

# Operation Results of Cubesat RAIKO Released from International Space Station

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The 2-unit size cubesat RAIKO is the nanosatellite developed by Tohoku University and Wakayama University. This paper shows the mission and system specifications. The satellite was released to space on October 4, 2012 from International Space Station, which was the 419-km alt. circular orbit. The techniques for 50-kg microsattellites by Tohoku University are transferred to this satellite, so a lot of functions are included although the power and mass budgets are strongly restricted. The primary missions are the photo storage by different 3 optical sensors, the de-orbit mechanism experiment by expandable thin films, and Ku-band downlink communication experiment. The satellite operation was finished by orbital decay on August 6, 2013. The telemetry data were successful received in total 123 passes, in which total 63 photo images were obtained and maximum 100 kbps (200 kbps) downlink was successful. Using color CMOS camera, gradually separating ISS could be confirmed. From the analysis result of house-keeping data, the solar generation power in sunshine was 3.38 W (no paddles) to 5.77 W (with paddles) in average, the temperature of onboard computer was in the range of 20.8 to 28.7 degC, and the battery temperature was 4.2 degC in average. The real flight data from the 10-month operation will be precious information for future nanosatellite projects.

**Key Words:** Nanosatellite, Cubesat, RAIKO, International Space Station

## 1. Introduction

The cubesat RAIKO was developed by Wakayama University and Tohoku University in Japan. The size is about 10 x 10 x 20 cm, and the weight is about 2.6 kg shown in Fig.1. The satellite development was started from October 2010 by inheriting the technology of 50-kg microsattelite RISING-2 of Tohoku University and Hokkaido University. RAIKO is one of first satellites released from Japanese Experimental Module (JEM) on International Space Station

(ISS). In this opportunity, total 5 satellites were released to space. RAIKO was stored in a release pod before the launch, and it was transported to ISS by Japanese H-IIB rocket on July 21, 2012 as a freight in HTV rapped by cushion. The release direction of pod was arranged by robot arm of JEM, and the cover of pod was opened and the satellites were pushed out to space by springs. The initial orbit was 419-km alt., 51.6-deg inclination. The satellite operation was finished by orbital decay on August 6, 2013.

In this paper, the missions and system specifications are shown at first, and the flight data analyses are shown. The detail of bus system and environment test reports are summarized in previous paper<sup>1)</sup>.

## 2. Missions

The primary mission of RAIKO is technology demonstration of new electronics or mechanism usable for 50-kg microsattellites, which are CMOS color sensor, CCD color sensor, CCD star sensor, and film deployment mechanism. The photo image is trimmed to 588 x 441 pixels, and the color depth is diminished to 8 bit/pixel from the original 10 bit/pixel.

**1) Photo of earth by Wide Field CCD sensor (WFC):** The view angle is 134 x 180 degrees, shown in Fig.2-a.

**2) Photo of ISS or earth by Panoramic Color CMOS sensor (PCC):** The 46 photos are obtained in 30 minutes after the separation from ISS, shown in Fig.2-b.

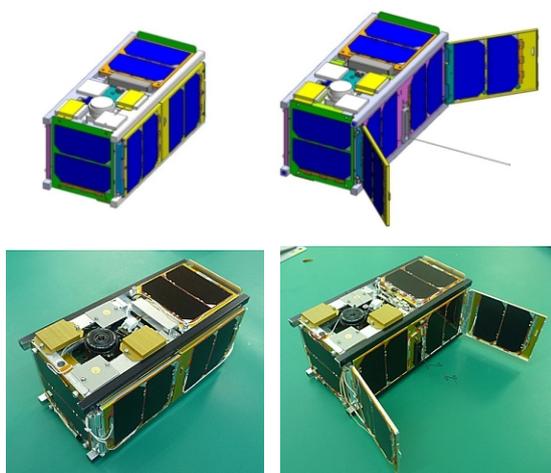


Fig. 1. Appearance of RAIKO (left: flight configuration, right: open solar paddles in space)

