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Anomaly Investigation using Telemetry Data of Horyu-2 for Single Event Latch-up

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SUMMARY

This paper describes anomaly investigation using telemetry data of Hoyu-2. Horyu-2 is a satellite launched to 680km sun-synchronous orbit in May 2012. The satellite suffered many anomalies, during which the satellite could not respond to commands. Based on Fault Tree Analysis and ground experiments using radio-isotope or an accelerator, the anomaly cause was inferred to be due to single event latch-up on one of two microprocessors. After each anomaly, the satellite recovered. In one occasion, the satellite kept data that proved the anomaly was indeed caused by SEL. Besides the two microprocessors, the satellite functions normally showing little degradation after 2.5 years in orbit.

KEY WORDS: Lean satellite; single event effect; anomaly investigation; on-orbit data

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1. Introduction

Launch of small-scale satellites developed by universities and companies has now become common. From 2010 to 2014, 25 satellites were launched by JAXA's H2A piggy-back program[1]. The small-scale satellite concept is changing from definition by size and weight to development concept to achieve low cost and fast delivery and the word "Lean satellite" discussed in ISO/CD 19683[2] has been introduced.

One of satellites launched by H2A was Horyu-2. Horyu-2 was developed by Kyushu Institute of Technology's satellite project team (composed mainly of students) and was launched on an H2A rocket on May 18th 2012. Unfortunately, Horyu-2 suffered an anomaly on June 5th 2012[3,4]. To confirm the problem, we conducted radiation tests using radio-isotope (^{252}Cf) and a large accelerator. As a result of the radiation testing, the problem occurring in Horyu-2 was suspected to be Single Event Latch-up (SEL) on onboard computer (OBC). It was a well-known fact that the SEL phenomenon occurs among micro satellite developers, but it is very rare that a near phenomenon was actually confirmed. This paper gives a supplemental inference about single event effect occurring on orbit. Horyu-2 has two microprocessor units (MPU-A and -B). MPU-A controls the satellite operation and processes sensor data. MPU-B transfers the data transferred from MPU-A to RF communication. Both processors were suspected to have suffered Single Event Latch-up (SEL). Once SEL occurs in MPUs, MPUs hang up and cannot process the data. Finally, the telemetry data from Horyu-2 was not updated and Horyu-2 could not receive commands from the Kyutech ground station. In addition to MPU hang-up, the power system suffered an over-current by the latch-up. During the latch-up, MPUs could not receive any signal from control PC and the response of MPUs is similar to the behavior observed in Horyu-2's anomaly. The over-current finally consumed the battery power. By fully consuming battery power, the hang-up on MPUs is dissolved and MPUs are reset.

Six weeks after we observed the first anomaly on June 5th, Horyu-2 recovered. However, Horyu-2 hung up again on Dec. 2nd 2012. In total, Horyu-2 suffered 9 times-SEE at least. In this paper, we will explain the detail of Horyu-2's anomaly by SEL and compare orbit data with experimental results. Satellite operation after the anomaly is also explained with mission component performance after 2 years.

2. System configuration of Horyu-2

Figure 1 shows the system configuration of Horyu-2. On-board computer (OBC) of Horyu-2 was composed by two micro-processors. The model number is H8 HD64F36057FZV. One micro-processor is MPU-A, which controls the whole satellite system and processes sensor data as voltage, current and temperature. The other micro-processor is MPU-B, which composes data from MPU-A and transfers data to a transmitter. MPU-COM was also used to make the call sign. The MPU-COM (PIC 16F876A) was orbit-proven and had a good reputation. Usage of the MPU-COM allows satellite developers to consist a robust system. In the worst case, Horyu-2 can send only call sign as long as the power system is alive. For the power control unit (PCU), bus voltage was 3.6V and battery capacity was 5710 mAh. PCU generates a regulated voltage with 3.3 and 5.0 V by using DC/DC converters. OBC was powered by 3.3 V. The CW data format of Horyu-2 is shown in Fig. 2. The data format of CW consisted of call sign part and telemetry data part. In the telemetry data part, the health data of Horyu-2 such as solar cell voltage, current, temperature and status of sub-system are included. Figure 3 shows the mechanical configuration of Horyu-2. The satellite size is 0.3 m cube and its weight is 7.1 kg. External panels were 1.5 mm thickness of Aluminum.

