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Mission Assurance Handbook for the University-built Lean Satellite Ver 4.0

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University Space Engineering Consortium (UNISEC)

Mission Assurance Handbook for the University-built Lean Satellite

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Abbreviation

ADCS	Attitude Determination and Control System
AIT	Assembly, Integration and Testing
AT	Acceptance Test
BBM	Bread Board Model
CDR	Critical Design Review
C&DH	Command and Data Handling
EM	Engineering Model
FM	Flight Model
FET	Field Effect Transistor
FMEA	Fault Mode Effect Analysis
FRR	Flight Readiness Review
FTA	Fault Tree Analysis
ISS	International Space Station
MA	Mission Assurance
MDR	Mission Definition Review
MCU	Micro-Controller Unit
MOSFET	Metal-Oxide-Semiconductor Field Effect Transistor
OBC	OnBoard Computer
ORR	Operational Readiness Review
PDR	Preliminary Design Review
QT	Qualification Test
Rx	Receiver
TRL	Technical Readiness Level
Tx	Transmitter

1. Introduction

This document summarizes the matters that all the members of lean satellite projects at universities and/or technical colleges (collectively referred as the Universities), including professors, staffs and students, must remember in order to improve the mission success rate. The phrase “Mission Assurance” means a series of activities to identify the factors in design, construction, operation of the satellite, etc. that will hinder mission success and to eliminate or decrease the effects of such factors.

Lean satellite is a satellite that utilizes non-traditional, risk-taking development and management approaches – with the aim to provide the satellite value to the customer and/or the stakeholder at low-cost and without taking much time to realize the satellite mission[1]. Most of so-called nanosatellites and micro-satellite, including CubeSats, fall into this category, especially the ones built by universities. Throughout the rest of this handbook, the word of “lean satellite” is used to refer to the nano-satellites and micro-satellites.

More than 20 years have passed since the universities started making satellites, and a lean satellite is now not just an educational tool for students but is used for cutting-edge scientific observation and business. Many start-up companies, the so-called “New Space,” have been launched by former students who experienced university satellite projects. They have become the driving force behind the growing space industry sector.

In Japan, more than 20 universities have launched lean satellites into orbit, but the mission success rate remains low. This trend applies worldwide, and according to Reference [2], 25% of satellites launched by the universities were DOA (Dead-on-Arrival; Contact is lost immediately after the satellite reached orbit), and less than 50% of satellites are said to be successful, even including those classed as partially successful.

The primary purposes of university satellites are education, technology demonstration, and scientific observation. Even when the main purpose is education, the educational effect by operation of the satellite is comparable to the effect obtained in development of the satellite. Accordingly, certain operations of the satellite, such as the acquisition and downlinking of data on the orbit, should be intended even in projects for educational purposes.

Improvement of the mission success rate of the university satellite does not only contribute to education of students who will enter the space business sectors after graduation, but also leads to improved results in challenging technology demonstration and scientific observation using such satellites. Such results will become a pathfinder of the larger scale missions and will contribute to growth of the space sector overall.

This document is prepared based on the analysis results of both the successful and failed missions presented at the Lessons Learned Sharing Meetings of the University Space Engineering Consortium (UNISEC) in 2020. The summary of the Lessons Learned Sharing Meetings is already published as Reference [3]. In Section 5.2 of Reference [3], the requirements to ensure the lean satellite mission success are listed as “Selection of Mission Assurance Requirements of Lean satellites.” The present document is intended to be a constant reference by professors and students participating in the satellite projects by revising the requirements in Ref.[3] based on the further root cause analysis of the failed projects. In particular, the following four items are considered.

- The appropriate management method in the university according to the project execution form
- The key points to achieve the project efficiently.
- The things to be done to improve the mission success rate at each phase of the project lifecycle from mission definition to post-operation, and
- The key points to make the university satellite program sustainable to improve the mission success rate steadily as a program not as individual projects.

Mission success rate of the university satellite is extremely low for the first project. It significantly improves, however, for the second satellite and subsequent satellites because the lessons learned in the first satellite can be used. However, failure cannot be completely avoided for the second and subsequent satellites. The mission success rate can be further improved by sharing lessons learned in the satellite projects by others. Therefore, the target readers of this document are not only the professors, staffs and students who are first engaged in the development of the satellite but also include those engaged in the projects of the subsequent satellites.

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2. Project Management

2.1 Schedule Management

It is quite rare for the university satellite to be successful in the mission from the first satellite. In many cases, **the mission fails due to the lack of time for the system test caused by poor schedule management coming from lack of experience.** Because the university satellite is usually launched by ride share or piggy-back, it is almost impossible for the satellite builder to determine the deadline of satellite delivery to the launch provider. Table 1 shows the milestone chart that should be used for schedule management with the satellite delivery date designated as "D". It is difficult to reduce the time required for (B) through (F). Time required for ordering and procurement of the material, parts, and components cannot be reduced by student effort alone. To what extent and for how long the entire system can be combined and tested to find the defects of hardware and software and correct them in (E) and (F) determines the mission success rate. Therefore, **maintaining the schedule by reducing the time required for (E) and (F) should never be considered**.

Table 1 Schedule Management Milestones

Timing	Milestones
Month D-A*	Mission profile of the satellite is decided. MDR
(A)	Proof of Concept (use of BBM) In parallel, designing of EM
MonthD-13	Feasibility of the conceived mission is confirmed. PDR
(B)	Order placement and procurement for the EM (3 months)
MonthD-10	Variety of hardware used for the EM is received and awaiting assembly
(C)	Assembly, integration, and test of the EM (4 months)
MonthD-6	Testing of the EM is complete and functioning as the satellite system is confirmed. CDR
(D)	Order placement and procurement for the FM (3 months)
MonthD-3	Variety of hardware used for the FM is received and awaiting assembly
(E)	Assembly, integration, and test of the FM (2 months)
MonthD-1	The hardware and software of the FM is completed and testing of the hardware (vibration, thermal, vacuum tests, etc.) is finished. The basic software of the ground station is completed. FRR or ORR
(F)	Software debugging (1 month)
D	Delivery of the satellite to the launch vehicle assembly site

* The timing differs dependent on the satellite project.

During Period (A) (the duration depends on each project), the mission feasibility should be confirmed using hardware like BBM. The proof of concept (PoC) should be obtained. When multiple missions are planned, some missions may need to be abandoned if the PoC is not obtained. Postponing the decision may lead to design changes at the EM or FM stages, which results in the cost increase and the schedule delay. If PoC of the main mission is not obtained, the mission requirements should be reviewed in detail. MDR is usually conducted at the beginning of Period (A) and PDR at the end of Period (A). After finishing Period (A), i.e. from PDR to the satellite delivery, the standard time is 13 months.

Period (B) (3 months) is the period waiting for delivery of the EM, but there are many things to be done during this period, such as the structural analysis and vibration test of the STM for the safety review, software development using the BBM, etc. The test schedule of the EM should be prepared and availability of the test facility should be confirmed during this period.

During period (C) (4 months) the EM is assembled, integrated, and tested. Assembly and integration should be conducted step by step using the material, parts and components received confirming compatibility of the interface, rather than conducting assembly and integration all at once after all the components are received. Incompatibility of the mechanical interface will require modification of the structures and/or circuit boards. Incompatibility of the electrical interface will require tremendous time for troubleshooting. As the members involved will not be accustomed to environmental tests, e.g. vibration and thermal vacuum tests, ample margin in the test schedule should be considered. Especially in the case of the first satellite, the vibration test of the EM will not be completed in a single test. The team should be prepared to do such tests multiple times. CDR is usually conducted at the end of the period (C), i.e. D minus 6 months.

During period (D) (3 months) order placement and procurement of the FM are performed, but a certain minor modification to the FM is unavoidable according to the test results of the EM. There are cases where an unexpectedly long time is required to revise the EM designs. During such time period, the schedule of the FM test should be established and the test facility should be secured. Considering the possibility that the time required for assembly and integration of the FM will require considerable time, two schedule plans of the FM, Plan A (the processes progress as planned) and Plan B (the processes do not progress as planned) should be prepared.

During period (E) (2 months) the FM is assembled, integrated, and environmentally tested (AIT). AIT requires at least 2 months because modification of the FM will be required when problems are found during the AIT. When the test is conducted by an outside testing organization, close communication should be maintained with the organization as the test schedule may have to be changed frequently. Usually at the end of (E), FRR or ORR is conducted to confirm that all the design and verification requirements are satisfied. The final review is done one month before the delivery to secure the time of modification if the need is identified by the review.

During period (F) (1 month), the hardware should not be changed/modified, instead the focus will be on debugging the software by the **end-to-end long-term operation test** (see 7.5). Even if a software bug is found, whether or not to modify the software before the satellite delivery should be carefully decided by comparing the risk of modification (the functioning part before modification may become nonfunctional) with the risk of non-modification (the bug may occur in orbit).

If a satellite includes newly developed components, the overall schedule may be delayed due to the progress of their development. It is advisable to consider Plan B and Plan C in advance in case these new developments do not proceed as expected and to set a predetermined decision point for transitioning to Plan B if the development is not completed by a certain deadline.

2.2 Team Organization

It is impossible for a university satellite project to find all the necessary talents in the students alone. The shortage should be filled by using staff members, expecting the growth of the student, cooperating with outside organizations, and by purchasing items. The solution should be selected considering mission difficulty, project budget, geographical conditions, etc. In any project, identification of the required talents in the team is extremely important to formulate the satellite missions. Table 2 provides the checklist to be used for identification of the talents for reference. Although this checklist does not determine whether the team organization is good or bad, it can be used to overlook the various aspects such as the team experience, the skill level of students, the diversity of the specialty, etc.

As the involvement of responsible faculty with experience in lean satellite projects, projects deepens (1,2,3), project management becomes easier. Even if the faculty member does not take on the role of project manager, having extensive project management experience (6,7) similarly makes the management process smoother. In such cases, since the team has already discerned what can be done by the team from what cannot be done by the team during the mission planning phase, the likelihood of making mistakes is considerably reduced. If the participating faculty and students span multiple disciplines (5,8), and there are dedicated staff members (4), with a significant number of doctoral and master's students participating (9), and many students have already experienced satellite projects (11), it becomes possible to set a high level of difficulty for the mission. However, overconfidence should be avoided.

If there are many external organizations with experience in lean satellite projects (12), it is possible to set a higher level of difficulty for the mission as they may fill in the gaps in expertise. However, if the external organizations are beginners, it could have the opposite effect. If the team becomes an extracurrcular activity or if the majority of the students are in lower academic years (9,10), it may be advisable not to set the mission difficulty too high.

Once the talents within the team are identified, it is important to effectively acquire the required expertise and knowhow that are not available in the team by outsourcing. The important thing to note is **the team members must fully understand the requirements of such components** and the specifications must be consistent with the mission requirements and system requirement, even when the development and manufacture of the components are outsourced. After the component is delivered to the university, **it is the responsibility of the university team to incorporate the component into the system for verification of the entire satellite,** and all the team members must remember such responsibility.

The university satellite project is not possible without devoted efforts by students even when dedicated staff are hired. Participation in the project by the students is supported by motivation. The level of motivation is different among the students. Some students are highly motivated. Some are not. The professors must keep in mind that the **responsibility to maintain and enhance such motivation entirely belongs to the professors**. It is natural that the motivation level is different. There is a possibility that the project schedule is delayed because a student whose motivation is not high is assigned an important task. The role of project manager is extremely important to catch the sign of schedule delay due to the student motivation and discuss the issue with the principal investigator, i.e. the professor. The project manager and the professor should continuously communicate each other, find the problem and the solution.

When the project is run as the laboratory project, the project activities can be linked to the bachelor thesis, master thesis, or doctoral dissertation. When this is not the case, it is necessary to make the students find a certain meaning in participating in the project. If the project is run by a small team yet as a time intensive project, there will be intensive mental pressure on the students. It is necessary to make every student have a clear view of what he/she can get once the project goal is achieved.

When the project is run as an extra-curricular activity where participation is decided at the discretion of each student, the participants are mostly young undergraduate students. The relationship between such student and the professor is not so close compared with a project run by a lab. Such project does not involve a competition with others like ordinary extra-curricular athletic activities and does not have a clear goal at several months ahead like a robot competition. Unless the professors demonstrate an attitude of actively participating in the project and to deal with student concerns early, it will be difficult to maintain student motivation only by the relationship among students.

It is absolutely important that the target launch date is secured to keep student motivation high. A project without a definite satellite launch date may not be run consistently. However, it does not mean that the students can build a reliable satellite once the target launch date is fixed. The professors must always say that the project success is not the moment when the satellite is made by the target launch date, but that the real success is to achieve the mission success in orbit. **The students will not really participate in the project unless professors say the mission success is the most important.**

If the development of the satellite takes too long time, a student can experience only a part of the process, which keeps maintaining student motivation difficult. The motivation comes when the student can experience the entire process of the satellite development up to operation of the satellite. Therefore, it is desirable to **keep the project lifecycle from start to operation within 3 years.** The project launch timing and personnel allocation should be planned by backtracking from the expected operational period required to achieve full mission success in orbit.

The establishment of the 3-year project lifecycle is very important. If a problem that is overlooked during development is found in orbit, such problem must be rectified by operation. Although what the team can do is limited, recovery from a hopeless situation may become possible if the members are familiar with the design of the satellite. They know a wide range of steps available for recovery. The majority of the university satellite projects are run as **a lab-type project** by a laboratory in an engineering department, where the students can generally participate in the project during the fourth grade (senior) and 2 years in the master's course. When the project period exceeds 3 years from start to launch, students familiar with the design of the satellite are no longer available at the time of satellite operation. In the case of the **research-oriented project** supported by a large amount of funding obtained by outside organizations in which many dedicated staff and graduate school students (master's course and doctoral students) participate, the dedicated staff should be **hired for the duration including operation of the satellite**, without limiting the term to the completion of satellite development. In the case of a **club-type activity** project in which students other than those in the professor's lab participate, a lifecycle exceeding 3 years will be possible. However, when the project period is too long, it is difficult to maintain student motivation. The students will not be able to spend much time on the project after the 4th grade, because they have to spend more time in

their final year projects (i.e. bachelor thesis). It is difficult to spend time in the satellite project without understanding of the research supervisor. Therefore, it is preferred to limit the lifecycle by approximately 3 years.
In the case of university satellites, while priority is given to the decisions made by the dedicated professor who is a P/I (Principal Investigator), critical decisions should be made not by this professor alone, but should be made after careful discussion between team members. The professors must be **open-minded and willing to hear opinions from others.**

When the project manager is a student, postdoctoral fellow, or junior professor, the senior professor (usually the P/I) should constantly oversee the status and should ask assistance from outside when required. As a student or postdoctoral fellow will not have appropriate contact with the outside, it will be difficult to obtain the assistance. Accordingly, it is **the responsibility of the senior professor to establish the appropriate contact with the outside**. The professor should not leave it to the student or postdoctoral fellow. Once the channel is made, however, it is better for the student or postdoctoral fellow who knows the issues the most to contact the outside directly to avoid a message game.

