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What we learned from the Tokyo Tech 50 kg-satellite "TSUBAME"

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ABSTRACT

A 50 kg-class micro satellite "TSUBAME" was launched in 2014. After a critical phase, the receiving sensitivity of the RF system on board the satellite dropped significantly and the way for command uplink was lost. A thorough investigation was conducted after the failure to determine the causes, based on the obtained telemetry and reproductive experiments in lab room. The detailed data analysis revealed many other malfunctions had occurred. In parallel with the investigation of the fault points, we also classified these malfunctions into several categories in terms of development phase, technological aspects, and management.

1. INTRODUCTION

During the last 10 years, small satellites have become one of the most exciting topic in space technology. At the beginning, these small satellites were mostly aimed to form train young researchers in graduate schools. In fact, some of the graduate students who have worked on small satellite projects at Tokyo Tech are now leading national space projects as professional engineers or researchers. Moreover, several members have also started their own space business taking advantages of the low developing cost and frequent launch opportunities of small satellites.

The number of small satellites launched has already reached a rate of over 100 spacecrafts per year. In this scenario, 50 kg class satellites are still a minority due to their difficulties to be designed, manufactured, tested, and operated, all factors which tend to escalate dramatically as the size gets bigger. However, the demonstration of advanced space technology and more complex scientific missions desires larger payloads rather than CubeSats. To fulfill the requirements by science and engineering experiments and buisinesses in space, a 50-kg satellite project named "TSUBAME" was started in 2009. After the completion of the development phase the satellite was launched into a 500 km sun-synchronous orbit in 2014 with a Russian DNEPR rocket. This was the fourth project for Tokyo Tech and therefore it was designed and managed based on the knowledge acquired from the previous CubeSats projects, CUTE-I (2003~), Cute-1.7+APD (2006~2008), Cute-1.7+APD II (2008~). Even though the initial operation in the critical phase seemed perfect, a week after the launch, a fatal malfunction of the RF command receiver on board the satellite was detected. Despite recovery operations, all signals from the satellite were lost three months after the launch. During these efforts, it has been possible to accumulate HK data broadcasted in Morse in cooperation with amateur radio operators all over the world. In parallel with the careful data analysis, it was also possible to conduct reproduction experiments in the lab to investigate the failure points. As a result, the malfunctions in the RF system were caused by the voltage converters. Furthermore, several other failures in both hardware and software were revealed, part of which could have been detrimental to the satellite system. During failure analysis, the meeting records were reviewed and discussed in order to understand the reasons that brought to take wrong decisions, as well as why the signs of the above failure were overlooked. This paper summarizes the TSUBAME project and describes the causes of the failure of the mission from a variety of perspectives: technical aspects, systems engineering, and management.

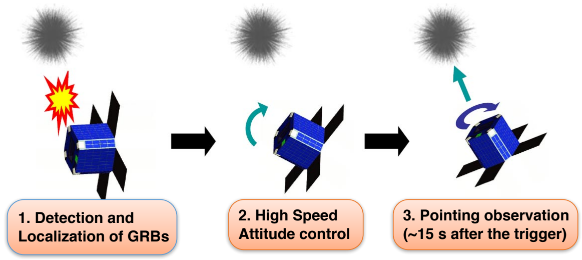

Figure 1: Schematic view of the GRB observation sequence with CMGs.

2. OVERVIEW OF TSUBAME

The conceptual design of TSUBAME was proposed in 2004 to the satellite design contest in Japan and was awarded the highest prize. After the contest, a chance for launch opportunity was found to be available. Here an overview of the challenging and thought-provoking project is presented.

2.1. Missions

TSUBAME was designed to measure the polarization of gamma-ray bursts (GRBs), powerful gamma-ray explosions in the far distant universe. In the proximity of the central engine of a GRB, the gravitational energy is converted into the relativistic outflow via unknown physical processes. Information on gamma-ray polarimetry allow scientists to derive the magnetic field in the gamma-ray emitting region. Considering the high luminosity of a GRB, even a small detector can measure the phenomena with sufficient signal to noise ratio. However, the unpredictability of the events themselves and of their location, as well as their limited duration, typically much shorter than 100 sec, make their observations more challenging. To investigate these transient objects, a high-speed attitude control system including control moment gyroscopes (CMGs) was developed. This solution enabled a slew speed of faster than 6 deg s^{-1}. In addition, the satellite also had a Wide-field Burst Monitor (WBM) as support sensor for real time detection and localization of GRBs. The observation sequence used is schematized in Figure 1: after the detection of the GRB by the WBM, the on board computer calculates the coordinate of the target, and then the satellite quickly points the target using CMGs and starts a pointing observation with X-ray polarimeter within 15 sec after the detection[1-2].

The satellite had also a high resolution optical camera designed by Tokyo University of Science. The goal was to combined the camera and the CMGs to challenge multi-pointing ground observations in a single pass, a technique that can be very useful for disaster monitoring.