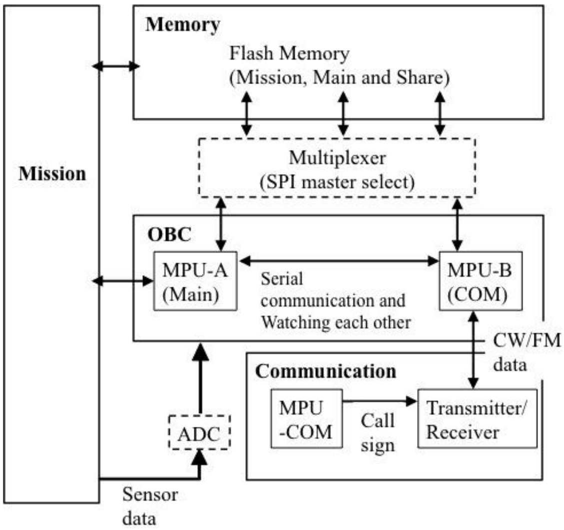

Fig. 1 System configuration of Horyu-2

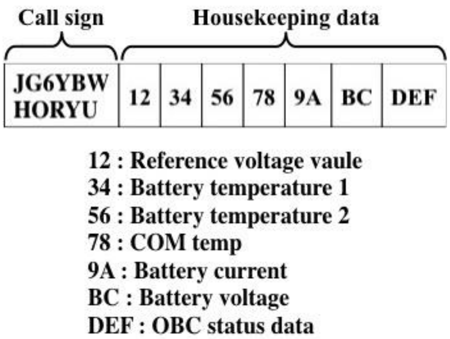

Fig. 2 CW data format of Horyu-2

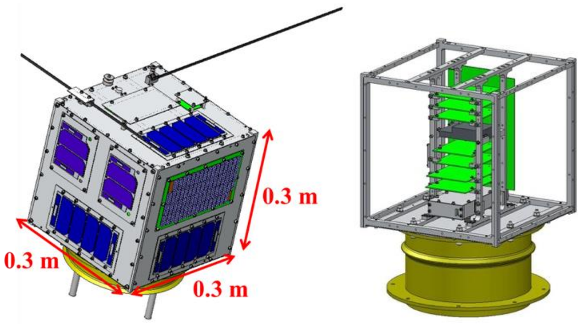

Fig. 3 Mechanical configuration of Horyu-2

3. Operation, anomaly and recovering profile

3.1. Operation profile

Horyu-2 was launched on 18th May 2012. The initial operation was good and smooth. The ground station at Kyutech could successfully receive signal from Horyu-2 from the first pass although the signal included a Doppler shift due to a high rotation speed. We could conduct satellite operation by receiving signals and sending commands for 3 weeks.

3.2. Anomaly and recovering profile

After the initial phase for 3 weeks, we were supposed to shift to mission phase of high voltage power generation. However, the first anomaly was observed on June 5th 2012. After the anomaly occurred, Horyu-2's telemetry data was fixed. Please see references 3 and 4 for details of anomaly investigation as FTA and experiment using a radiation facility. As results of the investigation, it was expected that SEL occurred in the micro-processors used by the OBC. We underestimated that such SEL would occur in the micro-processors and did not conduct a radiation test for SEL. A 3 mm thickness tungsten sheet was attached to the front surface of the microprocessor for SEL reduction, however this sheet was not attached to the other side of the microprocessor (i.e. the back side of the circuit board). As a result, it is considered that the measures were insufficient. Fortunately, Horyu-2 recovered on July 3rd 2012 and we could conduct the main mission[6,7] and take a picture of Earth. After approximately 5 months from recovery, Horyu-2 suffered the same anomaly and hung-up again. Horyu-2 was hung-up this time for approximately a year and a half. Table 1 shows the anomaly profile. Horyu-2 suffered in total 9 anomalies at this time. "Duration" in the table means the duration from the satellite resetting. There are 2 types of anomalies. For the case of MPU-A hang-up, the telemetry data part shown in Fig. 2 is fixed. MPU-A processes sensor data from mission part through analog to digital converter (ADC) and sends the processed data to the transmitter. If MPU-A hangs up, the sensor data cannot be updated. However, MPU-B is still alive and can compose data for transmitting with the data format. For the case of MPU-B hang-up, Horyu-2 sends only a call sign. Even if MPU-A is still alive, MPU-B cannot receive the processed data from MPU-A and cannot compose the data format. However, the satellite can at least send the call sign since MPU-COM built in the communication part has enough tolerance for space radiation. Each MPU usually monitors operation of other MPUs and sends a reset signal if each MPU detects an anomaly on another MPU. However, this reset system was not complete because of a kind of software reset but not hardware reset. For the next generation satellite[8] a hardware reset system, which shut downs the power supply from PCU to MUPs, will be adopted.

