TOKYO TECH NANO-SATELLITE CUTE-1.7 + APD FLIGHT OPERATION RESULTS AND THE SUCCEEDING SATELLITE

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Abstract: The Laboratory for Space Systems, Tokyo Institute of Technology had developed a nano-satellite, Cute-1.7 + APD. The satellite was launched as one of the subpayloads of the JAXA M-V-8 rocket on February 22, 2006, and deployed into an orbit using a separation mechanism that is developed in this project. The satellite conducted missions including house-keeping data retrieval, use of COTS devices, attitude determination, and amateur radio cooperation for two months. The succeeding satellite is also planned to be launched in 2007.

Keywords: Tokyo Tech, Cute-1.7 + APD, Aerospace Student Project, Nano-Satellite, Flight Operation Results.

1. INTRODUCTION

The Laboratory for Space Systems (LSS) at Tokyo Institute of Technology (Tokyo Tech) developed a 1 kg pico-satellite, "CUTE-I", launched on June 2003 (Iai *et al*., 2004a). CUTE-I fully conducted the missions and is still transmitting its house keeping data to the Earth. This successful experiment demonstrated how students can manage the development of a satellite from the first designing steps to the effective launch and operation. Based on this satellite development procedure and acquired nano-satellite bus technology, LSS started the next satellite development project, “Cute-1.7+APD” (Iai *et al*., 2004b), pursuing the search for innovation in small satellite systems.

The Cute-1.7+APD project has two objectives. First, facilitate future micro-satellite development by demonstrating a new design methodology, and second, provide flight experiment opportunities to space engineering researchers and students by using the highly utilizable satellite. The methodology, aiming to rapid and low-cost development, includes proactive use of high performance and low cost commercial devices in space. The Cute-1.7+APD nano-satellite is equipped with several COTS devices including widely used PDAs (Personal Digital Assistants) and radio transceivers. For the second purpose, this satellite contains an engineering mission shared with control engineering researchers. Three magnetic torquers and a control program upload function enable on-orbit experiments on advanced control algorithms in this mission.

The Cute-1.7 + APD, shown in Fig.1, was launched on Feb 22nd, 2006, and successfully conducted initial missions, including the effective usage of COTS devices, cooperation with amateur radio operators, retrieval of house-keeping data, and attitude determination. On May 6th, after 74-days operation, the satellite fell into a status in which the satellite does not respond to any commands from ground station. LSS investigated the cause of the situation and concluded the influence of radiation. After that, LSS have developed the second Cute-1.7 + APD with the prevention of the radiation effect. The second satellite will be launched by Indian PSLV rocket in 2007.

This paper, first, reports missions, design overview, and the flight operation results of Cute-1.7 + APD#1, the first satellite. After describing the cause of the status, we present the modification and development of Cute-1.7 + APD#2, the succeeding satellite.

Fig.1 Cute-1.7 + APD Flight Model

2. Cute-1.7 + APD#1 MISSION AND DESIGN

2.1 Missions

In an effort to search a rapid and low-cost satellite design, one mission is assigned to demonstrate space use of PDAs as main computers in this satellite. This approach comes from PDA's advances which are the low cost, the high computing performance, and the wide range of software development environment. In addition to these functional advantages, another objective is to acquire engineering knowledge to adjust commercial devices to space environment. For one, this satellite uses two PDAs which can be switched on malfunction for the purpose of redundancy.

Cute-1.7 + APD also conducts three missions for the purpose of providing space experiment opportunity using nano-satellite. One is the attitude control experiment using magnetic torquers where satellite's control algorithm can be tested. In another experiment, the satellite demonstrates a new APD (Avalanched Photo Diode) sensor, developed by Kawai lab. at Tokyo Tech, to observe the density of low energy charged particles in LEO. This sensor is planned to be used in a large observation satellite after passing this flight experiment. This satellite also provides a digital repeater function, a public massage box to ham operators. By using this function, ham operators can upload their massage to this satellite, and the massages are downlinked in a certain period.

