A Redundancy and Operation of Power Control System for a Deep-space Small Probe

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***Abstract*—a small deep space probe, Shinen2 was produced by the Kyushu Institute of Technology in collaboration with Kagoshima University. Shinen2 was lunched by an H2-A rocket as a piggy-back space probe with Hayabusa-2 of JAXA's probe in 2014. Shinen2 is exploring in the deep space beyond the moon. Shinen2 has three missions: the first mission is a structure mission, Shinen2 is composed of CFRTP (Carbon Fiber Rein Thermo Plastics), the second mission is a communication mission by WSJT (Weak Signal radio communication by Joe Taylor, K1JT), and the third mission is a measurement mission; Shinen2 has radiation sensors which measure radiations in deep space. Shinen2 principally has three units, CCU (Communication Control Unit), PCU (Power Control Unit) and SCU (Shinen2 Control Unit). This paper describes how to control PCU and functions of redundancy for PCU in space by SCU's function.**

***Index Terms*—space engineering, deep-space probe, power control in deep space**

I. Introduction

In deep-space development, there are a lot of technical subjects. For example, deep-space communication needs a deep-space network from JAXA, NASA and ESA, which has an international array of giant radio antennas that support interplanetary spacecraft missions for long-distance communication in deep space [1]-[2]. Therefore, it is hard for private companies to complete deep-space development because there are no giant radio antennas, nor deep-space communication systems. In addition, there is more radiation in deep space than near Earth; therefore, some electric components may be broken by being hit with radiation. This paper is focuses on the power control units and is written to distribute the power to each electric component and observed systems of the power control unit by other control units.

II. Shinen2

The small, deep-space probe Shinen2 was developed under collaboration with the Kyushu Institute of Technology and Kagoshima University [3]. Fig. 1 shows the outline of Shinen2, which is classified as a small probe.

Figure 1. The outline of Shinen2.

The aim of the deep-space probe is to substantiate deep-space communication with amateur radio-wave frequencies for the first time in the world. Shinen2 was launched by an H2-A rocket as a piggy-back space probe with the JAXA's asteroid probe, Hayabusa 2, in December, 2014. The outer shape of the Shinen2 has a quasi-spherical diameter of 50 cm, and a mass of approximately 18 kg. Shinen2 has three missions, which

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are a communication mission, a structure mission and a measure radiation mission.

The probe has three communication systems for amateur radio-wave frequencies in deep space. Deep space refers to the areas beyond the moon. The deep-space communications used were WSJT (Weak Signal communication by Joe Tyler) [4]-[5] systems and Beacon. Shinen2 is composed the CFRTP (Carbon fiber Reinforce thermos Plastics), which have never been used in space. Moreover, Shinen2 is equipped with a radiation sensor. It aims to measure radiation in deep space.

III. Shinen2 Communication System

A. *Each Communication Systems*

The Shinen2 has three communication systems of amateur radio-wave frequencies in space [3]. Below, an overview is listed for each system. In addition, Table I describes the communication parameters of the probe.

TABLE I. Communication Parameters of Shinen2

Type	Chanel	Parameter
Communication (C-line)	CH-1	Link direction : Up Frequency : 145 MHz Output power : 50 W Modulation type : 3K00F2D Communication type : AX25
	CH-2	Link direction : Down Frequency : 437.385MHz Output power : 0.8 W Modulation type : WSJT Communication type : WSJT
Amateur Radio Relay Experiments (A-line)	CH-3	Link direction : Up Frequency : 145.942 MHz Output power : 50 W Modulation type : 3K00F1D Communication type : WSJT, A1A
	CH-4	Link direction : Down Frequency : 435.270 MHz Output power : 0.8 W Modulation type : WSJT Communication type : WSJT, A1A
Beacon Signal (B-line)	CH-5	Link direction : Down Frequency : 437.505 MHz Output power : 0.1 W Modulation type : 500HA1A Communication type : Morse

1) *C-line for communication*

This communication system was designed for communication from the grand station to the probe, and was assigned an up-link line (Ch-1) and a down-link line (Ch-2).

2) *A-line for amateur radio relay experiments*

This communication system was designed for the amateur radio-wave operators to communicate with the telecom experiment, and was assigned an up-link line (Ch-3) and a down-link line (Ch-4).

3) *B-line for beacon signal*

This communication system used the probe identification line. It transmitted the information about the identification code and the probe operation, from the probe to the grand station on Earth. It used Morse code. Only a down-link line of communication was used. It was assigned Ch-5.

