

## Evaluation of Power Control System for Micro and Nano Satellites by Hardware-in-the-Loop Simulator

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### ABSTRACT

The evaluation method using Hardware in the Loop (HIL) simulator of power control system for micro and nano satellites is suggested. The results for two satellite projects, which are RISING-2 and RAIKO, are described. The generation power by solar panels and the consuming power by electrical units are supplied or consumed by external instruments. The power-related status data of real satellite are measured via the downlink. As a dummy satellite, satellite simulation software is simultaneously executed, and the status data are compared to ones of real satellite for updating the math models. Through this method, the power environment on orbit can be simulated in a long-term span, and the healthiness of electrical system can be sufficiently evaluated in a ground test.

### INTRODUCTION

Tohoku University developed the first satellite SPRITE-SAT (RISING) (Ref.1) and it was launched in Jan. 2009. However, the critical breakdown in some instruments was occurred because of the defect in battery charge and discharge function. To avoid the same failure, a lot of efforts are being made in the evaluation of power control system for the following three satellite projects of RISING-2 (Ref.2), RAIKO, and RISESAT from the beginning of development phases.

The evaluation method using Hardware in the Loop (HIL) simulator of power control system for micro and nano satellites is suggested. The results for two satellite projects, which are RISING-2 and RAIKO shown in Fig.1, are described. The generation power in solar panels and the consuming power in onboard instruments are supplied or consumed by external instruments. The power-related status data of real satellite, which is engineering model satellite in a room, are measured via the telemetry data. As a dummy satellite, satellite simulation software is simultaneously executed, and the status data are compared to ones of real satellite for updating the math models.

Through this method, the power environment on orbit can be simulated in a long-term span, and the healthiness of electrical system can be sufficiently evaluated in a ground test. The defects of electrical parts or power control algorithm can be found in early stage, and the quick evaluation can be carried out before or after an environmental test. After the start of real satellite operation, the simulation software including detail math models enables us to estimate the future power conditions with high precision.

### SYSTEM SPECIFICATIONS OF SATELLITES

#### RISING-2

The primary mission is the earth observation with a resolution of 5 meters from 628-km altitude by using a Cassegrain reflector telescope which diameter is about 10 cm and the focus distance is about 1 meter. The satellite is planned to be launched in 2013. The visible infrared and multi spectral images of cumulonimbus clouds can be observed by using a liquid crystal tunable

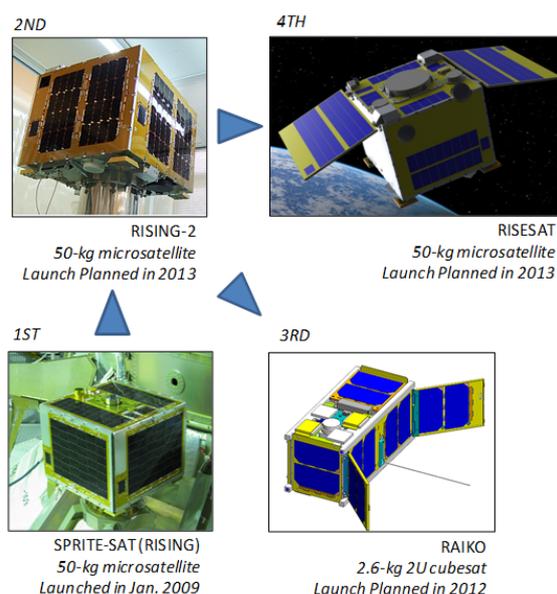


Figure 1: Satellite Series by Tohoku University

filter (LCTF) as well as usual color images. These observations are expected to solve a mechanism of guerrilla heavy rain and contribute to the establishment of basic technology for weather forecasting. The RISING-2 also observes the horizontal structure of sprite which is one of lightning discharge phenomena. The satellite mass is about 43 kg, the size is 500 x 500 x 500 mm, and the lifetime is more than 1 year.

**RAIKO**

The satellite mass is 2.66kg, the size is 10 x 10 x 20 cm, which is called 2U-size cubesat. This is planned to be launched to International Space Station (ISS) on Jul. 2012, and the satellite is released to space after Sep. 2012 in the altitude of 350 to 400km. The satellite is being developed by Wakayama Univ., Tohoku Univ., and Univ. of Tokyo.