In order to expand nano-satellies use in space, this satellite also conducts an experiment on deorbit technology using electrodynamic tether. Based on the concern on space debris, deorbitting technology composed of small components can be an important factor for future nano-satellite development. As a first step for this technology development, this satellite deploys 10m of an electrodynamic tether.

2.2 Design Overview

Fig.2 shows the functional block diagram of Cute-1.7 + APD#1. Thirteen blocks out of the total thirty employ commercial products including PDAs, memory cards, USB hub, digital cameras, and

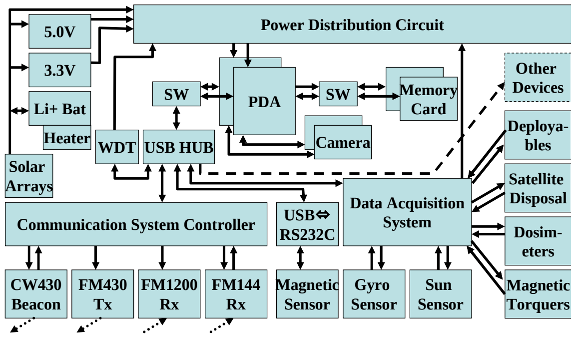


Fig.2 System Overview

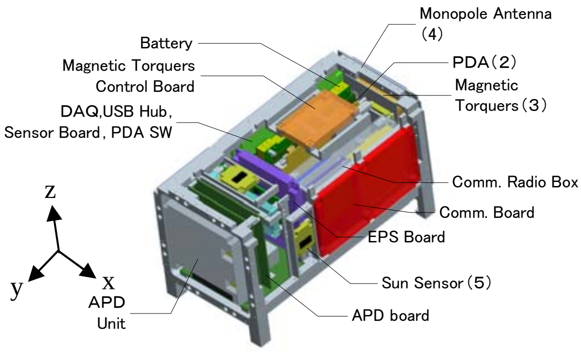


Fig.3 Components layout

handheld transceivers. Most subcomponents are connected to PDA through the Universal Serial Bus interface that enables plug and play. The connectivity contributes to designing each subcomponent as a module and expanding versatility of this satellite by providing easy connection to various mission devices.

Cute-1.7 + APD#1 measures 10×10×20cm weighs 3.5kg, and uses Al. 6061 components. The main MPU consists of two PDAs, and the communication module uses four frequencies; 144MHz AFSK for command uplink, 1.2GHz GMSK for public message uplink, 430MHz CW for beacon downlink, and 430MHz GMSK for packet downlink. The control actuator employs magnet torquer, and the attitude determination sensors are composed of 3-axis gyroscope, sun sensor, and 3-axis magnetic sensor. The EPS system uses 4 Li-ion battery in parallel and GaAs solar cells that generates 3W power supply in average. This satellite also contains a CMOS camera that is used for verifying the attitude control. The all devices are stored in a double-cube sized body (twice the size of CUTE-I), shown in Fig.3. Extra weight is added in order to extend the orbital lifetime of the satellite.

The separation mechanism of Cute-1.7 + APD#1 was also developed. The concept is fundamentally similar to the one used for the CUTE-I satellite and consists of 4 jaws, two nylon lines and a heater. The jaws hold the pillars of Cute-1.7 + APD#1 and are tightened by the nylon lines. On separation, the nylon lines are heated and cut at the heat point, releasing the pillars from the jaws. Then the Cute-1.7 + APD#1 pillars are pushed simultaneously by four springs and the satellite is effectively released. Several separation experiments under microgravity had been conducted with success in March 2005 at the Japanese Microgravity Laboratory (MGLAB). The total weight of Cute-1.7 + APD#1 and its separation system is 6.0kg.

3. Cute-1.7 + APD#1 OPERATION RESULTS

3.1 Operation Results

The Cute-1.7 + APD#1 was launched by the JAXA/ISAS M-V#8 Rocket as a subpayload with the main payload, JAXA "ASTRO-F AKARI" satellite on February 22nd, 2006. The satellite was mounted on the B3-PL, the third stage unit of the rocket, using its separation mechanism, shown in Fig.4 and 5.

