BIRDS Program Digital Textbook

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Revision List

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A	First writing of document	Sangkyun Kim	2018/12/05
B	Revision of Chapter 2 Addition of remaining chapters	Mengu Cho	2019/3/31
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Abbreviations in the document

BAT	Battery
BCR	Battery Charging Regulator
BPB	Back Plane Board
BW	Band Width
COM	Communication system
CubeSat	Cube Satellite
DNST	Doctorate in Nano-Satellite Technology
EPS	Electrical Power System
EPS/OBC	EPS OBC board
FAB	Front Access board
FM	Flash Memory
Kyutech	Kyushu Institute of Technology
ISS	International Space Station
OBC	On Board Computer
PCB	Printed Circuit Board
PIC	PIC microprocessor
PNST	Post-graduate study on Nano-Satellite Technology
RAB	Rear Access Board
RBF	Remove Before Flight pin
SC	Solar Cell
SEIC	Space Engineering International Course
SHM	Space Head Module
SRB	Solid Rocket Booster
STR	Structure system
TRX	Transceiver
UHF	Ultra-High Frequency
UNOOSA	United Nations Office of Outer Space Affairs
1U	1 Unit size, 10 [cm] x 10 [cm] x 10 [cm]

1. Introduction

A CubeSat is a type of small satellite that is made up of multiple standard cubic units. One CubeSat unit is an extremely small satellite of 10 x 10 x 10 [cm], with a mass less than 1.33 kg. Originally, it was proposed as an educational tool for space engineering technology, given its small size, light mass, and low budget. The first CubeSats were launched in June 2003, and they successfully demonstrated their functionalities in orbit. That success had huge impacts on the space community. From 2012 through 2017, over 700 CubeSats were launched, and that number is still rapidly increasing. Space agencies such as NASA have started to use CubeSats for various missions, even for deep space exploration. Currently, many CubeSat programs are being carried out for the purposes of remote sensing, communication, and scientific research.

The strengths of a CubeSat—its low cost and short development time—mainly come from a risk-taking approach, small team size, and aggressive use of commercial off-the-shelf (COTS) parts. It is a very good representative of the "lean satellite" concept recently proposed in an International Academy of Astronautics (IAA) study [1-1]. CubeSats have well-defined standards for their mechanical external dimensions, including their deployment method. The standards provide the advantage of launch compatibility, which drastically increases launch opportunities, making a constellation of CubeSats a reality. A constellation made of hundreds of 3U CubeSats is already being used for the business of remote sensing. But CubeSats are not only for business purposes; they are also very important educational tools, satisfying their originally proposed objective. Notably, many developing and emerging nations are trying to use CubeSats to build their space technology capacity.

Kyushu Institute of Technology (Kyutech) has been carrying out its BIRDS program since 2015. In the program, a BIRDS satellite project starts every October. In each project, inexperienced student members receive training and develop multiple 1U CubeSats. As of March 2019, four generations of BIRDS projects have been carried out: BIRDS-1, BIRDS-2, BIRDS-3 and BIRDS-4. The BIRDS program is a unique educational program that provides an excellent opportunity for learning systems engineering, project management, and cross-cultural teamwork, not only conventional space technologies. Since 2017, the BIRDS program has been partially supported by the "Coordination Funds for Promoting Aerospace Utilization" from the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT). With that funding, the authors aim to make the BIRDS program a sustainable education program that can be carried out as part of an educational curriculum for students ranging from senior undergraduate students to master's students. To do so, the authors have been studying about (1) reducing program costs, (2) reducing the burden on faculty, and (3) increasing the number of participating students. This textbook has been created as part of the funding project so that other universities can start an educational program similar to the BIRDS program in a sustainable manner.

The biggest issue involved in making a program like the BIRDS program sustainable is reduction of program costs. The greatest cost is incurred in developing a satellite. For each generation of the satellite project, the satellite bus is modified to adapt to different mission objectives. Even a minor change in the satellite bus could cost a significant amount. In order to reduce the satellite cost, we have tried to have a standardized satellite bus so that each generation of the satellite project can simply use the same bus without modification. Then the hardware cost can be minimized. One specific objective of this digital textbook is to introduce the standard CubeSat bus system, especially the electrical design. We call it the BIRDS BUS.

Standards are an important issue for any satellite program to reduce costs and increase development efficiency. For the electrical design of CubeSats, many researchers are trying to find proper standards for their own use. Sometimes, a standardized interface among the subsystems is a subject of study, aiming at plug-and-play systems for flexible and efficient development. If we want to use the same satellite bus design between different CubeSat projects, some amount of resource waste is inevitable. CubeSats have very limited resources in many aspects: they have a limited mass and size, and extremely low power generation. Even small wastes of their resources can make it impossible to accomplish mission objectives. A standard CubeSat bus system has to be flexible enough so that it can accommodate different mission payloads with minimal additional resources.

The BIRDS BUS is a standard CubeSat bus of electrical design to support the BIRDS program. Each BIRDS project develops 1U CubeSats for the capacity building of non-space-faring nations. Each project requires the development of multiple CubeSats annually. That is one of the key advantages of the BIRDS program, but it also puts a heavy burden on inexperienced student members. Standardized CubeSat bus design becomes very important for the quick training of student members because the team members have little experience with satellite development. They need a reference design for their training, and it should be very clear and easy to understand. Also, quick standard bus training makes it possible to allocate more resources to mission payload development. The BIRDS BUS has a specific goal of its design as a standard bus for the educational CubeSat project, and has some characteristics that differ from other CubeSat buses proposed as standard. Performance, efficiency, and flexibility are usually important factors for standard bus design. Those are targets of the BIRDS BUS too. The BIRDS BUS design, however, puts an emphasis on ease for beginners to learn and use it. For example, the BIRDS BUS uses a distributed system design, not for its performance but for the easy work sharing and simple coding work involved. Also, the BIRDS BUS needs to meet safety requirements without additional work, to avoid unnecessary time delays with the project.

Another objective of this textbook is to explain the basics of the CubeSat system. Beginner CubeSat project members come from various backgrounds. They often do not have even a very basic knowledge of CubeSat systems. This document contains basic information about CubeSat systems to quickly provide that basic knowledge.

Chapter 2 presents how CubeSat projects work as an educational project for capacity building. Specifically, BIRDS projects are introduced as an example of capacity-building projects for non-space-faring nations. Chapter 3 explains CubeSat systems in general, and detailed information is presented in Chapters 4 to 6. The CubeSat projects are not finished when the satellite is deployed in orbit; it continues with the operation of the satellite, so CubeSat operation is briefly presented in Chapter 7. Acquiring a frequency license is becoming extremely difficult work because the demand for these has become extremely high with the increasing number of satellites. Chapter 8 explains the frequency license acquisition procedure with an example of the UHF amateur radio band. Chapters 9 and 10 present the launch environment, the orbit environment, and the environmental test. Chapter 11 presents important points about the assembly and integration phases, and the major tests are presented. Chapter 12 discusses safety requirements and how to verify they have been met. We assume the CubeSats are released from the International Space Station (ISS). Chapter 13 discusses the cross-cultural and capacity-building aspects of BIRDS projects. Chapter 14 explores how to carry out the satellite project as a sustainable educational program at universities without heavy investment in faculty or a large budget. Chapter 15 is the final chapter and concludes this text.

Reference

[1-1] M. Cho and F. Graziani, “Definition and Requirements of Small Satellites Seeking Low-Cost and Fast-Delivery”, International Academy of Astronautics (IAA), February 2017.

2. CubeSat projects for capacity building

Among the developing/emerging nations, there is a strong demand for human resource development (HRD) to build space technology capacity through small satellite developments. There have been various HRD programs conducted by space agencies, companies, or universities of space-faring nations. The most famous and successful one is the one conducted by Surrey Satellite Technology Limited (SSTL)[2-1]. Jointly with the University of Surrey, SSTL accepted engineers from various countries, such as South Korea, Portugal, Chile, Algeria and others, and contributed to the realization of the first satellites for those nations. In the 2000s, however, once HRD programs were being carried out by space agencies or big companies tied with sales of big satellites, many of them ended in failure. Possible reasons are a lack of opportunity to build a satellite hands-on, not being able to participate in the entire process of the satellite project lifecycle, and so on. Also, even if the human resources were developed through training, the national space programs were not sustainable and many talented engineers left the space sector.

