed since the middle of 2012, a definitive cause for this phenomenon has not been identified so far. The power generated by the SAP has been presumed to be reduced due to the increase in SAP temperature. However, the occasions when both occurred do not correspond. Therefore, we decided to verify the *Suzaku* solar array degradation using the analysis model described below, and we discuss the results in the following section.

4. Analysis Results and Discussion

4.1 Analysis Model

We estimated the degradation of the solar array output to simulate the on-orbit radiation environment according to the JPL prediction method in the *Solar Cell Radiation Handbook* using the relative damage coefficient (RDC) obtained in ground tests [2]. Figure 3 shows the calculated integral fluence spectra of trapped protons and electrons derived from the *Suzaku* orbit and the elapsed year after launch using AP-8 and AE-8 trapped particle models. To obtain the equivalent 1-MeV electron fluence to the environment, the RDC of the HES cell was applied. To consider the shielding effects, a 100-μm-thick coverglass on the cell side and infinite thickness on the non-cell side were assumed.

Table I. Analysis conditions to predict solar array output

Solar cell area	24 cm^2 (4 cm × 6 cm)
Coverglass thickness	100 μm
Array configuration	30 strings × 131 cells in series
Launch date	2005/07/10
Orbit	Semi-major axis: 6928.1 km Inclination: 31.0°
Radiation environment model	AP-8 (Solar activity: min) AE-8 (Solar activity: max)
Solar intensity	1307 W/m^2 (*summer solstice)
Sun incidence angle	25°
Cell temperature	73 °C
Conversion factor to 1 MeVe- from 10 MeVp+	3000 (Voc)/4350 (Isc)

Figure 4 indicates the remaining factor of the outputs of the HES solar cell as a function of 1-MeV electron fluence; this was used to predict the radiation degradation. Table I summarizes the analysis conditions used to calculate the *Suzaku* solar array output. Current–voltage (I–V) characteristics of the SAP were computed by means of a solar cell predictive equation proposed by Picciano [3] using the derived remaining factor and each temperature coefficient.

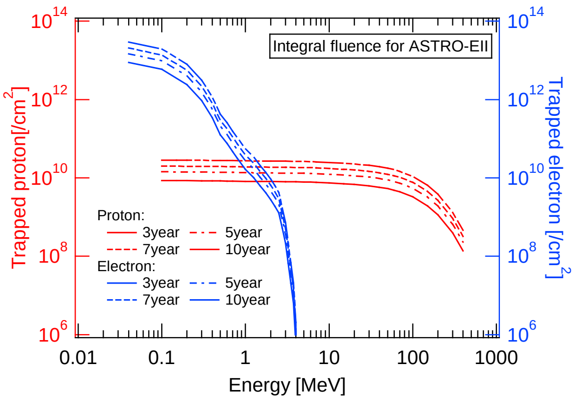

Fig. 3. Integral fluence spectra of trapped protons and electrons in the *Suzaku* orbital environment

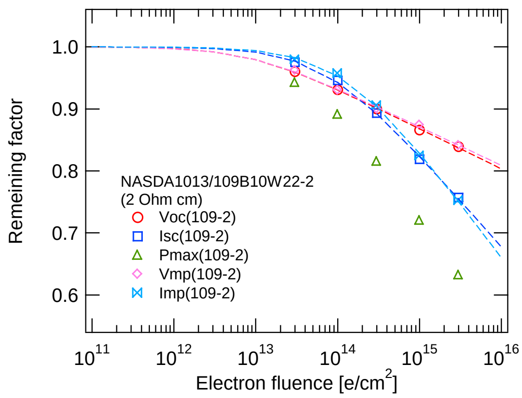

Fig. 4. Remaining factor of outputs of the HES solar cell as a function of 1-MeV electron fluence

4.2 On-orbit Performance Analysis

Table II summarizes the obtained equivalent fluences of a 1-MeV electron from each elapsed year and the predicted remaining factors of Voc, Vmp, Isc, and Imp of the HES cell. Figure 5 illustrates the calculated I–V characteristics based on these remaining factors and the conditions listed in Table I.

