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Development and operations of nano-satellite FITSAT-1 (NIWAKA)

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ABSTRACT

FITSAT-1 (NIWAKA) is a 10 cm^3 satellite that was deployed from the International Space Station (ISS) on October 5, 2012. It continued to operate until its orbit decayed on July 4, 2013. The main FITSAT-1 mission was to demonstrate a high speed transmitter module developed by our group (115.2 kbps, 5.84 GHz, FSK, 2 W RF output). Each of the JPEG VGA image (640 × 480 pixels) taken at the time of deployment was received in 2–6 s. The second mission was to make the satellite twinkle as an “artificial star” using high-output LEDs and investigate the possibility of visible light communication between the satellite and the ground. This light from the satellite was photographed in many places. Our FITSAT team succeeded in acquiring the light signal using a photomultiplier attached to a telescope. Moreover, we discovered that the FITSAT-1 rotation speed gradually increased.

1. Introduction [1,2]

FITSAT-1 (NIWAKA) is a 10 cm^3 satellite that was deployed from International Space Station (ISS) on October 5, 2012. It continued to operate until its orbit decayed on July 4, 2013. The main FITSAT-1 mission was to demonstrate a high speed transmitter module developed by our group (115.2 kbps, 5.84 GHz, FSK, 2 W RF output). Each JPEG VGA image (640 × 480 pixels) taken at the time of deployment was received in 2–6 s. The 5.84 GHz signal was received not only by our ground station, but also at Niigata, Japan, Ageo, Japan, Vermont, USA, and Bochum, Germany. The AMSAT-DL team succeeded in decoding 14 of the 20 images transmitted with the 5.84 GHz signal using a 20 m parabolic antenna at Bochum Observatory. The second mission was to make the satellite twinkle as an “artificial star” using high-output LEDs. These experiments were controlled by remote commands from the ground station using the 437 MHz and 1.26 GHz ham radio bands. The light from the satellite was pictured in Kurashiki Japan, Seoul Korea, Ebina Japan, Toyama Japan (movie), Kimizu Japan, Ehime Japan, and Kumamoto Japan. Our FITSAT-team succeeded in extraction of the light signal using a photo-multiplier attached to a telescope. Moreover, we discovered that FITSAT-1 is increasing its rotation speed from stored data in the satellite.

2. Structure

2.1. Overview

The top of FITSAT-1 has a 5.84 GHz patch antenna, 50 green LEDs, and a hole for the front camera lens (Fig. 1).

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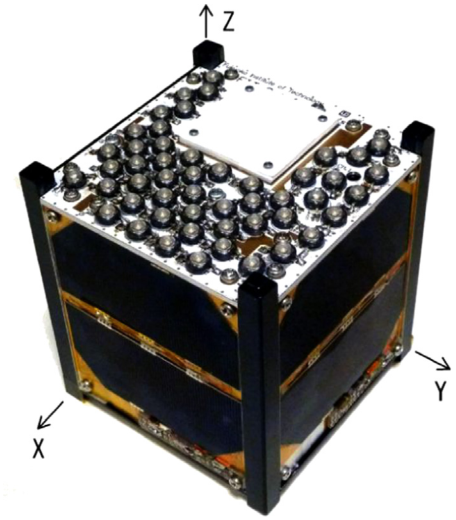

Fig. 1. Overview of FITSAT-1.

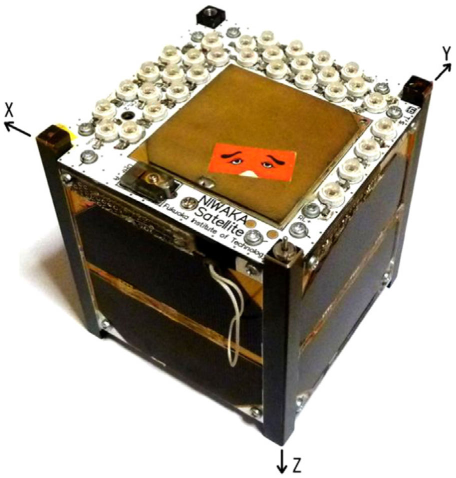

Fig. 2. Bottom view of FITSAT-1.

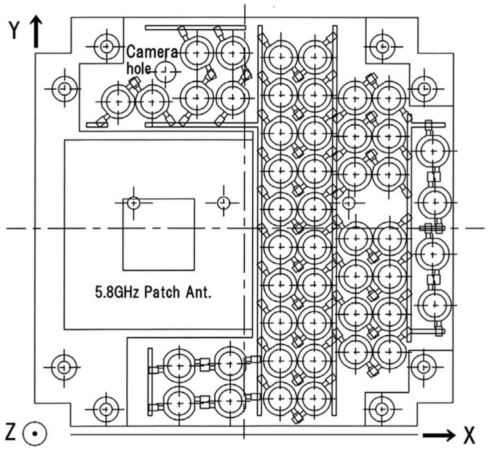

Fig. 3. Top panel (+Z plane).

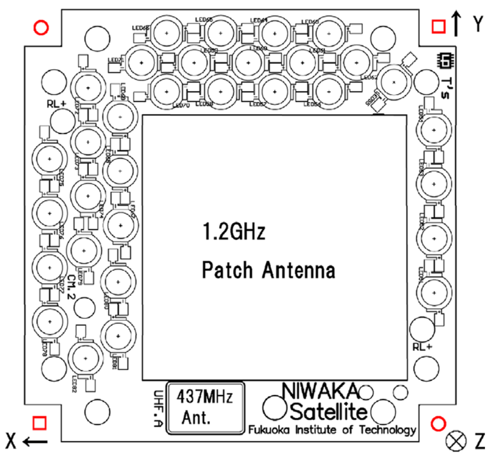

Fig. 4. Bottom panel ($-Z$ plane).

The 5.84 GHz patch antenna is 17 mm^2 copper strip protected by a teflon sheet. It generates a right circularly polarized wave. The 50 green LEDs are driven by pulses of over 200 W. Each of the four sides has two solar cells connected in series (Figs. 5 and 6). Each side generates 2.3 W (4.74 V $\times$ .487 A) in sunshine. The $-Y$ side also has a hole for a flight pin which is removed just befor flight and a conenctor for monitoring internal states. The bottom has a 1.26 GHz patch antenna, 32 red LEDs, a hole for the rear camera lens, and a hole for the 437 MHz whip antenna which was extended 30 min after deployment (Fig. 2).

The four corners of the bottom shown in Fig. 4 have deployment switches (red squares) and separation springs (red circles). The deployment switches turn on at deployment. The separation springs increase the distance between the satellites.

2.2. Body

The body of FITSAT-1 was made by cutting a section of 10 cm^2 aluminum pipe. Both ends of the cut pipe are covered with aluminum panels as shown in Fig. 7. The aluminum pipe is made of aluminum alloy A6063 and the panels are made of aluminum alloy A6061. The surface of the body is finished with black anodic coating (MIL-A-8625 Type III Class 1). The CubeSat slide rails and side panels are not separate, but rather are formed as a single unit. The thickness of the square pipe is 3 mm. In order to make the 8.5 mm^2 CubeSat rails, 5.5 mm^2 aluminum sticks are attached to the four corners of the square pipe.

2.3. Deployment switch

The deployment switch consists of a microswitch and a brass lever as shown in Fig. 8. In the deployer, the brass lever is pushed and the microswitch is turned off. When the satellite is released from the deployer, the brass lever is released, and the microswitch is turned on.

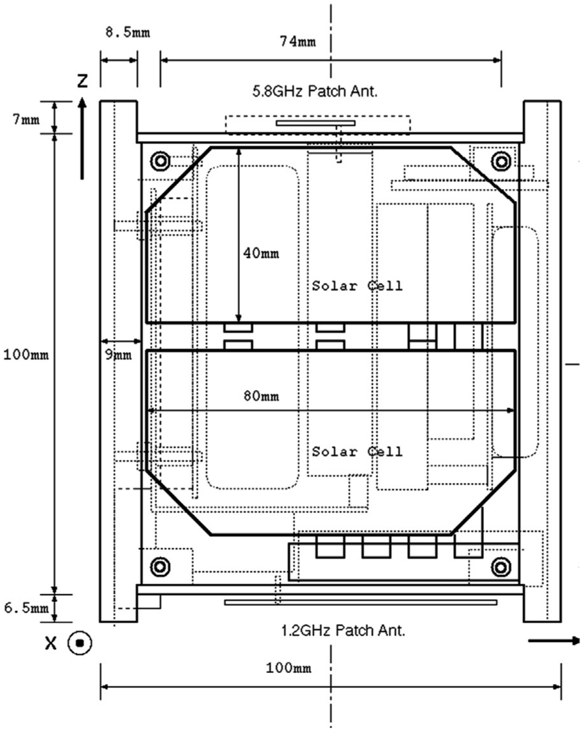

Fig. 5. Sides +X, −X, +Y.

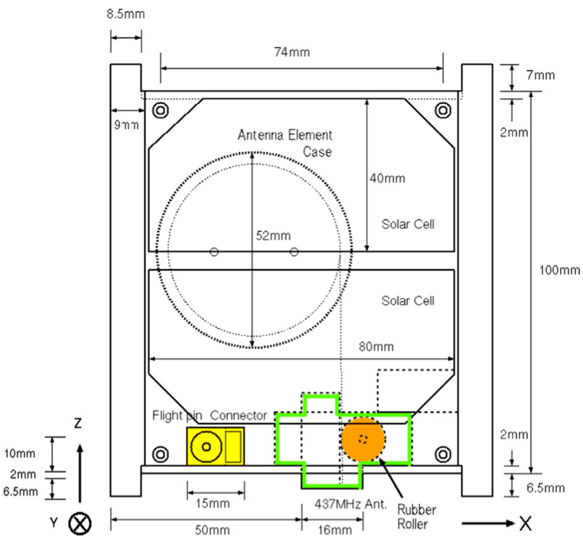

Fig. 6. Side −Y.

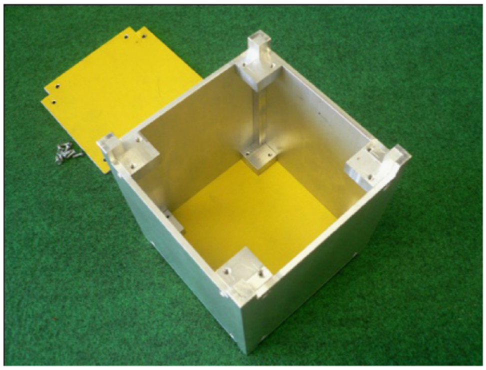

Fig. 7. Cutting square pipe.