The following two points are key to the success of HRD for space capacity building:

1. Experience the entire cycle of a satellite project, from mission definition to operation, in a hands-on manner.
2. Have a strategy for sustainability after the training ends.

Kyutech initiated a long-term fellowship program, DNST/PNST (Doctorate in NanoSatellite Technology/ Postgraduate study in NanoSatellite Technology), in 2011 in collaboration with the United Nations Office of Outer Space Affairs (UNOOSA) to promote the space capacity building of non-space-faring nations. It also started the Space Engineering International Course (SEIC) in 2013 as a postgraduate curriculum to provide a program.

The Kyushu Institute of Technology BIRDS Project was conceived as a way for non-space-faring nations to begin significant activities in space. The project started in October of 2015 with the following mission statement:

> *Make the first step toward creating an indigenous space program by designing, building, testing, launching, and operating, the first satellite for participating nations. (In some cases, the first university satellite.)*

It should be strongly emphasized here that the primary goal is not making the first satellite; the primary goal is to have a long-term and sustainable space program established in each BIRDS nation. Designing, developing, testing, and operating a nation's first satellite is just one way to help achieve that primary goal; there could be other ways.

BIRDS is a two-year satellite development program that is flexible in the number of participating nations to be accommodated. Table 2-1 lists the operational projects that have taken place thus far and the participating nations in each one.

Table 2-1. List of BIRDS projects to date

PROJECT	Start	Nations with a satellite in the project
BIRDS-1	Fall 2015	Japan, Ghana, Mongolia, Nigeria, Bangladesh
BIRDS-2	Fall 2016	Bhutan, Malaysia, The Philippines
BIRDS-3	Fall 2017	Japan, Sri Lanka, Nepal
BIRDS-4	Fall 2018	Japan, The Philippines, Paraguay
BIRDS-5	Summer 2020	Japan, Uganda, Zimbabwe

BIRDS projects are educational capacity-building projects that involve international cooperation. Two or three young engineers are sent from each participating country to Kyutech as full-time graduate students to learn space engineering using 1U CubeSat development work. The BIRDS program is designed so that each generation of satellites can be finished in two years, from mission definition to operation. Including operation in two years is critical to fit the entire satellite project into a master's degree course study timeline, which is two years. To keep to that time limit, the ISS was chosen as the satellite launch platform, because there is a launch opportunity at the ISS once every three months. The satellite design has also been simplified so that they can be delivered in a little over one year.

The first generation, the BIRDS-1 constellation, composed of five satellites, was successfully deployed from the ISS on July 7, 2017 (JST). The second generation, the BIRDS-2 constellation, composed of three satellites, was deployed from the ISS on August 10, 2018 (JST). The third generation, the BIRDS-3 constellation, composed of three satellites, was deployed from the ISS on June 17, 2019 (JST). As of December 2019, BIRDS-1 had already deorbited. BIRDS-2 and BIRDS-3 are still under operation by the BIRDS ground-station network. The BIRDS-4 project also started in October 2018. Figure 1 is a photo of the BIRDS-1 flight models with project members, and Fig. 2 shows the deployment moment of BIRDS-2 from the ISS on August 10, 2018. Figure 3 shows the flight model of the BIRDS-3 satellites.

Fig. 1. BIRDS-1flight models and project members

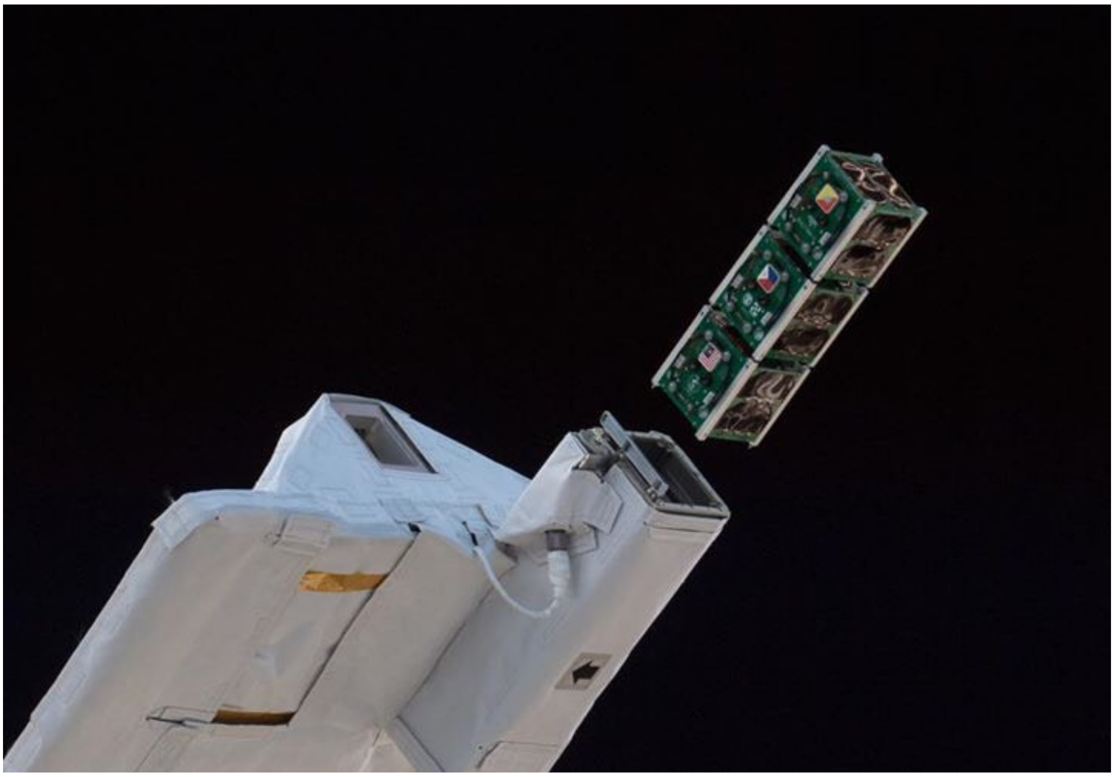

Fig. 2. Moment of deployment, BIRDS-2, August 10, 2018, ©JAXA

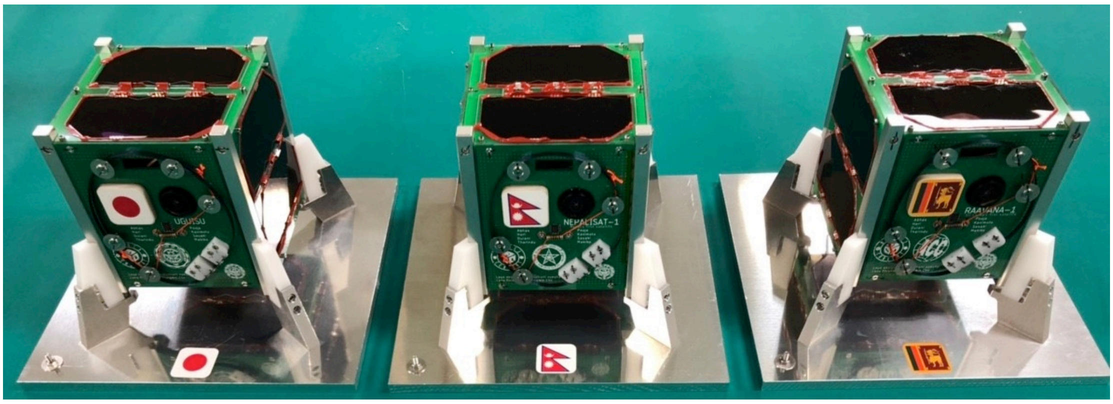

Fig. 3. BIRDS-3 flight models

Reference

[2-1] Alex da Silva Curiel, Susan Jason, Kasia Wisniewska, Faisa Price, Guigleilmo Aglietti, Martin Sweeting, “Lessons Learned from Three Decades of Collaborative Space Mission Capacity Building Projects”, 68th IAC, IAC-17-B4.1.4, Adelaide, Australia, 25–29 September 2017.

3. CubeSat system

The complete CubeSat system can be categorized into three segments, as shown in Fig. 4.