The concept of missions is to evaluate the technologies that can be utilized for future 50-kg microsatellites. The satellite has three cameras, which are a color CMOS camera for photos of ISS when satellite being released, a color CCD camera for earth observation, and a high-sensitive CCD sensor for star observation, which is planned to be used as attitude sensor.

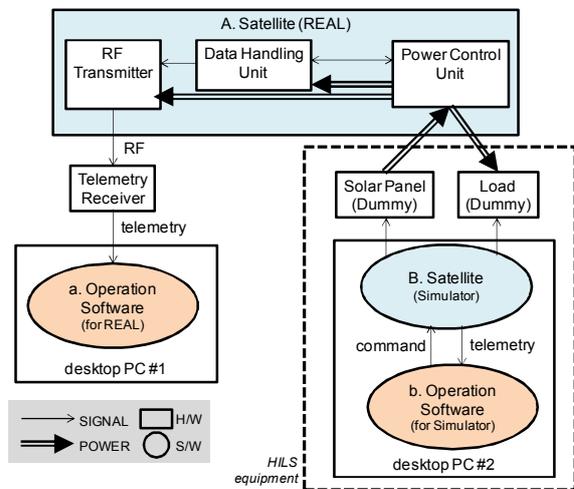
Also, other missions are carried out, which are the rapid de-orbit experiment using thin-film deployment mechanism opened at 300-km alt., the orbit determination experiment using Ku-band beacon signals, and the Ku-band data download experiment with the bitrate of 500-kbps.

**Comparison of Power Control System**

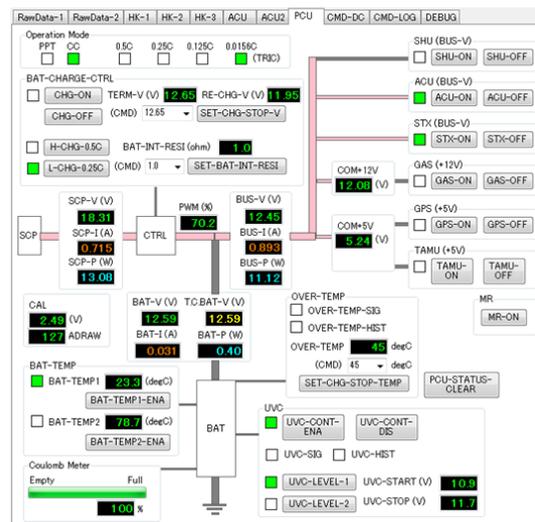
RISING-2 is using solar cells with 27.1-% power generation efficiency. The cells are mounted on 5 side body panels in which 8-series and 4-parallel (or 2-parallel) cells for each panel. The generation power is estimated as 41.1 W in 2-deg/s spin motion. The battery unit consists of 9-series NiMH cells (total 10.8V and 3700mAh) for industrial use.

RAIKO is using solar cells with 29.5-% power generation efficiency. Two cells are pasted in each panel, and there are total 6 panels before the open of paddles. After the success of paddles opening, there will be total 10 panels. The power generation is 3.19 W before the open of paddles, and 4.70 W after. The battery unit consists of 8-series NiMH cells (total 9.6V and 750mAh) for general use.

The reason using NiMH batteries is because there is few risks of explosion by overcharging. The charge and discharge are controlled by voltage and temperature monitoring, and the threshold values can be changed by commands.



**Figure 2: Hardware in the loop simulator for Power control system**



**Figure 3: Operation Software**

**SIMULATOR-BASED EVALUATION SYSTEM**

The environment of simulator is shown in Fig.2. The satellite engineering model (A), ground RF receiver and the operation software (a) for recording telemetry data are prepared. The simulation instruments are connected to power control unit (PCU) in satellite. The simulation software (B) is prepared and the power ON/OFF status are changed by commands from operation software (b). The satellite simulator can calculate the orbit and attitude, and estimate the solar generation power and bus consuming power. The instruments of solar power simulator, which is dummy of solar panels, and the electrical dummy load are remotely controlled from PC.