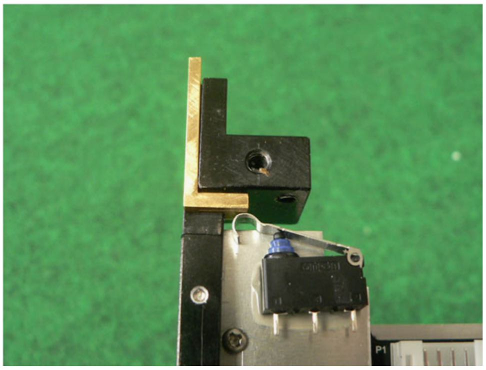

Fig. 8. Deployment switch.

Fig. 9. 437 MHz band antenna extender.

2.4. Antenna extender for 437 MHz band

The antenna element for the 437 MHz band is a .2 mm thick, 4 mm wide and 18.5 cm long phosphorus bronze strip. It is stored inside of the body in a spiral (Fig. 9). The antenna element is extended 17 cm through the antenna hole by a rubber roller on a small servo motor. The RF power is fed at the top of antenna extender with a small impedance matching circuit. The motor switch for the antenna extender is turned on 30 min after deployment.

2.5. Arrangement of main components

Fig. 10 shows the arrangement of the main components. Four batteries are mounted on the back of main

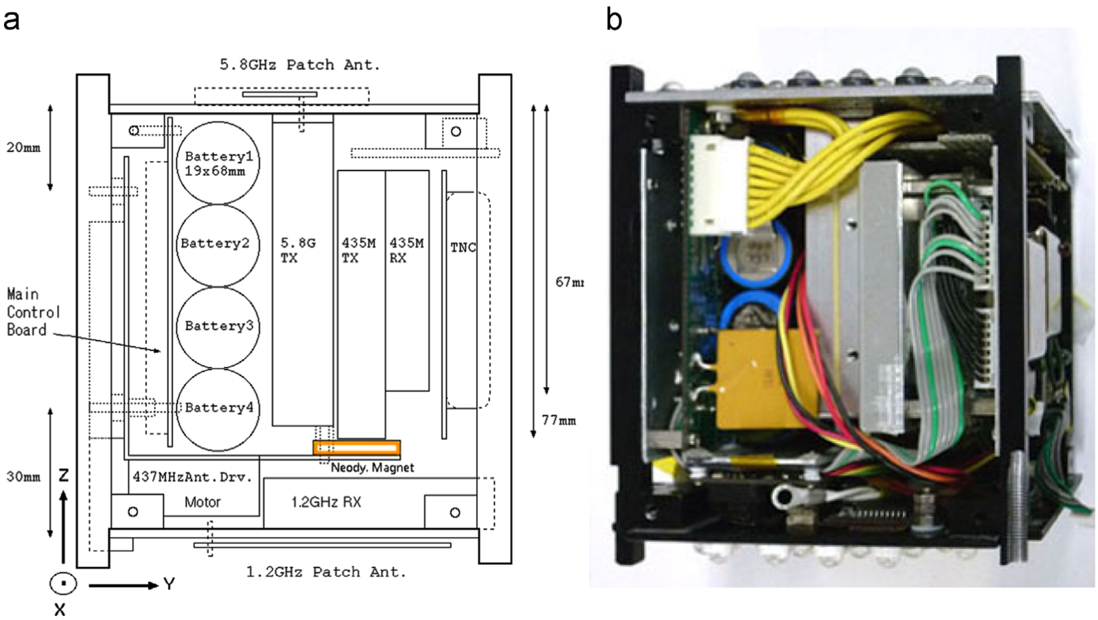

Fig. 10. Arrangement (view from $+X$). (a) Drawing and (b) Photograph.

control board. The 5.84 GHz transmitter module is placed just behind the 5.84 GHz pach antenna. The pach antenna and the 5.84 GHz module are connected with a short rigid cable. The 437 MHz TX, RX and TNC are placed adjacent to the 5.84 GHz module. The 1.26 GHz RX is placed just behind the 1.26 GHz patch antenna. The neodymium magnet is placed almost at the center of the *XY* plane near the bottom panel (Fig. 10(a)).

3. Orbit and posture control system

The orbit of the ISS is inclined 51.6 degrees from the equator. Since FITSAT-1 is deployed from the ISS, its orbit will be almost the same as that of the ISS. As a result, FITSAT-1 will travel between 51.6 degrees south latitude and 51.6 degrees north latitude. Since a neodymium magnet is mounted in FITSAT-1, the top panel ($+Z$ plane) of the body always faces magnetic north like a compass. The top panel has a 5.84 GHz patch antenna, green LEDs, and a hole for the front camera lens. When FITSAT-1 rises above the horizon, it will be to the south of the Fukuoka ground station, and both the 5.84 GHz antenna and the LEDs will be aimed accurately enough by the magnet aligning itself with the Earth's magnetic field (Fig. 12). The small circles at the front of satellites in Fig. 12 show the beam of the 5.84 GHz patch antenna. The LED beam is almost the same as the beam of 5.84 GHz. The small corners in front of satellites show the front camera angle.

The 437 MHz antenna element is extended 17 cm by a small servomotor through the antenna hole in the bottom panel ($-Z$ plane) like a tail. When FITSAT-1 passes to the north of the Fukuoka ground station, the antenna appears to stand upright. The vertical polarization of the transmitted radio wave coincides with the antenna of the ground station and the gain becomes the maximum. On the south pass, we will see the antenna element from the axial direction and thus the gain will be at the minimum. This means that in the northern hemisphere, the south pass will be optimal for the 5.84 GHz high speed transmission and flashing green LED experiments (red line in Fig. 12), and the north path will be optimal for sending commands and receiving stored telemetry data at 437 MHz. The 1.26 GHz patch antenna is designed as a backup system for receiving remote commands. The antenna faces space in the northern hemisphere. But the beam of the patch antenna is very wide. The antenna can receive remote commands on the north path.

The diameter of the neodymium magnet is 2 cm and its thickness is 5 mm. We measured the period of swing by suspending FITSAT-1 from the ceiling. The period is 36 s in 30 degree swing, and 50 s in 180 degree swing. When the satellite swings, the change of the magnetic field through the satellite causes eddy currents, and these currents will function as a damper. Since we want even more damping to suppress swing, we attached three permalloy strips (75×70 mm $\times 1$, 20×70 mm $\times 2$) as shown in Fig. 11(a) as a hysteresis damper. But we did not have enough time to measure the damping effect.

In the southern hemisphere, the orientation is the opposite. The bottom panel ($-Z$ plane) faces the ground, so the north pass is optimal for the flashing red LEDs experiment and receiving 1.26 GHz commands and the south path is optimal for sending commands and receiving stored telemetry data at 437 MHz.

4. Electrical power system

Fig. 13 shows the FITSAT-1 electrical power system. It consists of solar cells, a maximum power point tracker, DC–DC converters, a single lithium ion battery, three series lithium ion batteries, lithium ion battery controllers, two deployment switches, and a flight pin. The single battery supplies power for 5 V loads, which consist of the beacon

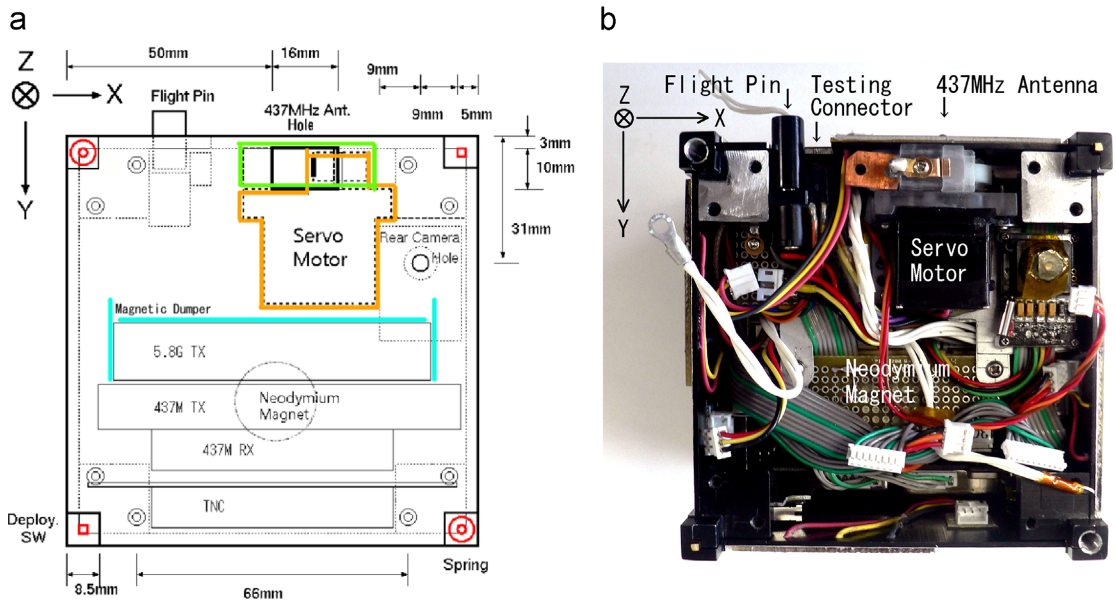

Fig. 11. Arrangement (view from $-Z$). (a) Drawing and (b) Photograph.

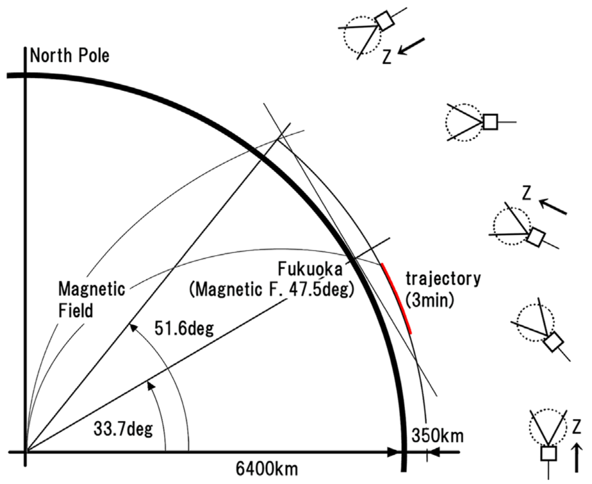

Fig. 12. Posture on the orbit. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

transmitter, remote command receivers, and data handling computers. The three batteries connected in series supply power for the 5.84 GHz transmission and flashing LEDs experiments. We used a common DC plug as the flight pin (Fig. 14). When the flight pin is inserted into the jack, it cuts off all battery circuits. If a DC 5 V plug is inserted instead of the flight pin, it charges all batteries in place of solar cell charging. The charging voltages are monitored by the monitor connector.