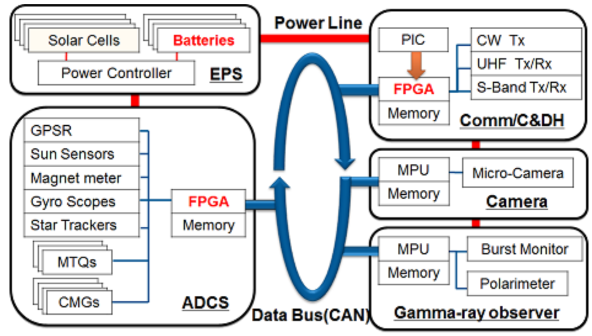

Figure 2: Block-diagram of the satellite system.

2.2. Configuration of the satellite

Figure 2 describes the function block diagram of TSUBAME. The satellite bus system consists of five sub-systems: Communication / Command&Data Handling sub-system (Comm/C&DH), Attitude Determination and Control sub-system (ADCS), Electric Power sub-system (EPS), gamma-ray detector sub-system (Science Payload), and optical camera sub-system (Camera). These components communicate each other via the Controller Area Network (CAN) bus. In addition, Comm/C&DH can communicate with the other sub-system via UART as a backup. This redundant data bus was included based on the experience inherited from Cute-1.7+APD II, which high speed data bus (USB) did not work in orbit and had to be controlled via backup UART line.

The satellite had three distinct attitude control modes: (1) spin-stabilized attitude mode for critical situations (with magnetic torquers), (2) non-biased 3-axis agile attitude control mode for the science observation (with CMGs) and (3) non-biased 3-axis precise pointing mode for Earth observation (with CMGs). To achieve these functions, the ADCS has several kinds of attitude sensors and actuators. It is here emphasized that at the time of the development it was difficult to purchase these components, which in the end were developed by 15 graduate students (See §3.1). Because, considering the different required performance, it was not possible to use components demonstrated in previous CubeSats.

During the design phase, the mode-transition was recognized to be one of the most critical operation since the satellite would have had to compensate the angular moment and smoothly run-up the rotators in CMGs. Moreover, high-speed attitude control would have put the satellite's life at risk. If the satellite had lost its direction, the satellite would have easily ended its mission. On the other hand, the control algorithm of CMGs was extremely complicated in return for the high torque[4]. Therefore, high performance commercial

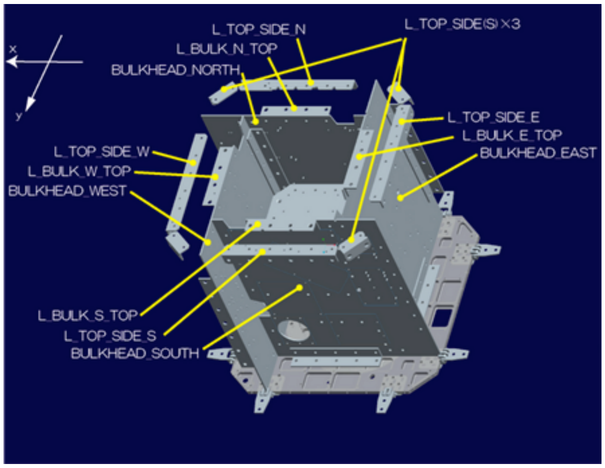

Figure 3: Inner lattice frame of TSUBAME.

grade CPUs were used rather than rad-hard anachronical devices. To deal with accidental freezing due to radiation effects, mutual surveillance routine was implemented, a decision which made the control topology fatally complicated.

The design of the Structure & Thermal sub-system (STR) started with a great focus on the vibration condition for the piggy-bag payload of the Japanese launching vehicle H-IIA, considered to be the worst condition. In order to satisfy the requirements, a rigid lattice frame nested in the outer panel was employed (Figure 3). Even though this structure actually fulfilled the required mechanical performance, few years later it was noticed that accessibility to the components, clearance for harnesses routing and radiation performance were sacrificed. The thermal design mostly failed at the beginning. In the observation with CMGs, the satellite consumed up to 90 W (50W of which for CMSs) which is one of the highest power consumption per unit surface area comparing with other satellites[3, 6]. To dissipate the heat in excess, the outer panels were covered with the OSR films instead of solar cells. A fault tolerant system was preferred for that small satellites to reduce the risk of accidental loss in the attitude control. However, since all the solar array panels (SAPs) were facing the same side of the satellite after the deployment, it was not permissible to accept any minor malfunctions in the ADCS. This situation made the ADCS to work stand-alone, which made the control software much more complicated.

Table 1: Summary of specification of TSUBAME.