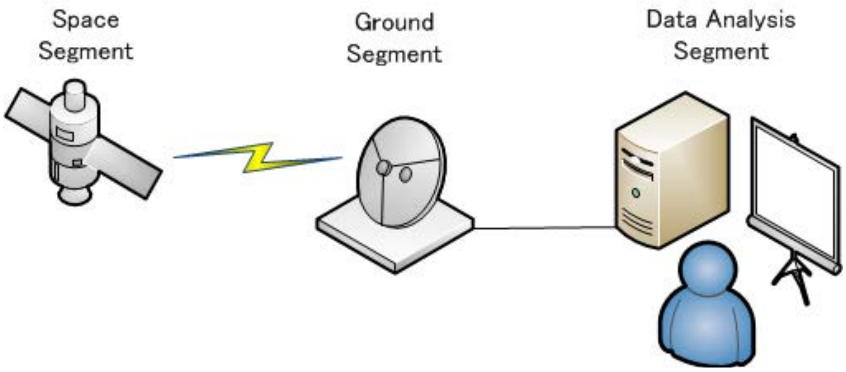

Fig. 4. Complete CubeSat system

a. Space segment

The space segment is the CubeSat itself in orbit. It is made of a CubeSat or multiple CubeSats, i.e., a constellation. The satellite design (mechanical, electrical, etc.,) requirements have to comply with the mission objectives. Clear interfaces between the bus and mission systems are required to be able to reuse the design for future projects, and the experience of system engineering is essential throughout the satellite project.

b. Ground segment

The ground segment consists of all the ground-based elements of a CubeSat system used by operators. Usually, the ground station becomes the major part of the ground segment. The ground station consists of an antenna, radios, a tracking device and computers to operate the ground station equipment and store the data. The ground station is used to send commands to CubeSats and receive telemetry (housekeeping) and mission data from the satellites. The telemetry data is used to monitor the satellite status and to create the satellite's operational plan. The ground segment also includes a component to distribute the mission data for further analysis.

c. Data analysis segment

The data analysis segment corresponds to the satellite users. This data analysis segment serves to analyze the payload data from the CubeSat, and final steps to get the value of mission object.

4. Systems engineering and project management

a. Systems engineering overview

Systems engineering has evolved along with space programs. One good example is the Apollo program that succeeded in sending humans to the moon and returning them safely to the Earth. To realize that unprecedented program, which involved a huge budget, many personnel, a complex design and a harsh operational environment, systems engineering discipline had to be successfully applied. Systems engineering makes it possible for complex space systems to perform flawlessly in a harsh space environment, where, in most cases, maintenance-free operation is required. There are various space engineering handbooks and textbooks, such as the NASA Systems Engineering Handbook and the INCOSE Systems Engineering Handbook. For general study of systems engineering, readers should refer to those references.

A satellite project is an ideal platform for studying systems engineering and project management. A satellite is very complex; therefore, without an overall systematic view, interface control, requirement management, etc., it will never be finished. A satellite involves many disciplines, such as mechanical, electrical, material, chemical, etc. A satellite needs to be thoroughly verified before its launch. One anomaly in the parts may lead to a total system failure. Therefore, failure mode analysis is very important to ensure the satellite will work in a harsh environment. A satellite project involves many members; therefore, a Work-Breakdown Structure (WBS) is an essential tool for project management. Risk management is also absolutely necessary for considering the various possibilities of risks becoming reality.

b. Mission definition

In a satellite system lifecycle, the mission definition is carried out at the first stage. It is extremely important for overall project success. The mission must be defined so that the system can satisfy the needs of the stakeholders, customers, or users of the system. Even if the system is perfectly built according to specifications, if the specifications are written based on misunderstood users' needs, the system will not be used. During mission definition, how to reflect the users' needs for the system is most important. In each BIRDS project, students spend the first three months working on this. They are expected to frequently discuss with the stakeholders in their home countries.

c. Requirement management

Once the mission has been defined, system design starts. System design is based on requirements. Every task in system development has a reason, i.e., requirement. As a satellite project is sometimes carried out by teams that are located at a distance from one another, written requirements often become the only source of communication. If the requirements are misunderstood, the system, subsystems, components, and parts cannot satisfy their purpose in a way that satisfies the purpose of the upper layer. In each BIRDS project, students are expected to make a Requirement Allocation Sheet (RAS). In the RAS, user (stakeholder) requirements, system requirements, and subsystem requirements are all listed in an Excel sheet. For each subsystem requirement, design requirements and verification requirements are written, along with an explanation of how to verify the requirements. The RAS serves as a bible for the satellite project. When there is a change in the satellite design, the RAS should be revised. The RAS is a living document; properly managing it helps the members understand the effects caused by any requirement change.

d. Work-breakdown structure

Satellite development requires teamwork and an educational CubeSat is an excellent way to learn it. In the BIRDS program, the project is run by a mix of Japanese and foreign students. They interact with and assist each other. The WBS lists all the work necessary in the system lifecycle, not only the hardware and software development. The tasks more associated with the project management side, such as application for a frequency license, must also be included. Each of the tasks listed is assigned to one of the team members. With a WBS, an overall project schedule can be drawn.

e. Risk management

Satellite projects are full of risks. In traditional satellite projects, each risk is carefully evaluated and maximum effort is spent on reducing the occurrence probability of risk events and/or reducing the resulting effects when risk events actually occur. In a CubeSat project, risk is evaluated mostly on the basis of project team members. There is no time to tackle all the risks. Therefore, the risks have to be prioritized based on the seriousness of each risk event, which is given by the product of the occurrence probability and the resulting effects. The idea of risk management is similar to safety management.

f. Failure Mode Effect Analysis and Fault Tree Analysis

Failure Mode Effect Analysis (FMEA) analyzes the effect of failure or malfunction of one particular component on overall mission capability. It is a bottom-up process. Fault Tree Analysis (FTA) analyzes the cause of an event affecting mission capability. The analysis is based on “and/or” logic. FTA is also very important during operation. As the satellite is in a place where humans cannot closely observe it. Therefore, the cause of any anomaly found in the operation must be identified through FTA.

g. Verification and validation

A satellite is based on requirements. At each phase of satellite development, the product has to be verified for whether it satisfies its requirements. Verification is to check whether *the system is built right*. Verification is done for each requirement. The verification method involves testing, analysis, demonstration, inspection, etc. Validation is used to check whether *the right system is built.* After all, the satellite must be used by users. The users evaluate the satellite for whether it satisfies their needs or not. To make sure the satellite passes validation, the mission definition phase is very important, as it translates each user requirement into system or subsystem requirements.

5. Space segment

In this chapter, CubeSat design is presented using the BIRDS BUS as an example. The BIRDS BUS design is a kind of electrical standard BUS for an educational CubeSat development project. It is mainly designed for an Electrical Power System (EPS) and data-handling system to satisfy the requirements of a standard bus. The communication system and external interfaces are also determined for the standard bus. The EPS design must efficiently comply with various launch service safety requirements. The data-handling system is designed to be learned with quick training. It uses a dedicated microcontroller for each subsystem. The microcontrollers are combined with simple serial interfaces and shared flash memories. The BIRDS BUS is made of two Printed Circuit Boards (PCBs), a Front Access Board (FAB) and an On Board Computer board (OBC). The FAB handles the EPS and the external interfaces. The OBC has the function of data handling and electrical power distribution. The communication system uses a different board than the UHF transceiver, and a deployable dipole antenna is attached to the external panel board.

After electrical specification is discussed, mechanical specification is also introduced.

a. Electrical specification

Electrical Power System

One of the critical safety rules is the three-inhibit condition for a cold launch. CubeSats are required to have no power to the electrical load before deployment. The cold launch must be guaranteed by more than three switches. If the CubeSat clears the three-inhibit condition, even if two switches fail, the satellite still has no electrical power, neither from a solar cell nor the battery.

Another important safety requirement is prevention of battery failure. Accidental battery failure, such as overcharging is regarded as a catastrophic hazard that may lead to death of personnel or destruction of the launch vehicle. Therefore, it needs to be prevented with a two-failure-tolerant strategy, i.e. three inhibits.