Solar cells are attached to four sides ($+X$, $+Y$, $-X$, $-Y$) of the satellite. Each of these sides has two solar cells connected in series and generates 2.3 W (4.74 V × .487 A) maximum of electric power. The generated power is withdrawn by a maximum power point tracker and fed to the 5 V load and the single lithium ion battery. The single lithium ion battery is charged until it reaches 3.8 V. The charging current decreases after this voltage is reached and then the three batteries in series are charged. The single battery supplies the 5 V load through a DC–DC converter in eclipse. The three batteries in series are protected from overcharging and over discharging by a battery controller IC (SII S-8233BAFT). If the voltage of the single battery goes under 3.5 V, the three series batteries supply power the 5 V load. That is, the priority of supplying 5 V load is (1) the solar cells, (2) the single battery, and (3) the three series batteries.

JAXA requires that all batteries have three independent switches connected in series (a flight pin and two deployment switches) on both the ground side and source side. We implemented this requirement using electronic switches. Since these three switches are connected in series, none of the batteries supply power until all of these switches have been turned on.

Fig. 15 shows the four lithium ion batteries (Hitachi Maxell INR18650PB2, 1450 mA H). The top one is used for the 5 V loads and other three cells are connected in series to supply power for the 5.84 GHz transmitter and flashing LEDs. The small elements attached to the batteries (Fig. 15) are thermal fuses connected in series.

5. Communication system and data handling system

5.1. Communication system

The communication system consists of two uplinks and four downlinks as shown in Fig. 16. The uplinks are used for remote commands. The 437 MHz band uses AX.25 packet at 1200 bps, while the 1260 MHz band uses DTMF signals. The 1260 MHz uplink is designed as a backup system for the 437 MHz band which fails to extend 437 MHz antenna.

As a downlink, FITSAT-1 (NIWAKA) always sends a CW beacon signal at 437.250 MHz. This signal includes

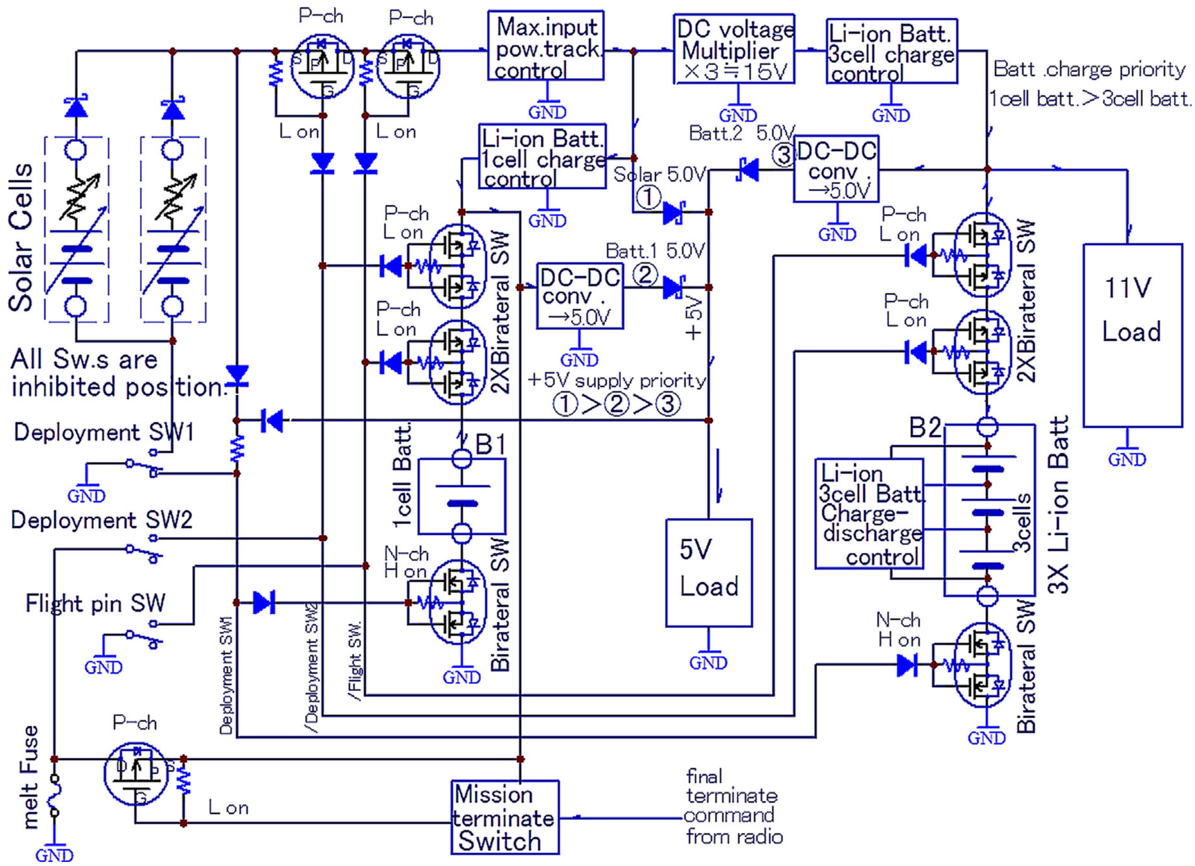

Fig. 13. Power system.

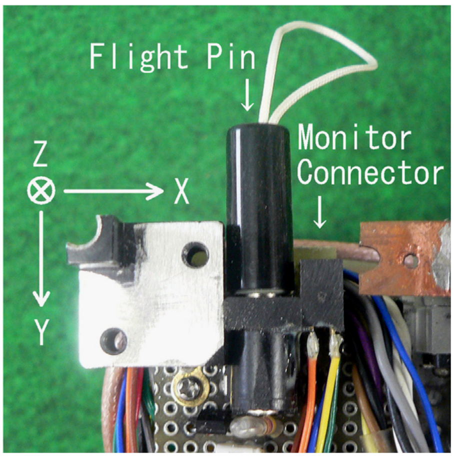

Fig. 14. Flight pin.

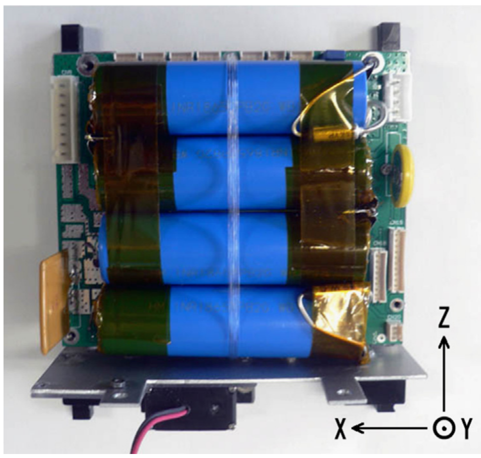

Fig. 15. Batteries.

telemetry data such as voltages and currents of solar cells and batteries, temperatures, timestamp, and other FITSAT-1 states. FITSAT-1 has another downlink, at 437.445 MHz, which transmits AX.25 packets at 1200 bps. It is used to send stored telemetry data. The light of the flashing LEDs is also a kind of downlink. FITSAT-1 has a high speed downlink system for image data. It uses 115.2 kbps FSK at 5.840 GHz. It can transmit a VGA (640×480 pixels) jpeg image within 2–6 s. Table 1 summarizes the FITSAT-1 radio modules.

5.2. *Relationship between communication and data handling system*

Fig. 17 shows the relationship between the communication system and the data handling system. Remote commands are sent as AX.25 packets at 1200 bps using the 437 MHz band from the ground station. The packet signals are received by the 437 MHz band FM receiver and decoded by the TNC. The RX CPU analyzes the commands and outputs signals on the command bus line which connects between CPUs and peripherals. The results of the remote commands are monitored by the TX CPU and send its acknowledge to the FM transmitter through the TNC. The TX CPU samples and stores the sensor data according to the received commands. When the RX CPU receives a download data command, it sends the signal on the command bus line. TX CPU receives the command, and sends the stored telemetry data to the FM transmitter through the TNC. The FM transmitter sends the AX.25 packets at 437.445 MHz with an 800 mW output. The 1.26 GHz band RX also receives remote commands by DTMF signal. These signals are decoded by a DTMF decoder and sent to the backup CPU. The backup CPU analyzes the command, and outputs signals on the command bus line.

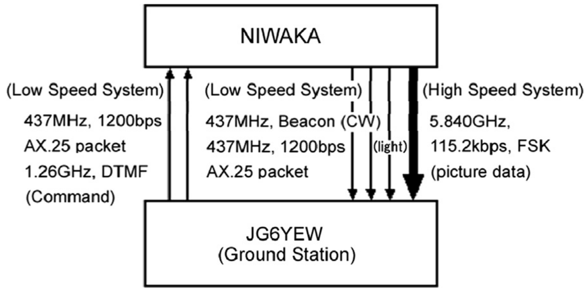

Fig. 16. Up-links and down-links.

The camera CPU receives the signal on the command bus line and executes the command. The shutter command takes 20 photographs and stores them in external memory. The image transmission command reads 20 images from the memory and transmits the data over the 5.84 GHz FSK transmitter.

5.3. High speed transmitter module

The 5.84 GHz high speed transmitter module was developed by our group (Fig. 18). The module generates a

Table 1
Radio modules.