After the separation from the rocket, the satellite successfully deployed its dipole antenna, and started to transmit the CW beacon including house-keeping data of the satellite. The radio reached to many amateur radio operators in all over the world at the first orbit, and LSS also received the signal in the ground station in Tokyo Tech. The house-keeping data confirmed the activation of the PDA. On March 7th, attitude data retrieval was conducted every 10ms successfully. On March 16th, as the data showed unexpected behaviour of power consumption, the operation was stalled to conduct missions and focused on understanding the situation.

Then, Cute-1.7 + APD#1 stopped accepting any uplink command in the evening March 16th when passing over Tokyo Tech, and now the satellite is not under control. Because the final operation was conducted completely without error, estimation can be that functional error had occurred in the satellite on orbit. The subsequent operations showed that the command processing system stopped its operation even though the command receiver operates its function without any problem. Therefore, the error might have been resulted from radiation damage on the command processing controller. After a careful radiation test in LSS, our team reached to the conclusion with the highest possibility of damage by the radiation.

To summarize what the satellite could conduct in the planned mission, the satellite, first, satisfied the usage of COTS devices including PDA on orbit in terms that the telemetry confirmed the operation of COTS devices. For amateur radio cooperation, Cute-1.7 + APD provided GMSK modulation method for the first time in CubeSat. The radio reached to ham operators in Japan, and LSS has received their reports. In the science module, basic operation was confirmed including the circuit around the APD sensor. Although the satellite could not fully conduct attitude control experiment, the attitude control system installed 3-axes active controller for the first time as CubeSat in Japan, and gyroscopes and sun sensor were confirmed to be in normal operation. The tether deployment mission was not conducted. LSS also found that the deployment mission had incompleteness in the proposed structure.

Cute-1.7 + APD#1 is now transmitting a continuous wave that is not modulated. The recovery operation will be continued throughout the orbit life, estimated to be 1 or 2 year. Meanwhile, the problems in Cute-1.7+APD#1 are thoroughly investigated and the satellite of the second improvement type is developed in order to achieve the missions except the tether deployment mechanism. Part of report on radiation effect on the satellite is described by Miyashita *et al.* (2005) and Omagari *et al*. (2006).

3.2 Satellite Telemetry

By referring to the change of the battery voltage recorded and downloaded since March 16th, we observed that the current consumption temporarily increased. The telemetry transmission was operated normally for a while after the uplink command analysis system stopped operating. Fig.6 shows the house-keeping data during this period. The telemetry disappears once at the evening on April 7th. About a week before the loss of signal, the voltage of the battery begins to decrease gradually. On the day of the loss, the voltage descent seems to below the operation voltage of the telemetry transmission system. Then, the satellite orbit went in eclipse for the first time on April 15; therefore, all satellite electric power could be turned off and the hard error was cancelled. Then telemetry revived on April 16 after the battery was charged again. Telemetry disappeared completely in the morning on May 6. A rapid decrease of the battery voltage was confirmed in the evening, May 5th, and over consumption of the current happened again.