Geometry	460 mm x 460 mm x 500 mm
Weight	48.6 kg
Mission Life	1 year
Orbit	Sun-synchronous orbit, Alt = 500 km
Solar cells	InGaP/InGas/Ge (130W@EOF)
Battery	Li-ion Polymer (22.2 V / 16.2 Ah)
Main bus	~31 V (Non-stabilized)
Power Consumption	2 / 30 / 90 W (Min / Norm / Max)
Communication system	S-band(Tx): BPSK (100 kbps) S-band(Rx): BPSK (9600 bps) UHF(Tx): CW / AFSK (1200 bps) x 2 VHF(Rx): AFSK (1200bps)
Attitude Determination	Sun sensors Magnetometers MEMS gyroscopes Fiber Optics Gyroscopes Star Tracker (Axelstar-I)
Attitude Control	Magnetic Torquer Control Moment Gyroscopes
Mission Components	Gamma-ray detector system - Gamma-ray polarimeter - Burst monitors Optical Camera system
Ground Station	FM/UHF: Tokyo Tech Station S-band:10m antenna Fukui Univ.Tech. (Downlink only) S-band: 2.4m antenna ISAS/JAXA (Uplink / Downlink)
Flight	Nov. 06th 2014 ~ Jan. 24th 2015

TSBUAME had a FM receiver and UHF transmitters. In previous satellite projects, great results were achieved using an amateur band in cooperation with volunteer amateur radio operators (who indeed received the first voice of Cute-1.7+APD, Cute-1.7+APD II and TSUBAME). CW was also convenient to track the satellite with coarse orbital element due to its small radar cross-section. For this purpose, TSUBAME always turned on the CW transmitter except that during the launch phase. The design of the amateur band communication system was carried on from Cute-1.7+APDII in which the commercially supplied radio transceiver was diverted. Unfortunately, the instrument used in the previous project was already discontinued, and therefore they were replaced with following model.

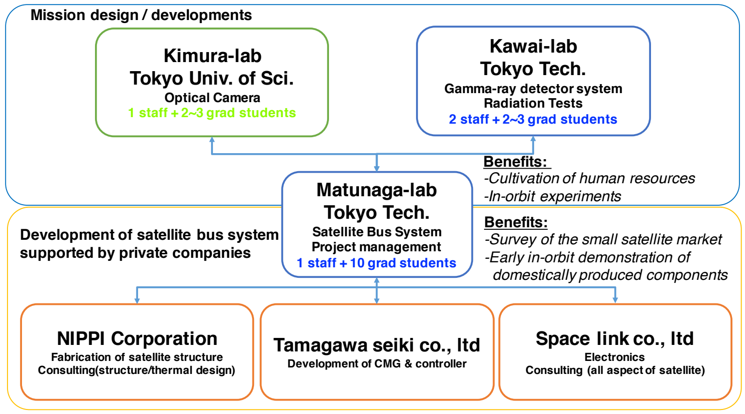

Figure 4: Development regime of TSUBAME.

This extremely important decision was made without much resistance. The meeting record of November 18th 2009 made mention for the first time of the replaced transceiver. At that time, a proposal to MEXT Japan for development funding was being prepared. In addition to the amateur band transceivers, an S-band communicator was also employed to transfer large amount of data, up to several tens of MByte produced by the science and camera missions. During the very early phase of the project, it has been decided to use an S-band transceiver which had already been demonstrated in space, although an S-band antenna was not available at that moment.

As is the case with the on-board RF system, it was planned to divert the ground station on the rooftop of Tokyo Tech for the previous projects, capable of amateur radio communication. On the other hand, the S-band antennas for telemetry downlink / command uplink were still not available, therefore Fukui University of Technology, which possesses ϕ10 m parabolic antenna, kindly offered a cooperative receive operation. Table 1 summarizes the resultant specification of the satellite.

3. DEVELOPMENT

3.1. Developmental Regime

The developmental regime of the TSUBAME project is described in Figure 4. The project team was organized by two universities (three laboratories) and three private companies which were involved in the team as research collaborators. The satellite had been mainly developed by ~15 graduate students who conducted simulation studies, design, tests, and document controls. This means that each sub-system had been developed by 2~3 graduate students. In addition, 2~3 experts were invited to attend the weekly team meeting as technical advisors. It should be noted that most of the graduate students tend to leave the school within three years in Tokyo Tech, therefore the turnover of the team member is rather high comparing to usual space companies. Fortunately, the results coming from the students were excellent and it took 1~2 years for the technology acquisition, after which they left the project. Therefore, the seamless handover of tasks has always been one of the main problems at the end of a fiscal year. However, many dedicated members supported the project even after their graduation using their non-working days.

To manage this challenging project, all developers attended a weekly meeting. At the end of the concept design phase, the duration of the meeting reached 5 hours due to the numerous issues to be discussed. The meeting was therefore divided into Science team meeting, Camera team meeting, and Satellite bus team meeting for more detailed discussions, while the plenary meeting was required to discuss the consensus among the all sub-systems: coordination of interfaces, environmental tests, and defect reports, etc. Despite the organization review, too much time has been spent in meetings, sometimes for inefficient discussions.