In the case of project organization where the project manager alone can oversee the entire system, a significant risk is posed as there may be an accident/incident involving such project manager. As such, multiple team members must be familiar with the entire system. Sharing of information between team members should be considered. Project management highly dependent on a single person is too risky and should be avoided. So, the organization of the development should be preferably established where all team members work together in a single room. To the contrary, it is not a lean satellite project where entire the system cannot be overseen by the project manager alone. As the system becomes complicated, the person with experience in lean satellite development (a person who has experienced the entire system lifecycle) should be appointed as the project manager.

Table 2 Checklist for Identification of the Talents in the Satellite Project

No	Item	Selections of Response							
1	Time available for the project (%) by the responsible professor (P/I) besides time used for lecturing	100	50-99	20-49	5-19	0-4			
2	Experience of the responsible professor in satellite projects	3 or more	2	1	0				
3	Faculty members involved in the satellite project (full-time in the department)	3 or more	2	1	0				
4	Dedicated staffs involved in satellite project	3	2	1	0				
5	Professors' area of expertise (multiple fields)	Astronautics	Science	Mechanical engineering	Electrical engineering	Communication engineering	Mechatronics	Computer science	Other
6	Project manager	Responsible professor (P/I)	Full-time professor other than P/I	Dedicated staff	Doctoral student	Master's course student	Undergraduate (in the professor's lab)	Undergraduate (not in the professor's lab)	
7	Number of satellite projects experienced by project manager	3 or more	2	1	0				
8	Subjects of study of participating students (multiple subjects allowed)	Astronautics	Science	Mechanical engineering	Electrical engineering	Communication engineering	Mechatronics	Computer science	Other
9	Grade of students (multiple grades allowed)	Doctor	Master	4th year	3rd year	1st/2nd year			

10	Participation of students other than those in the professor's lab of the responsible professor	Recommended	Limited						
11	Percentage of students with experience of the satellite project (%)	100	50~99	20~49	0~19	0			
12	Number of outside organizations independently involved in satellite project	3 or more	2	1	0				

2.3 Improving Project Efficiency

Activities in the satellite project are classified into three categories according to Reference [4]. The first category is activities to enhance the value of the satellite. This includes MA. The second category is activities that will not enhance the value but are necessary. The second category includes activities related with the safety review, the Space Activity Act, RF license, etc. The third category is activities that will create no value (useless activities, "Muda"). In a lean satellite project, the development and operation of the satellite becomes possible by a lean workforce and budget, reducing such useless activities to the minimum.

In the satellite project, useless activities frequently arise in moving and waiting. Such useless activities should be reduced and the time created by reducing the useless activities should be used for MA. Even when the satellite is developed in one campus, if individual teams are located in different buildings, the time required to move to and meet at a certain place for meetings and AIT is useless. The time required to move to the ground station for operation of the satellite is also useless. The environment for remote work and communication have significantly advanced during the Covid-19 pandemic. But their efficiency is still not high enough compared with face-to-face activities and communication. When the test facility is not available on campus, the time required to move the satellite and the team to and from the testing place is useless. Time lost in waiting for a response by e-mail communication will not create any value. Face-to-face communication among the team members located in the same room will save a significant amount of time. Things should be categorized as a matter to be recorded in text or not. The former items should be communicated by a text message. Otherwise, a quick oral communication is good enough. To improve the efficiency of movement and communication, it is recommended to have **the office, work room, test facility, and ground station in the same building**.

2.4 Frequency Coordination and RF License

Even when development of the satellite goes smoothly, changes in the basic design, changes of the mission, delay in delivery of the satellite, cancellation of the satellite mission, or restriction in operation of the satellite may become necessary as a result of frequency coordination and RF license application. Special attention is necessary when amateur radio bands and non-amateur bands are used by one satellite and a frequency not assigned in the primary allocation band is used.

The time required for frequency coordination in amateur radio bands and for obtaining the preliminary license is increasing due to the increase of the lean satellites. Especially the satellites whose mission is difficult to judge whether it conforms to the spirit of amateur radio communication or not are experiencing a long time in amateur radio frequency allocation. The project team should understand that a delay in the government procedures for radio license may lead to a delay in delivery of the satellite or loss of the launching opportunity in the worst case, **because a satellite for which frequency coordination or preliminary license has not been completed cannot be launched.**

As international frequency coordination and application for an RF license require expertise in the regulatory and technical aspects of radio communication, specific member(s) may be put under a heavy workload. More than one team member, including the project manager, should constantly monitor progress in frequency coordination. It is also desirable that more than one member should read Reference [5] if the radio license is obtained in Japan. In each country, the team should consult with an appropriate radio authority well in advance. It is good practice to outsource the work necessary for frequency assignment to an outside consultant in certain cases. Of course, certain project team members should constantly monitor progress even when the work is outsourced to an outside consultant.

2.5 Compliance with Safety Requirements

Noncompliance with safety requirements will result in design modification and/or rebuilding of the satellite, which will reduce the time used for MA. If the satellite does not pass the safety review, in the worst case a dummy mass will be launched instead of your satellite. There have been such instances in the past (see Figure 1). In order to avoid such a case, **problems associated with compliance with safety requirements should be identified at the respective phases when the conceptual design and detail design are completed, and should be consulted with the launch provider for confirmation.**

The verification method of compliance with safety requirements is an issue in the safety review. **A verification that requires the minimum effort for verification method should be agreed with the launch provider.** When the commitment to an excessive method is made (university professors tend to make an excessive commitment wishing to show their ability), such a commitment may become a burden to the project at a later stage. The resource should be allocated to the activities of MA, etc., limiting the efforts for safety verification to the minimum.

The person in charge of the system safety often needs to say a strong word to the person in charge of design and AIT. It is recommended to assign a person who can understand the technical rationale behind the safety requirement and explain it clearly to the system safety.

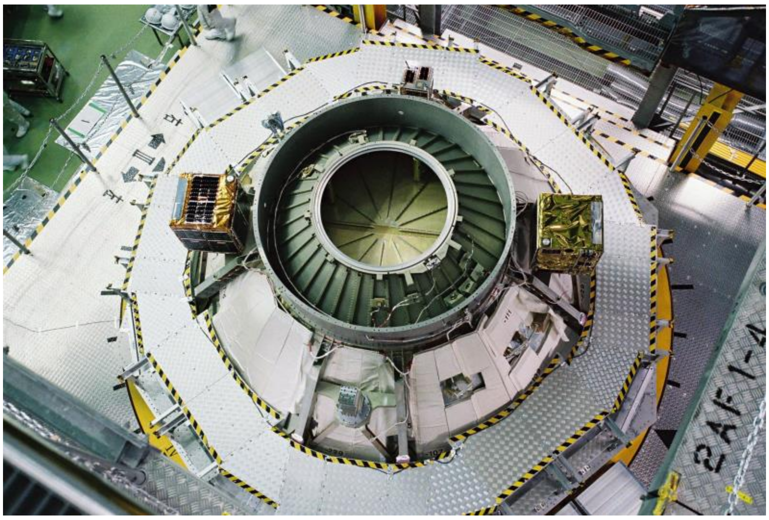

Figure 1 Small Piggyback Satellites installed in H-IIA Launch Vehicle 30 (The silver object located at 6 o'clock position is a dummy mass) (Source: JAXA Digital Archives)
https://s3-ap-northeast-1.amazonaws.com/jaxa-jda/http_root/photo/P100010489/5590ac570abed216cfe9acfe71681338.jpg

2.6 Documentation Control

Documentation is required because of the following reasons in the satellite project.

a) Regulatory affairs work (Safety review, frequency assignment, radio license, and Space Activity Act)
b) Communication among the project team (Necessary during development, testing, and operation)
c) Securing traceability to investigate in-orbit anomaly
d) Knowledge transfer
e) Sharing of knowledge and knowhow with other projects
f) Source data in writing research papers

For (a) and (b), documentation is necessary because satellite launch will become impossible without such documentation. With respect to (a), the students must engage in documentation work when the professor or the staff does not have enough time or the aptitude for documentation. Therefore, the documentation work for safety review should be assigned to students as an important task at the start of the project. The students must be motivated by the notion that the completion of the task determines whether the satellite launch can be made successfully. Nevertheless, the documentation for the safety review prepared by the students must be checked by the professors and staff.

With respect to (b), the documentation will be inevitably prepared by the persons in charge of each subsystem or the project manager as they feel the needs. No student, however, will be excited by such documentation work. The documentation work is also in in parallel with the development of the satellite. The documents made tend to become very minimum one unless the professor directs the student to prepare the documents for their own study. For (f), the documentation will be prepared by the professors and students (mostly the doctoral students) to write their own papers.

The documentation of (b), (c), and (d) is related to MA activities. **Such documentation is required to prepare for the situation where no one is familiar with the detail design of the satellite in the operation phase due to generation change within the university or for the purpose of smooth transition to the next satellite project**. However, such documentation will not be made by the students even if they are repeatedly directed that knowledge inheritance is important and that the knowledge should be documented. One idea to solve such problem is **to make the satellite project in combination with the bachelor thesis or master's thesis of the students**. The bachelor thesis and master's thesis are essential requirements for students in science and engineering courses. When development and/or testing of certain systems or components is selected as the theme of their thesis, details of the development and/or testing must be described in the thesis. While such thesis may not cover the entire satellite, very detailed documents will be prepared in specific areas. When the deployment mechanism of the antenna is selected as the theme of the bachelor thesis, for example, the student will make the very detailed record of what he/she did describing basics of the antenna, how the threads were connected, to what extent the tests were conducted and in what conditions, to what extent the tests were successful, and the possible factors of the failure of the test.

2.7 Defect Management

A defect will occur when we develop a satellite. It cannot be avoided. After all, the satellite development is a series of repeating the processes to find a defect and fix it before the flight. It is important to have a management system to collect the defect information and make the project manager or the person in charge aware of the defect. Based on the system, a proper action is done to each defect. The defect management system, which can be as simple as an Excel sheet, becomes increasing important as the satellite system becomes more complicated. The defect management system has been proven to be effective in several university satellite projects. I**<u>t is, however, important not to divert the limited resources to solve all the defects. It is important to prioritize the defects based on the effect on the mission success and work according to the priority list.</u>** Also, during the early stage of development, such as BBM phase, the person in charge may not regard the defect as defect and think that simply the development is not complete yet. If the person in charge changes in the middle, the defect may be left as it is. Communication between the project manager and the person in charge is important.

2.8 Relationship with External Stakeholders

University satellites are often requested by companies to do in-orbit demonstration of the product. It is good for the companies because they can save much labor and cost compared to the case where they build the satellites by themselves. It is also good for the university team because they can obtain funding from the companies. Also, if the product itself has research and development elements, the work may lead to the publication of papers as a part of joint research. When the university team receives such a request, however, they should clearly determine the interface and scope of work. For the system side (university), it would be much easier if they simply provide the power supply line and data line only and have the company make all the measurement circuits to obtain the in-orbit data. Efforts should be made to at least minimize the impact on the satellite bus design. If the area of responsibility remains vague, it may end up spending a large amount of human resources in the company payload, or an unexpected design change may become necessary at the project final stage. The principal investigator must be careful about accepting the offer from the companies. The principal investigator should think whether the team can handle the additional complication to the satellite system and coordination with the external stakeholders. The money will come with a price.

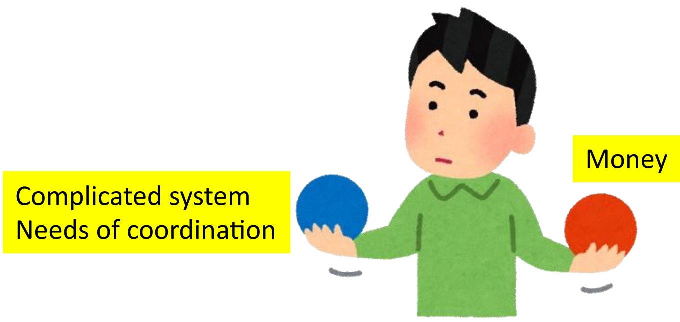

Figure 2 Trade-off to be made when external stakeholders are involved
(illustration credit: いらすとや)

2.9 Funding plan

Satellite projects are expensive. It is very difficult to predict how much it will cost, especially for the first satellite project. Funds are also needed for minimum infrastructure such as a ground station and a clean booth. If the satellite is a 1U CubeSat that does not have active attitude control and is equipped with only a UHF band communication device, it is better to assume that the total cost of EM and FM hardware will be about 10 million yen. Purchasing a foreign-made CubeSat platform will increase the price even further. It will be difficult to get the EM and FM together under 10 million yen. Adding infrastructure such as the ground station and the clean booth, as well as test instruments such as power supplies, oscilloscope, spectrum analyzer, etc., adds up to about 15 million yen. In addition, costs associated with testing and travel must be accounted. In total, as a ball park figure, the team should prepare about 20 million yen, excluding the launch costs, for the first satellite. From the second satellite, there will be no cost for the infrastructure. Also, the team can utilize the surplus parts from the previous projects, and the know-how cumulated will save the money for testing. It is not recommended to rely on student handwork to save the money for procurement as the quality decreases. If the external stakeholders are invited to fill the funding gap, the satellite complexity increases lowering the satellite reliability and increasing the project management workload. It is necessary to have a margin in the funding plan at the project start. It is dangerous to start the project without solid funding base.

2.10 Risk Management

Risk management can be considered a fundamental activity that underlies mission assurance. Risk is something that, if it materializes, could lead to unfavorable outcomes for a satellite mission, and it has the possibility of occurrence that is not zero. Risk management is a systems engineering process that involves identifying, assessing, and effectively reducing or preventing the impact of risks. While safety management and risk management are similar, risk management addresses issues beyond safety and encompasses all the aspects of satellite project. An event with a probability of 1, meaning it will definitely occur, is not considered a risk but rather an issue that needs to be addressed beyond the risk management.

Risk management is carried out following the flow in Figure 3. Firstly, risks that may hinder the success of the mission are identified. Risks encompass not only technical aspects but also various aspects related to project management (such as funding depletion, team member departures, delays in component procurement, etc.). Next, the likelihood of each risk materializing (probability of occurrence) is multiplied by the impact when it occurs (severity), and each risk is comprehensively assessed. A selection is then made to address them based on priority within the constraints of limited resources (personnel, budget, schedule, etc.) (see Figure 4). Measures to mitigate the risks are chosen, and the actions are implemented. As a result of implementing these measures, the severity and probability of occurrence (or both) decrease, prompting a reassessment of the prioritization of risks. As an example, Table 3 illustrates how the risk of "failure in antenna deployment leading to an inability to establish communication" is mitigated through risk countermeasures. Measures are implemented until the risk is reduced to an acceptable level. The tracking of risks in Figure 3 should be continued throughout all stages of the system life cycle, and during design changes, it is crucial to constantly examine whether new risks have emerged.

The most significant difference between lean satellites and traditional satellites lies in their approach to risk management (Table 4). Traditional satellites are designed with the premise that they must function reliably no matter what the environment is severe and no matter what the system become complex, leading to a strategy that aims to minimize risk as much as possible.

In contrast, risk analysis for lean satellites is primarily based on the team's experience. For beginner satellite projects with little prior experience, it is advisable to consult experts as early as possible in the project to identify potential risks. Risk mitigation measures should be implemented selectively, prioritizing only the most critical risks.