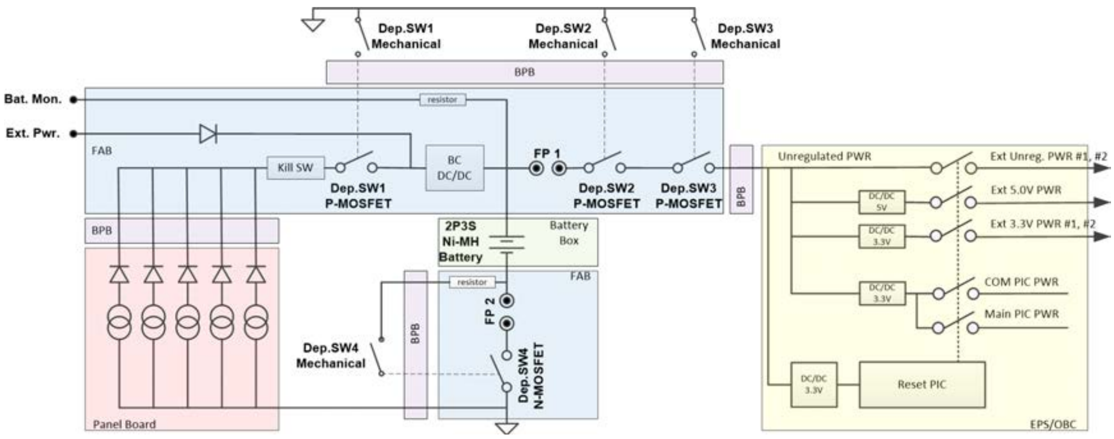

Fig. 5. Schematic diagram of EPS in BIRDS BUS

Figure 5 shows a schematic diagram of the EPS for the BIRDS BUS. It has four deployment switches, SW1, SW2, SW3, and SW4, to satisfy the cold launch requirement of a three-inhibit condition. The deployment switch for SW1 is located between the solar cells and the battery to cut off the power from the solar cells to the other electrical system of the satellite. SW2 and SW3 are located between the battery and the electrical load to cut off any power to the satellite electrical load with redundancy. The battery is the most high-density energy source on the satellite, and usually the most critical item for a safety review. SW4 is located between the battery and the ground of the satellite's electrical system. It separates the battery from the satellite system until deployment. These power switches can be controlled one-by-one through a dedicated deployment switch, or multiple switches can be controlled by one deployment switch with flexibility. The number of switches has increased from the BIRDS-2 design; however, the additional switches make it possible to use this design for a completely different launch service, such as conventional rocket launch service, without any modification.

The flight pins, FP1 and FP2, control the EPS mechanically from the outside. If the flight pins are inserted, the power lines are mechanically disconnected, and provide safety for the ground test and the satellite logistics. The BIRDS BUS completely separates the flight pins from the external power supply function and the deployment switches. The external power is directly connected with the Battery Charging Regulator (BCR) with a protection diode and supplies external power when the satellite needs a ground test or battery charging.

The safety regulations are different for each launch service, so the three-inhibit condition is not always required. For many launch services, SW3 or SW4 is unnecessary per the safety requirements. If SW3 and SW4 are not necessary, jumper switches JP3 and JP4 are connected to disable SW3 and SW4 for the solid connection of reliability.

Table 1. Three-inhibit condition for a cold launch

Deployment service	Inhibit	Switches for inhibit condition
Conventional rocket service	Solar cell to load	SW1 – SW2 – SW3
	Battery to load	SW2 – SW3 – SW4

The battery needs to be handled with caution because it is a high-energy-density device. For battery protection, three protection mechanisms are implemented in the BIRDS BUS against overcharging, overdischarging, and external short circuit. Cold launch condition switches can be used for the protection system to isolate the battery from other systems, i.e., the power source and the electrical load. In the BIRDS BUS, switches SW1 and SW4 disconnect the battery from the solar cell until the moment of deployment. Also, the BCR has the function of battery protection against overcharging between the solar cell and the battery. SW2, SW3, and SW4 disconnect the battery from the electrical load and act like a protective system against overdischarging. SW4 has another function of protecting against external short circuit to the battery. Usually, battery has enough insulation layers, and the BIRDS BUS has two layers of insulation around the battery. Even if an accident breaks that double insulation, SW4 isolates the battery and keeps it safe from short circuit as a third protective device.

Table 2. Three protection conditions for the battery

Protection items	Switches for protection
Overcharging	SW1 – BCR – SW4
Overdischarging	SW2 – SW3 – SW4
External short circuit	Double insulation – SW4

The BIRDS BUS uses an LTC3119 from Linear Technology Corporation as the BCR. There are many reasons for this selection, but the primary reason is that it supports the maximum power point control of the solar cells. The LTC3119 has a configuration pin name of maximum power point control, and the BCR input voltage keeps the same value as the pin of maximum power point control. Because of this control, maximum power can be available from the solar cell even if the electrical load condition changes. The previous EPS used three BCRs, and it needed additional blocking diodes after each regulator. We changed the BIRDS BUS design to use only one BCR and eliminate the blocking diodes, to reduce energy loss as the BCR contains a blocking function inside.

A satellite should have a passivation function to empty all energy sources once satellite operation is terminated. The BIRDS BUS has a kill switch unit. This kill switch unit supports the passivation of a BIRDS satellite when it has no reason to continue its operation in orbit. The kill switch is a combination of a MOSFET switch, a latch relay, and the latch relay driver. Once the switch is activated, the connection between the solar cells and the satellite is completely disconnected to empty the battery and permanently terminate the satellite. Because its activation is very risky, the BIRDS BUS has two kill switches in parallel as a kill switch unit to form redundancy. Each kill switch is independently controlled by two different microcontrollers so as not to simultaneously activate both kill switches accidentally or by any microcontroller failure.

This EPS is designed to support up to a 3U CubeSat. Actually, the power generation of the CubeSat depends on many factors, including orbit condition, solar cell performance, attitude control capability, and so on. BIRDS satellites use 3G30A solar cells from AZURSPACE. One solar cell generates 1.2 [W] in the ideal case of the maximum power point, and 3U CubeSats can attach a maximum of 18 solar cells on three surfaces if it has a deployable panel system. By very rough assumption, the maximum electrical power generation can be estimated at less than 21.6 [W]. The LTC3119 BCR supports a maximum input voltage of 18 [V], and the current capacity of each power line for the PCB and other devices is also designed to withstand a continuous current of 2 [A]. Considering the maximum voltage of the BCR and the continuous current capacity of the PCB, the BIRDS BUS can support up to 36 [W] of electrical power generation, more than the maximum power from solar cells of 3U CubeSat.

For the electrical load of mission system, the maximum power can be estimated by the nominal battery voltage of 3.8 [V] and the maximum continuous current of 2 [A]. One mission system can use the maximum power of 7.6 [W].

Command and Data-Handling System

The BIRDS BUS uses three dedicated microcontrollers (Reset PIC, COM PIC, Main PIC) for each of the three major subsystems, i.e., the EPS subsystem, the communication subsystem, and the command and data-handling subsystem. One additional microcontroller (FAB PIC) collects the electrical power information as a monitoring device. If a BIRDS satellite is a CubeSat for a practical mission object, there is no reason to use this many microcontrollers. Some loss of resources for overhead is inevitable when many microcontrollers need to work together, because they have to handle the cooperation work using some computing power and mutual communications. However, each subsystem should be simple with a dedicated single microcontroller to develop its function easily for a project member to do on-the-job training. If one or two microcontrollers do the work of all the bus systems, it may be too complex for a beginner, and it will be difficult to share the work among the team members. If multiple microcontrollers share the work of one single subsystem, however, the system becomes unnecessarily complex. One dedicated microcontroller for each subsystem is better for the training of the young engineers because of its simplicity.

The BIRDS BUS uses a simple 8-bit microcontroller family for several reasons. BIRDS projects are educational projects, so a simple and easy-to-use microcontroller is better than a high-performance microcontroller. The performance of a BIRDS BUS microcontroller may be lower compared to the microcontrollers used in other CubeSat projects, especially those with more practical missions. These simple microcontrollers are, however, sufficient for an educational project with a simple mission and no attitude control. When we need to improve data-handling performance, such as attitude control or any other onboard processing, additional PCBs with a more powerful microcontroller or a FPGA can be attached for those purposes.