3.2. History of development

Table 2 summarizes the timeline of TSUBAME project. The development of the base technologies for TSUBAME mission has been advanced since 2005, supported by Japan society for the promotion of science (JSPS) grant-in-aid for scientific research in parallel with the CubeSat projects. (= pre-Phase A)

In 2009, a developing fund, which seemed related to the supplemental budget for stimulating the economy, gave a change to materialize the satellite. The conceptual design was completed at the end of 2009 and after that we started the development of a bread board model (BBM). The conceptual design phase was rather fast and sloppy because the developing fund had a short expiration date. (= Phase A)

Table 2: Timeline of the TSUBAME project.

Mon-Year	Launch schedule	System events	STR	Electronics	Science	Project Manager
08-2009		Cal for proposal for "Small satellite research and development projects" by MEXT			BBM detector fabrication	S. Inagawa (M2)
09-2009		Preparation for the proposal and conceptual design				
10-2009						
11-2009				▲FM transciever purchased (a)	BBM detector beam test	
12-2009		Accepted by MEXT		▲FM GPSR purchased (b)	△DAQ trouble	
01-2010	24 months (limited by budget)		EM STR Design	BBM/EM elc Design	EM detector Design	K. Akiyama (M2)
02-2010				TID test-1	TID test-1	
03-2010				▲Causal DCDC passed tests (c)		
04-2010				TID test-2	TID test-2	
05-2010						
06-2010				TID test-3	TID test-3	
07-2010				SEE test-1~3	SEE test-1~3	
08-2010						
09-2010						
10-2010				SEE test-4	SEE test-4	
11-2010				SEE test-5	SEE test-5	
12-2010		S-band freq coordination applied	EM STR V-test		Ray-trace simulation	
01-2011		Amateur band freq coodination		SEE test-6	SEE test-6	K. Ishizaka (M2)
02-2011						
03-2011		Disaster in east Japan				
04-2011		Matunaga lab moved to ISAS/JAXA				
05-2011		▲Giving up S-band uplink (d); Negotiation with DNEPR	EM STR Therm/Vac test-1		EM detector Vacuum test	
06-2011					△HV discharge	
07-2011						
08-2011						
09-2011			EM STR Therm/Vac test-2	EM Elec integ test	EM detector V-test	
10-2011			FM STR Design	pFM Elc Design	△PMT breakup	
11-2011		pFM fit-check	▲Heater burnout (e)	SEE test-7		
12-2011	Dec-12	Contract with DNEPR	▲Failure in Ant position(f)	pFM Elc	EM detector beam test(1/4 mod	
01-2012	9 months	**CDR @Dec 28, 2011**	**FM STR completed**		FM detector Design	S. Morii (M2)
02-2012						
03-2012						
04-2012						
05-2012						
06-2012		pFM integration test-2		△EPS-Shunt failure	FM detector V-test	
07-2012				△MTQ driver failure		
08-2012						
09-2012					FM detector assemble	
10-2012		pFM Therm/Vac test				
11-2012				△ADCS sensor failure		
12-2012				FM Elc Design	FM detector beam test	
01-2013					**FM detector completed**	T. Kamiya (M2)
02-2013						
03-2013	Dec-13	FM integration test-1		△Batt charger spike noise⇒	△RS485 transceiver broken	
04-2013	6 months				△ROM accidental overwrite	
05-2013						
06-2013				△FM-Rx decode module failure		
07-2013				▲FM-Rx sensitivity degradation-1 (g)†		
08-2013					FM detector refurbish	
09-2013						
10-2013		FM electrical integration			Software debug	
11-2013		FM V-test		▲S-band Rx set to be OFF(h)		
12-2013	Dec-14	FM integration test-2		▲ADCS software bug(i)		
01-2014	8 months					M. Matsushita (M2)
02-2014						
03-2014				△CDH control Software failure		
04-2014				△CDH IP-core failure		
05-2014						
06-2014				△STT communication error	FM detector final calibration	
07-2014		FM final integration		**FM Elc Completed**		
08-2014		End to End test => Shipping		△FM Rx sensitivity degradation-2 (g)		
09-2014		Preparation for Ground station				
10-2014						
11-2014		Launch				

△ Identified failures
▲ Unrecognized failures (including mis-interpretations)
△/▲ Red colored failures are thought to be the direct causes for the fatal troubles seen in orbit.
† The FM-Rx sensitivity degradation was actually recognized in July-2013 but misunderstood.
TID Total irradiation dose test by irradiating Co-60 gamma-rays
SEE Single Event Effect test by irradiating Proton beam