### Framework of Software

As a case study, the satellite simulator program named SatSimulator is introduced. The program is written by C++ language, and doesn't have GUI but share the data with other programs using shared memory functions by Windows(R).

The SatSimulator can receive commands and send telemetries like as a real satellite. Using the shared memory (IF\_TLM\_CMD), the Socket server program is executed for the connection with ground operation software. It is important that the same ground operation software is used for real satellite and satellite simulator. Before the starting of satellite fabrications, the specification of satellite system will be refined by developing the satellite simulator and the ground operation software in detail. Also, using same format of commands and telemetries, the common onboard FPGA/CPU codes and ground operation software can be used in different satellite projects.

Using the shared memory (IF\_SCP), SatSimulator connects to the control software for commercial product of solar array simulator. The solar cell parameters calculated in SatSimulator are automatically set to the solar array simulator, which are the short current, the open voltage, the current and voltage at maximum power point.

To imitate the consuming power by onboard instruments, using shared memory (IF\_LOAD), SatSimulator connects to the control software for commercial product of electrical load. The total consuming power (W) calculated in SatSimulator is automatically set to the electrical load.

### Components in Program of Satellite Simulator

The program SatSimulator is written by object-oriented language. The State classes including status information, the Integration classes including numerical integration models, and the Thread classes including the behaviors of instruments are mainly classified.

The names of classes are listed in Table.1. About the category 1, the inside functions are different in each satellite, that is the derived-class functions are required. About the category 2, the class functions can be commonly used in every satellite.

### Procedure of Software in the Loop (SILS) Simulation

By the combination of SatSimulator and ground operation software, the behavior of imitation satellite can be confirmed. There are realtime mode, in which the cycle period is 125ms, and the fast calculation mode.

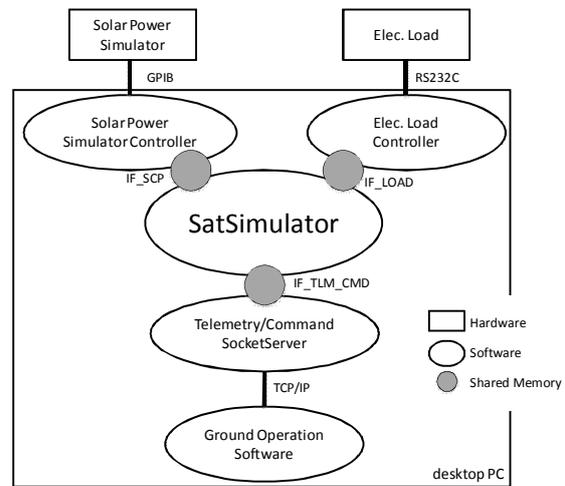


Figure 4: Satellite simulator and related software

Table 1: Definition of classes in SatSimulator program

Category 1. Classes of Instruments	
StateBAT	battery
StateGAS	geomagnetic sensor
StatePCU	power control unit
StateSAS	sun sensor
StateSCP	solar panels
StateSCU	central data handling unit
StateMTQ	magnetic coils
ThreadSCU	behavior of SCU
ThreadPCU	behavior of PCU
Category 2. Classes of Orbit and Attitude	
StateAttitude	status of attitude
StateMass	specification of mass
StateOrbit	status of orbit
StateTime	status of time
IntegrationAttitude	attitude dynamics model
IntegrationOrbit	orbit dynamics model
Thread AttitudeSimulator	procedures of orbit and attitude propagations and update of sensors

1) function of ThreadAttitudeSimulator.update ... after the orbit propagation (IntegrationOrbit.propagate) and attitude propagation (IntegrationAttitude.propagate), the status of orbit (StateOrbit), attitude (StateAttitude), sun sensor (StateSAS), and geomagnetic sensor (StateGAS) are updated.

2) function of ThreadSCU.update ... using the update values of sun sensor and geomagnetic sensor, the current of magnetic coils (StateMTQ) are updated.

3) function of ThreadPCU.update ... comparing the bus consuming power and solar generation power, the battery charge/discharge mode is selected. From the mathematical models of power system, which are described in next section, the voltage and current of solar panels and batteries, and the their status (StateSCP, StateBAT) are updated. The math models are including the power conversion loss or efficiency.