Moreover, anomalies can be classified as two cases according to order of anomaly occurring, case 1 from MPU-A to MPU-B or case 2 from MPU-B to MPU-A. For case 1, MPU-A cannot process sensor data and cannot save the data to Memory. For case 2, MPU-A can process sensor data and can save the data to Memory. The memory size is not so large and the satellite can store sensor data for only 2 weeks. This means that we can obtain the transient data for SEL current during anomaly occurrence if the satellite can recover within 2 weeks. This anomaly case corresponds to the anomaly on 2014/05/31. As of May 18, 2015, Horyu-2 hung up again and its CW data was fixed as "d1bebbfbb89e1fe2".

Table 1 Anomaly profile from June 6th 2012 to Jan. 30th 2017

Date	Event	Lifetime of MPU-A, days	Lifetime of MPU-B, days	Time to recoving from 2nd anomaly, days
2012/5/18	Horyu-2 was launched			
2012/6/5	Telemetry data fixed-->MPU-A hang-up	18	-	-
2012/6/30	Call sign only --> MPU-B hang-up	-	43	-
2012/7/3	Recovering			3
2012/12/2	Call sign only --> MPU-B hang-up	-	152	-
2014/5/31	Telemetry data fixed-->MPU-A hang-up	697	-	-
2014/6/1	Recovering			1
2014/6/12	Call sign only --> MPU-B hang-up	-	11	-
2014/11/22	Telemetry data fixed-->MPU-A hang-up	162	-	-
2014/11/23	Recovering			1
2014/11/24	Telemetry data fixed-->MPU-A hang-up	2	-	-
2014/12/12	Call sign only --> MPU-B hang-up	-	19	-
2014/12/21	Recovering			9
2015/3/19	Telemetry data fixed-->MPU-A hang-up	88	-	-
2016/7/1	Recovering			470
2016/7/4	Telemetry data fixed-->MPUA-A hang-up	3		
2016/11/18	Call sign only --> MPU-B hang-up		137	
2017/1/28	Recovering			71
2017/1/28	Sending command "Kill switch -1 on"			
2017/1/28	Sending command "Kill switch -2 on"			
2017/1/29	Receving CW			
2017/1/30	No CW			

3.3. Recovering scenario

Horyu-2 has recovered four times so far. The latch-up current was verified from experiment using ^{252}Cf and proton accelerator[3, 4, 5]. The flux of heavy ion emitted from ^{252}Cf was 1.2 to 6.2 1/cm^2/s. The energy of photon and flux were 65 MeV and 1.1 to 5 x10^7 1/cm^2/s, respectively. In the proton irradiation test, high energy conditions were selected to allow protons to penetrate the microprocessor package. The purpose of these test were to measure the latch current generated by SEL, not the simulation test of space environment. The measured latch-up current in the above experiment was approximately 0.2 A for each MPU. From the anomaly on 2014/05/31, we could obtain the current during latch-up. Immediately after recovering on 2014/06/01, satellite sensor data stored in the memory was downloaded from 2014/06/01. Figure 4 shows the latch-up current acquired on orbit. This latch-up current matches well with the current observed in ground experiments. At around 30 hours, the current value suddenly dropped to 0. This rapid dropping shows using up battery due to the latch-up and the satellite system reset at this time. After the dropping current, the current consumption of MPUs recovered to 50 mA for nominal operation.

The scenario for anomaly and recovering are as follows:

1. SEL occurs on MPU-A or B.
2. Increasing of current consumption due to latch-up
3. SEL occurs on other MPU
4. Increasing of current consumption again
5. Finally battery is completely consumed. MPUs are reset.
6. Recovering

Figure 5 shows the current consumption in the electrical power system (EPS) for nominal and anomaly operation. At Step 2, the EPS can feed enough power to overcome the latch-up current for MPU and also can feed a part of power to the battery. However, the power balance between providing and consuming is lost when SEL occurs on 2 MPUs at Step 3. Gradually, the battery voltage decreases. The EPS cannot provide the necessary power to drive OBC and the whole of satellite system is finally reset. There are some variations in the term to recover after the second SEL occurs. This seems to be the effect of satellite attitude. Horyu-2's rotation speed is so slow that its value cannot be acquired by the gyro sensor. Therefore, we expect that an attitude to minimize the output power of solar cells is maintained. Figure 6 shows the battery voltage profile before and after recovering. Horyu-2's battery voltage first drops at around 0.3 volts/hour and then gradually increases. This profile also supports the above scenario. The estimated state of charge at the recovering point was 3 to 10% and the voltage was too low to supply the power to components.