B. *Shinen2 Communication System Block Diagram*

Fig. 2 is the Shinen2 communication system block diagram.

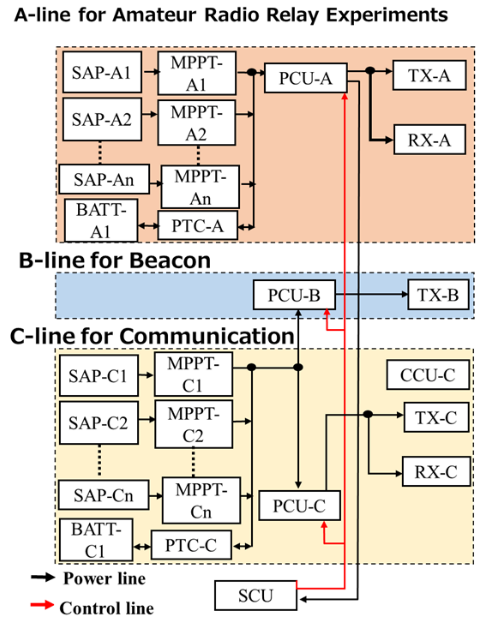

Figure 2. Shinen2 communication system block diagram.

The block lines represent power lines, and the red lines represent control lines. In the figure, SAP stands for Satellite Array Panel, MPPT stands for Maximum Power Point Tracking, PCU stands for Power Control Unit, CCU stands for Communication Control Unit, Tx stands for transmitter, Rx stands for receiver, and SCU stands for Shinen2 Control Unit. The SCU checks the living confirmation of all the Shinen2 units and HK data. HK data stands for House Keeping data, such as battery temperature, flow currents on PCU, and measure voltage on PCU. Moreover, SCU collects radiation sensor data from space. The SCU was made by NASA and Texas State University. The CCU transmits HK data and radiation data from the SCU. The CCU modulates the SCU data sent for transmitting to the grand station on Earth. The B-line for Beacon was used as a battery for the C-line, but the other B-line system was independent. The A-line was independent from the other line systems. The Shinen2 has five antennas. The two mono-pole antennas are down-link antennas. A path antenna was used for the B-line of the Beacon.

C. *Shinen2 Communication Type*

1) *WSJT system*

The down link of the C-line and the A-line communication system was adopted for the WSJT system. The WSJT system is a slight-signal communication program for small and low-power facilities. The WSJT system has a specific faculty. The slight signal level used is 10 dB lower than the CW signal level, which used an acoustic signal of PC, and integrated the noise level below the signal. Fig. 3 is the WSJT system image diagram.

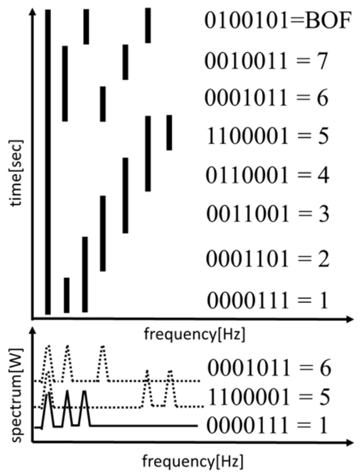

Figure 3. WSJT system image diagram.

In the 200 Hz to 1.4 kHz, seven spectrum slots per 200 Hz steps are prepared, and the lowest frequency is always used for the output. The other spectrum slots were assigned figures and control characters, for example 0 to 9 and BOF (Begin OF Frame). In order to achieve a constant transmission power and increase as much transmission power per slot as possible, a combination of the two spectrums was selected, and the other spectrums were 0 W. The power per spectral line was 0.8 W/3≒0.2 W. The number of spectrums is always three on the transmit signals. Error detection data analysis was always used.

2) WSJT system of Shinen2

Fig. 4 is the WSJT system of the Shinen2. The system used the characters -1, 0, 1, 2 and 3 for each frequency. It included eight characters with combinations of their characters.

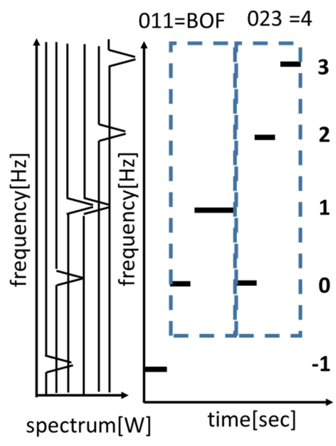

Figure 4. WSJT system of Shinen2.