	Frequency	Signal	
(Receiver)			
430 MHz RX	436–438 MHz	1200 bps, AX.25- packet (AFSK)/DTMF	
1.2 GHz RX	1260–1270 MHz	DTMF	
(Transmitter)			Power
430 MHz CWTX	437.250 MHz	CW	100 mW
430 MHz FMTX	437.445 MHz	1200 bps, AX.25-packet (AFSK)	800 mW
5.8 GHz TX	5.840 GHz	115.2 kbps (FSK)	2 W

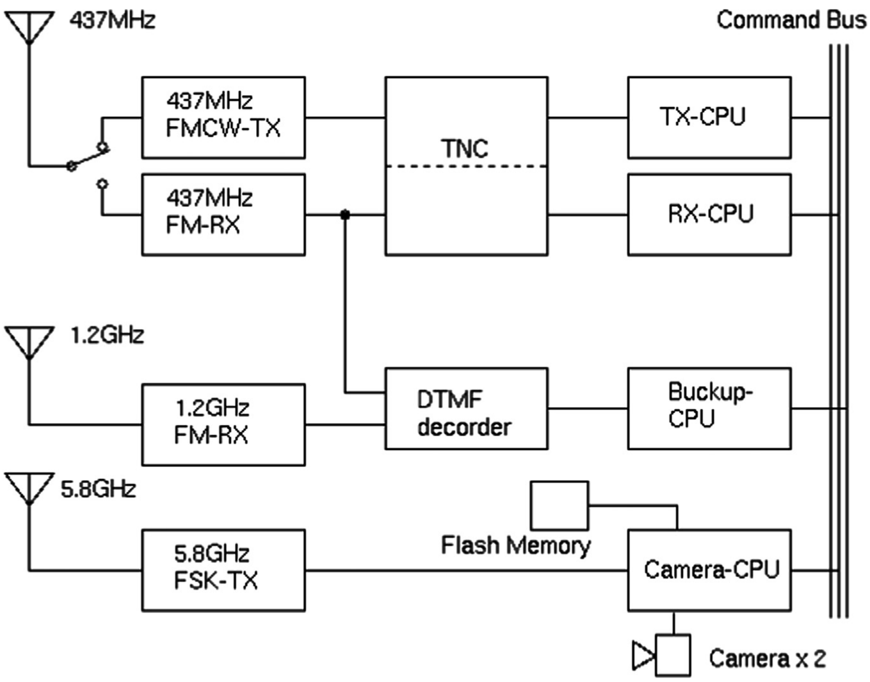

Fig. 17. Communication and data handling system.

2 W RF output from a 15 W DC input. It can send digital signals at 115.2 kbps. A simple FSK modulation is used. Although its frequency deviation is ±50 kHz, 99% of the energy is spread over 415 kHz (Fig. 19). The 90% energy band may be less than 300 kHz.

Fig. 20 shows the block diagram of the 5.84 GHz transmission system. Two cameras (C1098, Silent System) are connected to this radio module. The PIC16F886 micro-controller not only controls the transmitter PLL but also controls these two cameras (front-camera, and rear-camera). These two cameras take photographs every 5 s alternatively on a shutter command and 20 photographs are stored in external flash memory as jpeg images. The MPU also reads the image data from the memory in response to a download image command, and sends the 20 images to the FSK modulator.

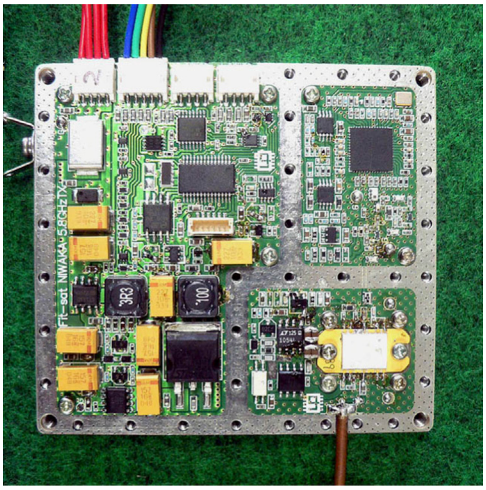

Fig. 18. 5.84 GHz transmitter module.

5.4. High output LEDs

The top panel (+*Z* plane) has 50 green 3 W LEDs (Fig. 3). Two green LEDs are connected in series, and 25 of these series LED pairs are connected in parallel (Fig. 21). A current of more than 20 A is applied and thus the LEDs are driven with pulses that exceed 200 W. The bottom panel (−*Z* plane) has 32 red 3 W LEDs (Fig. 4). Four red LEDs are connected in series, and eight of these sets of series LEDs are connected in parallel. A current of about 8 A is applied and the LEDs are driven with roughly 100 W pulses (Fig. 22).

There are two LED drive modes. In one mode, the LEDs flash Morse code patterns. Since the Morse code is modulated with a 1 kHz signal, if the light is observed on the ground and converted to an electrical signal, a Morse code audio output with a 1 kHz tone frequency can be generated simply by connecting it to an audio amplifier and speaker. The duty of the 1 kHz pulse is 15%, so average power of green LEDs is $200 \times .15 = 30$ W and that of the red LEDs is $100 \times .15 = 15$ W.

The other mode is the faint light detection mode. In this mode, the LED drive current is modulated with both a 10 Hz signal and a 5 kHz signal. The light is received by a photo-multiplier equipped telescope aligned with a 5.84 GHz parabolic antenna. The 10 Hz signal has duty ratio of 30%, and 5 kHz has duty ratio of 50%. So, the average power of the green LEDs will be almost $200 \times .3 \times .5 = 30$ W and that of the red LEDs will be 15 W.

6. 5.84 GHz high speed transmission experiments

6.1. Image data

A jpeg image is transmitted using 128-byte packets. Fig. 23 shows the format of the image data. The first 4

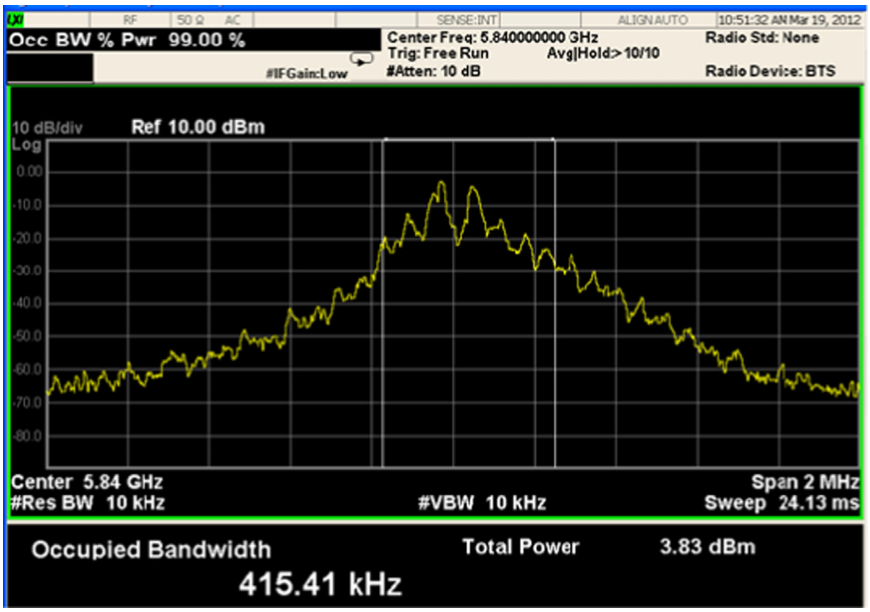

Fig. 19. Spectrum of 5.84 GHz signal.

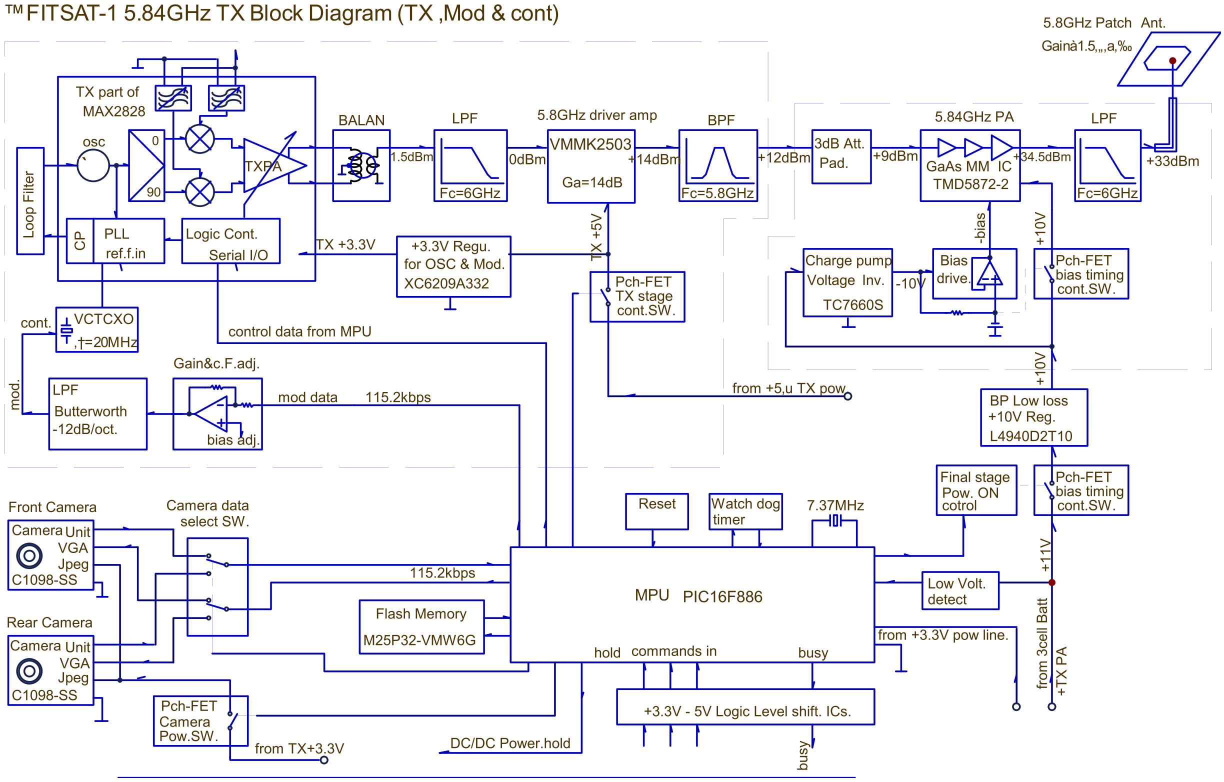

Fig. 20. 5.84 GHz transmitter module.

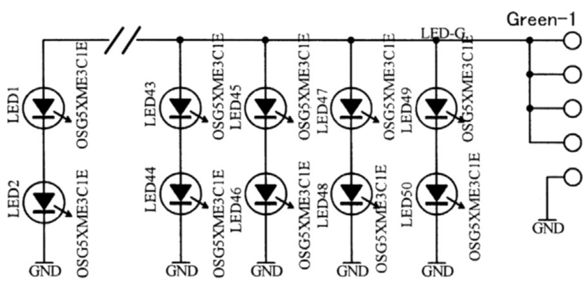

Fig. 21. Green LED panel.