The bus consuming power is estimated value in the early phase of development, and their values are replaced by correct measured values in the proceeding of system-level tests. The recognition of power conversion efficiency is important. In the first approx. estimation, the solar generation power is supposed by the 90% value of maximum generation power  $P_{mp}$  shown in catalogue of solar cells. Also, the voltage conversion loss from solar power to bus power is supposed to 20 %. In total, it can be defined that the 70 % of  $P_{mp}$  can be consumed by bus instruments in the initial design phase, and the efficiency is updated to real values through the system-level tests.

#### Battery Charge/Discharge Algorithm

By neglecting the power conversion efficiency and the limit of battery charging current, the simplified algorithm of battery charge/discharge algorithm is shown in Fig.5. The model equations are as follows in each mode. Where,  $P_{BAT}$  is battery charge/discharge power,  $P_{SCP}$  is solar generation power,  $P_{SCPM}$  is maximum limit of  $P_{SCP}$ , and  $P_{BUS}$  is bus consuming power. And,  $V_{BAT}$  and  $V_{TERM}$  are battery voltage and charging termination voltage.

- 1) MODE-DISCHG (mode of battery discharge)

$$P_{BAT} = P_{SCPM} - P_{BUS} \text{ (where } P_{BAT} < 0\text{)}$$

$$P_{SCP} = P_{SCPM}$$

- 2) MODE-TRIC (mode of full-charged battery)

$$P_{BAT} \approx 0, P_{SCP} = P_{BUS}$$

- 3) MODE-CHG (mode of battery charge)

$$P_{BAT} = P_{SCPM} - P_{BUS} \text{ (where } P_{BAT} > 0\text{)}$$

$$P_{SCP} = P_{SCPM}$$

#### Math Model of Solar Panels

Calculating the solar direction vector  $\hat{S}$  from the orbit and attitude, the parallel numbers of series cell arrays reflecting solar can be calculated. For example, there are 4 parallel arrays in each panel of RISING-2, so  $n = 4$  when solar is reflected from vertical direction to panel. The series number of cells is defined by  $m$ , and the maximum solar generation power is formulated by

$$P_{SCPM} = V_{mp} \times I_{mp} \times m \times n$$

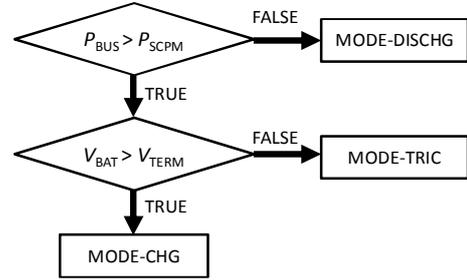


Figure 5: Algorithm of Battery Charge or Discharge

where  $V_{mp}$  and  $I_{mp}$  are the voltage and current at maximum power point, and the value of 1 parallel of RISING-2 is 8.43 W (= 0.452 A x 2.33 V x 8 series).

Using the  $P_{SCP}$  calculated by battery charge/discharge algorithm, the current  $I_{SCP}$  and the voltage  $V_{SCP}$  of solar panels can be calculated by the following formulas. The formula of  $I_{CELL}$  is derived by converting  $V-I$  curve in datasheet of solar cell to  $P_{CELL}-I$  curve and calculating the approx. curve. Where, the  $P_{CELL}$ ,  $I_{CELL}$  are power and current of each cell.

$$P_{CELL} = P_{SCP} / mn$$

$$I_{CELL} = \alpha_2 P_{CELL}^2 + \alpha_1 P_{CELL} + \alpha_0$$

$$I_{SCP} = I_{CELL} \times n, V_{SCP} = P_{SCP} / I_{SCP}$$

where  $\alpha_2 = 0.0693$ ,  $\alpha_1 = 0.337$ ,  $\alpha_0 = 0.00229$ .