In 2010, the preliminary design phase started. The first semester was spent on radiation tests to select devices for the flight. At the end of 2010, an S-band frequency coordination was applied to ITU. To expedite coordination proceedings we had negotiated with the University of Tokyo to share the S-band frequency which was already reserved for a micro-satellite "nano-JASMIN", On the other hand, we did not still have an S-band ground station for uplink at the time. (= Phase B)

Just before the violent earthquake occurred in 2011 in east Japan, the fabrication of the engineering model (EM) had already been finished. To avoid any complication, a thermal vacuum test has been conducted in Osaka, west Japan. In the situation, we encountered another luck, the launch opportunity of the DNEPR rocket. Note that the EM did not work at all at that time, but we decided to utilize this chance because the flight opportunity for a small satellite depends on luck and we experienced that most of rocket launches were postponed by 1~2 years in average, and we had convinced that we could finish developing a small satellite within a year. But this misconception was the start of a death march. By the way, before contracting with the launch service company, we had to fix the specification of the ground station although we still did not have an S-band antenna for uplink. And we gave up to uplink via S-band, because it takes several years to get a license for S-band transmission. Afterthought, this decision might be one of a cause for losing the satellite, while if we lost this flight chance, TSUBAME would have been still in the lab. After the contract with DNEPR, we held a critical design review inviting tens of researchers working on small satellites. Considering the reviewers' comments, we moved on to critical design phase. At that time, we could use only 9 months for designing, manufacturing, and testing the flight model before the launch, because the shipping process requires another 3 months. (= Phase C)

At the end of 2011, STR sub-system had finished the design and fabrication of the flight model to submit the structural information to DNEPR. On the other hand, the other members of the the satellite bus team were pressed for time. But they finished developing the pre-flight model to meet the deadline by sacrificing quality. The quality issues became obvious at the integration tests at mid-2012. Almost all components did not work in the tests, except for the communication system which was inherited from the previous CubeSats. In contrast, the development of the science detectors was rather easygoing, because we can replace the detector with dummy mass if we missed the deadline. To obtain reliable data to be accepted by scientists, the detectors must work correctly and be precisely calibrated. If not, the mission will be no meaning. Such high-level requirements made the science team calmed down in contrast with the bus team. Actually, the science team had carefully conducted performance evaluation and debug with the EM and the subsequent critical design had undergone without critical errors. At the end of 2012 we finished calibration and performance demonstration irradiating polarized X-rays at a synchrotron beam facility [1-2].

After that the science team had supported debug and revision of the bus system. Our strategy for achieving the mission was that give-up the launch in 2013 to ready for the next launched opportunity in 2014. Nevertheless, this risky decision enabled drastic revisions, as shown in Table 2, already identified failures marked by open triangles had been completely fixed within a year. And the launch in 2013 was postponed, in other words, we won a bet. The final six months before the launch were dedicated for software implementation. During the final end-to-end demonstration, we encountered an anomalous behavior of FM-Rx, but we did not have enough time to fix it. (= Phase D)

4. FLIGHT OPERATION

The satellite was launched on November 6th 2014 from the Yasny launch base. The satellite was injected into a sun-synchronous orbit with other 4 satellites. Three hours later, a German ham operator sent us a receiving report with the recorded Morse sound. Based on the HK data, it was concluded that the satellite had successfully deployed the four SAPs and almost finished de-tumbling and moved on to the sun acquisition operation. TSUBAME finally came back to Tokyo as a real satellite orbiting the earth. The first day of operation has been spent to gather HK data. After that, the bus components were turned on and checked out carefully. All the events encountered during the in-orbit operation of TSUBAME are summarized in Table 3.

4.1. Successes in orbit

In the first week, the satellite worked almost perfectly as we checked in the end-to-end test in the lab. The thermal design team was particularly concerned because the fluctuation range of the power consumption was rather wide, from 2W to 90W. The obtained HK data showed that the temperatures measured for various point of the satellite were almost equal to the simulated value[3]. This meant that we had successfully constructed the thermal math model of the satellite. Another success of the STR was the deployment mechanism of the four SAPs. The obtained bus voltage and the temperature of the outer panel suggested the SAPs were successfully deployed.

Table 3: Time table of events in orbit.