As a result, there is a possibility that the satellite may fail. However, even in the event of failure, lessons learned can be applied to the next satellite, allowing for a rapid follow-up launch. Instead of focusing on individual projects, mission success is pursued at the program level. Therefore, even if a single satellite fails, measures should be taken to ensure that at least minimal on-orbit data can be obtained for future improvements. For instance, risk mitigation should be implemented to enable the satellite to operate for at least one week in orbit and communicate with the ground.

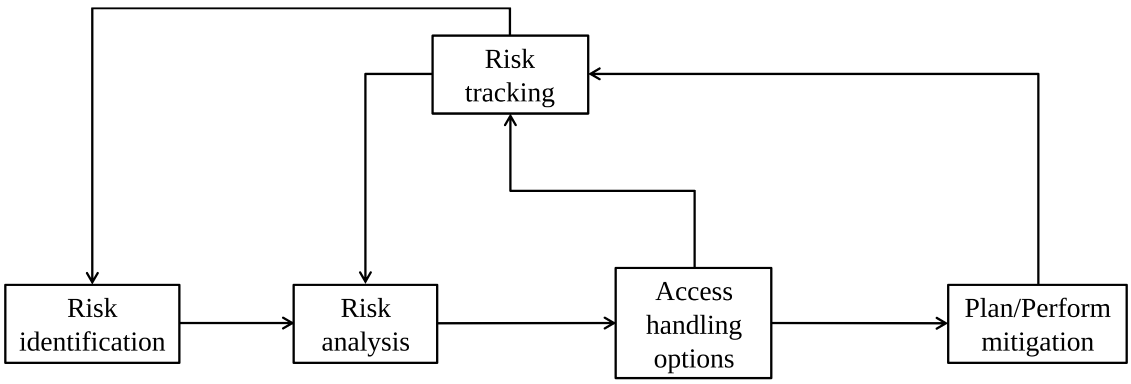

Figure 3 Flow of risk management

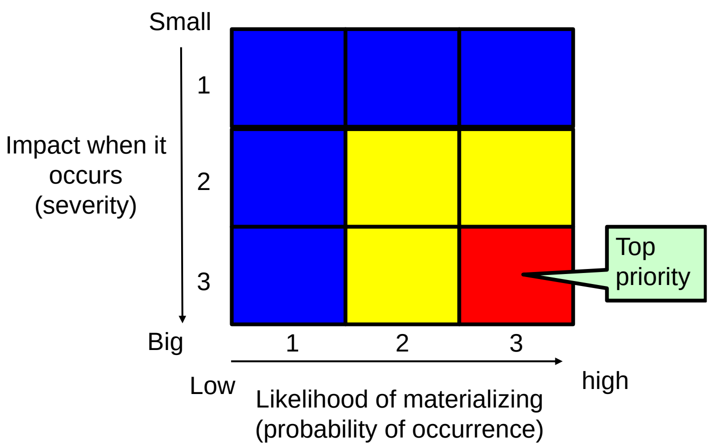

Figure 4 Risk analysis

Table 3 Example of how a risk is reduced. Risk considered is "failure in antenna deployment leading to an inability to establish communication"

Mitigation	Likeliness	Seriousness
	3	3

Increase the number of test	2	3
Change to a commercial product with flight heritage	1	3
Prepare two sets of radio and antenna	1	2

Table 4 Difference of risk management between lean satellites and traditional satellites

	Lean satellites	**Traditional satellites**
Risk tolerance	Large	Small
Risk evaluation	Based on team experience	Based on standard
Risk mitigation	Only high priority items	Almost all

3. Defining the Mission

3. 1 Feasibility

It is very unlikely that the knowledge and skills required for development of the satellite are fully covered by the team members. The idea to bring in talent from outside that cannot be filled internally by newly hiring staff does not always guarantee fulfillment of all the required talents. It is risky to expect the growth of student talents. The budget is also limited. In formulating the mission, such restrictions should be deeply taken into consideration. **A feasible mission fitting the available budget and staff** should be formulated. For the case of an educational satellite project, the project may fail if too many new development elements are incorporated.

Success of the university satellite depends on the professors. Even if the professors try something beyond their capability, the students may not be able to follow. The professor is not a god and does not know everything in judging the mission feasibility. It is important **to accept what is lacking in his/her ability, to ask assistance from outside, and not to try too hard in a weak area.** When assistance is requested to the outside, an attitude of faithfully accepting comments from an experienced person is important. The ability to decide whether the comment is valuable or not is required as a prerequisite, and an effort must be done to acquire such ability. As an initial point of access to external assistance, utilizing the CubeSat Salon (for details, see Reference [6]) would be beneficial.

3.2 Success Criteria

The success criteria are the guidance to make progress in the project. The success criteria are usually composed of three elements; minimum success (the minimum target to be achieved no matter what happens), full success (the target of results to be achieved when the system fully functions as required), and extra success (the target of results that is more than expected in addition to the achievement of full success) (Reference [7]). It is required to use quantitative indicators as much as possible (especially for the minimum success and the full success). Tables 5-7 show examples of success criteria.

Table 5 Success criteria example (Store & Forward mission)

	Criteria
Minimum success	Receive data from the ground sensor terminal by the

	satellite and subsequently transmit it to the ground station at least once.
Full success	Receive data from ground sensor terminals located in multiple countries and distribute the data to each respective country.
Extra success	Conducting the mission continuously for one week

Table 6 Success criteria example (Technology demonstration of a new transmitter)

	Criteria
Minimum success	Achieve downlink speed of 1Mbps
Full success	Do data downlink with 20 Mbps and succeed in decoding the data in full
Extra success	Do data downlink with 20 Mbps with bit error of 10^{-5} or better

Table 7 Success criteria example (Technology demonstration of a camera payload)

	Criteria
Minimum success	Return any kind of image to the ground
Full success	Capture photographs of human characters formed within a 100m x 100m area
Extra success	Capature photographs with the resolution of 5m/pixel or better

The success criteria should be defined at the start of the project. Whether or not the target, especially the target of full success, can be achieved should be checked at each project milestone such as the review meeting. If achieving the target is considered impossible, the criteria need to be changed. But, it should be thoroughly examined **whether the meaning of the entire project can be achieved (whether or not the results can satisfy the project stakeholders)**. If the feasibility of design change is reviewed, **whether or not the minimum success criteria can be achieved by design change should be seriously examined**. The minimum success criteria should not be changed easily. On the other hand, revision of the respective success criteria in the upward direction at a late stage of the project should be avoided because it may add something to the system requirements. Any addition to the system requirements at a later stage tends to cause a failure of the project.

The achievement status of respective success criteria will become the indicator to be used in formulating the satellite operation plan in the operation phase. As explained later in 8.2 Operation Plan, once the satellite is released into orbit, operation to achieve the minimum success criteria should be implemented as soon as possible.

3.3 Mission Scenario

The operation scenario of respective missions, i.e. concept of operation, should be formulated after what missions will be done. It should be considered how to operate the satellite by command link from the ground station, and how the data will be downlinked to the ground. Based on these, the functions and general performance that the satellite should be equipped with can be estimated, which is called functional analysis. Based on the functional analysis results, the satellite design requirements will be derived. Also, at this stage, **budget tables for the communication, power, and attitude control (pointing) functions should be prepared**. The budget tables should be revised constantly during the project. The accuracy should be improved with the progress of the design, manufacture, and verification of the satellite. If there is no or very little margin in the communication, power, and attitude control at the mission definition stage, such mission should be considered "unfeasible".

At this stage, the power budget should have a margin of achieving the full mission success even if the satellite loses one solar panel. The communication link budgets should have 10dB margin for the minimum success and 6dB margin for the full success for the downlink. For the command uplink, the margin should be approximately 20dB at the mission definition stage. In addition, the attitude budget is significantly affected by the accuracy of the sensors.

3.4 Risk Management

The satellite project is a series of processes **in which the unknowns (success or failure is unclear) are converted to knowns (confidence in success)**. There are always technical unknowns to achieve the mission success. The project without unknowns is not exciting. Even when the technology is already used by other organizations or teams, such technology is unknown as long as it is not used by the project team. All the unknowns are risk items against the mission success. In a satellite project, once the mission scenario is defined, the functional analysis is carried out. After the functional analysis, it becomes clear what technical unknowns exist in the project. In risk management, it is essential to assess the potential of failure for these "unknown" factors and the impact they would have on mission accomplishment in the event of failure (refer to Figure 4). As development and verification progress, the degree of "unknown" is expected to be replaced by "known," and the likelihood of failure should become somewhat clearer.

3.5 Mission Assurance for Satellites Built by External Funding

While it will not occur for the first satellite, as experience in satellite development and operation accumulates, the university team will often receive requests from external sources to develop satellites. Potential missions for externally funded satellites may include:

- Outreach activities targeting junir and high school students, as well as corporate promotions.
- On-orbit demonstration of technologies owned by companies, primarily in the manufacturing industry.
- Proof of mission feasibility for new space utilization ideas proposed by companies.
- Verification of principles and technological demonstrations for scientific measurement devices requested by science persons both within and outside the university.

The funding for these satellites is provided by the external commissioning entities. While there may be cases where the university includes its own mission payload, the primary focus is on external commissioned missions. In the case of these satellites, the required mission success rate is higher compared to the caseswhere the purpose is for education and research within the university or when external stakeholders partially participate (refer to 2.8). The objective is to "make a satellite for somebody else," and it is crucial to accurately reflect the commissioner's requests (customer requirements) in the mission requirements, success criteria, and mission scenario.

To do so, effective communication with the commissioner during the mission definition stage is crucial. When the commissioner's requirements are high, it is important not to take on more than can be handled. Assess the necessary resources, and at times, decline the offer if necessary. When receiving requests from companies or organizations familiar with dealing with so-called Old Space companies, which are accustomed to traditional space industry practices, there may be confusion about the approach taken in lean satellite development at the university. Therefore, having the common understanding of the development philosophy is important.

Furthermore, both the commissioner and the satellite developer should avoid the sentiment of "it's cheaper because it's a university." Adequate funding should be firmly requested. To achieve the minimum success criteria required by the external stakeholder, it is preferable to use satellite components with flight heritage. At the very least, developing components from scratch should be avoided. In terms of TRL (see Reference [8]), components with TRL of 6 or higher should be selected. Additionally, the cost of procuring components from the market should be accounted for the budget estimation. It is necessary to clarify in advance who will handle the official procedures such as radio licenses and space activity law applications.

4. Conceptual Design

4.1 Requirements Management (Consistency between the mission requirements, design requirements, and verification requirements)

The design of the satellite should be consistent with the mission requirements. The mission requirements should be decided during the conceptual design of the satellite based on careful discussion among the team members. Participation by experts and persons from outside with experience of satellite projects is preferable. When the satellite's mission is primarily education of the students, for example, it is desirable to build a satellite that will function with certainty so that the students can experience operation of the satellite. To use a component primarily made for R&D purposes (e.g., an antenna with a completely new design) is not consistent with the mission requirements. The design requirements should comply with the mission requirements. But the basics of system development is sometimes neglected because of the ambition of a university researcher. Such ambition should be removed through comments from another member of the project or from the outside. The professor must be **open to the opinions of others**.

On the other hand, there are cases where the design does not reach the level of the mission requirements. It is frequently the case where the communication link is designed assuming the maximum capacity to allow downlinking of the data required by the mission. But it is quite rare that the maximum channel capacity is achieved in actual operation. In reality, the amount of data that can be downlinked is typically much lower than 10% of the maximum communication capacity. A comment in the concept design phase is also effective in such a case.

4.2 Incorporation of the Lessons Learned from Past Projects

When the team has experience with some satellite projects, the lessons learned in past projects should be incorporated in the conceptual design. The items that successfully functioned in orbit and those that did not should be distinguished. T**hose that functioned should not be changed unless such change is very reasonably required. Correction or improvement should be applied to those that did not function after identifying the cause**. When components are procured from the outside, the team should have experience as to whether the procurement was easier and whether a good aftercare was provided. Based on the experience, whether to use the same component should be carefully considered.

4.3 Safety Requirements Compliance Check

After conceptual design is complete, **the issues of safety compliance should be identified before commencing the detail design**. This may be performed in Phases 0 and 1 of the Safety Review. As an experienced expert can easily identify the potential issues just by reading the conceptual design document, it is good to ask the review by such an expert.

Potentially safety critical items are the following, deployment (antenna or solar paddle), battery (especially the one without space heritage), energy storage device other than batter, e.g. super-capacitor, liquid or gas container, items that may scatter glass such as camera lens, propulsion (especially the one involving high pressure container), high voltage device, special structure material other than aluminum alloy.

For the second or later projects, it is recommended to get lectures from the system safety person of the previous projects about the safety related issues, such as what safety requirements were applied, what kind of verification was necessary, etc..

4.4 Verification Plan

Verification is an activity to confirm that the satellite is built according to the requirements. It can be done not only by testing, but also by analysis, drawing check, and others. The verification plan should be prepared during the conceptual design, which defines when and how compliance with the various design requirements should be verified. Such plan needs to be revised with the progress of design and development. It is important to keep in mind that a design that is not verifiable should not be used. **Optimism such as that the design will *probably* work should be avoided**. **A verification plan that is doable** should be made. It is easy to include a statement "to be verified by radiation test" in the plan. But it should be considered whether the test facility is available, team members have the required knowhow for performing the radiation test, etc. When the radiation test is not conducted, the design for radiation resistance should be made based on the condition that no radiation test has been conducted, such as by using parts with flight heritage.

Because most of the universities do not have all the test facilities, an outside testing center that offer testing services to outside users is usually used. Preliminary contact should be made with the testing center during the conceptual design phase to check whether the testing center is available and suitable or not. If the team has little experience in testing, **a testing center that can provide advices on the satellite design and testing should be selected.**

As explained in 2.5 Compliance with Safety Requirements, verification for safety requirements is required but it does not enhance the value of the satellite. Therefore, the efforts used for safety verification should be kept at the minimum level. **Efforts should be concentrated on the verification of requirements that will enhance the value of the satellite** (to increase the survival rate of the satellite, to increase the success rate of the mission, to improve the quality of data obtained in orbit, etc.). For an example, safety verification of the battery is the highlight in the safety review. Students often spend a tremendous amount of time in the battery screening. The students tend to have a feeling of being engaged in meaningful work because the work is real. While the battery screening is a necessary activity, the team members must understand that much effort should be concentrated on other matters to enhance the value of the satellite. However, when such fact is emphasized too much, the motivation of the student assigned to an inconspicuous task such as the battery screening may be lost. Therefore, careful consideration is needed.

For CubeSats released from the International Space Station (ISS), the minimum set of required tests is listed in Table 8. Where "R" means "required" and indicates the test to be conducted in respective phases. The mark "O" represents optional and the mark "N" represents not required. Details of the respective tests are explained in Section 7. As analysis used for verification, structural analysis (identification of resonance frequency, derivation of maximum allowable load, and safety margin) must be performed.

When the satellite is deployed directly from a launch vehicle such as piggy-back launch on H2A or Epsilon rocket, quasistatic load test (sine burst test), sine wave vibration test, shock test, etc. may be required in addition to those tests listed in Table 8.

Table 8 Tests to be conducted on CubeSat released from the International Space

Station

Test Item	EM(QT)	FM (AT)
Electromagnetic Compatibility Test	R	N*1
End-to-End Mission Test	R	N*1
Electrical Interface Test	R	R
System Functional Test	R	R
End-to-End Long-term Operation Test	N	R
Deployment Test	R	R
Fit Check	R	R
Thermal Test	R	O*3
Random Vibration Test	O*2	R

*1: Included in the End-to-End Long-term Operation Test for the FM

*2: To be conducted when specifically required for the satellite. No need to be conducted when not required.