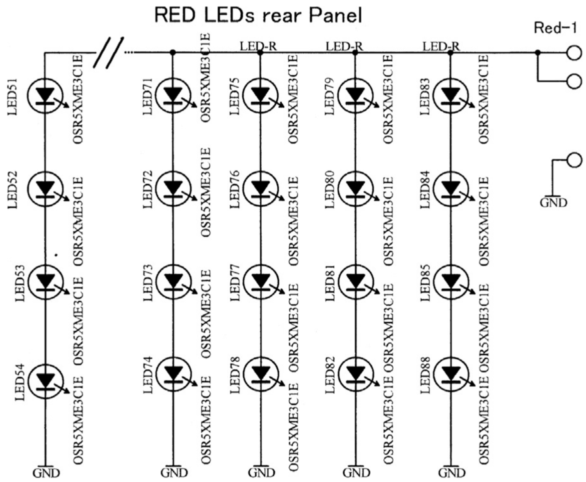

Fig. 22. Red LED panel.

bytes and the last 2 bytes do not hold jpeg data. Thus the data size of all the packets except the last is 122 bytes. A jpeg image starts with "FFD8" and ends with "FFD9". A jpeg image is reconstructed by connecting the data parts of each packet, which is acquired by removing the first 4 bytes and the last 2 bytes. Twenty VGA images are sent at a time. It takes 2–6 s to send each image. One packet (128 byte) is sent in 12 ms at 115.2 kbps. There is an 8 ms interval between each packet to read the 122 bytes data from the flash memory. Thus packets are sent every 20 (=12+8) ms. When we receive the signal, we hear a 50 Hz tone from the speaker. Due to the CubeSat weight limit, we could not attach an adequately large heat sink for the 5.84 GHz transmitter. So we inserted a 5 s pause between images to prevent heat buildup.

Packet ID (2 byte)	Data Size (2 byte)	Photo Data (122 byte)	Verify (2 byte)

(e.g.) 00 00 7A 00 FF D8 FF E0 ...
01 00 7A 00 09 0A 16 17 ...
...
12 34 56 00 ..... FF D9 ...

Fig. 23. Packet of image data.

Fig. 24. LNB.

Fig. 25. AR8600 receiver and FSK detector.

6.2. Image receiving system

The 5.84 GHz receiving system consists of an LNB (Fig. 24), an AR8600 receiver, an FSK detector (Fig. 25) and a computer for reconstructing the images. The LNB is attached to the focus of a parabolic antenna (Fig. 26). The LNB converts the 5.84 GHz signal to 440 MHz. The AR8600 receiver tunes the 440 MHz signal and outputs a 10.7 MHz intermediate frequency signal (Fig. 27). The FSK detector detects the 10.7 MHz signal and generates serial data for the computer. The parabolic antenna is mounted on the theodolite for the telescope. The theodolite can turn the parabola to a point in the sky accurately, but it cannot move fast enough to track the satellite. We turned the parabola to a point on the orbit, and then waited to receive the signal. When we received the signal, we started tracking. Although, it was impossible to track fully, we were able to receive 4 or 5 of the 20 images at a time.

The LNB consists of a wave guide, a patch antenna, 5.84 GHz amplifier, 5.4 GHz local oscillator, mixer, and 440 MHz amplifier. The patch antenna is the same one as the satellite, but reversed. Since the parabola reflects the signal, right circular polarization is changed to left circular polarization.

As the receiving frequency 5.84 GHz is very high, the Doppler effect is more than 150 kHz. Though the FSK detector has an indicator to show the frequency shift of Doppler effect, the tuning of AR8600 receiver was very difficult. As AR8600 receiver can set the receiving frequency by serial port, we developed a Doppler compensation system.

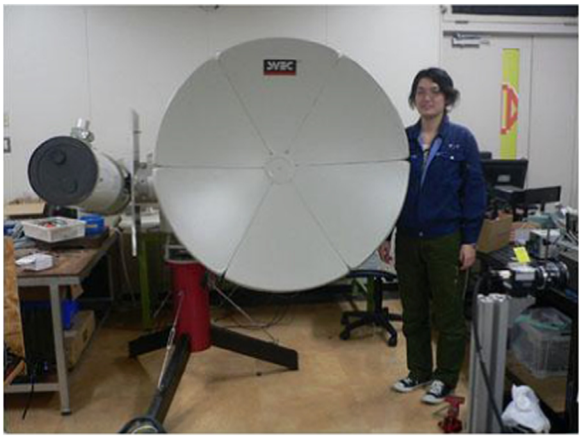

Fig. 26. Parabola mounted on theodolite.

6.3. Received images

FITSAT-1 has both a front camera and a rear camera. The shutter command takes 20 photographs every 5 s, alternating between cameras. The front camera mainly took photographs of the earth, and the rear camera took photographs of the ISS and space. Fig. 28 shows a photograph taken by the rear camera at 5 s after deployment. This photograph shows the ISS solar panels and the Japanese Experiment Module "Kibo" and its robot arm.

Fig. 29 was taken by the front camera 10 s after deployment. FITSAT-1 was deployed between Hawaii and the west coast of the US. The local time was morning. FITSAT-1 was in the borderline between sunlight and night. Thus the photograph has a dark side and a light side. The dark space can be seen at the upper left.

7. Optical communication experiments [3]

7.1. Flashing LEDs

We started the flashing LEDs experiment on November 21, 2012 using faint light detection mode. The first artificial light from space was photographed in Kurashiki, Japan and Seoul, Korea. Fig. 30 is a photograph of the flashing FITSAT-1 LEDs taken by Mr. Kazuhisa Mishima of Kurashiki Science Center. Fig. 31 shows a photograph of the flashing Morse code mode taken by Mr. Mishima.

Fig. 32 was taken by Mr. Tsuyoshi Watanabe at Ebina city, Japan. The faint light detection mode flashes at 10 Hz, and the shutter speed is 2 s, so there are 20 dashes in the image. Since the duty is 30%, the ratio of dash to blank is 3:7.

7.2. Detecting signal by photomultiplier

We were able to detect the light from FITSAT-1 by a photomultiplier mounted on a 250 mm diameter telescope. Fig. 33 shows the light signal in this faint light detection

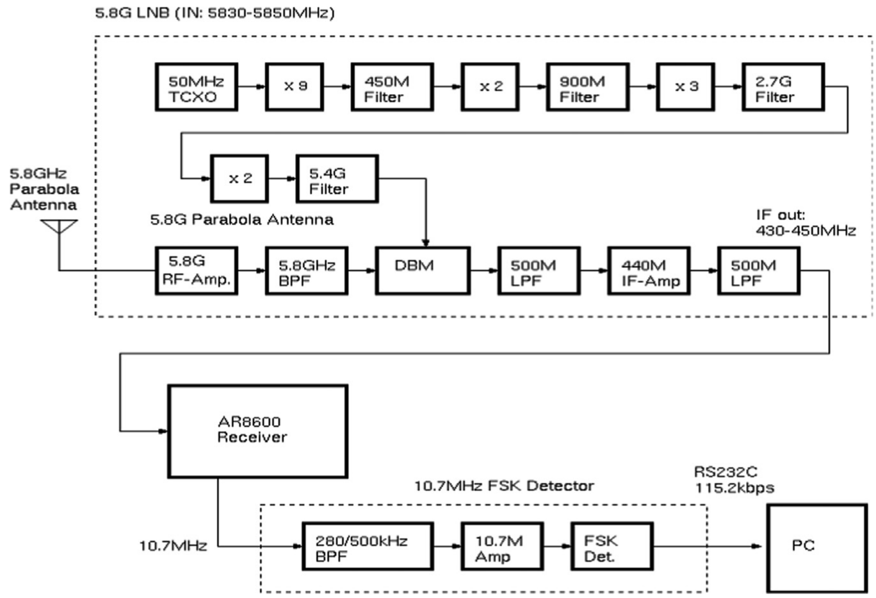

Fig. 27. 5.84 GHz receiving system.

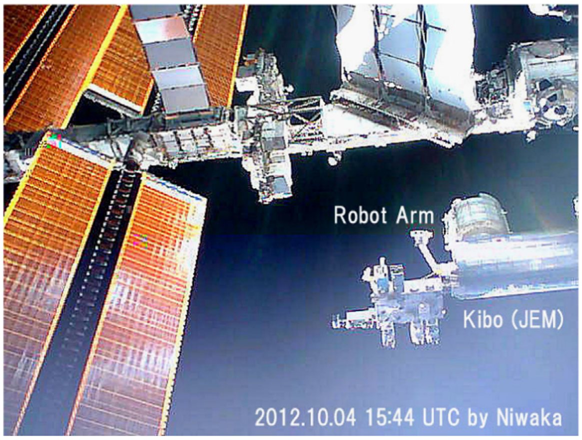

Fig. 28. International Space Station.

Fig. 29. Ground.

Fig. 30. Flashing NIWAKA at Kurashiki, Japan.

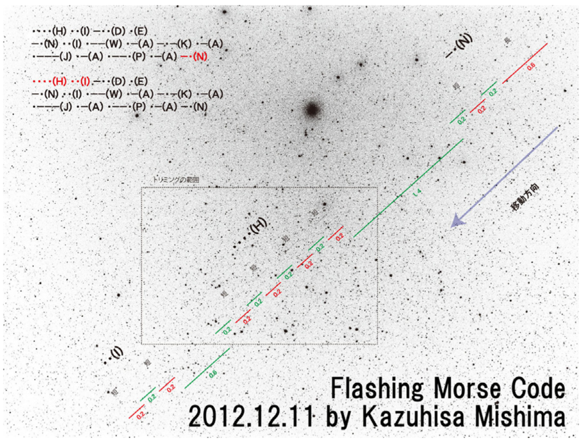

Fig. 31. Flashing Morse code.

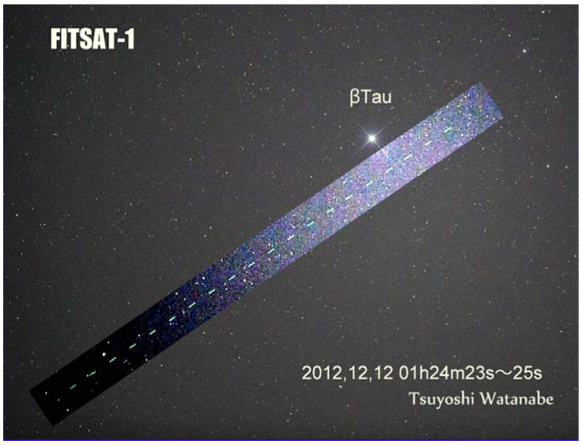

Fig. 32. Flashing NIWAKA at Ebina, Japan.