In Fig. 6, the calculated SAP generated current and power at an I/F voltage of 51.5 V are plotted together with the telemetry data. The results indicate that greater degradation of the solar cell proceeded 7 years after launch into orbit compared to the predicted performance degradation under the given space environment. Based on this difference, the deterioration in current generated by the solar array can be attributed to (a) the increase in SAP temperature according to the telemetry or (b) radiation degradation due to solar flares.

Table II Obtained equivalent fluence to 1-MeV protons and the remaining factors

1-MeV electron fluences [cm^{-2}] (Remaining factor)				
Elapsed year	3	5	7	10
Voc	1.82E+13 (0.969)	3.03E+13 (0.959)	4.24E+13 (0.951)	6.06E+13 (0.943)
Vmp	(0.969)	(0.959)	(0.952)	(0.944)
Imp	(0.989)	(0.983)	(0.977)	(0.968)
Isc	2.18E+13 (0.983)	3.63E+13 (0.973)	5.08E+13 (0.965)	7.26E+13 (0.954)

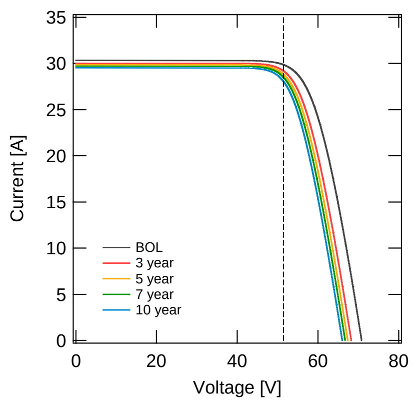

Fig. 5. Calculated I–V characteristics based on the *Suzaku* analysis conditions

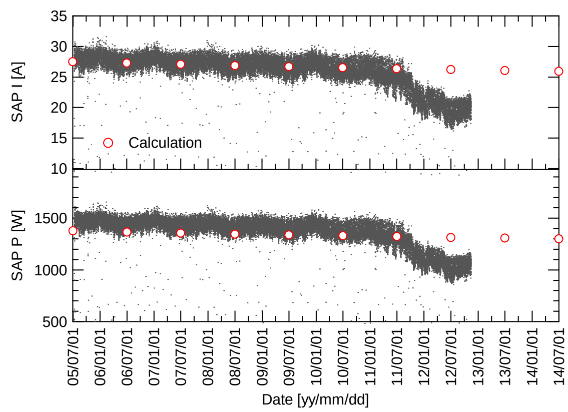

Fig. 6. Comparison of SAP generated current and power at 51.5 V between the on-orbit status and the calculated results

We predicted the variation in transition of the solar array output with cell temperature because the SAP-2 temperature telemetry indicated a sudden increase, although it occurred approximately 1 year after the SAP current began to decrease. Figure 7 illustrates the calculated I–V characteristics when the cell temperature changed to 73, 83, and 93 °C. In Fig. 8, the calculated SAP-generated current at 51.5 V is plotted together with the telemetry data.

The analysis results showed that the solar array operated at a lower current point in the constant voltage region of the I–V curve when the cell temperature was higher. As shown in Fig. 8, there was no temperature condition exactly consistent with the on-orbit transition. However, the deterioration in the current generated by the solar array can be explained by the assumption that a temperature rise of more than 20 °C occurred 6 years after launch. As a factor for the increase in SAP temperature, we are examining degradation in the cell adhesion to the substrate and in the thermo-optical properties of the CG and adhesive at that time.

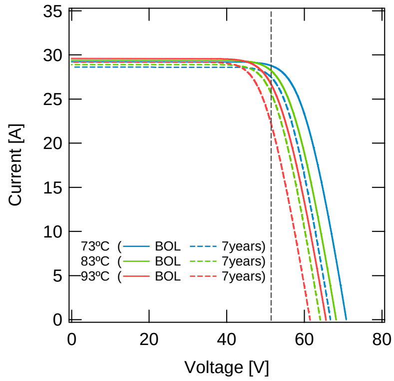

Fig. 7. Calculated I–V characteristics when the cell temperature was changed to 73, 83, and 93 °C