*3: It is required to demonstrate that the satellite is functional after exposure to -15°C and +60°C for verification of compliance with the safety requirements. (See reference [9]). When verification is impossible by design (allowable temperature range of the parts used that is obtained from the datasheet, etc.), testing is required. The thermal vacuum test and thermal cycle test in a thermal chamber are conducted when the project team (not the launch provider) judges them as necessary. Otherwise, they may be skipped.

The choice between analysis and testing as a verification method depends on the specific case. However, in many instances, doing an actual test is quicker than investing significant effort in analysis—such as for antenna patterns or mechanical motion. The verification method should be selected to minimize the required effort.

For university satellites, radiation testing is often not conducted. While total dose testing is easier to perform than single event testing, and thus is more commonly conducted, single event testing (such as latch-up testing) is critically important for low Earth orbit (LEO) missions lasting two or three years at most.

However, single event testing presents significant challenges for beginners, and access to test facilities is extremely limited. As an alternative, it is advisable to simulate a latch-up event to verify whether the satellite can successfully reset and restart in response to such occurrences.

4.5 Risk Management

In the case of lean satellites, risk mitigation starts from the ones with higher priority that is evaluated based on a combination of occurrence probability and severity (refer to Figure 4). However, it's important to note that quantitatively assessing occurrence probability and severity can consume time and mony. Therefore, in the context of lean satellites, experience and the Wisdom of the Crowd are often employed for these assessment. It is recommended to seek comments from experienced developers and experts in the field for risk assessment. When the conceptual design is finished, requesting an external expert review can provide valuable insights not only on issues related to safety requirements compliance but also on prioritizing risk items.

5. Detail Design

5.1 Selection of Parts and Components

Attention should be paid to delivery time, aftermarket service, and interface conformity when a foreign vendor (seller, manufacturer, etc.) is selected as the supplier of components. The members must understand that tremendous time is necessary for coordination with the vendor if any nonconformity of the interface is discovered. Even in the case of a domestic vendor, attention is also necessary when the experience of the vendor is not adequate. Even if a vendor is excellent in technology, it may have a problem with delivery time. **More attention should be paid to availability of the product, easiness of handling (simplicity of the interface), response to repair requests, etc.,** in vendor selection. Such factors are sometimes more valuable to the project than the size, price, and function.

It is important to have a margin in the number of parts/components to be procured. Failures or damage due to careless handling or overload during testing cannot be avoided. If the schedule is very tight and there is not back-up, there is no time to procure a replacement. Then, there is a risk that the launch will be postponed. If you have procured EM equivalent to flight products, you can use EM products in case of emergency. Even if it is not used in the actual flight, it can be used during operation as an FM backup (TableSat) that is used to check the uplink commands in advance and investigate the in-orbit anomaly. In addition, since the Covid-19 pandemic, it has become extremely difficult to procure various electronic components, including semiconductors, and early procurement is required as a part of risk mitigation. We must avoid a situation in which parts and components arrive at the last minute for the satellite delivery, leaving no time for system testing.

For components involving certain elements of new development, the interface of the work between the vendor and the system (project team) should be clearly defined, to clearly show to what point the vendor is responsible and to what point the project team is responsible. The satellite project should be regarded as the program, and specifications of the bus components should not be changed as much as possible, **to eliminate development work by the vendor for the second, third and later projects to allow delivery of the identical component.** This is preferrable from the aspect of short delivery time. Excessive discount or an academic discount from the vendor should not be expected because the vendor product is produced procuring raw materials and by labor of the employees. A good relationship with the vendor to allow for long-term relationship should be established without causing a financial loss to the vendor.

When the component is developed jointly with the vendor, the design and knowhow should be transferred to the vendor so that a **sustainable supply chain** system can be established where the vendor is fully responsible for the supply of the component. To maintain stable product quality, a vendor with whom a good long-term relationship can be maintained should be selected.

5.2 Risk Management, FTA and FMEA

During the detail design, FMEA (Fault Mode Effect Analysis) and FTA (Fault Tree Analysis) should be used in activities to sort out the technical risks. But few students learn FMEA or FTA in the university course and do not know the method. The same thing applies to the professors. It is important **to start analysis at the level that the team members can understand** without fully following the method available in literature.

For FTA, a flow chart of the mission scenario should be prepared, and it should be considered which component is responsible for a possible failure of the respective step. For FMEA, it should be started from categorization of the cases; (1) The mission can be executed without problem, (2) The mission can be executed with some problems, (3) Execution of the mission is impossible, and (4) Complete failure of the satellite (communication blackout) when the respective component should fail. With respect to whether or not the component fails, use of the following indicators will be used for convenience; (1) The component has a record of successful operation, (2) A similar component has a record of successful operation, (3) The component is designed and built by a manufacturer with a record of successful operation, (4) The component functions with certainty in the ground environment, (5) Design of the component is completely new, and (6) The component is built by students. In any case, **a failure of the part or component that may result in complete failure of the satellite (single point of failure)** should be first sorted out to determine the priority in activities to reduce the risks. When there are many single points of failures and it is difficult to deal with all of them due to the resource limitation, the items that has the large numbers of the product of the effect on the mission (the numbers listed from 1 to 4) and the possibility of occurrence (the numbers listed from 1 to 6).

FTA and FMEA should be **also applied to the activities** in addition to physical items such as parts and components. As a human makes mistakes, the results of a mistake, such as what happens when there is an error in sending a command or when the sensor is connected with polarity reversed, etc., should be carefully examined to incorporate a mechanism to make it more difficult for a mistake to occur or to make recovery action possible in the design even in the case of a mistake.

5.3 Aiming for a Satellite that can survive

The design of the satellite should incorporate a means so that **the satellite can avoid the risk of complete failure (loss of communication with the ground)** under any circumstances. Examples are as follows.

- Installation of the so-called "God PIC", Micro Controller PIC16F877 whose excellent radiation resistance is demonstrated in orbit, to allow power of the entire satellite system to be reset.
- Means to allow battery recharging even when the battery becomes completely empty or to ensure it enters safe mode when the voltage drops.
- A design that allows the satellite to function using power generated by solar panels even when the battery is dead.
- Redundant communication link when the satellite has some room in the interior volume.
- To make the power budget feasible in the following cases for the minimum functions of the satellite (certain missions can be executed so long as the communication link with the ground (up and down) can be established and substantial discharge of the battery is accepted)
  - ✧ Loss of attitude control
  - ✧ Solar paddle deployment failure
  - ✧ Loss of functioning of one solar panel in the case of 1U CubeSat. Without this feature loss of function of any one of solar panel, (usually 1U CubeSat is made of 4 to 6 solar panels), will make the satellite entirely unfunctional, which means that 4 to 6 single points of failure exist.

It is still necessary to verify that the system can avoid the risk of total failure as designed when these designs are incorporated. When the satellite restart after power reset, the system may become unfunctional at a half awake state. A test simulating the failure conditions in orbit should be conducted, and **it should be confirmed that the satellite can successfully restart from power reset.** Recovery of the battery from a completely dry condition should be confirmed simulating the power generation conditions in orbit using the solar array simulator, etc. Transition to safe mode should be tested using the actual satellite. For the power budget, system functionality should be confirmed in the worst case scenario of power conditions. A certain margin should be kept in the power budget, because certain errors in measurement of the power produced and power consumed cannot be avoided. Redundancy test of the communication system should be also conducted.

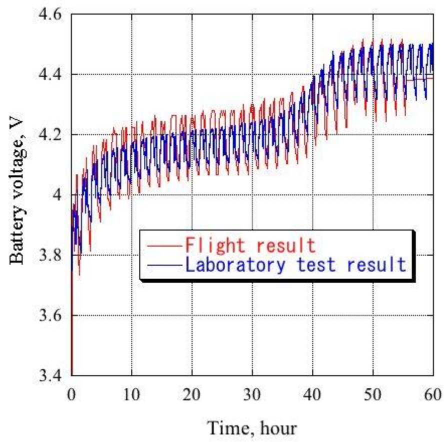

Figure 5 Data indicating the battery recovering from empty state

5.4 Avoid Excessive Protective Functions

In the design of satellite systems, a variety of protective functions tend to be installed. Examples are a safe mode to prevent the battery from drying up and a battery heater to protect the battery at low temperatures. But before incorporating such functions, **the risks and benefits of such protective functions should be carefully examined** as to whether they are really required. Automatic activation of the protective function is based on the condition that the voltage and temperature sensors function normally, but how much such sensors can be trusted should be considered. The safe mode may cause a risk of the system failing to restart because the safe mode may cause the system to go into a suspended condition, and some satellites have experienced such situation. The battery heater requires power, and such power consumption may make the battery dry up because of a negative power balance.

Instead of using the safe mode, a design may be used where power supplied to the satellite is automatically interrupted when battery voltage decreases to below the input limit to the DC-DC converter and the power reset function which shuts off the power of the satellite completely is activated. Then, when the satellite emerges from the eclipse, the satellite system will start up from the initial mode. A battery heater design whereby it can be restarted by a command from the ground monitoring the battery temperature in orbit is preferable to automatic activation. The battery temperature will not decrease all of a sudden in orbit. When the satellite orbit altitude is low, the temperature of the overall satellite will become higher. In such a case, appropriate insulation applied to the battery without a battery heater may be adequate for satellite operation.

5.5 Points to Note in Design Changes

Whether or not the design change is adopted should be always decided after evaluating **the benefits obtained and the new risks brought about by the design change**. Minimum success and full success are used as the criteria for such evaluation. Careful decision is needed when there is a risk that will jeopardize the minimum success. When the design change increases the possibility of full success, the risks associated with such design changes should be carefully examined. For an example, suppose there is an idea of crossed connections of two antennas and two communication equipment using the RF switch for multiplexing the communication link as shown in Figure 6. Such configuration is frequently considered if the communication equipment and antennas do not have a heritage of successful operation. Such configuration will improve the reliability of the communication link, giving more chances of having at least one combination of the antenna and the transceiver survives. There will be, however, a loss of RF output, a risk that switching of the RF switch will become impossible or it sticks in an intermediate position where the transceivers and antennas are disconnected, and in the worst case, there is a risk of no communication at all. Even without such crossed connection, communication can be established when at least one pair of communication equipment and antenna is functional and the minimum criteria can be achieved. The benefit obtained by a crossed connection is not considered to surpass the associated risks.

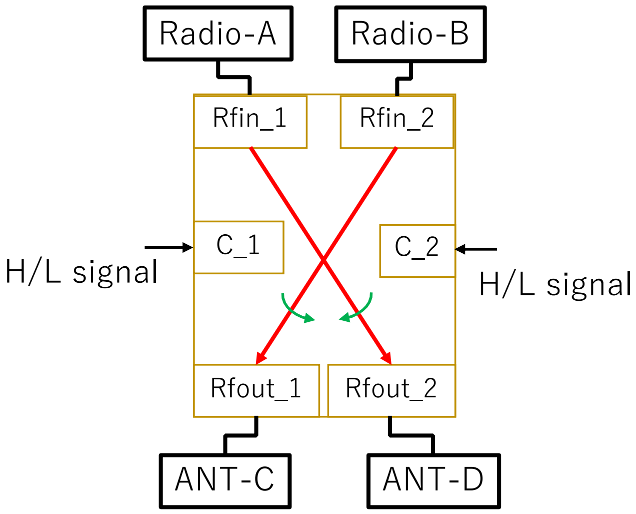

Figure 6 Study on Crossed Connection between Transceivers and Antennas using the RF Switch

5.6 Satellite Design allowing Easy Operation

Easy satellite operation should be intended considering how to execute the mission. For second and subsequent projects the lessons learned from past operations in the past should be incorporated to the maximum. When the project is for the first satellite, hearing from a university who has experience with satellite operation is helpful. For example, the stored command (reserved command) system will make starting the satellite's missions possible at any point above the ground other than

Japan. When a series of operations are reserved, it will not be required to uplink individual operations one by one. It will increase the data volume because data can be downlinked at different ground stations (however, frequency coordination should be carefully made).

To improve the uplink success rate, a simple uplink command should be used so that the command can be uplinked with a small number of bytes. As command encryption will only decrease the success rate of the uplink, the benefit obtained from encryption is low in the case of a university satellite in which confidentiality is not really required.

The software of the ground station is preferably designed to be compatible with remote operation and automatic operation to allow operation possible even when the number of operation staff decreases.

If the power reset is done, it is recommended to keep the history of attitude control parameters and housekeeping data before the reset. The attitude control parameters often require the uplink over multiple satellite passes. If the parameters go back to the initial setting after each reset, every time it takes a lot of time to restart the attitude control. Also, the housekeeping data history is useful for the anomaly investigation.

5.7 Satellite Design that is Easy to Test and Easy to Assemble, Integrate and Test

Satellite should be designed considering the easiness of assembly, integration and testing. Fasteners (screws and bolts), cable harnesses, and connectors are essential parts in assembly of the satellite. Assembly of the satellite will become easy when the type and quantity of such parts are small. Particularly, as **workmanship errors can frequently occur related to the harnesses and connectors**. A design that minimizes the use of such parts should be considered. If the harness use cannot be avoided, it is desirable to outsource the harness making to a professional rather than in-house making by students. A mechanism to prevent mistakes in fitting the parts is also required. Mounting the parts on the PCB may be asked with the front and back faces mistaken. A mechanism that prevents such mistake is required. **It is not a solution to prevent a mistake just by the worker being careful. A mechanism to prevent human mistakes should be incorporated in the design.**

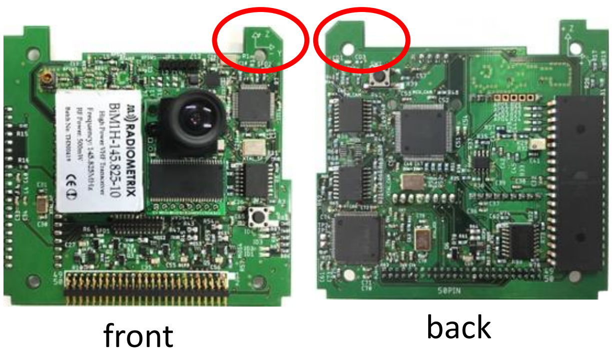

Figure 7 Design not to mistake the front and back of the PCB. The diagonal notch marked with a red circle should be on the right side when facing the front.

It is frequently required to remove a component with a problem during the system test, especially the first system functional test. The satellite should be designed so that disassembling the entire satellite is not necessary when the components and a small number of the associated parts are removed from the satellite. The connector should be durable for frequent connection and disconnection because connection/disconnection is required in component removal and installation. When the connector is forcibly disconnected, the connector may be damaged. A device to disconnect it smoothly should be prepared. It is recommended to prepare test beds for the electrical interface test and software development, because such tests can be made without installing the entire satellite system in the satellite.

Access ports should be provided in the outer panel of the satellite to allow access to the processors (microcontrollers) after assembly of the satellite is complete. A design that does not allow access to the processor from outside should not be used unless you are fully confident in your software capability. When more than one satellite with identical designs are built, identification should be applied to the exterior of the satellite to identify each satellite. For example, in Figure 8 the identification sticker is applied on the GPS antenna of each satellite.