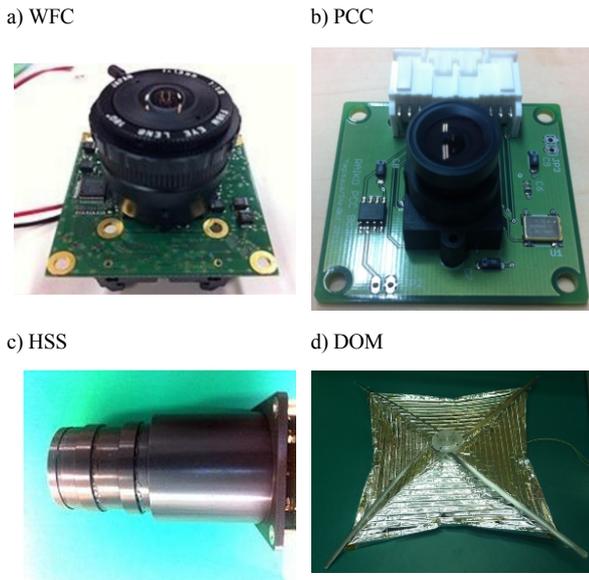


Fig. 2. Mission components

**3) Photo of star by High-sensitive CCD Star Sensor (HSS):** The onboard processor is not included and the image is analyzed in ground. The view angle is 22.7 degrees, shown in Fig.2-c.

**4) Demonstration of De-Orbit Mechanism (DOM):** The 50 x 50 cm aluminized polyimide film is stored, and it is opened by uplink command when the satellite altitude is decreased to 300 km. The air drag will be increased to 5.6 times before the deployment, and it can decay less than 4 days after the open, shown in Fig.2-d.

**5) Demonstration of Ku-band 13GHz transmitter:** The newly developed 100-mW output Ku-band data transmitter and 1-mW output Ku-band beacon transmitter were demonstrated. The micro radio bands have merits of high speed data communication, the availability of frequency bands. It is not influenced by ion atmosphere, and convenient for scientific radio observations. On the other hand, the beam width is very narrow, and high performance tracking antenna is required. The frequency data are accumulated by the observation of RAIKO, and the feasibility of orbit determination by frequencies is investigated. The orbits of very low altitude satellites are easily changed by strong air drag, and the orbit determination method is required by developed institutions.

### 3. System

#### 3.1. Satellite

The system specifications of RAIKO are shown in Table.1. The mass is 2.603kg, which is less than required 2.66 kg from launch side. To extend the life time maximum, the almost maximum weight was defined. The altitude at the beginning of life is 419 km. It has sun sensors and magnetic sensors as attitude sensors, and the de-tumbling control by magnetic coils can be available, which are three air coils stored in each axis with magnetic moment of 0.003Am<sup>2</sup>, 0.009Am<sup>2</sup>, and 0.005Am<sup>2</sup>. The position can be measured by GPS receiver. The solar cells are ZTJ Photovoltaic Cell, and they are used in two series (4.82V, 438mA/parallel). Using two 10 x 10 cm

Table 1. System Specifications

Size	W 100 x D 100 x H 227 mm (structure)
	W 113 x D 113 x H 227 mm (envelope)
Weight	2.603 kg (< 2.66 kg)
Orbit	circle, 51.6-deg inclination
	419 km (at separation), 300 km (end of life)
Life	about 10 months
Attitude	
sensors	sun sensors, magnetometers, GPS receiver
actuators	3-axis magnetic coils
Power	
solar cells	ZTJ Photovoltaic Cell (>29.5% efficiency)
	2 series x 6 parallels (no paddle open)
	2 series x 10 parallels (paddle opened)
batteries	8-cell NiMH (total 750mAh, 9.6V)
power generation	3.19 W (avg. in sunshine, no paddle open)
	4.70 W (avg. in sunshine, paddle opened)
power consumption	4.90 W (communication mode)
	1.05 W (standby mode)
Communication	
uplink	S-band, 2GHz approx., 1kbps
	U-band, 400MHz approx., 1200bps
downlink	S-band, 2285MHz, 0.1W
	9600bps to 100kbps
	Ku-band, 13275 MHz, 0.1W,
	9600bps to 500kbps
ground station	Ku-band, 13275 MHz, 1mW, 2-Hz beacon
	Tohoku Univ., Kagoshima Univ., Fukui Univ. of Tech.