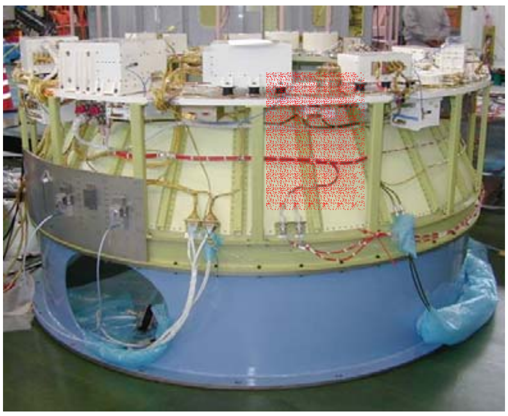


Fig. 4 B3-PL and Cute-1.7 + APD subpayload

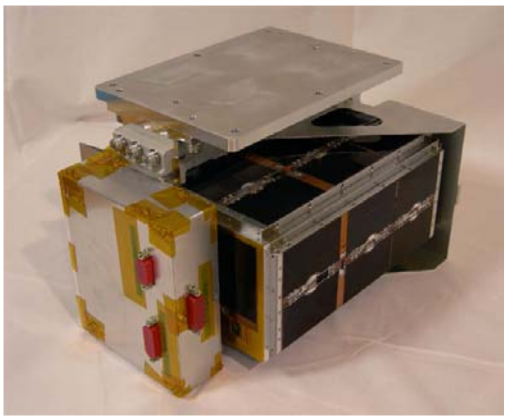


Fig. 5 Cute-1.7 + APD#1 and the Separation System

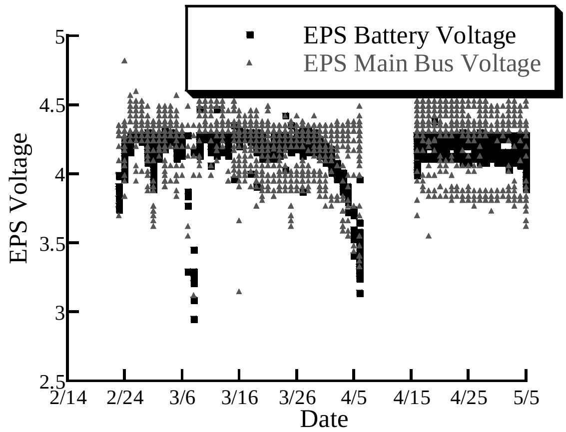
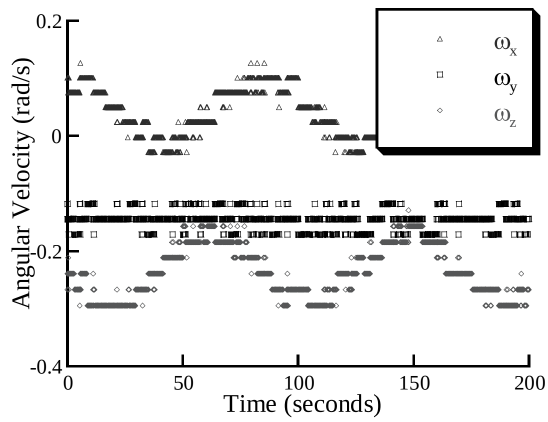
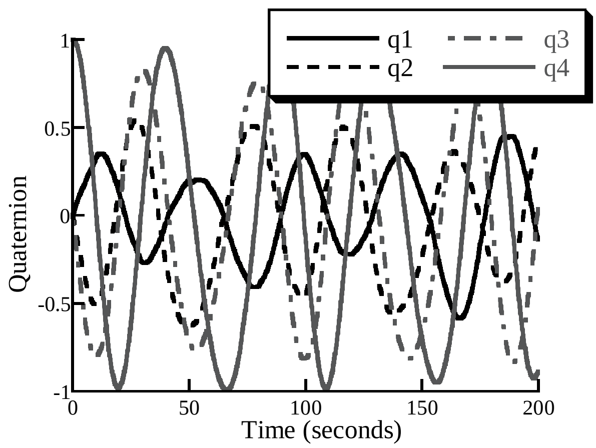


Fig. 6 Flight Data of Battery and Main Bus Voltages

Fig. 7 Reception reports from the world powered by google earth. Plots are the points where radio amateurs received the signal from Cute-1.7 + APD#1.