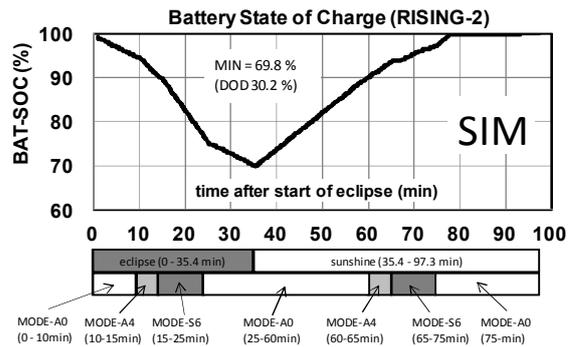
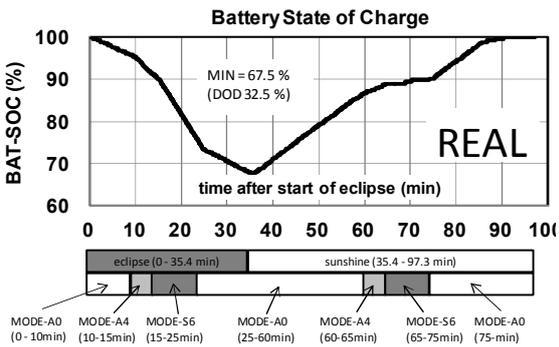
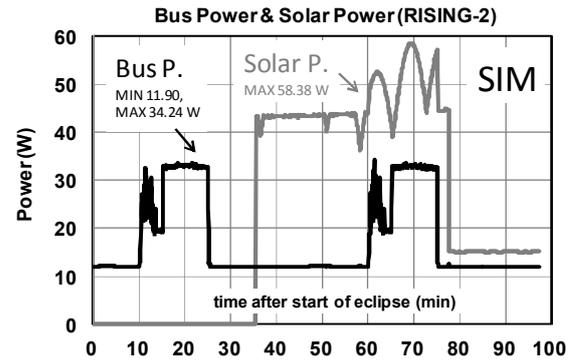
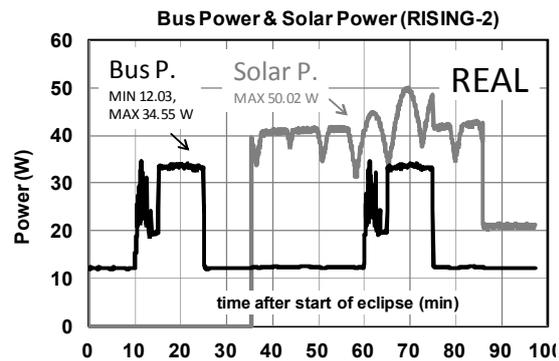
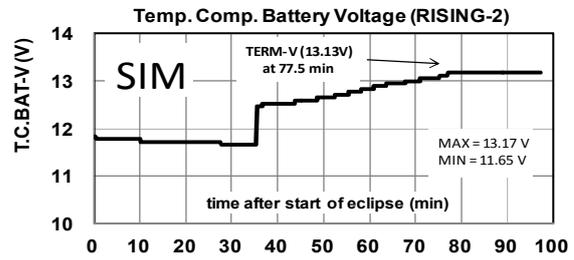
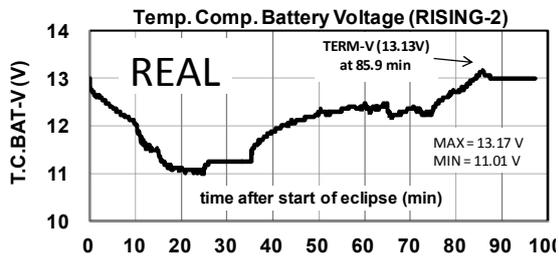
#### Math Model of Battery Unit

The math models of battery voltage  $V_B$  and battery current  $I_B$  are defined by calculating from the battery power  $P_{BAT}$ , battery temperature  $T_B$  (degC), and the battery state of charge  $L_B$  (0 to 1). The models are different when charging ( $P_{BAT} > 0$ ) and discharging ( $P_{BAT} < 0$ ). The models are defined by the real charge/discharge tests for an individual cell using a thermostat chamber, when the temperatures are 0, 25, and 40 degC. Also, the real charge/discharge tests under the condition of constant current, which are 0.5C and 1.0C, and the measured data of time, voltage, current, and temperature are processed. Using the numerical technique of simultaneous equations, the model coefficients can be determined as follows.