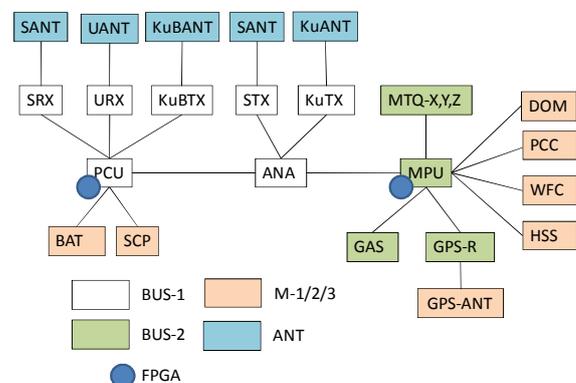


Fig. 3. System relation diagram

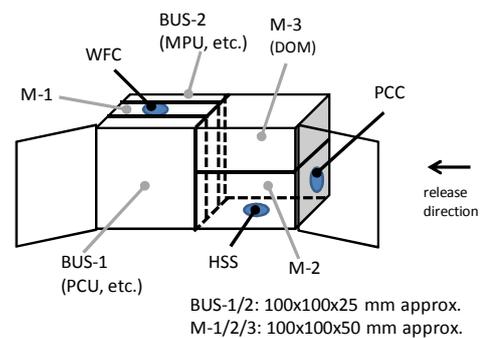


Fig. 4. Sub components arrangement

solar paddles, solar areas are increased to 10 parallels from original 6 parallels at launch. The commercial Ni-MH rechargeable batteries are used. The estimated solar generation in sunshine is 3.19 W before paddles open, and 4.70 W after the open. The consuming power is 1.05 W in default stand-by mode, when command receivers (U-band and S-band) and beacon transmitter (Ku-band) are available. To download the telemetry data, the communication mode is switched on only when the satellite is passing over the ground station. In this mode, consuming power is increased to 4.56 W by transmitter and onboard processor.

The system relation diagram is shown in Fig.3. The onboard electrical boards and consuming power are S-band receiver (SRX, 668mW), Ku-band beacon transmitter (KuBTX, 338mW, 2Hz mode), U-band receiver (URX\*), S-band 100-mW transmitter (STX, 1673mW), Ku-band 100-mW transmitter (KuTX, 4940mW), power control unit (PCU\*), analog measurement board (ANA), multi processor unit (MPU, 2182mW), solar cells (SCP), battery unit (BAT), sun sensors (SAS), magnetic sensors (GAS, 187mW), three magnetic coils (MTQ, 137mW/each), Panoramic Color CMOS sensor (PCC, 346mW), Wide Field CCD sensor (WFC, 494mW), High-sensitive CCD Star Sensor (HSS, 557mW), GPS receiver (GPS-R, 812mW), de-orbit mechanism (DOM, 2384mW). \*PCU+URX = 374 mW. The electrical boards are installed by separating five sub spaces (BUS-1/2, M-1/2/3) shown in Fig.4. For the stable data processing, flash-type FPGAs are used in PCU and MPU each. The command decoder is included in MPU, but the PCU can recognized REBOOT command of MPU power.

### 3.2. Ground Stations

In the operation of RAIKO, total 5 communication links are available: 1) U-band command uplink, 2) S-band command uplink, 3) 100-mW S-band telemetry downlink, 4) 100-mW Ku-band telemetry downlink, and 5) 1-mW Ku-band 2-Hz beacon downlink. Two antennas for each band are installed on counter panels except for 4). In the default configuration just after the satellite separation, 1) is always powered on, and 2) is repeating 5-min on and 5-min off for power saving. The other transmitters are powered on by ground commands. The command data speed is 1200bps FSK (U-band) or 1kbps FSK (S-band), and the telemetry data speed is 9600bps to 100kbps in S-band, or 9600bps to 500kbps in Ku-band with BPSK modulation, which speed can be changed from ground command.

In daily operations, three ground stations are participating: 1) U-band uplink and S-band downlink by Tohoku University with 2.4-m dia. antenna, 2) S-band uplink and Ku-band downlink by Kagoshima University with 1.4-m dia. antenna, and 3) S-band downlink by Fukui Univ. of Tech. with 10-m dia. antenna, shown in Fig.5. Usually, the S-band commands are sent from Kagoshima Univ. remotely operated from Tohoku Univ., and the S-band telemetries are received at Tohoku Univ. and Fukui Univ. of Tech. The Kagoshima station is located in 1100-km south west and Fukui station is located in 400-km south west to Tohoku station.