In Fig. 4, on the left graph, the vertical axis is the frequency, and the horizontal axis is the spectrum. On the right graph, the horizontal axis is the time. On the right graph of Fig. 4, when there are three numbers, they are converted to the corresponding character, as shown in Table II. Table II shows the assignment of the code to the eight characters. For example, by Fig. 4, when the grand station on Earth received the code “011”, it obtained the data of the “Beginning of the Flame”. In addition, when Earth received the code “023”, it obtained the data “4”. Using Table II, they were able to analyze the received data of the Shinen2. The down-link data were composed of 13 bytes, which are shown in Table III. The synchronism codes were 2 bytes, the Beginning of the Flame was 1/3 byte, the data class was 2/3 byte, each data between one and eight was 8 bytes and the circuits character were 2 bytes.

TABLE II. ASSIGNMENT OF THE CODE EIGHT CHARACTERS

Code	Character	Code	Character
011	BOF	023	4
012	0	031	5
013	1	032	6
021	2	033	7
022	3		

TABLE III. CONSTRUCTION OF DATA FLAME

1	2	3	4	5	6
Sync1	Sync2	BOF+ Class	DATA1	DATA2	DATA3

7	8	9	10	11
DATA4	DATA5	DATA6	DATA7	DATA8

12	13
CRC1	CRC2

Moreover, the communication speed of the WSJT was 1 bps, and the down-link data was needed to receive 2 minutes per 13 bytes, because it was considered to roll the Shinen2. In addition, Shinen2 sent the same data two times, because the received data improved the construction.

IV. RADIATION SENSOR

The Shinen2 has a radiation sensor for measuring radiation [3], such as the Van Allen radiation belt in deep space, which is developed by NASA and Prairie View A&M University. Fig. 5 shows the radiation sensor.

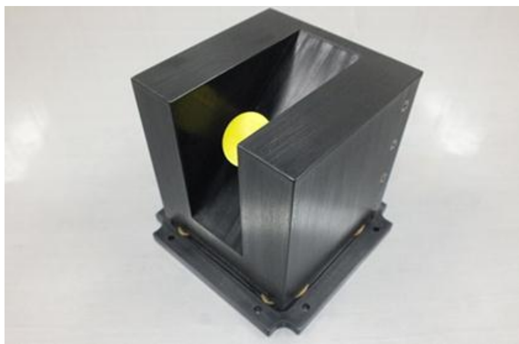

Figure 5. Radiation sensor for measuring in space.

The sensor is able to measure radiation distribution in space by a CMOS sensor, which has two sensors [6]-[7]. Table IV shows the telemetry frame format of the Shinen2. Each frame has 8 bits, such as a frame sync stand for synchronization, sensor 1 data and sensor 2 data. Normally, the frame sync sends the code 10101100 (0xAC). Sensor 1 and sensor 2 are pixel values (0x00 to 0xFF). There are start bits and stop bits for distinguishing each piece of data sent on the 24-bit frame.

SCU gathers the radiation data from the radiation sensor. Some data are preserved on the EEPROM for radiation measuring and for checking radiation value.

TABLE IV. TELEMETRY FRAME FORMAT OF THE SHINEN2

Bit number	8 bit	8 bit	8 bit
Frame data type	Frame sync	Sensor 1 Data	Sensor 2 Data

V. POWER CONTROL UNIT (PCU)

In this chapter, power control unit of Shinen2 development is shown in Fig. 6, which shows the PCU electric board in Fig. 6. The Shinen2 power control system applies the KSAT2 technology, which was launched in February, 2014. The Shinen2 battery capacity is 52 Ah, which uses a lithium ion battery and its battery is a 1 series 16 parallel circuit for redundancy and has plenty of capacity [8]. Table V is battery performance of each type. In addition, the Shinen2 battery has a battery protection circuit, which protects from overcharge, over discharge and short circuit. Table VI is the battery protection circuit performance.

Figure 6. PCU electric board.

The electricity of SAP of the C type is over 8.73 W, and that of the A type is over 7.93 W, which applies single silicon cells for cost saving.