3.4. Probability of SEL

The probability of averaged lifetime on orbit can be calculated from Horyu-2's anomalies. Figure 7 shows a plot of duration for SELs that have occurred on Horyu-2. The probability of SEL occurrence obeys the well-known Poisson distribution[9]. This plot also obeys the Poisson distribution. The average lifetime can be estimated as 59 days.

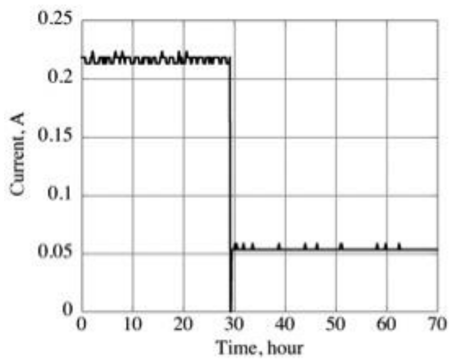

Fig. 4 Latch-up current acquired on orbit

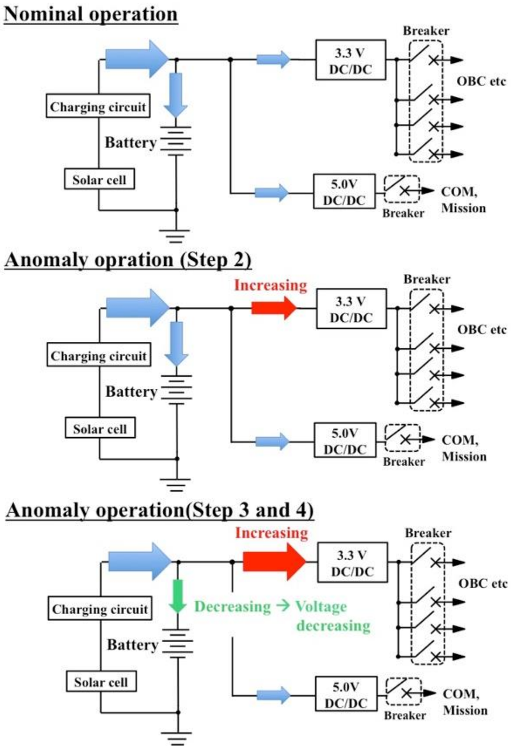

Fig. 5 **Nominal and anomaly operation of EPS**

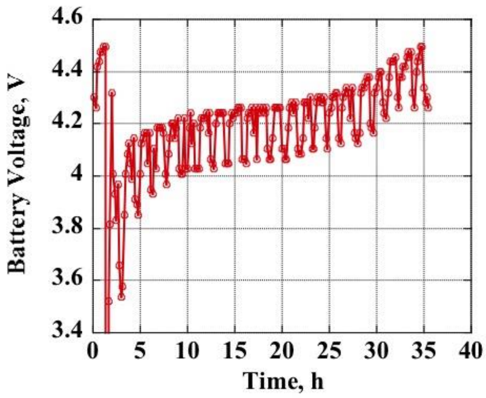

Fig. 6 **Battery voltage profile for recovery on 2014/6/1**

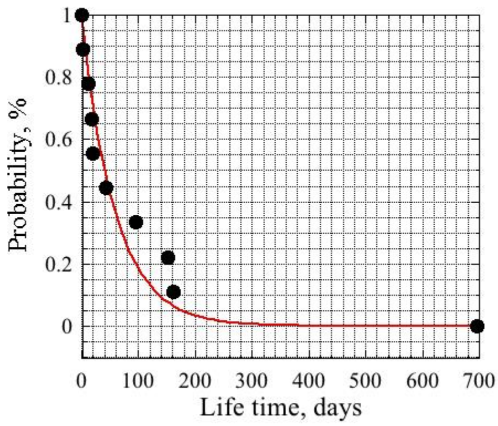

Fig. 7 **Probability distribution for SEL occurred on Horyu-2**

3.5. Operation of Horyu-2 after anomaly

Horyu-2 passes three or four times per day over the Kyutech ground station. Although operation after Horyu-2's hang-ups was reduced to one time per day, the operation of sending commands and receiving CW signal was checked every day. We could identify recovery partly thanks to many amateurs in the world. After the fourth recovery on 2014/12/21, many mission components were performed again. A result of high voltage power generation is shown in Fig. 8. High voltage generated by the array was the same as the previous result performed on July 2012. Figure 9 shows the total output power of solar cells initially and at latest. The solar cell mounted on Horyu-2 was a thin dual junction type without a cover-glass. By comparing initial and latest power, it can be seen that there is no difference. These results show the high voltage solar array and bus solar array have enough tolerance for two years service in PEO environment.