It is recommended to fabricate jigs used for assembly, storage, tests, etc. of the satellite (Figures 9 and 10) to prevent an accident during tests and assembly. The satellite should not be placed directly on the desktop because damage may be caused. The design of the jig should consider how to hold the satellite. In the case of CubeSat, a Pelican Case, etc. is used to carry the satellite, but at the last moment it must be held by hands when it is set for the vibration test and thermal vacuum test (never hold the satellite using just one hand). For satellites other than the CubeSat, the design should allow for installation of the I-bolt used to hoist the satellite in the upper structure of the satellite. **Holding the satellite by hand should not be considered.**

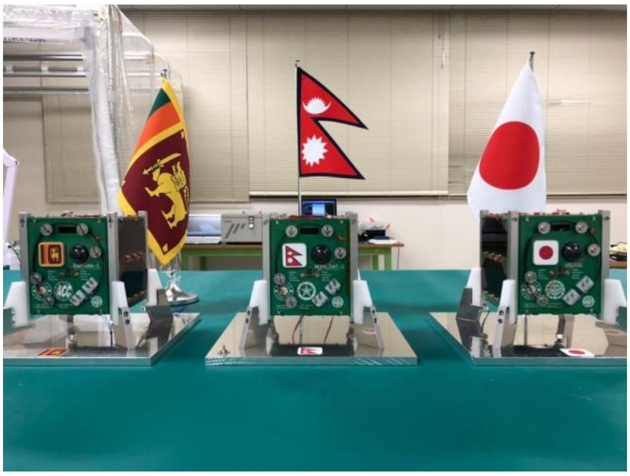

Figure 8　Jig for Satellite Storage

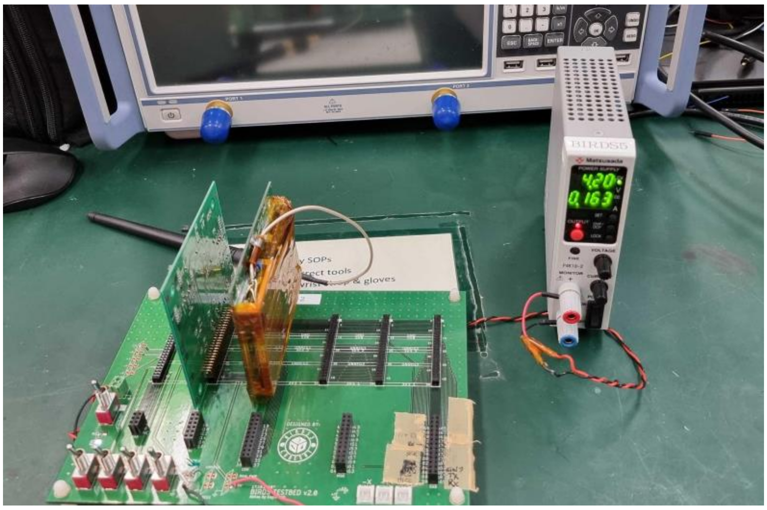

Figure 9 Testbed for Component Test

Figure 10 State of the System Functional Test (The satellite is placed on the test jig)

5.8 Understanding of Design Basis

Normalcy bias is a common behavior by which a human being considers what he/she cannot completely understand as probably OK, and justify such decision groundlessly. **<u>In the satellite development, the words "probably" or "will be" should be avoided when making a decision</u>**. The design should be based on firm grounds. Especially for critical design items that will decide the fate of the satellite and the mission, all effort to understand the grounds of the design should be made until you are convinced. When you do not understand, opinions should be obtained from different people, and you should accept comments from people with experience in deciding the principles of the design and verification method. It is important that **<u>you admit that you cannot understand if you cannot understand an item</u>**. It is a common practice to use the same design as in the past in the development of second and subsequent projects, but a problem may sometimes occur when a design change is applied to a certain item when considering that such change will be effective but without understanding the design grounds. For an example, the threshold value to activate the over current protection circuit to exit from the single-event-latch-up should be determined in principle by measuring the latch-up current by a radiation test. If the value is already decided, the team should understand the rationale behind the number.

5.9 Before advancing to FM Phase

In the EM phase, efforts should be concentrated on **completion of the satellite functions and improving the team skills**. For that purpose, an EM that is functionally equal to the FM (all components other than the solar panel are installed) and can even serve as a flight spare should be made and thoroughly tested. Assembly and testing of the actual satellite system by the team improves skills. (This is very important for a university satellite for which a majority of the team members lack experience.) By confirming that the satellite system will **be able to achieve the minimum required mission** by the end-to-end test in the EM phase, a fundamental change of the system should be avoided when the project is moved to the FM phase.

If there is a function that could not be verified in the EM, the decision not to install the function in the FM is necessary, unless the function is essentially required for the mission success. A new problem will naturally be found after the project moves to the FM phase, but handling of such defect requires higher costs, a longer time, and more mental pressure. A system defect found after moving to the FM may need **to be discarded unless such system is critical to the mission success,** and works should be concentrated on the items with higher importance.

To allow such decision, all team members as well as the project manager should share understanding of which mission should be given priority, and prioritize which items should be achieved as a minimum (success criteria).

In addition, works at the FM stage is often carried out in a clean room or a clean booth. When a person participate in a satellite project for the first time, mostly likely the person has no experience working in the clean room environment. Before moving to the FM stage, the rules regarding the works in the clean room environment should be confirmed by all the team members.

5.10 Safety Requirements Compliance Check

Phase 0, 1, and 2 safety review is normally conducted after the detail design and testing of the EM is complete. Documentation for safety review requires a very long time. **Such documentation work should be performed not only by the members in charge of safety review but by all the project team members maintaining high motivation.** In Phase 0, 1, and 2 safety review, the method to verify compliance of the FM with the safety requirements is discussed. Attention should be paid to the method of verification so that verification can be made without a problem **by close communication between the members in charge of safety review, members in charge of satellite construction, and members in charge of verification of the FM.** There are some risks that the satellite does not pass the Phase 3 safety review if verification is not made correctly because of a lack of communication. In such a case excessive time loss may occur to repeat the work for verification, and in the worst case the team has to start the design from the beginning.

5.11 Satellite Interface

During the assembly and integration stages of both EM (Engineering Model) and

FM (Flight Model), significant time is required for adjusting interfaces between components. Even if individual component works on its own, issues often arise when connecting them together. Satellite assembly is frequently hindered by interference between components or interference between a component and the satellite structure. Interface incompatibility is a major cause of schedule delays in satellite projects. When planning to purchase all the bus components off-the-shelf and focus on developing the mission payload, it is advisable to procure all the bus components from a single company if possible. In the case of CubeSats, there are over 30 companies worldwide as of 2022 that sell the entire satellite bus as a CubeSat platform. Though the abundance of options may pose a challenge, it is crucial to carefully examine the datasheets provided by each company and, if necessary, engage in teleconferences with them to clarify interfaces before proceeding with the purchase. The required interface information is listed in Reference [10]. Even when purchasing individual pieces of component, it is essential to clarify interfaces in advance, and Reference [10] provides a list of information that should be clarified. The architecture of CubeSat interfaces is predominantly based on the so-called PC-104 bus and backplane types, each having its own advantages and disadvantages. Referring to Reference [10] for each, it is advisable to decide on the architecture based on careful consideration.

6. Satellite Assembly and Integration

6.1 Quality Control

Most of the parts used in the lean satellite are parts mass-produced for terrestrial consumer products, not for space applications. Quality assurance of such parts is provided by the manufacturer as mass-produced products. The possibility of defects in those parts are quite low and there is no need to inspect individual parts in the project. **A failure of parts, if it occurs, is mostly due to inappropriate handling of the parts after delivery such as electrostatic discharge, humidity, and contamination**. Practices such as the use of antistatic wrist straps during work, confirmation of adequate grounding of equipment and worktables before starting work, using globes during the work, not to make the opening upward, etc., should be enforced within the team as a common practice.

The quality of individual electronics parts is assured because their manufacturing process is established and matured already as mass-produced items. But, the quality of components made from those parts is not assured. The components refer to a transceiver, a computer board, a power control unit, etc. The components are not mass-produced items. They are one of a kind product. Their manufacturing process is not established. Even when the same components are ordered in multiple quantities, it is not guaranteed that all the components have the same quality. **When such component is delivered, a basic functional test should be conducted before it is incorporated in the system to check for possible defects.**

6.2 Contracting the Work or Building Inhouse

The decision to contract a portion of the work required to build the satellite instead of making everything inhouse is required in the case of the university satellite. **The decision to build inhouse because of insufficient budget may result in schedule delay or mission failure**. The decision to make the students work on items that require handyman skills (harness, solar panel, soldering, etc.) for a university satellite should be made carefully. As some students may have excellent handyman skills, it may be possible to have such work done by them, but when it is difficult to find such students, the work should be contracted outside. **The purpose of the educational satellite is not acquisition of handyman skills by the students but to make the students learn systems engineering and project management by practice in the project**.

Students may not be motivated if the components has no new developments, such as buying outsourced components or using the components already flight-proven in previous projects. However, what is important is that students think what kind of tests are necessary for the satellite to work as a system when these components are assembled, and how to integrate the components with other ones, while synchronizing with the overall system development schedule. The educational effect of systems engineering and project management obtained in those processes is greater than simply making a new component.

In addition, there are many cases where components purchased from the outside do not work when their functionality is checked upon delivery. There are often cases where there is a problem in handling the component correctly rather than the defects in the components. To select a vendor, it is necessary to consider factors such as the easiness of handling, the prompt response to the customer inquiry, and the well-writing operation manual, and others. At the same time, it is important to make a serious effort to think about the causes of malfunctions in your own way.

6.3 Safety Requirements Compliance Check

The records during the FM AIT (Assembly, Integration and Testing) are the basis of the critical verification documents in the Phase 3 safety review. Before entering the manufacturing phase of the FM, it is crucial for the launch provider and the project team to reach an agreement on hazard control methods (Phase 2 of safety assessment). During the FM manufacturing process, the hazard control methods incorporated into the FM based on this agreement need to be verified. Before entering the FM manufacturing stage, the AIT team members must understand the procedures they need to follow and the documents they need to produce. Effective communication between the System Safety team and the AIT team is essential for this purpose.

Figure 11 Communicaiton between AIT team and the System Safety team is important （illustration credit:いらすとや）

The records should be prepared during the FM AIT as much as possible. Note that making the record is not simply taking photographs. The records should be prepared while precisely understanding what items need to be verified and what data and photographs are required. The material certificate of the structural parts and components and the proof that the satellite has been assembled according to the assembly procedure, etc. are particularly important. **Assembly of the satellite should be basically done by two persons or more, and one person must concentrate on confirming the procedure and recording the work.**

7. Testing

7.1 Electromagnetic Compatibility Test

In the case of the lean satellite, electromagnetic interference with other satellites and the launch vehicle need not be considered because the power is off during the launch. However, restricting the RF radiation level below the allowable limit is required by the safety requirements because of a possible safety risk when the power is turned on by mistake (see Note below). The effect of the RF noise produced by the satellite on the functions of the satellite is important with respect to electromagnetic interference, and the effect on the uplink communication should be especially considered. It is too late if it is found that the uplink communication does not work in the satellite during the end-to-end long term operation test using the FM. **An adequate margin in the uplink line should be confirmed in the EM test**.

First, the receiver sensitivity of the transceiver should be measured under ideal conditions when the transceiver EM is delivered. The minimum RF signal strength the receiver can decode the uplink signal should be measured with the transceiver placed in a shielded box and the RF signal from the signal generator injected via RF cable. Such signal strength means the minimum (ideal) signal strength that the receiver can decode in the noise floor generated by the receiver. When the transceiver is installed in the satellite and connected to the antenna, the noise floor will increase but will never decrease. In addition, the RF signal is received through the antenna, which will produce various losses (line loss, polarization loss, pointing loss, reflective loss, etc.). Considering these circumstances, communication during actual operation will not be established unless there is an adequate margin in the ideal conditions where measurement is done with the RF cable directly connected to the receiver unit under external noise-free environment.

For a CubeSat, the effect of noise from other components can be evaluated by a test whereby a complete satellite is placed in a shielded box as shown in Figure 12. Even when the satellite is larger than the CubeSat, the test including some factors of antenna loss is possible when the electromagnetic anechoic chamber is used. These tests should be conducted in the EM phase to verify if the communication system design satisfies the requirements.

Figure 12　Receiver Sensitivity Test in the Shielded Box

Note: When the MOSFET is used as the inhibit switch against satellite power-on, the FET may be activated by excitation of the line connected to the gate of the FET by the radiated electric field of the ISS. That will require the design install a pull-up or pull-down resistor to the FET gate. When the resistor is not installed, analysis and verification will be required.

7.2 End-to-End Mission Test

It should be confirmed that the minimum mission can be achieved by the end-to-end test with the ground station during the EM phase. In the end-to-end test, the following process should be confirmed by transmitting the command from the ground station, which is received by the satellite receiver, and then the command is sent to the C&DH system, which in turn sends the command to the mission payload, and after performing the mission the data are sent to the transmitter, which transmits such data to the ground station, to be displayed on the computer screen at the ground station. For an example, when the mission is imaging the Earth's surface, the process starts by sending a shutter command from the ground station and is completed when the image taken can be confirmed at the ground station. As explained above, **the core element of the mission should be completed in advance. The fact that such mission is practically possible should be demonstrated by the test. Then the detail making should be started.** This test is preferably conducted by actually transmitting the RF signal, but when the electromagnetic anechoic chamber cannot be used, it may be conducted by connecting simulated communication equipment in the ground station with the satellite transceiver via RF cable.

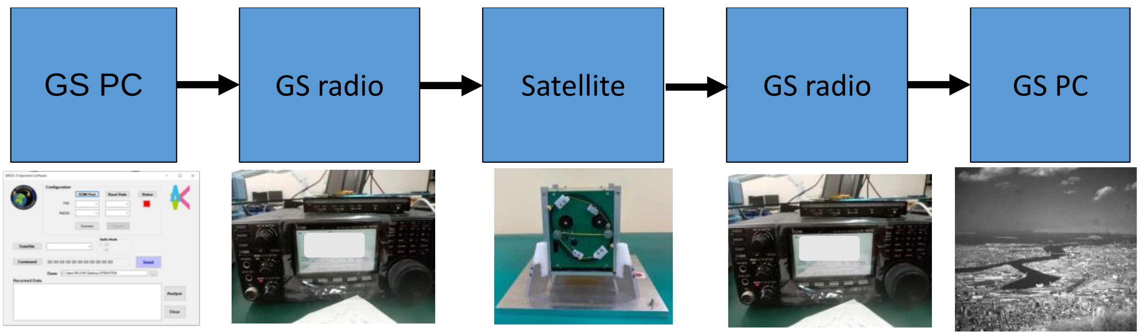

Figure 13 Concept of End-to-End mission test

7.3 Electrical Interface (Integration) Test

The interface test with the other components of the satellite should be conducted when the components are delivered but before they are installed in the satellite structure. This test is required for both EM and FM. **Successful testing for the EM does not always guarantee that the test for FM is successful.** The components used for the lean satellite are basically hand-crafted in small lots. The components for EM and FM are not produced in the same lot. Accordingly, all the components of the EM and FM are not always the same. In the test as to whether interfacing with the C&DH system, power system, etc. is successful, whether equipment ON/OFF is possible, whether data can be transmitted normally, and whether the system functions correctly are also checked. It is desirable to prepare a test bed to allow for easy installation and removal of components and not to cause any damage to the connectors of the components.