TABLE V. BATTERY PERFORMANCE OF EACH TYPE

Battery type		Lithium ion battery Type: NCR18650B
Connect		1 series 16 parallel
Voltage		3.6 [V]
Full charge of voltage		4.2±0.03 [V]
Battery capacity		52 [Ah]
Operation guaranteeing temperature	Charge	0 to 45 [℃]
	Discharge	-20 to 60 [℃]
	Storage	-20 to 50 [℃]

TABLE VI. BATTERY PROTECT CIRCUIT PERFORMANCE

Detective of over-charge voltage	4.3 [V]
Start charge voltage	4.1 [V]
Detective of over-discharge voltage	2.5 [V]
Start discharge voltage	2.9 [V]
Detective of eddy current and voltage drop	0.5 [V]
Detective of eddy current at KSAT2	5 [A]

Table VII is the solar cell performance. Each solar cell has a MPPT (Maximum Power Point Tracking) control circuit, which the type is spv1040. MPPT is 1 chip per 1 array for redundancy and is not over the maximum value. Table VIII is MPPT control IC performance. Table IX is the electric component consumption of the Shinen2. The Shinen2 power supply unit is needed to supply electricity of stabilization for a successful mission. The tasks are showed in the following.

1) To supply the electricity of stabilization to each component.
2) To only use each battery to the moon.
3) To protect from the radiation of space
4) To design redundancy.
5) To protect from degradation of the batteries.

TABLE VII. SOLAR CELL PERFORMANCE

Maximum power point voltage V mp	2.59 [V]
Maximum power point current I mp	0.454 [A]
Conversion efficiency	18 [%]
Maximum power P max	2.78 [W]
Cell of C type	11 array
Cell of A type	10 array

TABLE VIII. MPPT CONTROL IC PERFORMANCE

Input voltage	0.3 to 5.5 [V]
Output termination voltage	4.4 [V]
Efficiency	74 [%]
Size	6.2 ×2.9 [mm]
Operating temperature limit	-40 to 155 [℃]
Normal rated power	3 [W]

TABLE IX. ELECTRIC COMPONENT CONSUMPTION OF SHINEN2

Component	Unit	Consumption
SCU	W	0.3
PCU + CCU	W	0.5
Rx	W	0.156
Radiation sensor	W	1.4
Tx (C type)	W	3.72
Tx (A type)	W	2.8

Shinen2 has a breaker for protection of discharge and breaking of some electric components. The type is LTC4361. The breakers are located along the power lines of each component. Its breaker can restart within 130 ms and its response time is under 1 μs at over current.

VI. RADIATION TOLERANCE TEST

There were three purposes for conducting this test. First, in space, there is more radiation than on Earth, like the Van Allen radiation belt, which is a radiation belt composed of protons and electrons held together by the gravity of the earth. It is important to know the resistance radiation for operating the Shinen2 in space. Secondly, it is to learn how to work on a PCU if the PCU board is hit by radiation. Finally, for the Shinen2, the purpose was to test how long the probe can operate in space.

In this case, the Shinen2 is tested with the TID (Total Ionizing Dose), which is a degradation of the apparatus generated for the quantity of multiplication about radiation exposure times. Fig. 7 shows a semiconductor which mounts radiation hits. If a large amount of radiation hits it, ionization also occurs in the same location, and there are fixed potentials and interface states; therefore, degradation occurs.

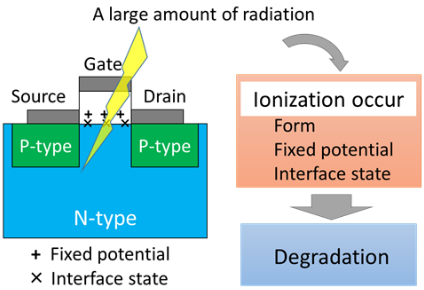

Figure 7. Semiconductor under a large amount of radiation

For example, the TID test procedure: first, an exposure dose is fixed for the operative number of years, for example one satellite needs 200 Gy for two years. Second, an electric board is added for the distance to become the exposure dose within a prescribed period, such as to put an electric board on one of the satellites for a distance which has 57 Gy per one hour. The total Gy are 200 Gy within 3.5 hours. The final purpose is for checking the data sent to the PC, because it checks the operation of the electric board.

Shinen2 TID experiments are tested in the Center for Accelerator and Beam Applied Science at Kyushu University, where test machines are available, such as the Cobalt-60 Gamma-Ray Irradiation Unit and FFAG Accelerator [9]. The Shinen2 uses the Cobalt 60 Gamma-Ray Irradiation Unit shown in Fig. 8. In the test, the Shinen2 is monitored, and voltages, currents and other data are operated by connecting wires to a PC in another room in order to avoid exposure by the Cobalt 60.