In addition to mission executing, a camera for earth observation was also checked. Figure 10 shows a photo taken over Bangladesh on Jan. 2015. The photo had a lot of lacking data due to defective errors in the ground station. However, the camera function has enough tolerance to survive for two years in space.

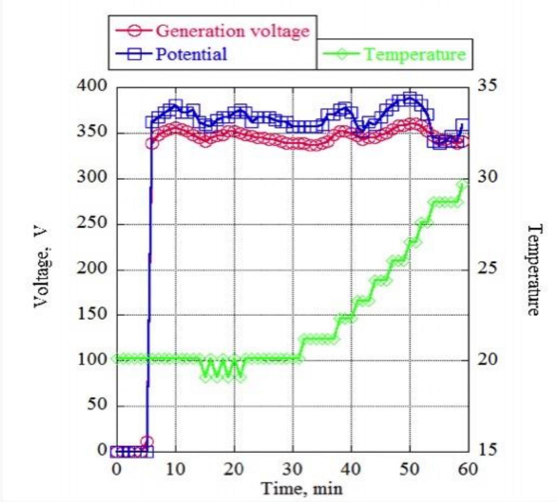

Fig. 8 High voltage power generation on Jan. 2015

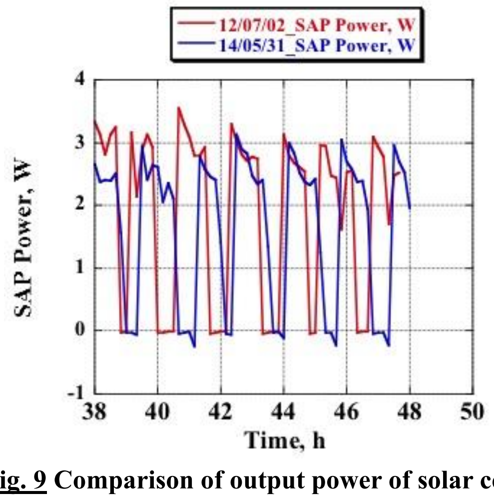

Fig. 9 Comparison of output power of solar cells

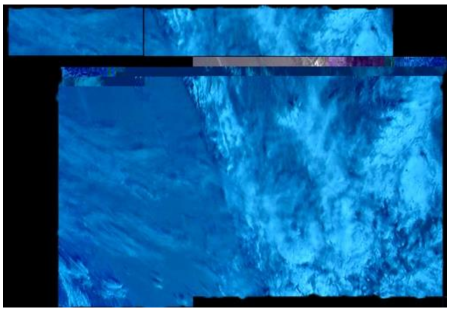

Fig. 10 Photo taken over Bangladesh on Jan. 2015

4. Discussion

For the project members, the design that allowed the satellite to send a call sign even if the OBC hangs-up was the most important. The project could track the satellite without giving up because the satellite kept sending a call sign. This is largely a result of a reliable COM system using ensured MPU. However, a radiation test should have been conducted and this anomaly could have been predicted before launch. A kind of software-reset system is not effective for such a SEL. The radiation testing is also important for determination of proper circuit breaker setting for an over current.

The majority of Lean satellite use COTS parts for the bus system. To achieve low cost and fast delivery, usage of COTS parts is essential. As a result, using COTS parts reduces the reliability of the satellite system. For worst cases such as Horyu-2's hang-ups, a reboot system similar to a personal computer by turning off the power will be a key technology for Lean satellites.

The satellite project team kept operating and monitoring for about 2 years from Dec. 2012. Of course, many amateurs supported the project members. However, the action of patiently continuing to do the same thing was the most important thing.

5. Post operation

After the recovering on 2017 Jan. 28th, we checked the satellite health data by downlink. Immediately after the recovering satellite, all temperature data were very high and some of temperature sensors seemed to show the abnormal value. Most of temperature data were out of operational temperature range of components. Especially, Battery and COM's temperature were extremely high. We decided to send a kill command. After sending kill command, generated power from solar cells to battery and load are cut. On 2017 Jan 30th, we confirmed that Horyu-2 finally stopped the sending CW.

6. Conclusions

This paper described Horyu-2's anomalies due to SEE. The most important knowledge from the anomaly investigation was an acquisition of latch-up current during hang-up. The value of the acquired latch-up current matches with that of the latch-up current observed in radiation tests using ^{252}Cf and proton source. From the statically analysis, the averaged life-time for Horyu-2 was estimated as 59 days.

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