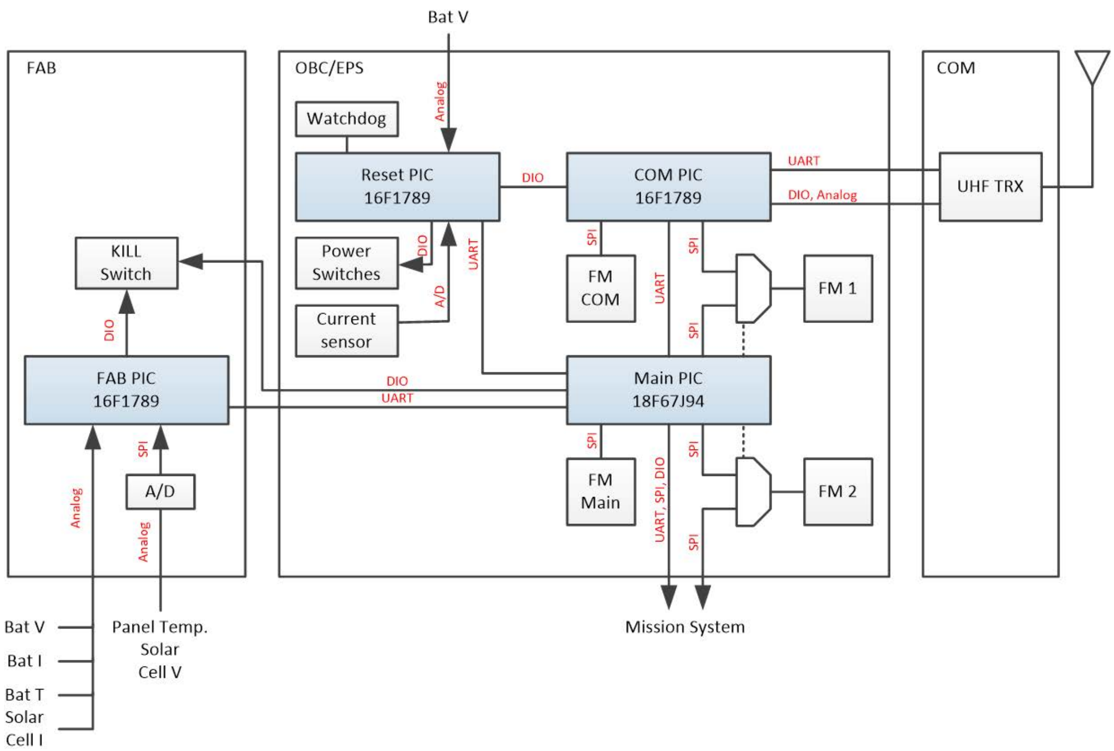

Fig. 6. Schematic diagram of the BIRDS BUS data-handling system

Figure 6 shows a schematic diagram of the data-handling system. For easy training with a microcontroller, the BIRDS BUS uses just one family of microcontroller. The PIC microcontroller series was selected because of its flight heritage with many CubeSat projects. For example, the simple 8-bit PIC16F1787 microcontroller has been used in previous Kyutech satellites and functioned without problems. Due to the memory size limitation of the PIC16F1787, the PIC16F1789, in the same PIC family series, with 28 [kbytes] programming memory has been selected for the BIRDS BUS. It would be better to use the same PIC16F1789 microcontroller throughout all of the subsystems; however, the Main PIC requires high speeds and enough computational power compared to the other microcontrollers, because it handles all the satellite data. There can be a data transmission bottleneck between the BUS system and the Mission system, and there must be adequate programming memory to handle various mission system data in future projects. Because of that, a more powerful PIC microcontroller, PIC18F67J94, is used for the Main PIC. It has enough programing memory at 128 [kBytes], and it is easy to modify its programs following the requirements of the mission system. Also, it supports a maximum 64-[MHz] clock speed for data handling. The Main PIC has a 10-pin digital interface with the mission system. These digital interface pins can be configured to serial interfaces. Up to five channels of UART interface are available, for example.

Non-volatile memory is required for the data storage of the data-handling system. The BIRDS BUS has four non-volatile memories. Two of them are dedicated storage for the Main PIC and the COM PIC, and the other two are shared memory with a multiplexer. One of the shared memories is between the Main PIC and COM PIC, and the other is between the Main PIC and the mission system. Each of the shared memory multiplexers is controlled by the Main PIC. The BIRDS BUS uses a simple UART serial interface for the regular interfaces between microcontrollers. It is easy to use but its speed is limited to 115,200bps. Shared memory supports large amounts of data transfer when the speed of the serial interface is insufficient. The BIRDS BUS uses only one type of flash memory as its non-volatile memory, a SPI interface NOR-type flash memory of 1 [Gbit] capacity. That is sufficient for a CubeSat if it has ordinary mission objectives. Because only one type of flash memory is used, a common library code for memory handling is available for the coding work. Not just for the non-volatile memory, but also for the serial interface, the BIRDS BUS uses just two common serial interface protocols. There are many kinds of serial interfaces for an embedded system, but only UART and SPI serial interfaces are used for the BIRDS BUS.

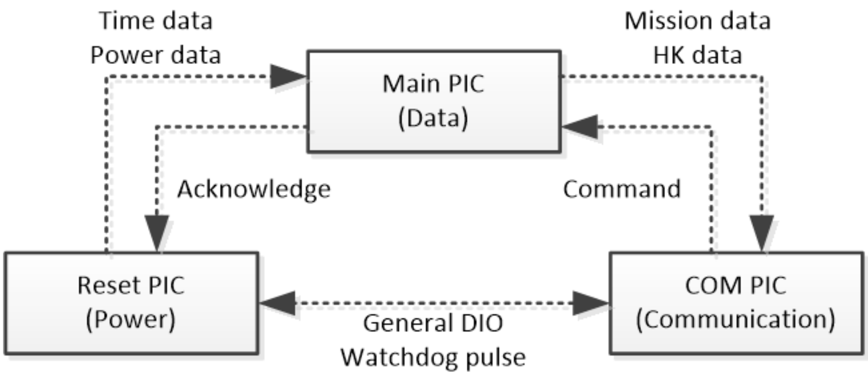

Fig. 7. Simple ring network for the data-handling system

Because the BIRDS BUS is a kind of distributed system for data handling, it needs well defined interfaces between the three major microcontrollers. Those three microcontrollers are connected to each other by UART for the primary interface, and construct a very simple pseudo ring network, as shown in Fig. 7. Regular messages are transmitted between the microcontrollers in this simple ring network. The Reset PIC controls the electrical power supply for the entire CubeSat system. If other microcontrollers fail to send acknowledgements to the regular messages, the Reset PIC can reset the microcontroller power to force a power reset. These power controls should be very reliable, and the Reset PIC has very simple and clear programming code to minimize trouble. Because of the low probability of reset through the Reset PIC, it also keeps the satellite time data. Each of the satellite's electronics parts, however, has the possibility of failure in orbit because of the single-event effect due to radiation. The Reset PIC is not an exception. In the case of Reset PIC failure, a simple external watchdog is attached to the Reset PIC to recover from the failure.

The three major microcontrollers need to act as a combined data-handling system, and that requires time synchronization in many cases. Each microcontroller has its own primary clock source with a dedicated oscillator. However, one 32.768-[kHz] oscillator in the OBC is used as a common clock source for all three microcontrollers. The common clock source becomes the secondary clock source of each microcontroller to create a timer interrupt at the same time between the three microcontrollers. This simultaneous timer interrupt simply synchronizes the timing of the data-handling activities, and the satellite time management becomes much easier because of this common clock source. This synchronized data handling is especially useful for the regular messaging work of the UART ring network.

In the BIRDS BUS, only the COM PIC handles communication with the ground station. It exchanges data with the Main PIC through the UART ring network or the shared flash memory. The UART interface is sufficient for small amounts of data; however, larger data such as image data needs to use the shared flash memory for efficiency. Usually two kinds of data are transferred to the COM PIC from the Main PIC.

One is housekeeping data, the basic information about the satellite's condition, and the other is the mission data from the mission system. Data is transmitted to the ground station by UHF transceiver.

The COM PIC takes commands from the ground station and sends most of the commands to the Main PIC for further processes. Also, the COM PIC has its own flash memory to keep the data. A simple command to download the data does not need to be processed by the Main PIC, so it can be directly processed by the COM PIC with a rapid response.

The Main PIC handles all of the satellite data. It collects power supply system information from the FAB PIC and Reset PIC. And, the Main PIC is the data bridge between the bus system and the mission system. All data from the mission system comes to the Main PIC first through the serial interface of UART, SPI, or shared flash memory. As mentioned, most of the commands from the ground station are handled by the Main PIC too, and the Main PIC also controls one kill switch (the FAB PIC independently controls another kill switch to minimize risk).