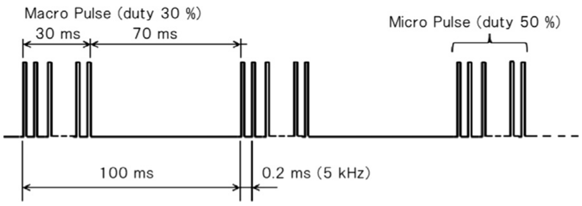

Fig. 33. Light signal in faint light detection mode.

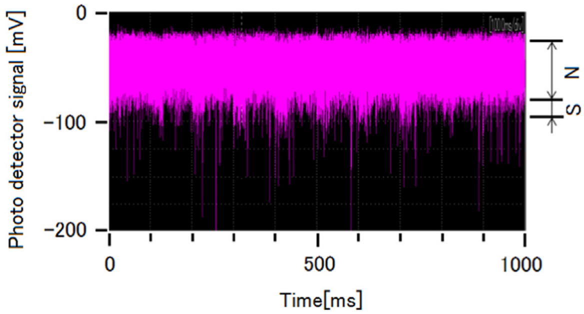

Fig. 34. Output of photomultiplier.

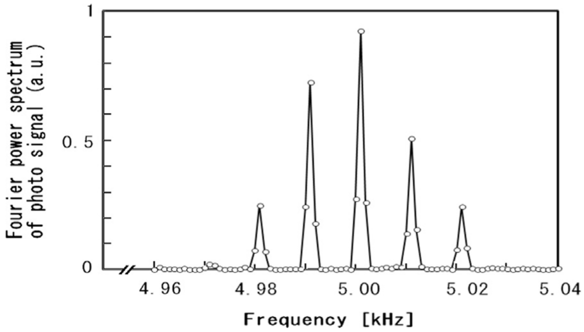

Fig. 35. Fourier transformation of the light signal.

mode. The light flickers at 10 Hz with a 30% duty, and the light is also modulated at 5 kHz with a 50% duty. That is, a light pulse of .1 ms with .1 ms blank continues for 30 ms, then a blank period continues for 70 ms. This series iterates with a 2 min cycle.

Fig. 34 shows the output of the photomultiplier. The data was stored by a data logger during a 100 s period. There is optical data here for a 1 s period. This means that the light from FITSAT-1 crosses the surface of photomultiplier in 1 s. The data was very noisy. The S/N ratio was .1. This noise may be not only the light of other stars, but also urban lights reflected by the sky.

Fig. 35 shows the Fourier transformation of the light signal. There is a peak at 5 kHz and the side bands appear every 10 Hz. The microstructure of the band width is 1 Hz. This is the inverse of the number of 1 s measurement. The macrostructure of the side bands, that is the envelope of the side bands is about 30 Hz. This coincides with the inverse of the number of 30 ms macropulses. Thus we were able to identify the signal from the photomultiplier as being the light from FITSAT-1.

8. Telemetry data

8.1. Beacon signal

The beacon signal transmits the current telemetry data using Morse code. It consists of six units. The first one starts with “HI DE NIWAKA JAPAN”, and is followed four telemetry data items beginning with “S1”, four telemetry data items beginning with “S2”, … , and four telemetry data items beginning with “S5”. There is a 14 s blank between each unit. The period from “HI …” to “s54” is about 2.5 min. Two receivers (437 MHz and 1.26 GHz) operate during these 14 s blank periods and receive remote commands from the ground station (Table 2).

The four telemetry data items in each unit such as “s11”–“s14” are one byte of data represented as two hexadecimal digits. These data items are sent by standard Morse code. The actual values are computed as follows:

s11: RSSI of 437RX	s11 × (5/256) [V]
s12: Total voltage of solar panel	s12 × (5/256) [V]
s13: Total current of solar panel	s13 × (5/256) × .4 [A]
s14: Voltage of one cell battery	s14 × (5/256) [V]
s21: Current of one cell battery	
(s21 × (5/256) − 2.5) × .4 [A]	(> 0: discharge)
	(< 0: charge)
s22: Voltage of 3 cell series battery	s22 × (5/256) × 3 [V]
s23: Current of 3 cell series battery	
(s23 × (5/256) − 2.5) × 10 [A]	(> 0: discharge)
(s23 × (5/256) − 2.5) × .1 [A]	(< 0: charge)
s24: Standard voltage of 2.5 V	s24 × (5/256) [V]
s31: Voltage of solar panel (+X)	s31 × (4.5/256) × 2 [V]
s32: Voltage of solar panel (+Y)	s32 × (4.5/256) × 2 [V]
s33: Voltage of solar panel (−X)	s33 × (4.5/256) × 2 [V]
s34: Voltage of solar panel (−Y)	s34 × (4.5/256) × 2 [V]
s41: Temperature of 3 cell series battery	s41 × ((4.5/256) − .5)/9.01 [°C]
s42: Temperature of one cell battery	s42 × ((4.5/256) − .5)/9.01 [°C]
s43: Temperature of +Z panel	s43 × ((4.5/256) − .5)/9.01 [°C]
s44: Temperature of −Z panel	s44 × ((4.5/256) − .5)/9.01 [°C]
s51: RSSI of 1.26 GHz	s51 × (4.5/256) [V]
s52–s54: Time after last reset	s51 × 65536 + s52 × 256 + s53 [s]

8.2. Temperature changes in the beacon signal

Daily reports on the beacon signal from Australian ham radio operator VK5HI revealed an interesting result. NIWAKA has four temperature sensors to monitor the batteries and LED panels. All of the temperatures had a peak around January 4, 2013 (Fig. 36). On that day, the orbital plane of FITSAT-1 was turned towards the sun the most. The sun illuminated FITSAT-1 for a longer period and FITSAT-1 went into the shade of the earth for a shorter period. In order to measure the average temperature, we used the data as close to the midpoint between sun and shade as possible.

8.3. Stored telemetry data

FITSAT-1 can store a set of 90 telemetry data items that can be retrieved by remote command. There are two types of sampling. The first one is "second sampling" shown in Table 3. It can vary the sampling rate from 1 s to 15 s, so it can measure from 90 s to 1350 s (22.5 min). It is mainly used to measure the movement of FITSAT-1 from the voltage changes of the solar panels. The second one is "minute sampling" in Table 4. It can vary the sampling rate from 1 min to 15 min, so it can measure 90 min (almost one full orbit around the world) to 22.5 h (15 orbits). It is mainly used to measure changing temperatures. The stored data are transmitted using 1200 bps AX.25 packets at 437.445 MHz.

Table 2
Telemetry data of beacon signal.

HI DE NIWAKA JAPAN				
S1	s11	s12	s13	s14
S2	s21	s22	s23	s24
S3	s31	s32	s33	s34
S4	s41	s42	s43	s44
S5	s51	s52	s53	s54

8.4. Changing temperatures by minute sampling

Fig. 37 shows 450 min of temperature measurements from 23:00 of October 13, 2012 with a 5 min sampling period. It shows almost five orbits. The green line shows the temperature of top panel (+Z plane), and the purple

Table 3
Second sampling.

Voltage of solar panel +X [V]
Voltage of solar panel +Y [V]
Voltage of solar panel −X [V]
Voltage of solar panel −Y [V]
Total voltage of solar panel [V]
Total current of solar panel [mA]
One cell battery voltage [V]
One cell battery current [mA]
Three cell battery voltage [V]
Three cell battery current [mA]

Table 4
Minute sampling.

Temp. of three cell battery [°C]
Temp. of one cell battery [°C]
Temp. of +Z panel [°C]
Temp. of −Z panel [°C]
Total voltage of solar panel [V]
Total current of solar panel [mA]
One cell battery voltage [V]
One cell battery current [mA]
Three cell battery voltage [V]
Three cell battery current [mA]

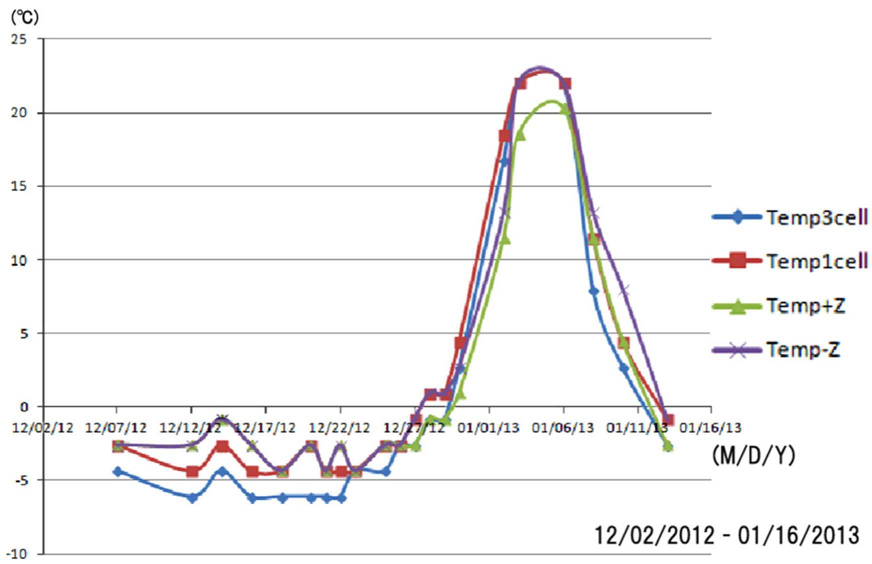

Fig. 36. Changing temperatures around January 4, 2013.