In Kagoshima station, the Ku-band beacon signals are also received by 45-cm dia. small antenna. The radio frequencies are analyzed by using spectrum analyzer and computer

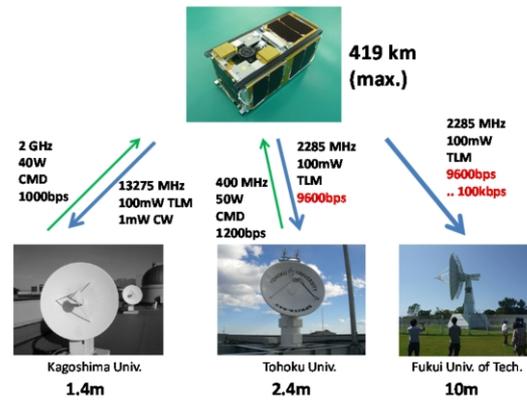


Fig. 5. Ground System

software analyzer, and the observations are used for the researches of atmosphere disturbance determination and orbit determination.

### 3.3. Onboard Processor

The core of multi processor unit (MPU) is FPGA with flush ROM, and not including CPU. By describing the logic circuits by VHDL codes, various parallel processing can be realized with high reliability and stability. The board is including the 40-MHz external clock, 2-MB SRAM, 12MB flash ROM. The primary tasks are: command decoder and execution, generating telemetry signals, power on/off commands to PCU, receiving house-keeping data from PCU such as voltage, current and temperature, writing/reading memories for mission photo data, magnetic coils control, timer command execution, and automatic recording of HK data in invisible pass.

The three typical operation modes are executed: a) initial operation mode, b) power saving operation mode, and c) communication mode. In mode a), the every sequence is automatically executed. Firstly, total 46 photos are taken and the data are saved in flash memories with 30-second intervals in 30 minutes after satellite separation. Secondly, the solar paddles are opened, the mode flag is cleared, and MPU is turned into sleep mode.

In mode b), MPU is turned on for 30 seconds, and turned off for 5minutes repeatedly. PCU can turn off/on the MPU by the SLEEP command from MPU, or REBOOT command from ground station. After MPU is turned on, when no commands come in 30 seconds, MPU send SLEEP command to PCU, and MPU is turned off for 5 minutes. It can be cancelled and forcedly turned on by REBOOT command from ground. When MPU receives a command from ground, it extends 12 minutes to SLEEP mode. The transmitters have individual OFF timers, and they are turned off automatically in 6 or 12 minutes.

In mode c), the MPU and transmitter are powered on, and command and telemetry operation with ground station are available. This mode can consume a lot of power, so the communication time must be shortened as much as possible.

Normally, cubesats does not have enough power, and this kind of power saving operation must definitely work well. The simulation results of solar generation power (Solar P.), consuming power (Bus P.), and battery state of charge per round are shown in Fig.6. The simulation detail was shown

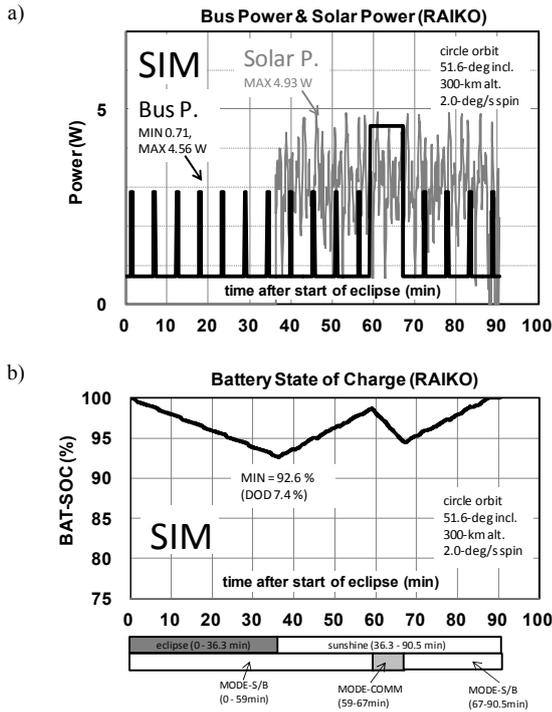


Fig. 6. Power control simulation: a) solar power and consuming power, b) battery state of charge

in earlier work<sup>2)</sup>. From the graph, the consuming power is rapidly increased every 5 minutes. In the range of 60 - 68 minutes, the communication mode is working, and after that, the power saving mode is started again. In the eclipse with no communication, the 7.4-% battery is used.