7.4 System Functional Test

After the electrical interface test with the delivered components is successfully completed, **the satellite should be assembled promptly and the system test with all systems incorporated should be started**. The functional test of all the systems should be conducted before the environmental test to confirm that the satellite is assembled correctly. The following items should be checked at that time.

a) The modes from release of the satellite into orbit to the time when the steady state is reached. Such modes include receiving of the beacon data from the satellite, deployment of the antenna and solar panel, tumbling control (de-tumbling), transition to sun pointing, etc.
b) All operations to be executed in the initial operation. Such operations include uplink to the satellite, housekeeping data acquisition, command transmission and mission data reception to be executed as a minimum (equal to the minimum success criteria).
c) All the operations to be executed in steady state operation. This includes mission command transmission, mission data receiving, and different types of attitude controls equal to the full success criteria.
d) Confirmation of the functions incorporated in the satellite as countermeasures against failure, such as power reset, transition to safe mode, resetting, etc.

It is important to examine **the details of data transmitted from the satellite** in this test, and whether housekeeping data, mission data, etc. are consistent should be checked. For example, in the case of housekeeping data, it should be checked whether the battery voltage and current change consistently with the operating conditions of the onboard payload and with the power input from the solar panel, and that they are consistent with the power budget prepared in advance, whether the images are taken as planned, whether the sensors of the attitude control system send the correct data and actuators like the reaction wheel and magnetic torquer function correctly according to the input from sensors, and whether RF signal is transmitted according to the power and frequency as contemplated, etc. **When a problem is discovered in such system functional test, the problems should be solved before starting the environmental test**. As the trial and error process at this stage will require a tremendous amount of time, adequate margin should be allocated in the schedule. **A schedule where conducting the thermal vacuum test takes place one week after the satellite is first assembled should not be planned.**

7.5 End-to-End Long-term Operation Test

A majority of the university satellites fails because the FM end-to-end long-term tests could not be conducted before satellite delivery due to a delay in the schedule. The end-to-end long-term operation test of the FM has the following aspects.
a) Flight software debugging

Although the system test is considered to be complete using the EM before the FM, verification of minor updates to software made after the FM is necessary. The functioning of built-in software directly linked with hardware in the actual system is not guaranteed even when it functions on the simulator PC used for programming. **Functioning of the software in any situation (in normal and also in emergency conditions) that the satellite may encounter from the time the satellite is released in orbit to the time when the satellite operation is terminated** should be confirmed. This test includes transmission of the mission command and receiving of the mission data, to confirm whether the mission can be achieved.
Although this test is almost the same as the system functional test, in the long-term operation test simulating operation during the first week in orbit using the actual time scale is desired. This is because a problem is most likely to occur in this one week period. Software bugs are inevitable, and as the time passes, and while the number of bugs found decreases, the long-term operation test will improve reliability of the satellite. However, even if a new bug is found, there is a risk when we replace

the sfotware. Beyond a certain time prior to the satellite delivery, a decision not to rewrite software may be made even if a bug is found, depending on its criticality.

b) Operation rehearsal

The end-to-end long-term operation test should be conducted **using the control software of the ground station**. Any communication with the satellite should basically be made only by the uplink and downlink signals. By such processes, the method to understand the satellite's condition from housekeeping data and the processing method of the mission data should be learned. In addition, the satellite's response to the uplink command can be understood. Using the control software of the ground station will improve the operation team's proficiency. By experiencing the operation with the satellite at hand, the anxiety of having communication with the satellite in orbit by RF signals alone will be reduced.

c) Confirmation of communication between the ground station and the satellite

In the end-to-end long-term operation test, communication between the ground station and the satellite should be made by RF signals as much as is flight representative. The problem of the radio station license should be resolved, or the test should be conducted in an electromagnetic anechoic chamber. The communication with the satellite by RF signal will confirm the communication link budget. In the communication link budget of the lean satellite, the items that are difficult to know precisely are the **loss between the satellite antenna and the transceiver and the noise floor around the transceiver**. The loss between the satellite antenna and the transceiver is determined by fabrication of the antenna and its peripheral circuit and the skill in installation. In the case of CubeSat, the components are closely packed and the RF noise environment around the transceiver is extremely complicated. As shown in Figure 14, the uplink signal intensity is extremely reduced due to the free space path loss when it arrives at the satellite. The two elements above determine the success rate of the uplink. In order to check whether the communication link works, an **uplink signal with a known intensity is sent via free-space radio wave and whether or not the uplink is successful or fails should be measured.** Under actual flight conditions, it should be taken into consideration that the success rate of the uplink will be further reduced due to the Doppler shift.

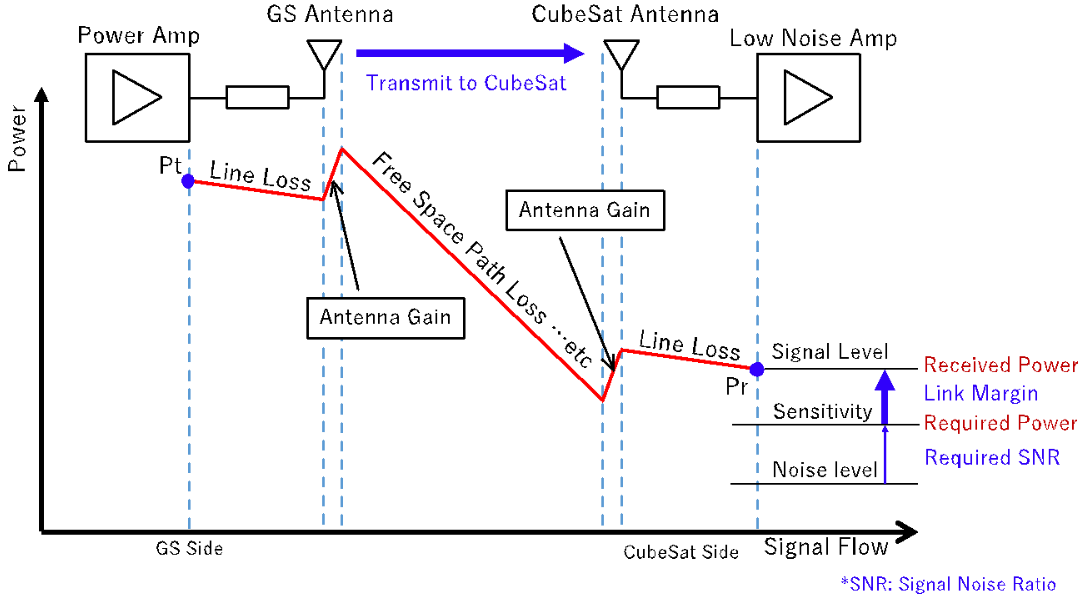

Figure 14 Communication Link Budget (Uplink)

7.6 Deployment Test

The missions of many lean satellites with deployable systems have failed. Many CubeSats have deployable UHF/VHF antennas retained by threads. Considering that the missions of about a quarter of the university CubeSats ended up as DoA (Dead on Arrival) (Reference [2]), it can be reasonably considered that the deployment of such antenna failed in many cases. There are many satellites in which deployment of the solar panel also failed and the success rate of satellites with the deployment of film or with separation between the master satellite and subsatellite is not high.

When such facts are considered, we can say that in many cases the deployment test on the ground was not sufficient. Because actuation of the mechanism with movable parts in microgravity and the vacuum environment in space is certainly difficult and computer simulation is also difficult, verification using the actual mechanism such as the EM and FM cannot be skipped. For the EM, tests assuming all adverse conditions should be repeated. The testd should be done in the same conditions that will be encountered in orbit as much as possible. When the antenna is deployed by cutting the thread with a heated cutter, successful deployment should be confirmed by the low battery condition immediately after the satellite is separated and released, and **in the condition where the heat cutter is exposed to low temperatures**. Figure 15 shows the example of the deployment test in a low temperature condition. Because the number of deployment tests increases as the deployment system becomes more complicated, the design should consider the ease of conducting the test and the allowance in the limit to the number of tests. Effort to make the test environment as close to microgravity and vacuum condition as possible should be also made.

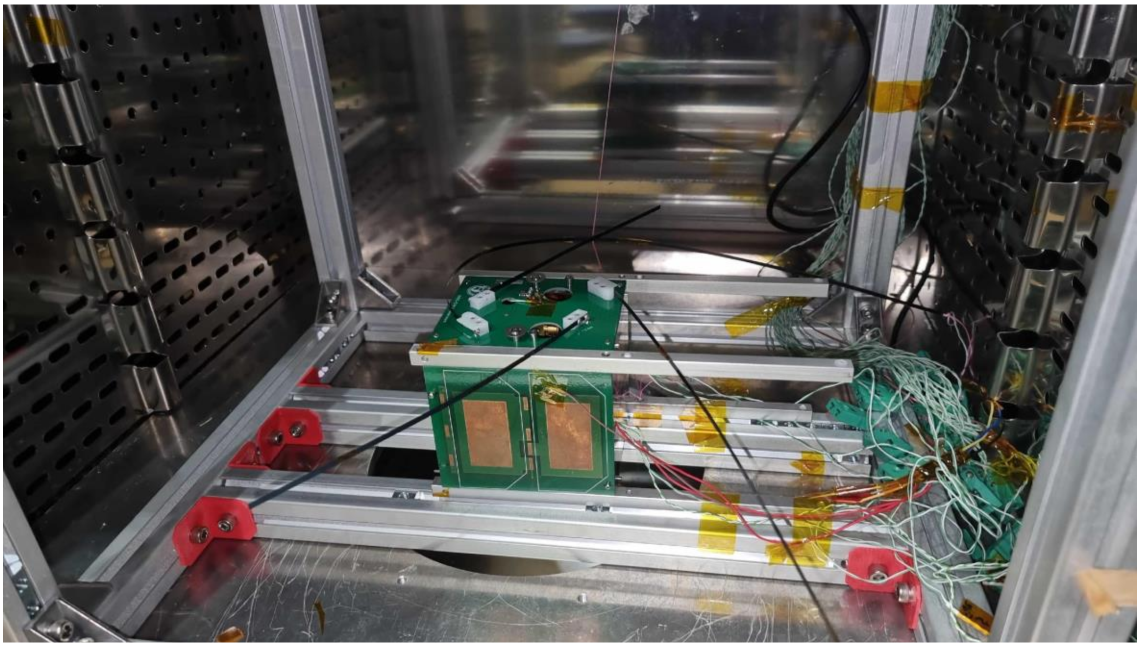

Figure 15 Antenna Deployment Test in Low Temperature Environment in the Thermostatic Chamber

7.7 Fit Check

The purpose of this test is to confirm that the mechanical interface between the satellite and the launch vehicle is consistent. In the case of CubeSat, it should be checked that the CubeSat can be inserted into and ejected from the POD smoothly, and that the satellite envelop fits in the POD (no contact between the items attached to the satellite surface with the inside of the POD). Recently it is quite rare that a university team develops the satellite separation mechanism. **Development of the separation mechanism by the university should be avoided** unless there is a very good reason. The safety verification of the separation mechanism may sometimes be more burdensome than the safety verification of the satellite itself. Therefore, it will be necessary only to confirm that the separation mechanism provided by the launch provider (PAF-239M etc.) or POD mechanically fits the satellite.

In the case of CubeSat, it does not mean that the satellite is assembled according to the CAD drawings, even when respective structural parts are fabricated according to the drawings. Distortion, etc. cannot be avoided. A case where the satellite cannot be inserted into the POD when the satellite is delivered to the launch provider has actually happened even for 1U satellite. As distortion increases with the size of the satellite, more care needs to be taken. The simplest method of the fit check is **to insert the satellite into the official POD supplied by the launch provider**. This method is preferably applied both for the EM and FM phases. The fit check must be conducted before securing the satellite's screws with Loctite or similar adhesives. At this stage, it is essential to verify that the satellite fits smoothly into the POD without any issues.

As jigs used for fit checks such as the official POD are lent for a limited time, the lending period should be discussed and determined with the launch provider in advance. Such jigs are specially manufactured for space vehicle use and are very expensive, so very careful handling is required. When even one part of such jig may be damaged, **compensation will be very high (more than ten thousand dollars)**. There have been actually such instances before.

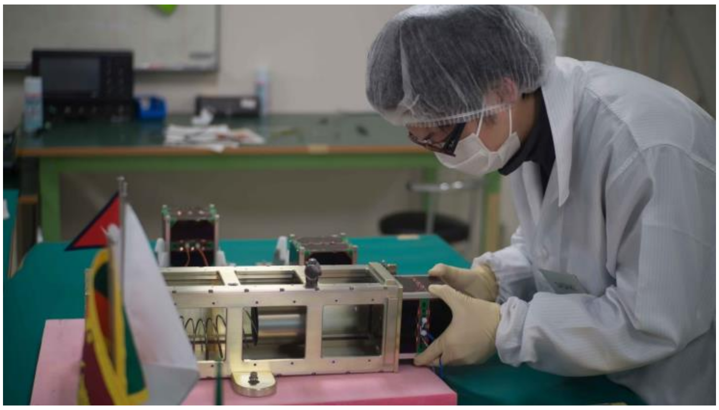

Figure 16 Fit-check

7.8 Thermal Test

Items in the thermal test of lean satellites and large satellites are the same. Accordingly, there is no difference in the test method.

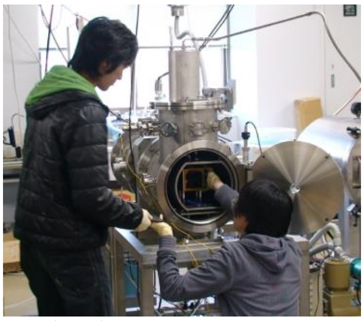

Figure 17 Thermaal vacuum test of large satellites (left) and thermal vacuum test of lean satellite (right)

However, the temperature difference in vacuum and in atmosphere is not that large for a satellite like the 1U CubeSat. Therefore, a high temperature test and low temperature test in a thermostatic chamber may replace the thermal vacuum test. (See Annex-F to Reference [11]) Even in such a case, a functional test with the entire satellite placed in the vacuum chamber should be conducted at least once.
The thermal equilibrium test of the lean satellite is conducted to obtain data for thermal analysis and for verification of the thermal analysis results because active temperature control is hardly performed for parts other than the battery heater. Many lean satellites are operating in orbit already and sufficient temperature data on their orbits are available. In particular, most of the surface area of CubeSat is covered by solar cells and there is no significant difference in the thermal radiation. The time required for thermal analysis can be saved by obtaining the high and low temperature conditions of a thermal test using the highest and lowest temperatures in operation, as far as the temperature data of CubeSats in the same orbit are available. As a lot of data from CubeSats released from the ISS are available, it is recommended to use such data. See Ref.[12] for an example. Attention should be paid

to use the data under full solar illumination, i.e. no eclipse in orbit, in calculation of the high temperature conditions, because those cases may be present due to the high beta angle.
If there are components that generate significant heat due to continuous power on (such as DC/DC converters or RF amplifiers), it is advisable to place the satellite and a heater inside a vacuum chamber (a standard vacuum chamber without a low-temperature shroud is sufficient) to simulate the worst-case high-temperature conditions. This test helps determine how high the temperature of these components can rise.