Figure 8. Cobalt 60 gamma ray irradiation unit

The Shinen2 has had very few successful missions in being able to communicate with the Shinen2 at the distance of 380000 km from the moon to the earth. It requires one week or less in space; therefore, the total radiation amount is less. However, the Shinen2 approaches the earth after a year and a half, which attempts to communicate to the grand station on Earth. It needs resistance radiation for communication. Generally, there are irradiated with 200 Gy for two years on the Geostationary orbit (GEO) [10]. The Shinen2 goes into deep space, which is farther than the GEO; therefore, it is expected to get more radiation than the satellites on the GEO. In the test, the SCU was irradiated with 400 Gy, which is double that of the GEO, because it measures the maximum resistance radiation of the SCU component. The TID test environment is shown in Table X.

TABLE X. TID TEST ENVIRONMENT FOR SHINEN2

Radiation type	Cobalt 60
Radiation dose rate	109 Gy /h
Irradiation total time	4 h
Radiation dose	436 Gy

In the result, CPU of PCU which is used PIC16F877A were broken by the TID test. The value is shown in Table XI. In the test, PIC16F877A has a radiation tolerance of over 190 Gy. It can work for at least 1 year.

TABLE XI. RADIATION DOSE ON PIC16F877A IN TID

Component	Irradiation time	Radiation dose
PIC16F877A (CPU)	108 minutes	196.2 Gy

VII. SHINEN2 CONTROL UNIT (SCU)

The Shinen2 Control Unit (SCU) was designed for deep-space communication, radiation measurement in deep space and controlling the Power Control Unit (PCU). Below is the main action of the SCU. In addition, the House Keeping data are data which helped the SCU perform normally, such as current, voltage and thermal.

- Controlling the PCU
  - ➢ Observation of the PCU for precise actions
  - ➢ Sending the telemetry data when starting the PCU
- Gathering House Keeping (HK) data
- Gathering radiation sensor data
- Sending HK data and radiation sensor data to the Communication Control Unit (CPU)

The SCU observes PCU for precise actions when restarting incase PCU does not perform the actions exactly. Fig. 9 shows the SCU FM electric board.

Figure 9. SCU FM electric board

VIII. RESULT

The Shinen2 was launched in December, 2014, and the Shinen2 down-link data was received at the grand station on Earth. Fig. 10 shows the received data of the Shinen2. The Shinen2 down-link data was analyzed by a HDSDR (High Definition Software Defined Radio), which is a freeware-software defined radio program for Microsoft Windows, and typical applications include radio listening, ham radio, SWL (short-wave listening), radio astronomy, NDB(Non-directional Radio Beacon)-hunting and spectrum analysis, whose software is an advanced version of Winrad, written by Alberto di Bene [11]. The received data has effective noises on received software, because it is difficult to control antennas for receiving the data with low power. Therefore, all spectrum data of the Shinen2 could not be received. This chapter describes the result of the received data from the Shinen2, and the Shinen2 checks if the PCU worked in deep space by the received data value. Usually the battery voltage is 4 V; the received data on the Shinen2 remained at about 4 V in deep space.

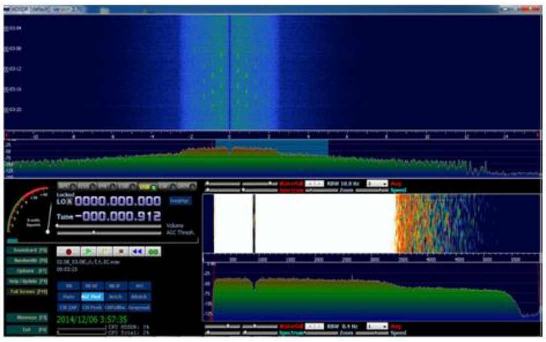

Figure 10. The received data of Shinen2

The Shinen2 received the last data at 2.3 million km for approximately six days. However, only three days worth of data could be analyzed. It was difficult to analyze the data from the other days. Table XII shows a record of the Shinen2 data, including date, time, distance, type and call sign from the ham operator who used the amateur radio wave. Table XIII is the analyzed data from 12/3/2014-12/5/2014.