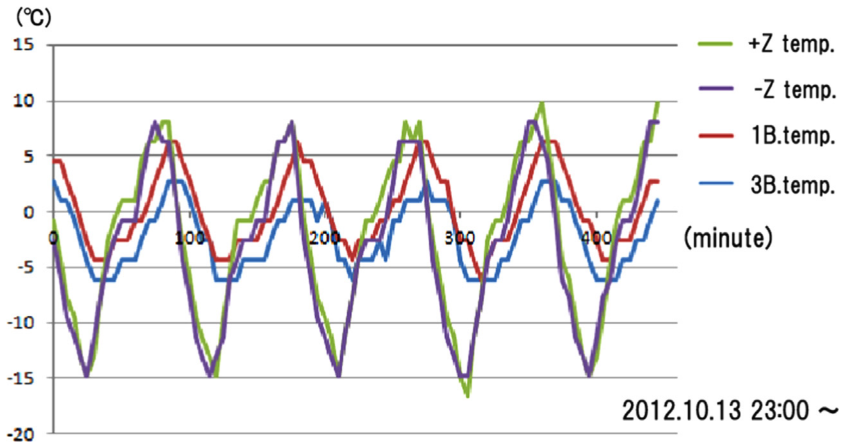

Fig. 37. Changing temperatures over five orbits. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

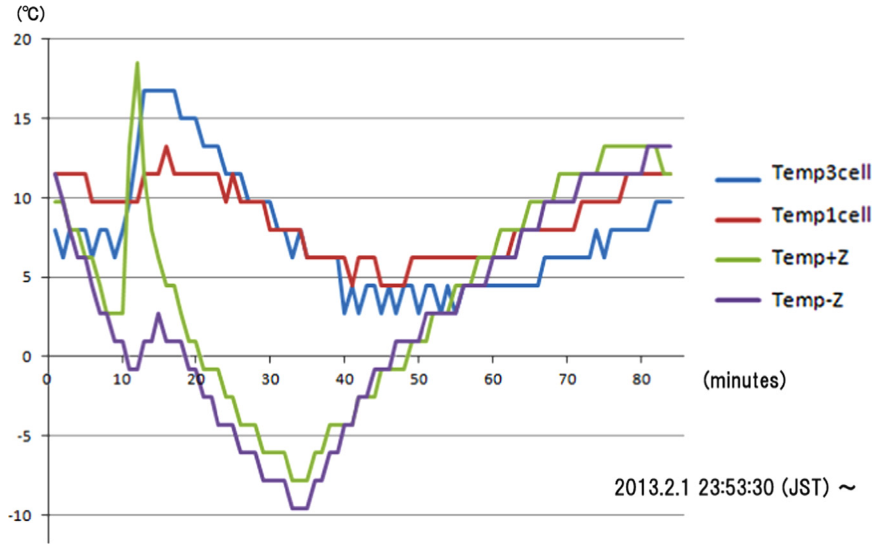

Fig. 38. Changing temperatures during LEDs flashing.

line shows the temperature of bottom panel ($-Z$ plane). They change from -15 degrees to 10 degrees.

The red line shows the temperature of the single cell battery, which always works for transmitting the beacon signal and receiving remote commands. The blue line shows the temperature of the three batteries connected in series which are used only for the flashing LEDs experiments and high speed transmission. Since the single cell battery is always charging and discharging, the temperature is always 2–3 degrees higher than the three series batteries.

Fig. 38 shows 90 min of temperature measurements from 23:53:30 of February 1, 2013 with a 1 min sampling period. The flashing LEDs start about 10 min after entering into shadow of the earth. The temperature of the green LED panel ($+Z$ plane) increases 15 degrees during the 2 min the LEDs are driven. The red LED panel ($-Z$ plane) also increases 3 degrees due to heat conduction. The temperature of the three series batteries also increases 10 degrees due to the internal resistance of the batteries. Since the single cell battery is close together with three series batteries, it also increases by 3 degrees due to heat conduction. Since the thermal capacities of batteries are greater than that of LED panels, the temperatures of batteries decrease more slowly than that of the LED panels.

8.5. *Changing voltage and current of the flashing LEDs measured by second sampling*

Fig. 39 shows the changes in the current from the three series batteries with 6 s sampling in the 10 Hz flashing mode. The current starts at 3 A and ends at 5.5 A after 2 min. Similarly, Fig. 40 shows the changes in the voltage of three series batteries. It starts at 11.8 V and ends at 11.1 V. Thus the power drawn starts at around 35 W and ends at around 60 W. As the temperature of LED panel increases due to heating, the characteristic curve of LEDs moves to left and the current increases. The temperature of the batteries also increases and the batteries become active. This also causes the increasing current. The duty ratio of the 10 Hz flashing mode is 30%, and the signal is also modulated with 5 kHz of a 50% duty square wave. So the peak (pulse) current may be from 20 A to 37 A.

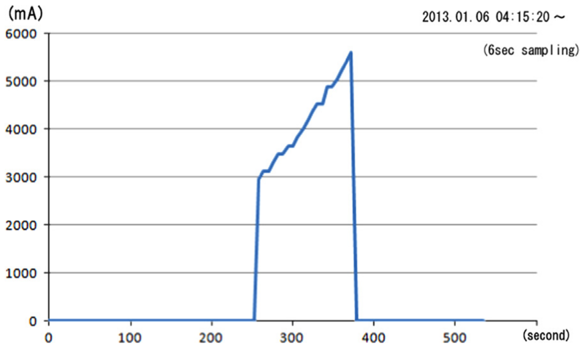

Fig. 39. Changing current at flashing LEDs.

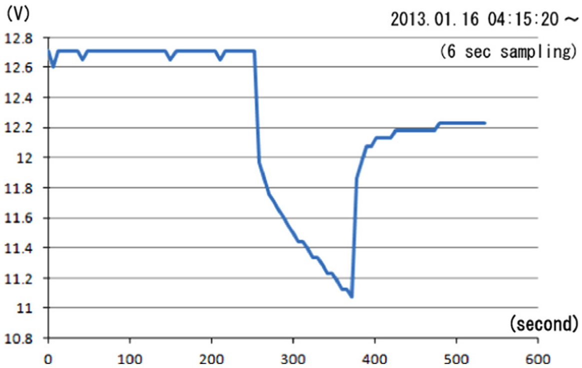

Fig. 40. Changing voltage at flashing LEDs.

$$I \times 0.3 \times 0.5 = 3\ \text{A}$$

$$I = 20\ \text{A} \tag{1}$$

$$I \times 0.3 \times 0.5 = 5.5\ \text{A}$$

$$I = 37\ \text{A} \tag{2}$$

There are four electronic switches connected in series with the LEDs. These four switches consist of two deployment switches, one flight pin, and the flashing control switch. As the current is large, the internal resistance of these switches will cause voltage drops. So the actual power at the LEDs may be 30–50 W (average).

8.6. Changing voltages of solar panels

Fig. 41 shows the changing voltages of the solar panels from 11:24 to 11:27 (JST) on November 6, 2012 with a 2 s sampling period. FITSAT-1 passed the area of dusk on the earth at this time. That is, although the ground was dark, the satellite was in sunlight. If we received the same data in the area of sunshine on the earth, the sunlight reflected from the earth generates voltages in the solar panels and the graph shows smaller changes. The voltages change in the order blue (+X), red (+Y), green (−X), and purple (−Y). This means that the satellite is rotating around the Z axis from right to left with the period of 34 s.

Fig. 42 shows the voltage changes of solar panels from 3:36:00 to 3:40:30 (JST) on November 19, 2012 with 3 s sampling. The satellite passed from an area of sunlight to shade. Therefore the reflection from the earth decreased with time. The rotation of the satellite is in the same direction but the period of rotation changed to 22 s.

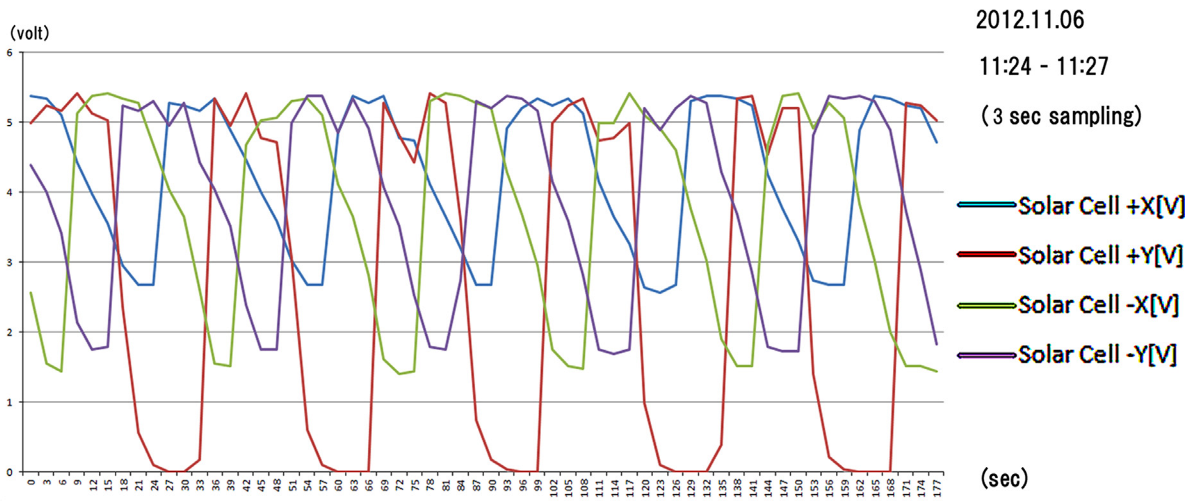

Fig. 41. Changing voltage of solar panel 1. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

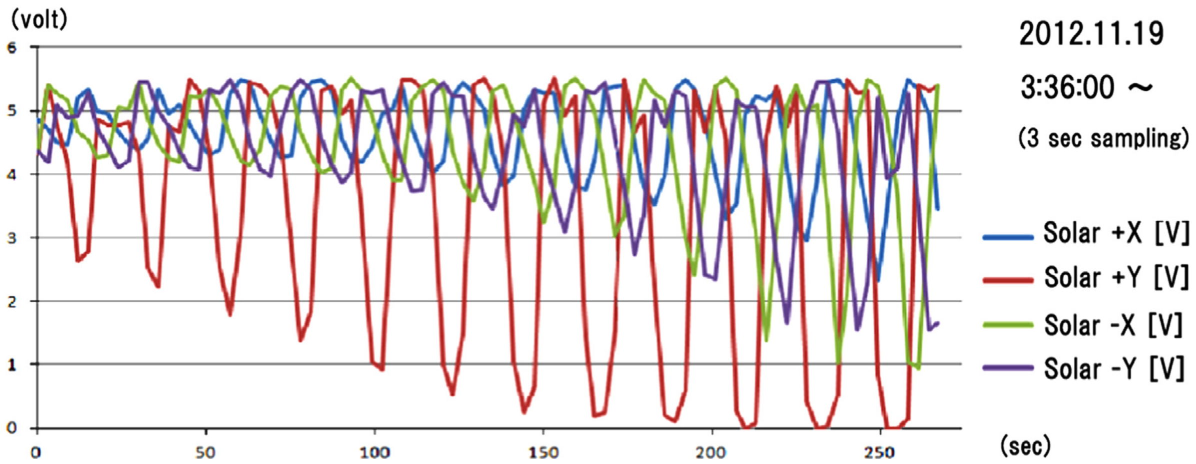

Fig. 42. Changing voltage of solar panel 2.