Time (JST)	Events
2014/11/06-16:35	Launched
2014/11/06-20:05	Receiving report from Germany
2014/11/06-21:00	First AOS at Tokyo Tech
2014/11/07-10:14	FM-Tx1 ON ▲Low success rate of CMD uplink (1)
2014/11/07-22:25	FM-Tx2 ON
2014/11/08-10:00	▲Abnormal increase of spin-rate (2) ⇒ FTA / reproductive simulation
2014/11/08-22:20	GPS ON ⇒ OFF
2014/11/09-09:59	S-band Rx ON
2014/11/09-22:08	We moved on to the normal operation mode (GPS ON) ▲Success rate of uplink getting worse. (3) ▲Failure in GPS positioning (4) ▲Bat-Temp was lower than expected (5)
2014/11/12-20:30 ~2014/11/13 9:00	▲FM-Rx signal strength indicator decayed to zero (6)
2014/11/14~	▲Preparation for S-band uplink (7)
2014/12/12-11:33 ~ 2014/12/12-22:30	▲TSUBAME fell into the safe-mode (8) => ▲S-Rx OFF (9), FM-TX* OFF
2015/01/27- 12:11~	▲CW transmitter breakdown (10) (Sat Temp increased before breakdown)
2015/02/04	License for S-band uplink approved

EPS also worked perfectly even though it had been developed from scratch, since TSBAME required a maximum power of 90 W, which is about 20 times larger than that of previous CubeSat. The newly developed linear regulator, capable of an automatic optimization of the operation point on the C-V curve of the solar cells to deal with drastically varying power demand, supplied a stabilized 31 V power to the main bus as expected. On 2014-12-12, the satellite fell into the safe-mode, arise from a low-voltage alert from the battery manager system. This phenomenon could be explained by the short of the main bus at the DC/DC converter for the FM transmitters. After the converter had burned out, the battery system successfully charged up the battery and restarted the satellite system[6].

Another important progress of the project came from the attitude control. In the critical phase, TSUBAME controlled its attitude by using magnetic torquers with reference to magnetometers, sun-sensors, and MEMS gyroscopes. The obtained HK data showed that the satellite successfully had acquired the sun and faced the SAP to the Sun. The sun-sensors had never misidentified the Earth albedo with the Sun. After the de-tumbling, the sun-angle had been maintained within 15° in spin-stabilized attitude. These good results showed that the technology for designing, simulating, fabricating, and testing the flight components had been acquired[5].

4.2. Failures in orbit

Table 4 summarizes the failure events occurred in orbit. For the three months of operations, ten failures have been recognized and marked with filled triangles in the table including minor issues. These failures and their causes are described below.

(1) The first symptom was a low success rate of command uplink comparing with Cute-1.7+APD II. It was confirmed that the ground station had not had any problem in the communication with the CubeSat. After that, it was noted that the radio waves could have interfered with the reflected waves from the SAPs. For the same reason, CW signal showed modulation synchronized with the spin motion of the satellite. This means that the position of the FM/UHF antennas were incorrect.

    The Comm/C&DH team decided the position of FM/UHF antennas based on the simulation and experiments by using a 1/4 dummy model at the end of EM phase. In critical design phase, they changed the positions of antennas based as stated above without any design verifications. In addition, this critical decision was not reported in the weekly plenary meeting.

(2) On 2014-11-08, it was realized that the spin-rate of the satellite was gradually increasing beyond the designed spin-rate from a trend chart. A reproductive experiment was performed in a Hardware in Loop Simulator, which allowed to detect a bug in a feedback loop in the control program which accelerated at each passage of the satellite through the south and north magnetic poles. This software was developed at the end of the FM phase, but this failure were not identified by software simulator before the launch.

(3) The success rate of the command uplink decreased. Maybe correlated with that, the signal strength indicator of FM-Rx, "S-meter", also declined. This receiver was employed in very early phase of the project without any discussions. In fact, The phenomenon was registered twice before the launch. It was encountered for the first time on July-2013. Unfortunately, rookie member of the Comm/C&DH team concluded that it was due to an aging degrade or a degrade by a mis-operation without any objective evidences. Then, they replaced the

degraded device with a new one. The second time occurred few days before the shipping, too late to solve the problem. At that time, the operator tried to recover this phenomenon by rebooting the satellite and succeeded in temporal.

(4) After the satellite moved into the normal operation mode, the GPS receiver turned ON permanently. However, the GPS had not succeeded in the positioning except for a time synchronization. The GPS receiver had been purchased as for space-use, and it was tested on ground after the final integration. Unfortunately, flight backup is not available, therefore it has not been possible to identify the causes of the failure.

(5) The battery temperature was lower by ~5 ºC than expected. The power consumption suggested that the battery heater was working. Therefore, the peel-off of kapton heaters might have been the cause of the low battery temperature. A reproductive experiment was performed in a vacuum chamber, and it was found that the kapton heaters with adhesion failure had blown up by outgas. Consequently, we tested 6 samples and 3 of them blew up in vacuum conditions. If the battery heater had blown up in orbit, the heater might have peeled off from the battery. According to the meeting records, the battery assembly passed a thermal-vacuum test once in the EM phase. However, the acceptance test for the FM battery assembly in a vacuum condition had been omitted.