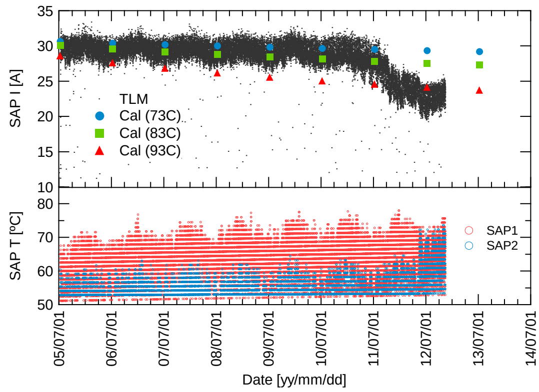

Fig. 8. Comparison of SAP-generated current between the on-orbit data and calculated temperature dependency

The slight decrease in SAP current after 2011 was predicted due to the relatively moderate radiation environment of the low Earth orbit (LEO) for the HES solar cell. However, for the radiation degradation to be a factor explaining the decrease in SAP current, a certain type of radiation exposure needs to have increased since July 2011 to accelerate the degradation of the cell. Therefore, we suspected the radiation degradation of the solar cell to be due to solar flares because solar activity is expected to reach its maximum from 2012 through 2013.

Figure 10 shows the number of occurrences of class-M and class-X solar flares and high-energy proton fluxes observed by the GOES-13 satellite in its geosynchronous orbit. Figure 10 shows that the proton fluxes increased with frequent occurrences of solar flares since 2011, which corresponded to when degradation of the *Suzaku* solar array performance was observed. In general, the Earth is protected from high-energy radiation coming from outer space by a magnetic shield, especially at low latitudes. On the other hand, radiation from the Sun is known to reach the ground at the South Atlantic Anomaly (SAA) because of magnetic anomalies. *Suzaku* cruises along the SAA. The calculation results are consistent with the on-orbit deterioration under the assumption that the solar cells were irradiated with an equivalent 1-MeV electron fluence of 3.0×10^{14} particles/cm^2 7 years after launch. At present, we are examining the equivalent fluence for its validity.

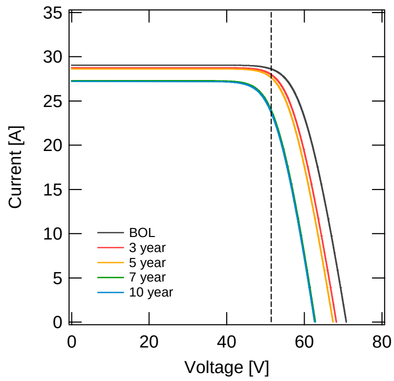

Fig. 9 Calculated I–V characteristics when the SAP was exposed to a solar flare 7 years after launch

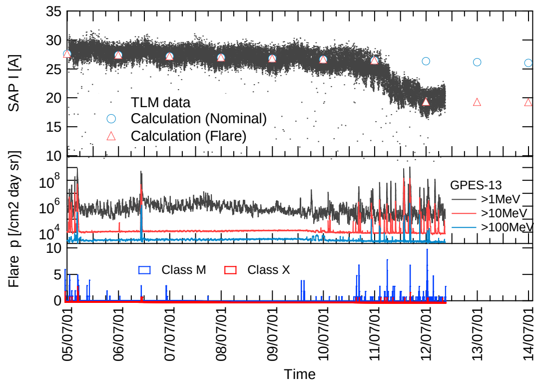

Figure 10 Comparison of SAP-generated current between on-orbit and calculated data upon exposure to a solar flare

5. Summary

Suzaku has been successfully making observations since its launch in July 2005. However, the current generated by the solar array was confirmed to be gradually but continuously decreasing since the middle of 2011. The SAP current deterioration could be attributed to the increase in SAP temperature as indicated by telemetry and radiation degradation due to solar flares. Based on analysis results, the deterioration can be explained under the assumption that the temperature rose up to around 93 °C 6 years after launch. On the other hand, the calculated results showed good consistency with the on-orbit deterioration under the assumption that the solar cells were irradiated with an equivalent 1-MeV electron fluence of 3.0×10^{14} particles/cm^2 7 years after launch. At present, we are examining the equivalent fluence for its validity.

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