Communication System

The BIRDS BUS Communication System (COM) has not been newly developed for the standard bus. Its specifications are mainly selected from the heritages of previous generations, BIRDS-1 and BIRDS-2. The BIRDS BUS uses UHF frequencies of the amateur radio band for both the uplink and downlink directions. One transceiver handles the communication in half duplex mode, and Gaussian Mean Shift Key (GMSK) is used for modulation. The BIRDS COM needs to support an educational mission object, so there is no need to provide high-speed communication between the satellite and ground station. Actually, a relatively low communication speed has advantages for the stability of the communication link by its higher energy per bit. The baud rate for communication is just 4800 [bps] for both directions, and the data format follows the AX.25 protocol. A simple dipole antenna is attached on the external panel board, as shown in Fig. 10. A 1U CubeSat is too small to have a solid antenna on the structure as the dipole antenna for the UHF frequency. The BIRDS BUS uses a deployable antenna with a heat cutter. The antenna is stored wound up on the surface of the panel board by a string of ultra-high molecular weight polyethylene. The heat wire cuts the string after the satellite is deployed in orbit.

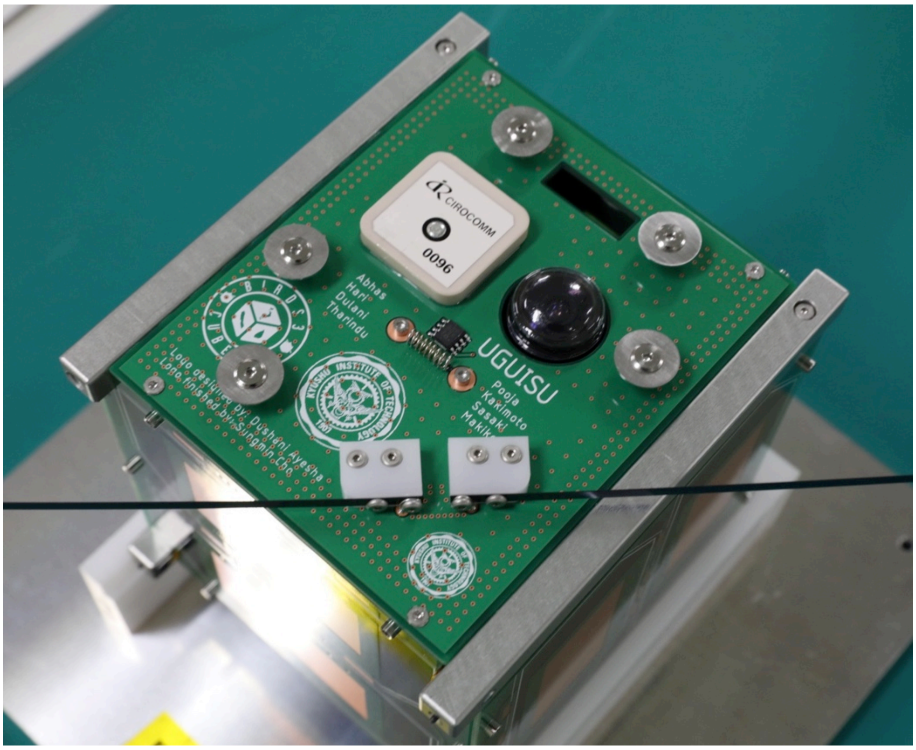

Fig. 8. BIRDS-3 external panel board and dipole antenna

These COM specifications are determined for easy construction of a ground station without any customized devices. The BIRDS project members have to build their own ground station in their respective countries for the satellite operation. The UHF frequency, the GMSK modulation, and the standard AX.25 protocol are very common specifications for amateur radio data communication, and many devices are already available on the market.

BIRDS BUS in the BIRDS-3 project, FAB and OBC

The FAB is the main body of the standard bus EPS. In the BIRDS-3 satellite, it collects the generated electrical power from the solar cells of five external panel boards, and controls the electrical power using deployment switches, remove-before-flight pins, and a BCR. Two switches, SW1 and SW4, are controlled by one deployment switch, and SW2 is controlled by another deployment switch. The two flight pins, FP1 and FP2, are also used for the three-inhibit condition, as shown in Fig. 9. However, the flight pins perform the limited protection function of safety switch in the case of BIRDS-3. Even if it is under controlled conditions for an extremely short time compared to the conventional rocket launch service, after the two flight pins are pulled out before the deployment in ISS, only one switch, SW2, is placed between the battery and the electrical load. Because of this, FP1 and FP2 are regarded by JAXA as only one inhibit in the case of BIRDS-3. SW4 has been added to the power system to support this issue. SW3 is deactivated by connecting the jumper pin of JP3 because it is not necessary.

BIRDS-3 uses the small detection switch shown in Fig.10 as the deployment switch, which gives the control signal of the MOSFET switches, SW1, SW2 and SW4. Two detection switches are inserted in the tip of the BIRDS-3 CubeSat rail. When BIRDS-3 is inside the pod, the detection switches are pressed and maintain the open status for SW1, SW2, and SW4. After BIRDS-3 is deployed from the pod, the detection switches are released, and the switches become closed.

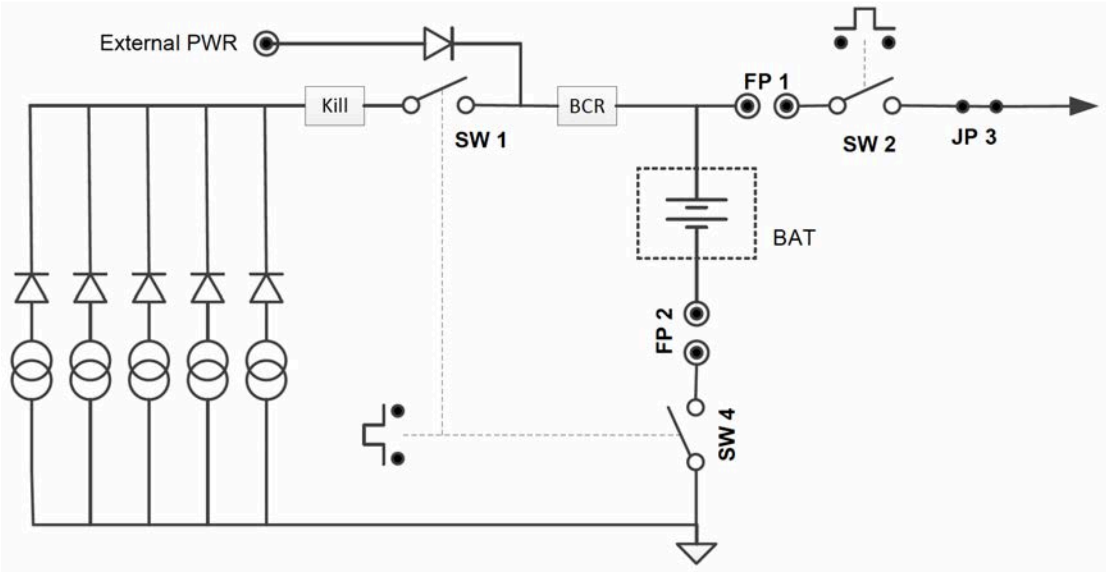

Fig. 9. Schematic diagram of the BIRDS-3 EPS


Fig. 10. Deployment switch (left) ©C&K; deployment switch in the rail (right)