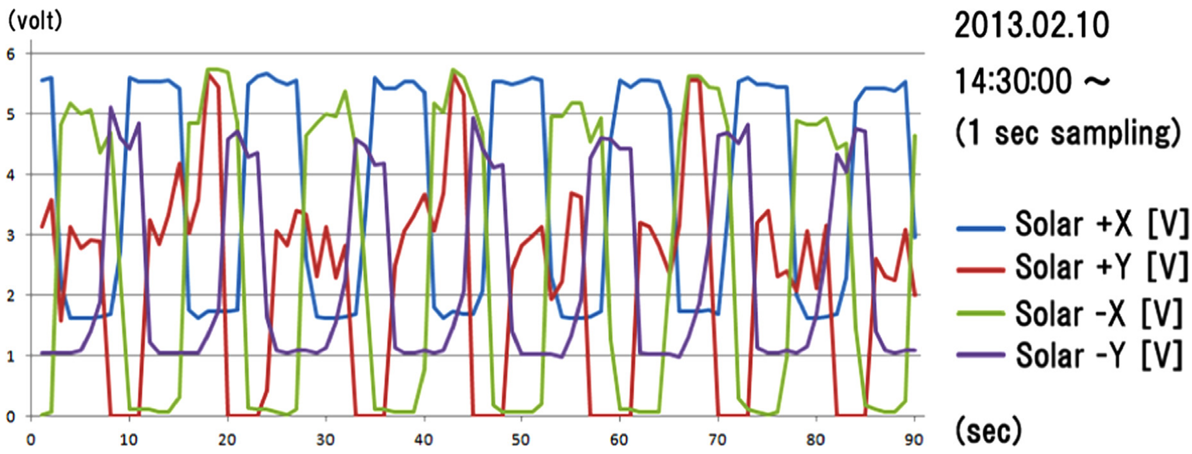

Fig. 43. Changing voltage of solar panel 3.

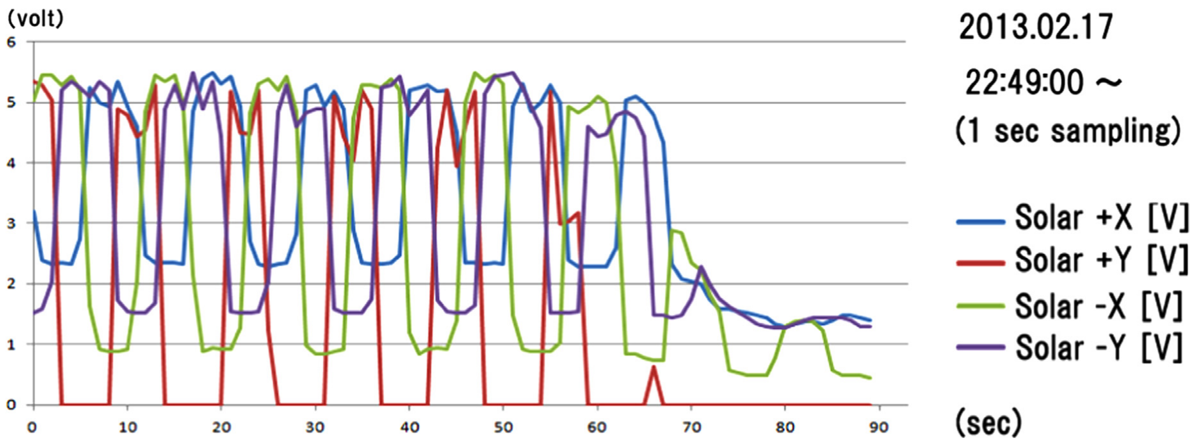

Fig. 44. Changing voltage of solar panel 4.

Fig. 43 shows the voltage changes of solar panels from 14:30 to 14:31.5 (JST) on February 10, 2013 with 1 s sampling. The term of rotation changed to 12 s.

Fig. 44 shows the changing voltages from the solar panels from 22:49:00 to 22:50:30 (JST) on February 17, 2013 with a 1 s sampling period. In the last 20 s, the

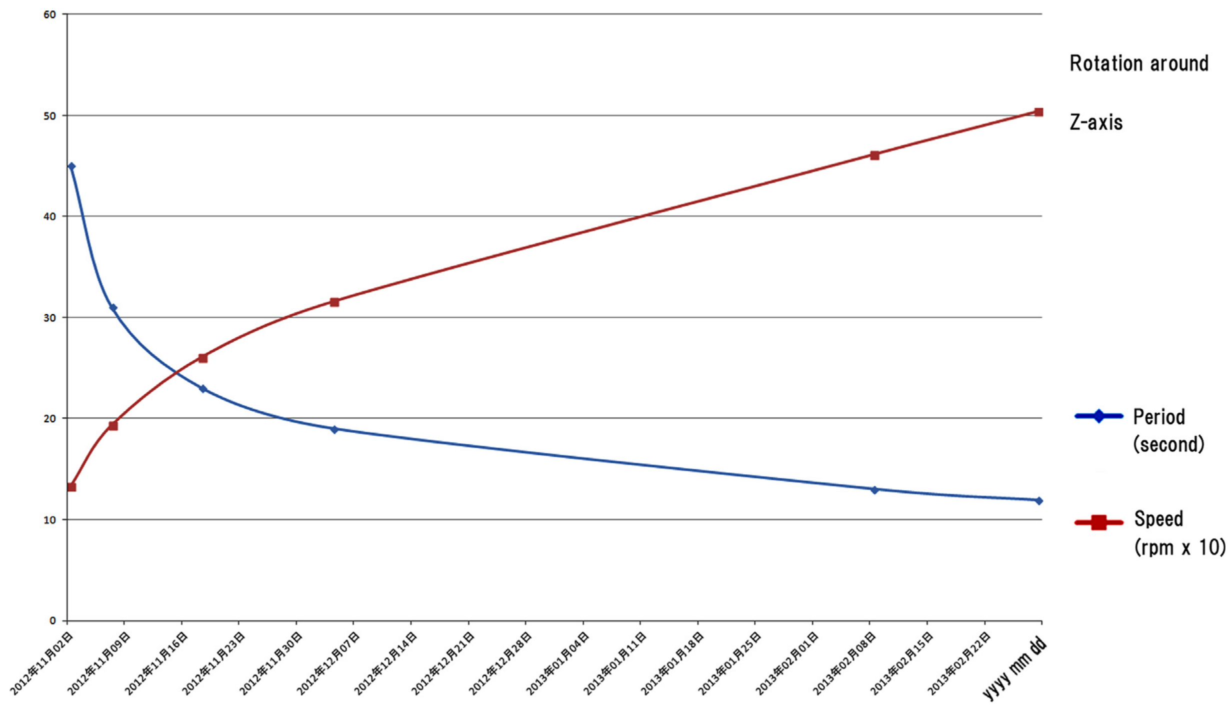

Fig. 45. Rotation change around *Z* axis.

satellite went into the shade of the earth. The period of rotation changed to 11.6 s.

Fig. 45 shows the changing speed of FITSAT-1 rotation around the *Z* axis. The rotation speed increases. We are now working on constructing a model to explain this increasing speed. This analysis will appear in another paper.

9. Conclusions

FITSAT-1 (NIWAKA) was deployed from the ISS at 15:44 (UTC) on October 4, 2012, circled the world more than 4300 times before its orbit decayed on July 4, 2013. Since FITSAT-1 uses the ham radio band, we received more than 500 signal and telemetry reports from all over the world in the first two months. All reports showed NIWAKA operating as designed. We received more than 1500 reports before the orbit decayed.

The 5.84 GHz signal reception experiment has been carried out successfully not only our ground station, but also by ham radio operators in Japan, Vermont, USA and Bochum, Germany. The flashing LED experiment was started one month after the high speed transmission experiment. The light was first observed and photographed at the Kurashiki Science Center and by the Korea Advanced Institute of Science and Technology. In the following experiments, we received many photographs taken throughout Japan, including Ebina, Hatano, Kimizu, Toyama, Hokkaido, Ehime, and Kumamoto. All missions were performed successfully in the first three months as planned. These results show that NIWAKA was designed and manufactured properly. Also, we discovered a phenomenon in which the rotation around the *Z* axis of the satellite increases with time. We are now developing a model for this increasing rotation.

Acknowledgment

We would like to thank the many people who helped to develop FITSAT-1 (NIWAKA) and enable its operation. JAXA advised us on developing FITSAT-1 and deploying it from ISS. We used the Nanosatellite Testing Center at the Kyusyu Institute of Technology for space environment testing. Logical Product Corp. developed FITSAT-1's 5.84 GHz system and main circuit board. Advance Technology Institute provided the GaAs solar cells for FITSAT-1. Hitachi Maxell Energy Ltd. provided the lithium ion batteries. Mr. Ryuichi Hirata and the staff of the FIT Machining Center made the FITSAT-1 body. Our students each developed their part of FITSAT-1. In particular, Mr. Toshiki Otsuka, an undergraduate student, made the 437 MHz antenna extender and Mr. Kenta Tanaka, a graduate student, developed most of the software.

Since FITSAT-1 uses the popular ham-band of 437 MHz for its beacon signal, many ham radios in the world supported operations of FITSAT-1. The Japanese ham radio station JA6PL sent more than 140 telemetry reports. An Australian ham radio station, VK5HI, sent more than 560 of telemetry reports. This covered almost a whole pass over that location. A Swiss ham radio station, HB9FFH, made a web-page which converts from Morse code data to telemetry data. Many ham radio stations also participated in the 5.84 GHz high speed transmission experiment. Japanese ham radio stations JA0OGZ, JA0CAW, and JE9PEL, and American ham radio station N1JEZ succeeded in receiving the signal from FITSAT-1. German ham-radio team AMSAT-

DL succeeded not only in receiving the signal, but also reconstructed 14 of the 20 images transmitted using the 20 meter parabola dish antenna at Bochum observatory.

Many amateur astronomers around the world also assisted the flashing LED experiment. The first photographs were taken by Mr. Mishima of Kurashiki Science Center in Japan and Prof. Jun-ho Oh at KAIST (Seoul Korea). After that, we received many photographs from amateur astronomers. Prof. Simone Corbellini in Torino Politecnico made a web-page which shows the regions where the flashing LEDs can be observed and a trace of where the LED beam points. This web page shows where the flashing LEDs can be seen in the constellations if latitude and longitude of the observation point are entered.

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