7.9 Vibration Test

Items in the vibration test of the lean satellite and large satellite are the same. Therefore, the test methods are the same. Because the vibration test records constitute the critical documents in safety review, the records should be written clearly.

7.10 Attitude Determination and Control System Test

Simulating microgravity or external torque on Earth is challenging, and ADCS (Attitude Determination and Control System) system tests often tend to take software-based approaches. However, critical functions essential for mission success should undergo physical testing using actual hardware. In passive attitude control utilizing permanent magnets and hysteresis dampers, ensuring the correct orientation of the magnets is sometimes crucial for mission success. A reliable method for checking the polarity of magnets involves placing the satellite on an air-bearing table and examining whether the satellite aligns with the polarity of the magnets.

Fig.18 Polarity check of permanent magnet by an air-bearing table.

Hysteresis dampers and magnetic torquers are used to stabilize the attitude of satellites. The satellite is placed on an air-bearing table inside a coil cage that generates an external magnetic field. Disturbances are introduced to the satellite, and the time it takes for the satellite's attitude to stabilize as per the design is examined. It is important to note that the magnetic torque should be greater than the damping force due to atmospheric resistance. Even if the satellite's attitude seems stabilized, it might be due to atmospheric resistance. Before installing hysteresis dampers or magnetic torquers, it is crucial to measure the damping time for attitude disturbances without them and compare it with the actual installed configuration. When employing pointing functions using reaction wheels, etc., validating attitude control algorithms through Hardware-in-the-Loop testing with an air-bearing table is recommended.

Calibrating sensors is extremely important in attitude control, and it should be ensured that sensors measure correct values when installed on the actual satellite. Magnetic sensors, in particular, are affected not only by residual magnetic fields inside the satellite but also by magnetic noise generated when the satellite is operating. Therefore, sensor calibration in the installed state on the actual satellite is necessary. Additionally, to prepare for the case where mistakes are found after the launch, it is desirable to make the gains and zero values for various sensors adjustable through uplink commands.

7.10 Test Configuration (Test-as-you-Fly)

The tests should **be conducted in conditions similar to the actual operating conditions**. The condition of the satellite and mission accomplishment or failure should be determined by transmitting the actual operating command and analyzing the data received from the satellite responding to such command by the software in the ground station. As no external cables are connected to the satellite in operation, the external cables should not be connected as much as possible in the system test. Unintended noise may be introduced via external cables. For the mission equipment, its functioning when incorporated in a satellite system in a vacuum environment (not simply a transmission of the simulated data with the switch engaged but by actual measurement and relaying the data) should be confirmed.

7.11 Use of the Outside Testing Organization

Universities having all the necessary test facilities inhouse are limited, and in many projects testing using an outside testing center is required. It is desirable to select a **testing center with sufficient experience to provide advice for the design and testing of the satellite** when the experience of the project team is not sufficient. In a test conducted by the external testing center, it is required to complete the required tests in the prescribed time frame. Meetings with the testing center in advance using the test specifications and/or test plan are essential to meet such requirements. What materials and equipment need to be brought to the testing center and what support can be obtained by the testing center should be defined clearly, indicating the purpose of the tests and testing conditions by video conference, etc.

7.12 Evaluation of Test Results

All effort should be made to correctly evaluate the consistency of the test results. If test results that are not good or are worrisome are left unattended, unexpected bugs may be hidden. The pass/fail criteria of the test should be established before the test, but indefinite results within the allowable limit that are difficult to decide may sometimes be obtained. In such a case, you should try to explain why the result deviated from the nominal value. In addition, when incomprehensible events occur randomly (relatively frequent in the thermal vacuum test), what you have noticed should be recorded and the events should be resolved. **Optimistic attitudes, such as thinking that the event is just imagination or that the event will not occur in orbit, based on normalcy bias should be avoided**. As very specialized equipment/apparatus are used in the RF test, etc., erroneous RF signal strength may be obtained by mistake in operation of the equipment/apparatus. When test setup work is asked of a single person only, a mistake may be unnoticed. A system **where more than one member examines the test plan and the test report** is desirable.

7.13 Defect Management

As a result of testing, there will always be defects. In another word, testing is to find and fix problems on the ground before they occur on orbit. As described in "2.7 Defect Management", defects found during testing should be collected, prioritized, and handled based on the priority. When setting the priorities, it is necessary to conduct risk management properly and evaluate the impact on mission success if a malfunction occurs in orbit. In failure analysis, the team should make full use of FTA, which will also serve as a rehearsal for FTA to be carried out when a problem occurs after launch. FTAs require logical thinking, and it is important to think with a cool head.

When the team disassembles the satellite to investigate a malfunction or to retest after repair, the stress impact on the satellite should be considered. There is a limit to the number of times the connector can be inserted and removed, and the number of times the fastener can be used. Vibration tests, etc. give cumulative fatigue to each part of the satellite. It should be carefully decided whether or not to perform all AT tests again as a retest.

7.14 Storage of Satellite

It may take an unexpectedly long time from the date all the tests are successfully completed to the date the satellite is delivered. The possible causes of such delay are various, such as delay of launch vehicle, extension of safety review, delay of the RF license. When the satellite needs to be stored for a long time, care should be taken because the separation switch is under stress for a long time and deformation of parts may occur. The battery of the satellite needs to be supplementally charged as needed, and charging should be made by more than one member according to the procedure. **Human error cannot be avoided, even if members are familiar with the work**. A device that prevents hands from using wrong pins during the battery charging should be included in the design. It is also recommended to consider including a flight pin in the design to prevent satellite startup, antenna deployment, etc. by mistake while the satellite is stored.

7.15 Confirmation of Compliance with Safety Requirements

The Phase 3 safety review is conducted after completion of the FM tests. It is the event to examine whether the satellite is constructed according to the safety requirements based on a variety of the evidence (verification results). The verification documents should include the results of the verification methods that are agreed with the launch provider in Phase 2 safety review. The verification documents should not be provided to the launch provider all at once after all the tests are completed. The documents should be provided once they are done without waiting for other documents become complete. The details of the documents should be agreed with the launch provider upon from the FM AIT phases.

8. Satellite Operation

8.1 Preparation and Maintenance of Ground Systems

Preparation of the ground systems should be completed before delivery of the satellite, and whether communication can be established with the FM should be confirmed. The following matters should be considered to determine the place where the ground systems are located.

a) No high buildings around the site and a satellite at a low angle of elevation is kept in line of sight

b) No electromagnetic noise source (RF emission source) around the site

c) Space to set up the communication equipment, etc. is available near the antenna

d) A comfortable environment is maintained in the room where the communication equipment is placed, which is closely located to the ordinary office and 24-hour access is allowed.

e) Easy access to a place where the antenna is located is ensured for inspection and maintenance

Items a), b), and c) are required to enhance the performance of the communication link. As a high frequency electrical signal is easily attenuated by the coaxial cable (attenuation can be easily calculated when the frequency and the coaxial cable type are known), item c) is very important. When the antenna is located far from the communication equipment, conversion to a low frequency signal near the antenna should be considered.

Items a), b), and c) tend to be focused when determining the antenna location, but items d) and e) are also necessary when considering a long-term operation, and a balanced approach considering both requirements is necessary. For example, when inspection and maintenance of the antenna becomes necessary, timely operation of the satellite will become impossible in case of an emergency as it may take several days to obtain access permission, arrange for a contractor (access to the antenna by students is not permitted), etc.. If the radio station is located in a room to which access at night is not allowed, operation of the satellite at night becomes impossible, resulting in a 50% loss of visible time of the satellite from the beginning. While operation via the network is possible, in critical situations such as immediately after the satellite is released into orbit it should be operated using all the visible time. Operation is better performed by members sitting in front of the communication equipment unless members have adequate experience in network operation. It is required that the operation room is located close to the office room when operation at night is considered, and where the members should spend hours between the visible time and the visible time during the night should also be considered. When operation in midsummer and midwinter is considered, working in a utility space on the rooftop where the communication equipment is located will not be comfortable.

Figure 19 Antenna broken by a typhoon

Periodic maintenance of the antenna is essential as the antenna is exposed to weather. If you feel there is difficulty in uplink or the Morse code tone is weak, the direction of the antenna should be checked. Figure 20 shows the typical antenna pattern of a Yagi antenna, which shows that the gain decreases by 10 dB when the antenna direction changes by 10 degrees from the centerline, and the communication margin will be sacrificed. Attention should be paid in adjusting the antenna direction because **the magnetic north indicated by a compass is not the geographical north as shown on a map**. The cable connects the antenna and the communication equipment using more than one connector. Contact failure, corrosion, etc. of the connector are frequent causes of a failure of the ground station.

Whether the ground system is functioning properly can be confirmed measuring the RF field strength of the signal received from the satellite. For your own satellite, it is impossible to know whether a problem exists in your satellite or in the ground system. So, it is recommended to determine the satellite that should be used as the calibrator (the satellite transmitting the beacon signal for years) and to track such satellite and to measure the RF field strength.

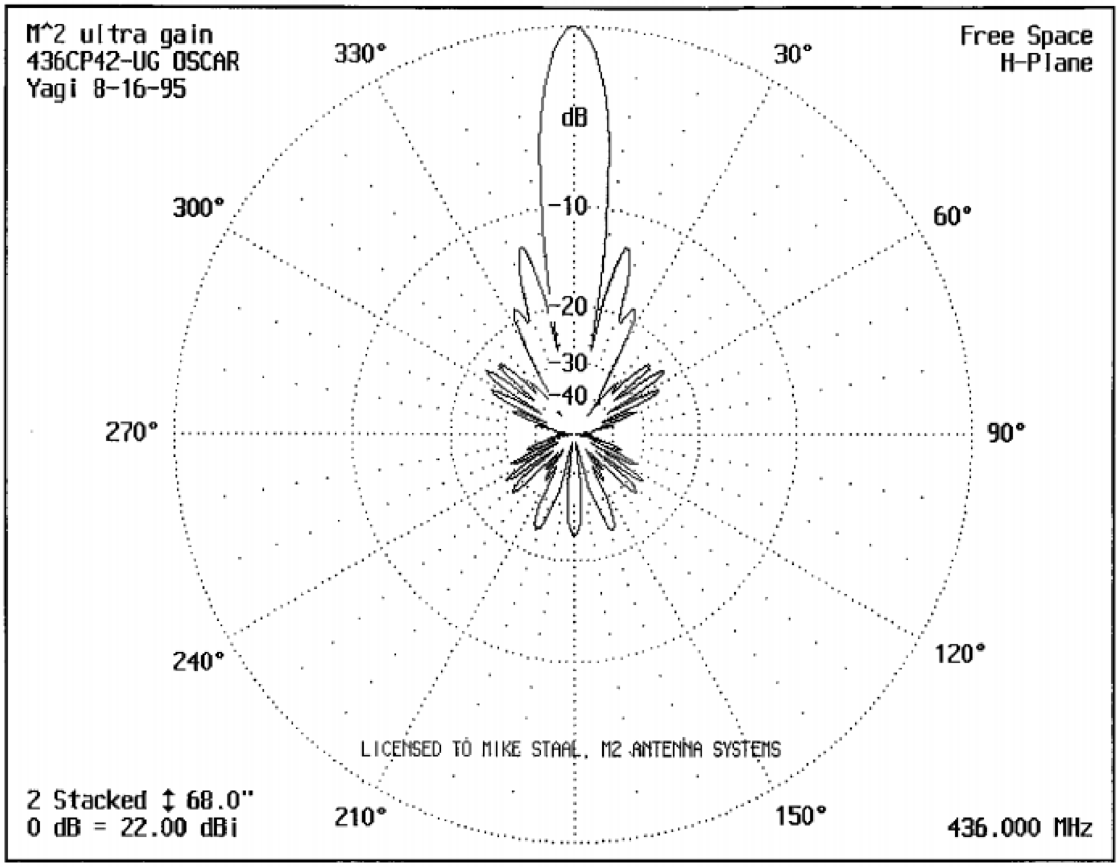

Figure 20 Antenna Pattern Example of Yagi Antenna for Ground Station

8.2 Operation Plan

The lean satellite is made using non-space-qualified commercial-off-the-shelf (COTS) products that are not guaranteed to function in space, and testing conducted prior to launch is limited. Accordingly, unexpected problems in orbit cannot be avoided, which may frequently result in complete failure shortly after the start of operation.

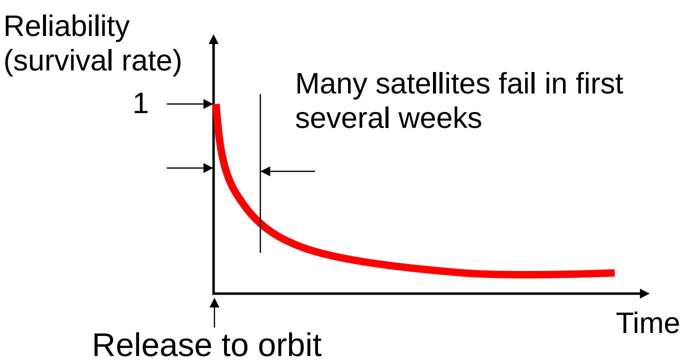

Figure 21 Decrease of survival rate of satellite in orbit

Accordingly, the following should be implemented.

a) Check the functions that are essentially required for the survival of the satellite,

such as the battery and solar panels.
b) The uplink and downlink should be established and an Integrated Test (In Japan, the examination by the radio authority to check the communication is established or not after the satellite launch is called "Integration Test". In different countries, different term may be used for the final exam before issuance of the full radio license.) should be conducted to obtain an official radio station license.
c) The mission to realize the minimum success criteria should be performed as early as possible. This should be preferably done within one week from release of the satellite in orbit. However, it should be assumed that the satellite's attitude will be unstable for nearly one week after deployment, and mission planning should be carried out accordingly.
In the case of the first satellite, members will be occupied in decoding the CW Morse code and analyzing the basic housekeeping data sent from the satellite with excitement. You should, however, proceed to execute the mission as soon as possible. There have been many satellites **where communication was lost while the team was busy analyzing the received CW Morse code**. The reason the acquisition of a regular radio station license needs to be hurried is because the **public release of the satellite mission's results is restricted if you have only a preliminary license**, as operation of the satellite immediately after release in orbit is made with the preliminary license.

When verifying the health status of a satellite, the entire operations team should share a clear understanding of which housekeeping data points to focus on in advance. Key parameters to monitor include:
Whether the direction of current flow to the battery switches appropriately between eclipse and sunlight.

- Whether the battery voltage increases after exiting an eclipse.
- Whether each solar panel is supplying current as expected.
- Whether the power supplied from the solar panels matches the sum of the power charged into the battery and the power consumed by the loads.
- Whether there is a correlation between the temperature of the solar panels and their output current.
- Whether the satellite has experienced any unintended resets.
- Whether the rotation speed measured by the gyroscope matches the variation in solar panel output.
- Whether the attitude determination is correct, which can be verified by taking pictures with an onboard camera and checking for inconsistencies.