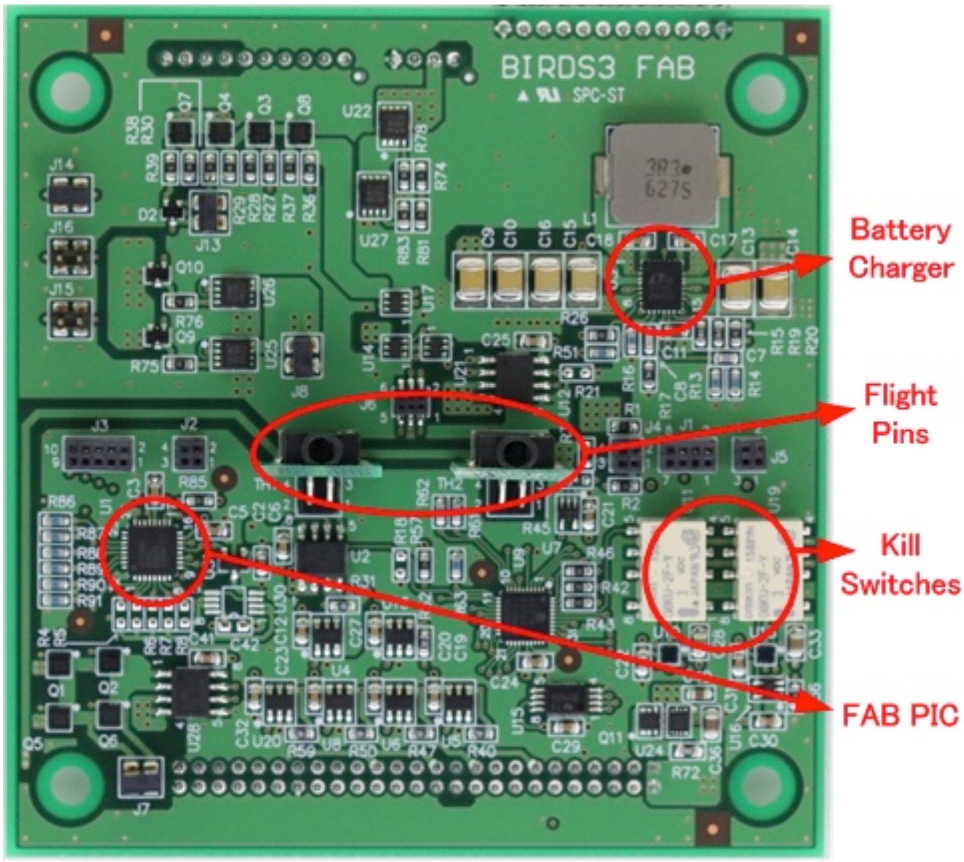

Fig. 11. BIRDS-3 FAB

Figure 11 shows the BIRDS-3 FAB. Two remove-before-flight pins are located in the center of the board. This is a jack switch, which has two contacts with 1 [A] of rated current capacity, and supports 2 [A] of rated current for the EPS of the BIRDS BUS by parallel connection. The two kill switches are located at the bottom right part of the board, and the battery charger is also shown on the right side. The FAB PIC is in left side in Fig.11 and monitors the voltage and current from the solar cells including the temperature of the external panel board. The battery condition is also monitored for its voltage, current, and temperature.BIRDS BUS uses an LTC3119 Buck-Boost DC/DC converter as its battery charger because it has sufficient power capacity with the maximum power point control. It can adopt the input voltage from 2 [V] to 18 [V], which is enough to support 2 to 6 solar cells in series connection. The output power ranges from 0.8 [V] to 18 [V] with a maximum current of 5 [A]. The printed FAB circuit board is also designed to support a maximum continuous current of 2 [A].

All three major microcontrollers are located on the OBC board with the data storage flash memories. Each microcontroller is dedicated to a different subsystem and connected with an UART serial interface to build a ring network following BIRDS BUS design. The COM PIC is the microcontroller responsible for the communication subsystem. The Reset PIC is responsible for the electrical power subsystem. The Main PIC is in charge of the command and data-handling subsystem. Figure 12 shows the OBC board with its very simple layout. The OBC board PIC microcontrollers (Fig. 13) are one-chip microcontrollers with multiple functions. The OBC board has no additional devices, such as analog/digital converter, serial interface controller, and so on.

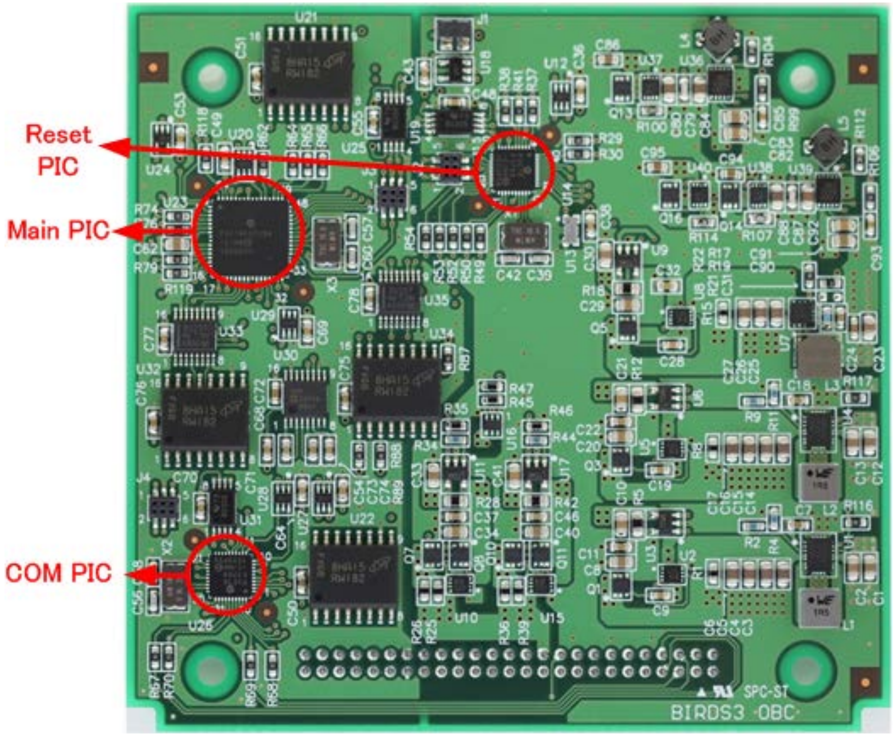

Fig. 12. BIRDS-3 OBC board

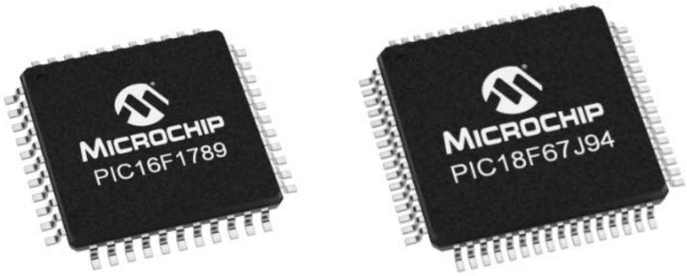

Fig. 13. PIC microcontrollers for BIRDS BUS, ©Microchip

The OBC board also houses the power distribution functionality. Figure 14 shows a block diagram of the BIRDS BUS power distribution. Many power switches are controlled by the Reset PIC and distribute the power. Each power source is monitored with the current sensor, and overcurrent protection circuits are also present. The Reset PIC controls the power of the two other microcontrollers, the COM PIC and Main PIC, and acts like a watchdog for those two microcontrollers. The BIRDS BUS has five power lines for the electrical power supply to the mission system. Two of them are unregulated power directly from the battery. There is also a 3.3[V] power supply with two power lines, and a 5 [V] power supply with one line. In the case of BIRDS-3, two unregulated power lines are used for the COM and antenna deployment system, and the two 3.3 [V] power lines are used for the FAB PIC and mission systems. No devices use the 5 [V] power in BIRDS-3. If the number of mission system is larger than these power lines, additional power switches must be installed on the mission board to better distribute the electrical power like in a mission system. Such additional switches are usually controlled by the Main PIC.