(6) The value of the S-meter was originated in an analog output from the wave-detector of the FM receiver and then converted into digital data via an ADC. In case of a malfunction occurred in the FM receiver, the measured value should have been lower, but still a non-zero value (a fact confirmed by a flight backup). Therefore, the obtained value of S-meter=0 suggested that the failure had occurred at the latter digital layer. If the ADC or the MPU which controlled the FM receiver had failed, the Comm/C&DH would have still kept the previous measured value. The only way to reset the S-meter to zero can be identified with a shut-down of the satellite system triggered by a rapid drop of the battery voltage.

The difference of the power consumption between before-and-after the malfunction was –2.3 W, which corresponds to a power consumed by a DC/DC converter supplying 6 V to the FM receiver and its controllers including the conversion loss. A reproductive experiment of the voltage converters was conducted in vacuum conditions and it was found that one of the sample had burned out after 1 week from the start time. A total of 6 were tested, 3 of them burned out. The time for burnout fluctuated widely, from a week to a month. If the DC/DC converter had been the cause of this malfunction, the qualification tests would have been definitely enough.

(7) The team proceeded a license application for S-band uplink using a ϕ3m antenna at ISAS/JAXA right after the FM-Rx had broken. As described in §3.2, the S-band uplink was already identified to be unfeasible for the difficulties encountered to get an antenna within the short preparation period. However, before the launch it was discovered that a ϕ3 m parabolic antenna system at ISAS/JAXA could have been used with a minor upgrade (in fact, no one had grasped the technical feasibility of this application, except for the manufacturer). Presumably, reflecting the emergent situation, JAXA and the Ministry of Internal Affairs and Communications of Japan processed with unprecedented speed.

(8) According to the reports received from HAM operators, TSUBAME fell into the safe-mode due to an alert for low battery voltage from the EPS on 2014-12-12. The FM-Tx1/2 were powered by the same model of DC/DC converters that burned out in FM-Rx. If that had been the case, the EPS successfully protected the battery system from an overload and booted in safe-mode.

(9) The S-Rx was turned off by default according to the system design due to the unavailability of the S-band uplink station (§3.2). The S-Rx should have been ON as a backup communication line, a fact which occurred on 2014-11-09. In addition, it was planned to change the default setup to be able to use S-Rx at any time. However, the final way to communicate with TSUBAME was lost.

(10) About three months after the launch, the CW signal from TSUBAME was definitely lost. A few days before, the HK data suggested a marginal increase of the temperature, and the CW transceiver also powered by the suspicious DC/DC converter.

After the loss of the radio waves from TSUBAME, the team tried to observe it with an optical telescope to measure the spin period, but the poor visibility conditions prevent from obtaining significant data.

Table 4: Classification of the failures.

#Failures in orbit			3	4	6,8,10	7	5	1	9	(3)	2
#Direct cuases of the failures			a	b	c	d	e	f	h	g	i
Phase of development		BBM	▲	▲	▲	▲					
		EM					▲	▲			
		FM							▲	▲	▲
Technology	System Design	System design				▲			▲		
	Structure Thermal Design	Thermal			▲		▲				
		Structure									
	Electric Design	Parts selection	▲		▲						
		Circuit	▲								
		PCB									
		RF	▲					▲			
	Software Design	Software									▲
	Quality Control	Fabrication	▲				▲				
		Test	▲		▲		▲	▲			▲
		Operation							▲		
Management		Manpower				▲				▲	
		Scheduling				▲				▲	▲
		Budget									
		Configuratin				▲		▲	▲		
		Risk management		▲		▲			▲		
		Review/Approve	▲			▲	▲	▲	▲	▲	▲

Note ––– Rows (causal events) are arranged in chronological order.
Failures 6, 8 and 10 seem to originated in the same reason(Burn-outs of the same DCDC converter).

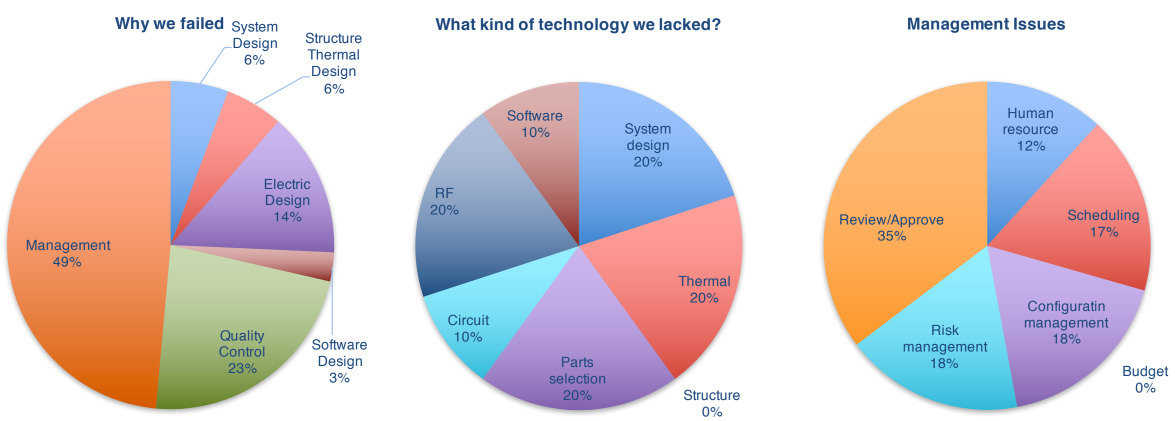

Figure 5: Breakdown of the failures by category.