$$V_B = \sum_{i=1}^6 \alpha_{Li} L_B^i + \alpha_{T2} T_B^2 + \alpha_{T1} T_B + \alpha_I I_B + \alpha_0$$

$$I_B = P_{BAT} / V_B$$

In the case of RISING-2, which 9-series battery specs are total 10.8V in discharge and maximum 3.7Ah, the coefficients in charging mode are  $\alpha_{Li} = +12, -73, +229, -384, +325, -107$  ( $i = 1 \sim 6$ ),  $\alpha_{T1} = -3.76 \times 10^{-2}$ ,  $\alpha_{T2} = +4.09 \times 10^{-4}$ ,  $\alpha_I = 0.352$ ,  $\alpha_0 = 12.03$ . In



**Figure 6: History of power status (RISING-2) from telemetry data of real engineering-model satellite**

**Figure 7: History of power status (RISING-2) from satellite simulator**

discharging mode,  $\alpha_{Li} = +25, -65, +65, +22, -89, +46$  ( $i = 1\sim 6$ ),  $\alpha_{T1} = +5.36 \times 10^{-2}$ ,  $\alpha_{T2} = -7.00 \times 10^{-4}$ ,  $\alpha_I = 0.302$ ,  $\alpha_0 = 6.99$ . Where, the unit of  $T_B$  is not K, but degC.

In RISING-2, the parameter of TCBAT-V (temperature compensate battery voltage) is being calculated in onboard processor. It is the converted voltage in 0A and 25 degC in charging mode, and 0.37A (= 0.1C) and 25 degC in discharging mode. This value is stable for the change of battery temperature and battery current, and is purely reflecting the battery state of charge. This value is suitable to be compared with the threshold values of charging termination or emergency low voltage.

## EVALUATION TEST OF RISING-2 POWER SYSTEM

### Test Conditions

The power balance analysis is carried out using SatSimulator and real satellite (engineering model) of RISING-2. When the satellite is pointing to nadir direction, the 15-mins observation mode of consuming maximum power, which is 5 mins of MODE-A4 (30.51 W typ.) and 10mins of MODE-S6 (31.98 W typ.), is supposed both in sunshine phase and eclipse phase. That is, the satellite is consuming power more than 30 W in 30 mins per round. In other duration, the satellite is in typical low-power mode of MODE-A0 (11.87W). The graphs show the history of 97.3-min period, and the order is 35.4-min eclipse and 61.9-min sunshine.

This test is carried out in the configuration shown in Fig.2. The ground operation software of (a) and (b) are both executed, where (a) is for recording the telemetry data from real satellite, and (b) is for sending commands to change the instruments ON/OFF and for recording the log data of SatSimulator. Finally, the both recorded data about power system are compared. The conditions set in SatSimulator are the descending local time of 12:00, the inclination of 97.9 deg, the altitude of 628 km, the fixed temperature of 25 degC, the fixed solar strength of 1367 W/m<sup>2</sup>, and the nadir pointing attitude.

### Results of Power Balance Test

1) History of temperature compensate battery voltage ... Both in the real satellite and the SatSimulator, the T. C. battery voltage is reaching to the terminate voltage of 13.13 V before the end of sunshine. The range in the real satellite was 11.01 to 13.17 V. The raw value of battery voltage without temperature compensate is in the range of 10.07 to 13.58 V, and it is easy to recognize the state of charge by using T. C. battery voltage.

2) History of the state of charge (SOC) ... The SOC of real satellite is calculated in onboard CPU, and the SOC of SatSimulator is the result of integration of battery current. As the result, the depth of discharge (DOD) was 32.5 % in real satellite, and 30.2 % in SatSimulator. It was confirmed the SOC can reach to 100% before the end of sunshine.

3) History of bus consuming power and solar generation power ... The consuming power set to real satellite is the result of calculation in SatSimulator, and the values are basically same both in real satellite and SatSimulator. The solar generation power in sunshine was max. 50.02 W in real satellite, but it was max. 58.38 W in SatSimulator because the adjustment of conversion loss in the math model of peak power tracking control is not sufficient.