#### 4. Flight Data Analysis

On 06OCT2012, which is the second day after the satellite separation, the command communication between RAIKO and Tohoku Univ. ground station, and the telemetry data from RAIKO was firstly observed. After that, telemetry data were successful received in total 123 passes, in which total 63 photo images were obtained and maximum 100 kbps (200 kbps) downlink was successful. The example photos are shown in Fig.7. The panoramic color CMOS sensor has the function of automatic gain and exposure control, so the target is almost lightened with dark background. The some photos are including the shape of ISS, and it can be confirmed that ISS is gradually separating.

In the 20 days before the orbital decay, the command link could not be established, so the final communication was July 15, 2013. During this period, the satellite beacon signal of 13 GHz was received every day, so it is estimated that the power was not serious condition and the orbital tracking was normal. It is assumed that the frequency lock function of on-board receiver was easily terminated because the satellite rotation speed was fast. Unfortunately, the demonstration of de-orbit mechanism could not be carried out because the execution command was not accepted.

##### 4.1. House-keeping data analysis

The house-keeping data of all the life time are analyzed,

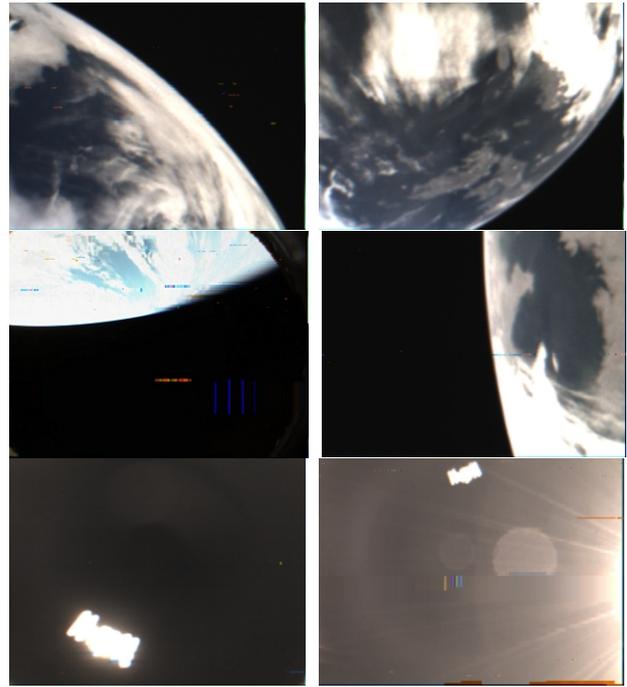


Fig. 7. Photos by RAIKO

and some statistics graphs are obtained. All the data are obtained in observation passes not including onboard recording data of invisible pass.

**1) Solar generation power:** From the data set of single pass in about 8 minutes, 5 % data from upper and lower limits each are eliminated because of avoiding the affects by noise data, and the average values are calculated in each pass. The results from all the passes, the one graph is summarized by local time history, and the other one is summarized by life time shown in Fig.8-a1) and Fig.8-a2). From the statistics, the average generation power in sunshine without solar paddles is determined as 3.38 W when eliminating the half sunshine data less than 1W. In the first 8-month operation, it can be estimated that the solar paddles are not opened because the simulation value with no-paddle is 3.14 W, and the sun sensor inside of solar paddles were not detecting the light. After Jun. 13, 2013, the value of sun sensor was increased, and the generation power was clearly improved to 5.77 W in average.

**2) Battery discharging voltage in eclipse:** From the measurements in eclipse, the minimum values of each pass are summarized in Fig.8-b1) and Fig.8-b2). after eliminating 5% data at upper and lower limits each. The typical discharge voltage is 9.6 V in normal temperature, and the lower limit is 8.0 V. In the graph of local time history, the voltage is decreasing after the finish of sunshine around 7 or 8 pm. In the graph of lifetime history, the voltage is changing up and down because of the change of battery temperature or the state of charge. After the first 6 months, the operation was limited in sunshine because real-time photo was priority mission, so there was no data of battery discharge in night side. When the state of charge is same, the voltage is usually lower under the low temperature. The characteristics of battery were normal in the lifetime.