5. DISCUSSION & CONCLUSION

As described in the previous section, a 50-kg satellite was developed and launched. Most of the bugs were identified and corrected during the development, but ten of them were not recognized or were misidentified by the team. This means that detection and recognition of bugs were the turning points of the project. The mentioned ten failures were classified in several categories in terms of time, technical and management perspectives. The ten failures are listed in chronological order of occurrence of failures from left to right in Table 4. Failures labeled (6), (8), and (10) Table 3 in are assumed to arise from a common reason, the burnt out of the same DC/DC converters. Figure 5 illustrates the ratio of these categories.

5.1. Occurrence of the Most Critical Errors.

Most of the direct causes of the technical troubles were sowed at the beginning of the project and had never been looked back. At the beginning, the satellite system was designed within a half year by almost beginner graduate students. Therefore, false preconditions in subsequent development phases were the most critical aspects of the project. This is not unusual, but the design errors should be identified before moving on to the next phase. As described in §3.2, the timeline of the project was accelerated by the launch schedule. This situation made the basis of the three steps development of BBM, EM and FM to collapse at the first BBM phase. This conclusion may be also confirmed by the high ratio of the management issues occupying nearly 50%, left panel of FIGURE.

5.2. Lesson Learnt

The central panel of FIGURE describes the technologies lacked in the project. All the thermal issues listed here arise from the malfunction in the heat dissipation of the electronics in vacuum conditions. These problems were not encountered in the previous CubeSat projects because of their small power consumption. In addition, the thermal design of the entire satellite system was analyzed in component unit and had no concern with the inside of the components. On the other hand, most of the circuit designer were not conversant in thermal design. Actually, students do not learn similar practical techniques in the standard curriculum of Tokyo Tech.

Most of the students who worked on the satellite bus system had a background in mechanical engineering. This situation can explain the high occupancy of electronic issues. The technical capability is very important not only for the development, but also for inspection and review. In fact, we could not identify small indications of the possible in orbit malfunctions before the launch. The sensitivity to the bugs could have been improved by the individual skill-up rather than modification of the review system.

To compensate for the deficiency in the design skill, various advisors who experienced development of full-scale satellites in space companies were invited to meet the team. However, their design concept was completely different from our philosophy accumulated from small satellite projects. A particularly striking example is the attitudes toward "reset". Previous CubeSats were designed to willingly reset the CPU in emergencies. and it had been proofed that this is one of the best fail-safe protection for a small satellite with numbers of fault point candidates. In fact, Cute-1.7+APD II has been experiencing tens of reset per year and is still operating. On the contrary, frequent system reset is non-permissive in commercial satellites, therefore they employ fully customized radiation tolerant devices. The un-unified design philosophy resulted in an inconsistent fail-safe system design.

5.3. Management issues

The right panel of Figure 5 shows the management issues to be concerned. The team succeeded in financing with an enormous effort. It should be noticed that this is one of the positive sides of the early contract with DNEPR, which enabled to raise the funds. With respect to the science aspect, the X-ray polarimeter could have been a unique, unprecedented device at that time. Another positive point is the early realization of the launch. The other satellites projects that passed the launch opportunity are still on ground. If the launch had delayed for two years, our satellite would have competed against two large satellites from India and China/Swiss. On the other hand, this risky decision also made the development schedule to collapse as described in §3.2. and §5.1. This unfeasible schedule was the reason for missing bugs in the BBM phase. The key external factor is the unclear launch schedule which was postponed twice in two years, and it was not possible to wait until the completion of debugging. To avoid this fault, it is not desirable to take into account the postponement of the development period, while it is more preferable to estimate the development period much more precisely.

In this project many difficulties were encountered in the configuration management. In case of full-scale satellite projects, the configuration is managed with huge amount of documents. However, it was not possible to apply this system due to the limited amount of human resource. The frequent turnover of the students also made the configuration management much more difficult. To improve this aspect, more flexible designing tools using UML or any other new technology might be needed.

The team failed in designing the fail-safe system. As described in §5.2, this was due to "A failure of imagination" spoken by Frank Borman at the Apollo 1 investigation hearings[7]. To imagine the failure cases correctly is essential to apply a risk management approach, which requires a strong level of knowledge and direct experience. Excluding the malfunctions, the review/approve system could have also been improved by the accurate fault prediction. The other problem of the review/approve system was the culture of "reading the situation" often seen in Japan, which prevented from investigating the true nature of the events.

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