(a) Gyro Data



(b) Quaternion

Fig.8 Attitude Determination Results

3.3 Amateur Radio Cooperation

The signal transmitted from the satellite reached to many amateur operators all over the world, shown in Fig. 7. Over a hundred ham operators have reported the signal reception. Trough the cooperation with those operators, the satellite received OSCAR (Orbital Satellite Carrying Amateur Radio) name. The OSCAR name uses “OSCAR (Oscar)” in a part of the name of the satellite and applies a sequence number after the name, which are assigned by AMSAT-NA. The OSCAR series satellites use amateur radio frequencies to communicate with ground stations. CUBESAT-OSCAR-55(CO-55) is issued to CUTE-I, which is the first number of “CUBASAT-OSCAR” series, and CUBESAT-OSCAR-56(CO-56) was issued to Cute-1.7+APD#1. These two satellites were admitted worldwide as amateur satellites and contributed to amateur radio operators.

3.4 Attitude Determination

The satellite’s attitude determination system consists of a three-axis gyro sensor, a three-axis magnetometer, and sun sensors. The gyro sensor is a combination of three gyroscopes and the sun sensors consist of simple photodiode arrays fixed on the walls of the satellite. Although the satellite is equipped with the magnet meter, the data could not be used because of a technical problem concerning data transfer from the sensor to main computer.

The satellite uses two attitude determination methods; a geometrical method and a REQUEST (Bar-Itzhack, 1996) based method, both of which require the Earth magnetic vector and the sun directional vector. The magnetic vector and the sun vector refer to a dipole model and a circular approximation of the ecliptic plane respectively, and the satellite contains its Keplerian element calculated from uploaded TLE data.

The geometrical method uses the magnetic sensor primarily when the satellite is near the equator of the Earth, and the method rely on the sun sensor primarily when the elevation angle of the sun seen from the satellite is high. The method determines one axis of the satellite attitude at first, deriving one vector from the primary sensor in the inertial frame. To determine the other two axes, the method rotates the body frames about the first axis so that the angle between the other axes and the vector derived from the secondary sensor can be minimized. The REQUEST, expanded from QUEST, is a method to calculate quaternions recursively using angular velocity obtained by the gyro sensor.

Fig.8 shows attitude data effectively retrieved on 7th March from gyroscope at 10Hz. Fig.8(a) shows the angular velocity, and Fig.8(b) shows the quaternion computed from this data. In Fig. 8(a), ω_y shows nearly constant value of -0.15rad/s, and ω_x and ω_z behave in sin-wave motion with the shift of 90 degree. The inertial moment of Cute-1.7 + APD#1 is

(2.19E-02 9.78E-03 2.18E-02) kgm^2, i.e. approximately an axisymmetric rigid body, and these motion correspond to a torque free motion of an axisymmetric rigid body spinning with nutation. The Y axis is the smallest inertial moment, and when the satellite rotates about the axis with nutation, the angular velocity of Y axis is constant while these of the other 2 axes are sin-wave motion. The nutation rate of the satellite is about 80 seconds. The spin rate of the satellite, therefore, becomes about 40 seconds from nutation speed and the inertial moment of the satellite.

The data of the sun sensor acquired on February 27 is shown in Fig. 9. The coordinate system is body fixed coordinate system that is shown in Fig.3 where the red vectors indicate direction of the sun in body fixed coordinate. According to the data from the sun sensor, the satellite was rotating about the Y axis at this moment. The cycle of the rotation is about 30 seconds. Compared with the rotation axis given by the gyroscope data, the data shows approximately same tendencies of rotation about the major axis in the principal axes frame.

Through the Cute-1.7 + APD#1 project, the attitude determination and control system was that can be installed in micro satellite was developed, and the examination was conducted on orbit. The data of the gyro sensor and the sun sensor could be acquired. The acquisition of magnetic sensor data, attitude control experiment and attitude determination experiment, however, was not able to be conducted.