The math model of simulator is being updated through the system-level electrical tests, in which the power conversion efficiencies and the consuming power of instruments can be actually measured. Carrying out this kind of power balance evaluation, the defect in power system will be found in the early phase of development, and the detail math model can be understood before the launch. Using the simulating software only, the power condition supposing various irregular situations can be evaluated in advance of troubles, and it will contribute to decrease the defects happens after real operations.

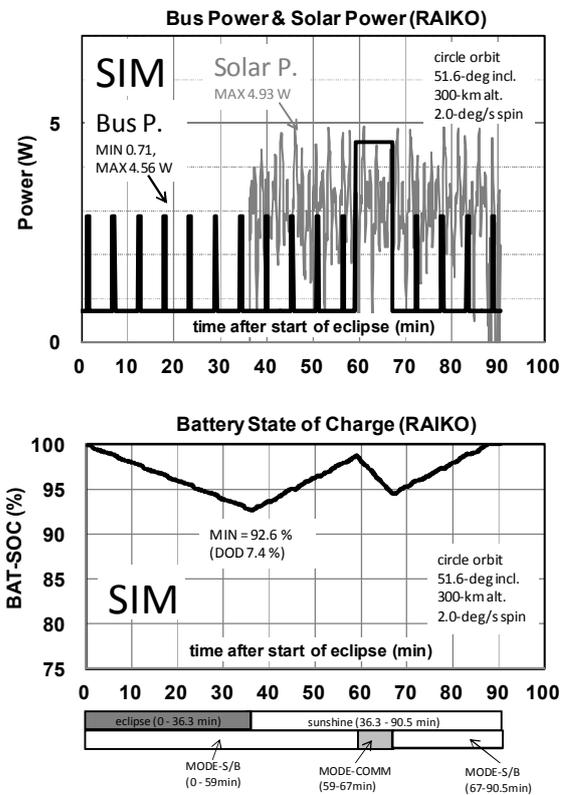


Figure 8: History of power status (RAIKO) without solar paddles

### EVALUATION TEST OF RAIKO POWER SYSTEM

In the case of RAIKO, the evaluation by only SatSimulator was carried out using the configuration of simulator (B) and ground operation software (b) shown in Fig.2.

The histories of bus consuming power (Bus P.), the solar generation power (Solar P.), and the battery state of charge (SOC) per round are shown in Fig.8. The orbit of RAIKO is not sun-synchronous, so the time of eclipse and sunshine can change in seasons. In this analysis, the worst case, in which the rate of eclipse in round is longest, was supposed. In this case, the elevation angle of solar to orbital plane is almost zero. It was supposed that the satellite has the spin motion with 2.0-deg/s in each axis. The period per round is 90.5 mins, and the graphs show in the order of 36.3-min eclipse and 54.2-min sunshine.

The operation modes of RAIKO are complex because of insufficient of solar generation power. The mode of Standby (MODE-S/B, 0.71W) is normal, where the command receivers of U-band and S-band and the power control board are active. The main processor

(MPU) using FPGA is not powered on any time. It is waken up only 30 sec after 5-min sleep to record the house-keeping status and execute the timer commands. In the communication mode (MODE-COMM, 4.56W), the telemetry transmitter of S-band is turned on in 8 mins per round.

This result is calculated supposing the solar paddles stored, where the solar panels are 6. The DOD is 7.4 % per round, and the SOC can reach to 100% before the end of sunshine. When the paddles are opened, the power generation is increased to 1.47 times, and the other instruments such as Ku-band beacon transmitter (0.675W) can be turned on any time.

Like this result, the reasonable operation scenarios can be appropriately planned using simulation evaluation.

## **CONCLUSIONS**

This paper showed the method of power system evaluation using Hardware in the Loop (HIL) simulator. Firstly, the satellite specifications of RISING-2 and RAIKO were introduced, and the software framework and math models were defined as well as the simulator environment of software and hardware. In the case of RISING-2, the results of power system behavior of real satellite (engineering model) and simulator were compared, and the practicability of simulator environment was shown. In the case of RAIKO, the unique operation plan under the insufficient power generation was supposed, and the feasibility was evaluated using the simulation software.

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