**3) Temperature of battery and MPU:** Two temperature sensors are pasted in battery and MPU. In each observation

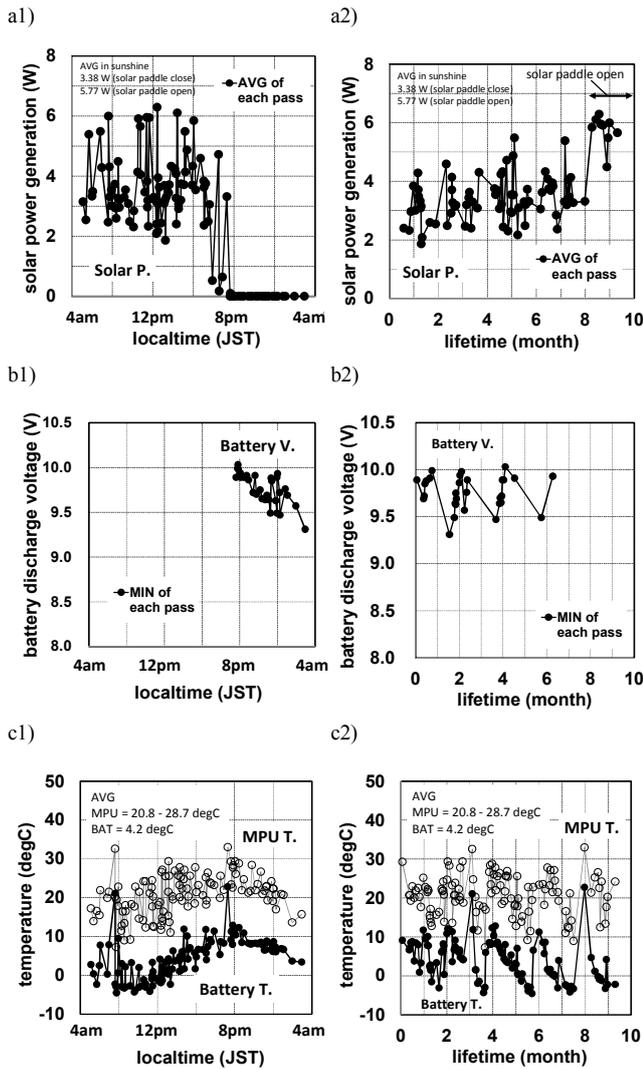


Fig. 8. Flight Data Analysis: a) solar generation power per round and in lifetime, b) battery discharge voltage per round and in lifetime, c) temperature per round and in lifetime

pass, the average temperature of battery and minimum temperature of MPU are plotted in Fig.8-c1) and Fig.8-c2). after the 5% upper and lower limit data are eliminated each. The power of MPU is turned on at the beginning of observation pass, and the temperature is gradually increasing in the pass. From all the data, the average of minimum or maximum values in each pass is 20.8 degC or 28.7 degC. On the other hand, the average of battery temperature from all the data is 4.2 degC. In the local time history, around the finish of sunshine (8 pm), the temperature values are peak, and then gradually decreased. In the life time history, the solar angle to orbital plane is changed in seasons, and the battery temperature is largely changed to high or low in some timings.

#### 4.2. Orbit History and Orbit Estimation

For the low-earth satellites less than 400-km alt, it is important to estimate the change of altitude for the operation planning. Based on the TLE of total 354 records until the end of life released by United States Strategic Command (USSTRATCOM), the orbital history was calculated. Also, using the orbit propagation software, the drag efficiency  $C_d$

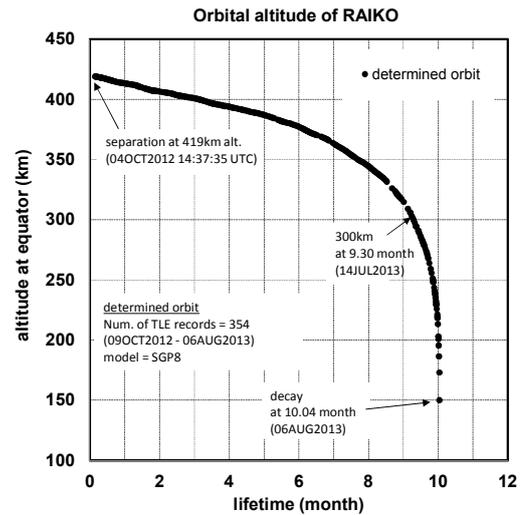


Fig. 9. Orbital altitude of RAIKO



Fig. 10. Paddle latch and inside antenna

was determined.