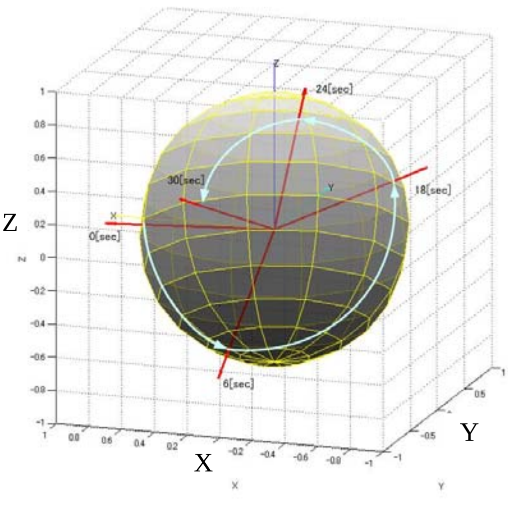


Fig. 9 Direction of the sun in body fixed coordinate system

4. Cute-1.7 + APD#2 DEVELOPMENT

4.1 Missions

The second satellite of Cute-1.7 + APD conducts missions; facilitation of satellites design, attitude control experiment using magnetic torquer, amateur radio cooperation, APD sensor demonstration experiment, following the first satellite. This satellite excludes the electrodynamics tether mission.

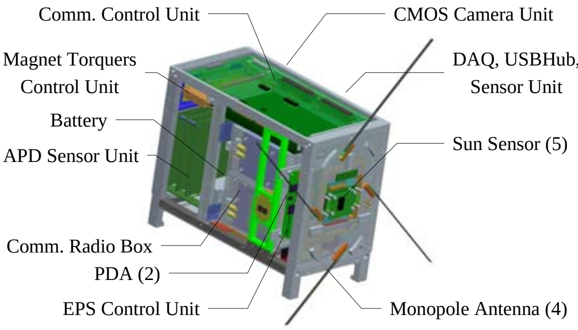


Fig. 10 Cute-1.7 + APD#2 Components Layout

Fig. 11 Cute-1.7 + APD#2 under development

4.2 Project Outline

The second design of a satellite in this project started in April 2006 and is planned to be launched in 2007 by PSLV Rocket from India. This satellite uses the approximately same bus components including two PDAs, four communication channels, 3-axis gyroscope, three axis magnetic sensor, sun sensors, and a CMOS camera. The design of this satellite is shown in Fig.10 and 11. As the concept of this series of satellite includes design of a high versatility satellite, the second satellite should have been developed from the first satellite only by exchanging the subcomponents connected through existing interface. The operation results of the first satellite, however, showed a few requirements to be modified.

The first modification includes designing a radiation tolerant circuit. In the first satellite, because of the SEL occurred in the microcomputer of communication, the satellite became not to be able to conduct remaining missions. The alternative is to use a current watch circuits that can detect the SEL and restart the component. The circuit showed effective tolerance to radiation in the ground experiment.

Another modification is to increase the power generation of the satellite. The orbital operation showed relatively smaller power generation than the estimation, which affected operation procedure of the satellite. The power generation is enhanced by increasing the dimension of the satellite. The structural change also contributes to assembling process. As many missions were installed to the first satellite, the high dense of components required long time to assemble. Though exceeding the CubeSat size, the dimension does not affect to the satellite design as the interface to separation mechanism corresponds. This satellite measures 220×180×120mm, weighs 3kg and generates 6.6W in average

The attitude control system also needs improvements. In Cute-1.7 + APD#1 the magnetic sensor data was not available to determine the attitude of the satellite. The problem caused by data transfer error between bus devices needs debug. In addition, in the first satellite, each attitude sensor data, gyro sensor, magnetic sensor, and sun sensor, were not obtained at the same time. The second satellite requires the data at the same time or a time-stamp function for the precise attitude determination of the satellite. The output torque of the actuator is also increased. The change on the structural design and measurement of the residual magnetic field in the satellite resulted in needs for improvement of the magnet torquer. The torque is increased by dividing a coil into three and connecting parallel, which enlarge the current supply to magnet torquers.

5. SUMMARY

LSS developed the Cute-1.7+APD nano-satellite, pursuing a new design methodology of nano-satellites and providing space use opportunity. The satellite was launched on Feb. 2006 and conducted initial operation, COTS devices use in space, attitude determination, and cooperation with ham operators for two months. The next satellite has been developed aiming the same objectives and using the modified design of the first satellite. The launch of the second satellite planned in 2007.

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