TABLE XII. RECORD OF SHINEN2 DATA

Date	Time	Distance [m]	Type	Call sign
12/3/2014	10:31:23	109,219	C	JR8LWY
12/4/2014	10:36:35	522,381	C	JH6VAX
12/5/2014	0:03:03	749,948	C	SQ5KTM
12/6/2014	11:29:59	1,343,720	C	JH6VAX
12/7/2014	15:23:42	1,808,184	C	JH6VAX
12/8/2014	21:54:00	2,308,134	C	PE1ITR

TABLE XIII. THE ANALYZED DATA FROM 12/3/2014 TO 12/5/2014

Type C Battery Voltage	3.88 [V] to 4.06 [V]	Type A Bus voltage	3.88 [V] to 4.02 [V]
Type C Battery Current	0.14 [A] to 0.25 [A]	Type A Bus Current	0.65 [A] to 0.88 [A]
Type A Bus Voltage	3.88 [V] to 4.04 [V]	Type C Battery Voltage	-
Strain Gage 1	0.01 to 0.0139	Strain Gage 1	0.145 to 0.146
Strain Gage 2	0.01 to 0.0139	Strain Gage 2	0.0137
Type A Battery Thermal	15.92 [℃] to 22.32 [℃]	Type C Battery Thermal	13.2 [℃]
Type A Battery Top thermal	18 [℃] to 23.2[℃]	Type A Battery Top thermal	23.78 [℃]
Surface Z + thermal	15.14 [℃] to 19.2 [℃]	Surface Z thermal	17.86 [℃] to 31.6 [℃]
Message-1	-	SAS_A_I	0.05 [A] – 0.833 [A]
Message-2	-	SAS_B_I	0.07 [A] – 0.14 [A]
Message-3	-	SAS_C_I	0.43 [A] – 1.64 [A]
Message-4	-	SAS_D_I	0.06 [A] – 1.196 [A]
Message-5	-	SAS_E_I	0.402 [A]
Message-6	-	SAS_F_I	0.010 [A] – 0.68 [A]
Type A Battery Thermal	13.57 [℃] to 23 [℃]	SAS_G_I	0.039 [A]
Type A Bottom thermal	14 [℃] to 31.6 [℃]	Surface Z thermal	19 [℃] – 21.8 [℃]
Type C RX-RSSI	1.343 [V] to 1.6 [V]	Type A Bus Current	0.78 [A] to 1.74 [A]
Type C RX-I	0.022 [A] to 0.026 [A]	Main Tx I	0.554 [A] to 0.71 [A]
Type C RX-NSQ	0.02[V] to 0.14 [V]	MAIN NASA I	0.45 [A] to 0.71 [A]
Type A RX-RSSI	0.62 [V] to 0.64 [V]	SUB-Tx-I	0.397 [A] to 0.8 [A]
Type A RX-I	0.025 [A] to 0.03 [A]	Type A Bus Current	0.42 [A] to 1.58 [A]
Type A RX-NSQ	0.02 [V]	NASA Top thermal	19.45 [℃] to 22.9 [℃]
Tx- main Thermal <-Y>	27 [℃] to 36 [℃]		
Tx- sub Thermal <-Z>	21.4 [℃] to 33.9 [℃]		

Table XIV shows the compared ranges of each operation limit and the received data of Shinen2. It shows the data to be within the range. Therefore, PCU can work in deep space and SCU does not break and can be controlled and observed at each electric component.

TABLE XIV. THE COMPARE RANGES OF EACH OPERATION LIMIT AND THE RECEIVED DATA OF SHINEN2

component name	Value	Control range
Type C battery voltage	3.88 [V] to 4.06 [V]	～ 4.2 [V]
Type C battery current	0.14 [A] to 0.25 [A]	～ 5 [A]
Type C battery thermal	13.2 [℃]	0 [℃] to 45 [℃]
Type A bus voltage	3.88 [V] to 4.02 [V]	～4.2 [V]
Type A bus current	0.65 [A] to 0.88 [A]	～ 5 [A]
Type A battery thermal	15.92 [℃] to 22.32 [℃]	0 [℃] to 45 [℃]

IX. CONCLUSION

The Shinen2 was launched in December, 2014 and had three types of communication lines: a Communication line (C-line), an Amateur Radio Relay Experiments line (A-line) and a Beacon line (B-line). The A-line and C-line were used for the specific communication modulus, WSJT, which was able to communicate with the low power transmitter in space.

The Shinen2 has a Power Control Unit (PCU) which supplies power to each electric component while in deep space; it applies some technology of KSAT2 which was made by Kagoshima University. The Shinen2 Control Unit (SCU) controls the Shinen2 electric components and equipment. In addition, the SCU observed the PCU in order to perform actions precisely.

The Shinen2 could receive the HK data and radiation sensor data in deep space. In addition, the data was normal while in deep space, therefore PCU of Shinen2 could work in deep space.

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