The orbit can be calculated from the numerical model including 6-degree gravity potential, sun and moon gravity, and air drag. For the air drag determination, the cross-section area was defined by  $0.0277\text{m}^2$ , and the mass was defined by 2.603 kg. The cross section area is 1/4 of all the surface area because the cross section area of sphere is 1/4 of surface area. From the calculation result, the suitable air drag coefficient was 2.37. The determined orbit are plotted in Fig.9.

#### 5. Found Defects and Recovery Operation

From the flight data, it was confirmed that the solar paddles and spring UHF antenna are not opened in the first 8-month operation, which should have been automatically opened at 30 minutes after the satellite separation. By this defect, the link margin of UHF command link is not sufficient, and the S-band command receiver still repeats 5-minute ON and 5-minute OFF from the limitation of solar power generation.

The solar paddles are sustained by a stainless latch part shown in Fig.10 in which the spring force of UHF antenna is working from the inside of paddles and the thin aluminum plate is being distorted. It is supposed that the lock could not be released because the friction of latch part was larger than expected. The effect of antenna spring was neglected during the development. The trouble happened because the

experiment and modification was not sufficient. The concept that the trigger of opening mechanism was concentrated into single point was supposed to be better solution, but it resulted that the inconvenient mechanical design was forced.

However, the defective of paddle open was under the supposition because this mechanism was first trial in space. To avoid critical situation, the S-band command antenna and receiver were installed as redundancy, and the communication mode about 40 minutes per day can be permitted under the power saving mode without paddle opened.

When the command communication has insufficient link margin, the macro commands were plenty prepared. For example, the sequence of camera power on, trigger writing to RAM, power off, and starting download can be carried out by only single command. The direct command of camera power on/off is not used in usual operation, the waste of power can be avoided.

For ground system, it is contributing the operation style by multi stations had been prepared before the launch. The software and observations in each station are shared using cloud storage service, and the rapid data confirmation and update are affordable. The knowledge obtained by joint operation of RAIKO will contribute in the future satellite projects.

## 6. Development Backgrounds

RAIKO was developed by a university staff and three graduate students (structure, electronics, and test support). The power control board and communication boards are developed by company, and the other electricity boards and onboard VHDL codes are developed in university. It spent total 21 months from started concept work to finish the flight model.

This satellite is not required a lot of environment test except for 4-Grms random vibration test. Total 9 days were used for environment tests including two-day vibration tests, baking by vacuum chamber (49 degC, 1e-4 Torr, 72 hours), and thermal vacuum test (-5 degC to +50 degC, 1e-4 Torr, 4 days including 5 cycles). The size of satellite is very small, so the almost tests can be carried out only in university equipment or neighbor public test facility.

This satellite is third satellite by Tohoku University, and the experience of previous 50-kg satellites are inherited. The electricity boards are using same concept, and the only board size is minimized for RAIKO. Also, the procedure documents of electricity test can be made after the small modification. The FPGA onboard coding and ground operation software can be finished less than 20% time compared to be developed from the first.

## 7. Conclusions

This paper showed the mission and system specifications of RAIKO. In the total 10-month operation, telemetry data were successful received in total 123 passes, in which total 63 photo images were obtained and maximum 100 kbps (200 kbps) downlink was successful. From the analysis result of

house-keeping data, the solar generation power in sunshine was 3.38 W (no paddles) to 5.77 W (with paddles) in average, the temperature of onboard computer was in the range of 20.8 to 28.7 degC, and the battery temperature was 4.2 degC in average. The real flight data from the 10-month operation will be precious information for future nanosatellite projects.

## Acknowledgement

This work was the part of UNIFORM Project supported by The Ministry of Education, Culture, Sports, Science and Technology (MEXT).

## References

- 1) Yagisaya, H., Sakamoto, Y., Tanabe, Y., Sugimura, N., Kuwahara, T., Yoshida, K.: System Description and Result of Ground Test for Cubesat RAIKO, *Proceedings of the UN / Japan Workshop and the 4th Nanosatellite Symposium*, Nagoya, Oct. 2012, paper: NSS-04-0310.
- 2) Sakamoto, Y., Kuwahara, T., Tomioka, Y., Fukuda, K., Yoshida, K.: Evaluation of Power Control System for Micro and Nano Satellites by Hardware- in- the- Loop Simulator, *The 26th Annual AIAA/USU Conference on Small Satellites*, Logan, UT, USA, Aug. 2012, paper: SSC12-X-8.