For amateur radio satellites, it is beneficial to use ground station networks such as SatNOGS. While it provides only a downlink, amateur radio operators worldwide attempt to receive signals from the satellite, which can be extremely helpful in assessing its condition immediately after deployment. If requesting reception assistance from amateur radio operators, the satellite should be designed with appealing features that motivate them to contribute. Proactive information sharing well before launch is crucial to building interest and engagement.

8.3 Handling Anomaly and Failures in orbit

As explained in 8.2, communication with the satellite may be interrupted at any moment. But the team should **never give up** even in such a case. There is a satellite that recovered after two years without communication. It is important to maintain motivation within the team. What is the most important is the **positive attitude of the professor (principal investigator)**. All the team members should bear in mind the importance of identifying the cause, even if the satellite fails completely, to reflect the lessons learned from such investigation on the second and subsequent satellite projects. In the case of a satellite where the second satellite succeeded after the failure of the first satellite, this was achieved through a thorough investigation of the failure causes in the first one, and the results were reflected in the design of the second one. **You cannot be successful only by chance**. When the main mission becomes impossible to accomplish while communication is still maintained, it is important to continue acquiring operation data in orbit from the surviving satellite, because lessons learned in operation from such data can be reflected in the design of the subsequent satellites.

It is recommended to perform the FTA along the flow of communication when a failure (including communication interruption) occurs. It is recommended **to investigate whether a problem occurs within each block or at each interface of blocks along the information flow from the ground station ⇒ satellite ⇒ ground station** shown in Figure 22. Whether the problem is in the ground station or not can be easily checked using the flight spare and the ground station equipment. The problem in the satellite is investigated by checking the possible causes of the failure. The observed events should be listed first along with how frequently the events occur, when they occur, the particular location in orbit and other relevant information. The telemetry data should be analyzed. The uplink command history and the actions of the satellite to each command should be checked. Sound data and unsound data are separated. The data trends are investigated. Using the flight spare, experiments to replicating the observed event should be done.

To do FTA, the final flight software source code, the design documents of the satellite and flight spare, etc. are important. But the most helpful is the members who actually developed the satellite. A failure that occurred in orbit is not always unrecoverable. Recovery from the defect may be possible by working out an alternative plan in operation. To make such recovery possible, the operation team should understand the satellite design. It is strongly desired that a **project schedule is established so that members engaged in the development remain in the team during satellite operation**. It is strongly recommended to make the flight spare because it plays an important role when a problem occurs in operation. The flight spare is also very useful when a replacement part becomes urgently necessary due to a mistake during the FM AIT. The EM may be used as the flight spare.

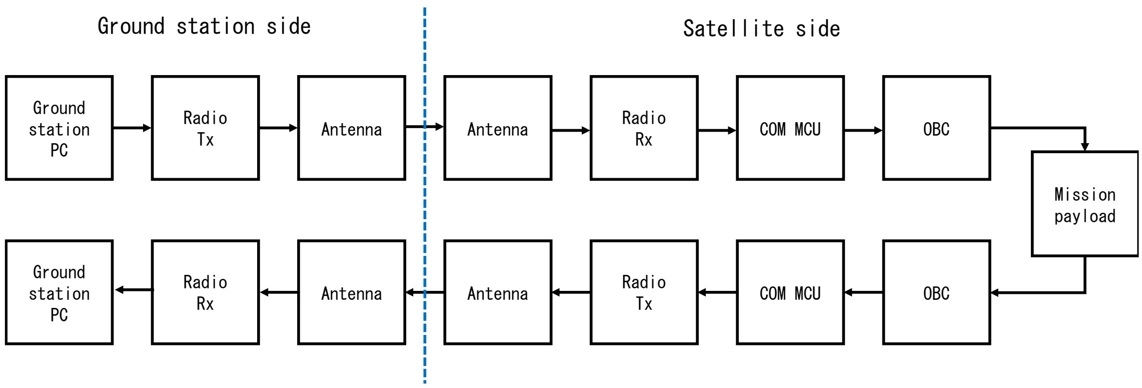

Figure 22 Information Flow Ground Station ⇒ Satellite ⇒ Ground Station

9. After Satellite Operation

9.1 Lessons Learned

Lessons learned are the essential factor in the practical application of the experience and knowledge obtained in the satellite project in subsequent satellite projects or activities in the real world. There are two opportunities to summarize the lessons learned. When the satellite is delivered and when the satellite operation is finished. The lessons learned should be summarized before graduation of the core members when the operation expands for a long time like two or three years. It is recommended that the responsible professor (principal investigator) should record what has been noticed in a notebook while the project is ongoing. No definite method is prescribed in summarizing the lessons learned, but the most important thing is to create an atmosphere where the members participated the project can discuss freely and openly. The importance of the lessons learned exists when they are effectively utilized, **the responsible professor (principal investigator) should refer to the lessons learned of the past project when the situation requires.**

Figure 23　Toward the next project (illustration credit: いらすとや)

9.2 Recording, Reporting and Publication of Results

The progress and records of the entire project including operation of the satellite and the management should be summarized and documented in addition to the design and test results of the satellite. Such documentation will provide valuable guidance and will be used as a reference by students participating in subsequent projects. Documentation should be prepared by the project manager or responsible professor overseeing the entire project, but motivation is necessary to promote the writing of such document. Giving a presentation in the space technology conference such as Nanosatellite Symposium and other conferences such as UNISEC Space Takumi Conference will be good opportunities.

The variety of cooperation and assistance was obtained from outside organizations or persons during the progress of the satellite project. For such organizations and persons, reporting of what is obtained by the project is the best reward. Accordingly, when the summary of the project becomes available to some extent, it is recommended to hold a reporting session to such organizations and persons. The materials used for presentation in such sessions can be conveniently used later as a record of the project. The results of the satellite's mission should be published to a variety of audiences by papers, etc., and not limited to sharing among a limited numbers of persons related to the project. The purpose of the university satellite is developing human resource and making progress in science and technology. In the case of a satellite intended for technology demonstration or scientific observation, **its results should be ultimately returned to society by publishing the results**. Even in the case of a satellite intended for the education of students, what educational results can be obtained by the satellite project should be made public so that other universities can use it as a reference, considering the nature of the lean satellite as the method of education. Publication of such scientific or educational results should not be restricted to publication as a peer reviewed papers in journals. Needless to say though, publication as a peer reviewed article in a journal is desirable for the responsible professor or student (doctoral student in particular) when their academic career is considered.

9.3 Sharing of Knowhow

For the success of the lean satellite mission, the correct functioning of the satellite bus supporting the mission is essential. There were so many failures of the mission caused by failure of the satellite bus. To achieve an advanced mission, advanced bus technology is required but it does not mean that all the bus equipment needs to be newly developed. For the satellite bus that has a sufficient record of operation in orbit, it is desired to use **reliable and proven technology,** sharing the data, knowhow, and software in the community. For sharing of knowhow, the knowhow needs to be remade to a form that can be shared. It is this work that takes time. Because it is difficult to construct a platform for information sharing all at once, it is desirable to begin with **the extent possible**. The in-orbit data (temperature etc.), the record of defects that occurred in orbit, the list of the parts installed, etc. are considered as high demand, so the willingness to share such data with other projects is desired.

10. Sustainability of University satellite Program

10.1 Viewpoint as a Program

The approach to improve the satellite bus and mission payload as a series of programs rather than as an individual satellite project is important. To achieve excellent results as the satellite program consistently, how to cumulate the lessons, knowledge, and knowhow obtained should be considered carefully. There is no definite answer in the case of the university satellite, depending on the conditions of individual university, professors, etc. but it is desirable that persons with actual experience of the project life cycle continue to serve in subsequent projects, in addition to recording the lessons in documentation. This does not apply to the students because they graduate. The lessons should be inherited by the professors and staff. Even in the case of staff, there are issues to be considered such as the funding to continue employment, tenure according to the university rules, or career advancement as a researcher in the case of a postdoctoral fellow. When the lessons are inherited by the professor, **it is necessary that such professor continues to engage in satellite projects as a program director**.

As an alternative method by which the lessons are inherited by a group of students, it is possible that senior students convey lessons to junior students based on the results of operation in preceding projects by overlapping multiple satellite projects simultaneously for respective grades. This is a method **to retain experience as collective intelligence**. However, this method will require the professors to make every effort to acquire the necessary funds.

To construct a sustainable system to inherit lessons will be difficult in an organization where only the students are directly assigned to a responsible professor, because such organization will impose excessive burden to the professor. The organization where the postdoctoral fellow and assistant professors support the project as middle level members is desired. For that case, **a system where junior researchers can build up their academic career** is required.

When the technology becomes fully mature after experiencing a number of orbital operations, an approach whereby the results of the projects are returned to society is desired. One way is to transfer the design and knowhow to a company. Another way is to make them available as opensource. Information such as electronic circuits and structures can be left in the form of drawings. Then, it is possible to prevent the technology from belonging to a particular person by transferring it to a company or making it open source. But information such as software whose development work is mostly done by single person is difficult to make the information transferrable. Most students are not trained to write software in a way that others can understand. For professors whose is not specialized in software the software is a black box. What the professor can do is to suggest putting as many comments as possible only. At present, there is no method other than making the software open source to increase the chance of reviewed by many people. How to transfer the software know-how is still an issue for university satellites.

10.2 Strengthening the Research Base in University

The university is "a group of small private shops" in nature. The university satellite projects are run as a laboratory project of the responsible professor in many cases. **To make the satellite project continue as a research program and steadily obtain outcome, support from the university management is required**. But support from the university will require a return to the university. For that reason, the

professors may be asked by the university to do work what they do not want to do or they are not good at. If the professor does not want to do such work, the idea to make the university a project sponsor should be abandoned and enterprise(s) outside the university as a sponsor should be sought.
When support from the university is sought, the university satellite is often used as a tool of student recruitment. When the value of the project is limited to such effect, however, the support from the university will be limited. The effects on education, research activities of the university, or both must be demonstrated. This is relatively easy for educational activities. In recent education provided by faculty of engineering, the design capability and incorporation of Project Based Learning (PBL) are required as prompted by JABEE. (Note: This is the case of Japan. JABEE stands for Japan Accreditation Board for Engineering Education.) In a bachelor course of education, learning from a wide perspective is required in addition to learning by specializing in specific fields. Particularly, in the department related to space engineering, systems engineering is one of the most important subjects, and practical training in addition to learning by lecture is required. The satellite project is the subject best fit for such purpose, and it will not be difficult to award credits to a student who participates in the satellite project. When the satellite project is included in the curriculum, support from the university will be obtained continuously. But it should be noted that the amount of funding granted by the university will not be large enough. Support from the university should be considered as a chance from which a satellite project can grow out from the personal project of the professors.

When you consider expanding the satellite project in the university, coordination with other professors cannot be avoided. It is one step forward from **the project of Professor XX to the project of Professors XX, YY, and so on**. Coordination among professors is expected to have positive effects such as diversification of team members, increase in expertise within the team owing to the increased number of professors, diversification of the satellite mission (this is remarkable when coordination is established between professors in science and engineering), the increase of chances to obtain funding from outside, etc. There is also the associated risk that may arise of possible inconsistency between the students when the students become aware of the walls existing between different laboratories. To solve such problem, daily cooperation between professors is necessary. With respect to cooperation between laboratories, this is true not only with professors in space sciences (installation of scientific observation equipment, etc.), but should also be considered professors in satellite data application. In particular, as a pilot project using the team's own satellite in the fields of IoT and AI may draw the attention of professors who are interested in data analysis but may not be interested in building a satellite, active cooperation may become possible.

10.3 Funding of Project

Even if the research base in the university is established, it is very rare that funding sufficient to continue the making and launch of the satellites is provided by the university. The team needs to acquire the funds necessary to continue such program, but such funding should be **achieved by the efforts of individual professors**. It is recommended that a funding plan have adequate allowance because expenses will easily increase due to factors that cannot be estimated at the start of the project (repair of purchased parts, purchase of additional parts, etc.). As continuity of the program cannot be guaranteed when the program relies only on KAKENHI (Grantin-Aid for Scientific Research, a competitive government research funding aimed at mostly university professors) or other competitive research funding from the Government, it is important to acquire multiple funding sources. While adequate funding should be acquired, the design of the satellite bus should be a type that can be purchased at low cost.

10.4 Cooperation with Outside Organizations

Cooperation with outside organizations or persons is essential for continuing the construction of satellites as a program. It is important to maintain good relationships with companies who supply key components. Needless to say, the project team should also have a good relationship with the community of amateur radio operators and the space agency.

Cooperation with other universities and outside research institutes, as well as cooperation with other laboratories in your university, brings many benefits when you want to expand the program. **Cooperation with organizations abroad is especially beneficial because students can experience international projects**. The students can learn matters such as finding out the needs of satellite use in other countries in planning the satellite mission. Physical distance and difference in time may become a problem in cooperation with foreign organizations. Simultaneous development of the satellite bus in your country and development of the mission payload outside your country, with such payload being assembled in the satellite bus in your country for delivery of the satellite will be possible when the interface between the satellite bus and the mission payload is clearly defined, and such project has actually been made. In a cooperative project with a foreign organization, the requirement for paperwork under the Security Export Control (different terms may be used in different countries) must be confirmed, and when publicly known technology (information available in open source) is not used, very careful checking is required. Nowadays, many universities have a department that specially handles the security export control matters, and contact with such department in advance is strongly recommended.

References

[1] "Definition and Requirements of Small Satellites Seeking Low-Cost and Fast-Delivery", Edited by Mengu Cho and Filippo Graziani, International Academy of Astronautics, 2017, Code ISBN/EAN IAA: 978-2-917761-59-5

[2]Michael Swartwout, Clay Jayne, University-Class Spacecraft by the Numbers: Success, Failure, Debris. (But Mostly Success.), 30th Annual AIAA/USU Conference on Small Satellites, 2016

[3] "Lessons Learned Case Analysis for Micro/Nano satellite Mission Success", University Space Engineering Consortium, JAXA-CR-21-002, JAXA, 2021 (in Japanese)

[4] Toyota Production System, Taichi Ohno, Productivity Press, 1988, ISBN 9780915299140

[5] Manual for International Frequency Coordination Procedures for Small Satellites, (In Japanese)
https://www.tele.soumu.go.jp/resource/j/freq/process/freqint/001.pdf

[6] CubeSat Salon (https://unisec.jp/cubesatsalon)

[7] JBDB-08012D "Success Criteria Making Guideline", JAXA Chief Engineer Office, January, 2018 (in Japanese)

[8] https://www8.cao.go.jp/space/comittee/27-kagaku/kagaku-dai20/sankou1-3.pdf

[9] JX-ESPC-101133-D , "JEM Payload Accommodation Handbook, Vol.8, Small Satellite Deployment Interface Control Document", Revision D, July 2020.
https://humans-in-space.jaxa.jp/kibouser/library/item/jx-espc_8d-d1_en.pdf

[10] ISO-17981 "Space Systems -CubeSat Interface", 2024.10

[11]ISO-19683 "Space Systems – Design qualification and acceptance tests for small spacecraft and units", 2017.07

[12] Adolfo Jara, Pooja Lepcha, "On-orbit Electrical Power System Dataset of 1U CubeSat constellation for Machine Learning Models", Mendeley Data, May 2022,
DOI:10.17632/8kp25ycf63.