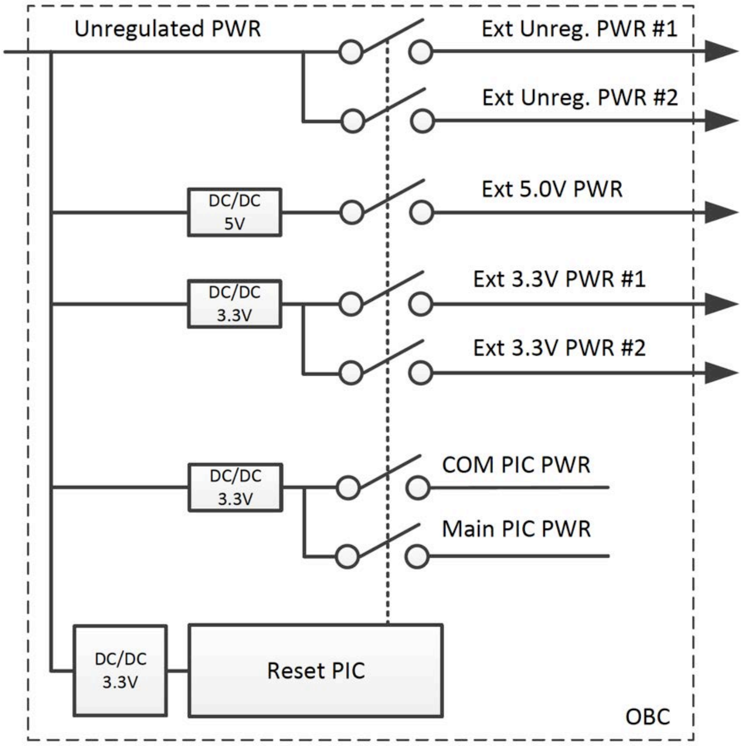

Fig. 14. Power distribution on the OBC board

Backplane Board

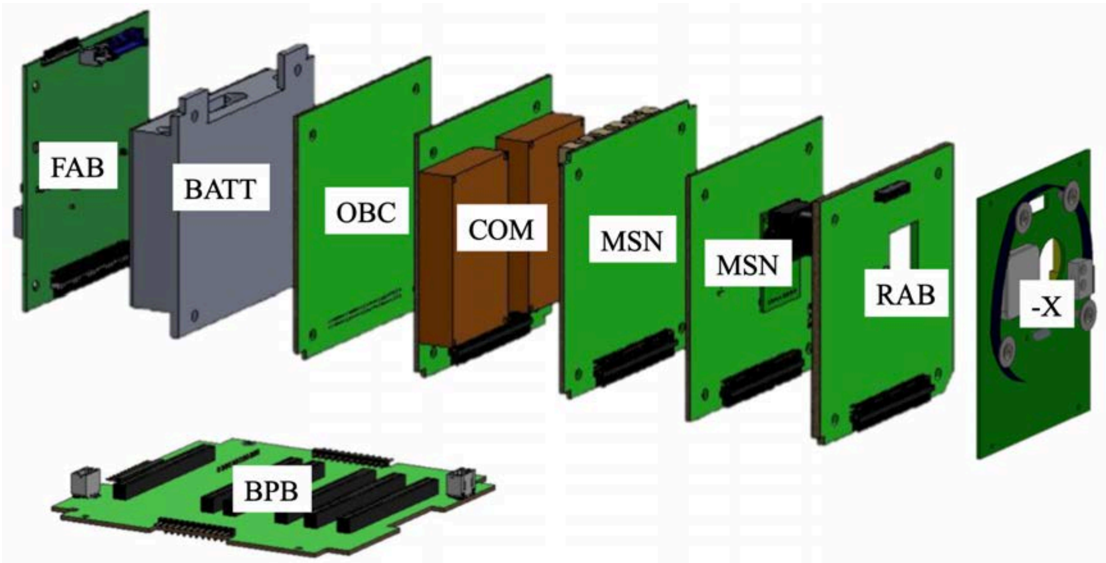

Fig. 15. Internal view of a BIRDS CubeSat

Figure 15 shows an internal view of a BIRDS CubeSat with one BackPlane Board (BPB), seven internal boards, one battery box, and one external –X panel. All internal boards are connected via the BPB using 50-pin connectors to minimize the use of a harness. Many CubeSat designs have already been developed to minimize the use of a harness, which increases the complexity of the assembly work and the risk of failure. The BPB system is one such design. Kyutech has used the BPB style since BIRDS-1. The BIRDS BUS also uses the BPB system to connect each satellite board. It offers many advantages not just for its harnessless design but for the standard design. The BIRDS BUS BPB uses 50-pin connectors, as shown in Fig. 16. It has fixed pin assignments for the power lines, the bus system data lines, and the mission system. When a board is developed for a new project, it can be used with other boards from previous projects without trouble if it follows the fixed-pin assignments. Having the pin assignment fixed, we expect little trouble with the bus system. But for mission payloads, the fixed-pin assignment sometimes limits the design flexibility. To assure flexibility, one idea is to have software-defined routing. One example is to use a device such as a Complex Programmable Logic Device (CPLD), whose details are given in Ref. [5-1].

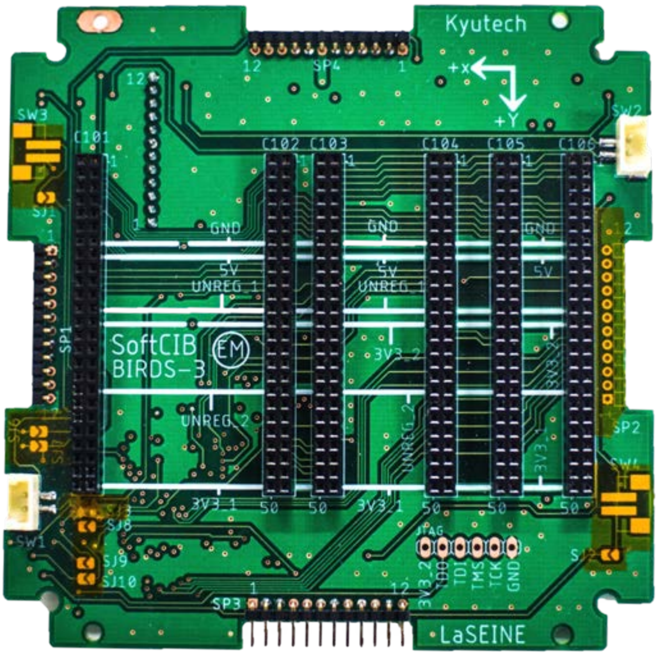

Fig. 16. Front view of the BPB

b. Mechanical specifications

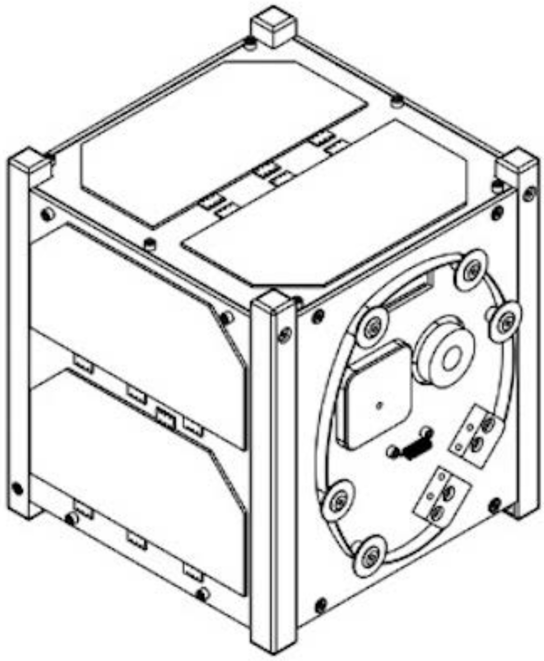

Fig. 17. External view of a BIRDS-3 satellite

Figure 17 shows an external view of a BIRDS-3 satellite as an example. BIRDS-3 is a 1U CubeSat and has a communication antenna on its +X external panel. The external size of the satellite should follow the CubeSat standard of 100 [mm] x 100 [mm] x 113.5 [mm] shown in the following figures:

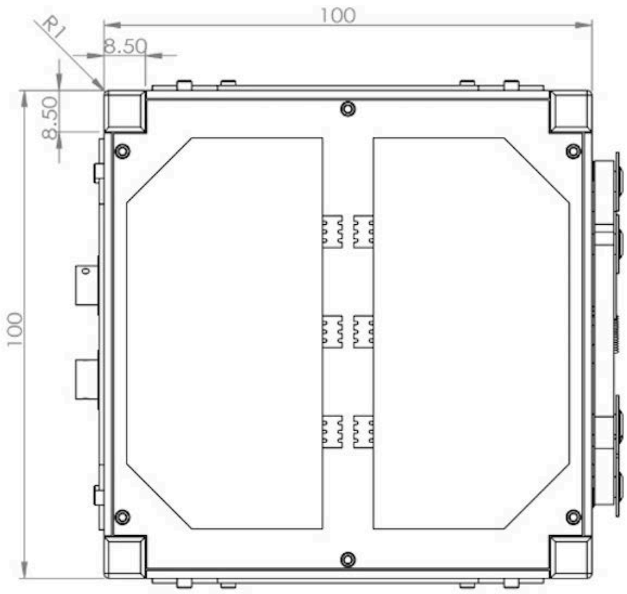

Fig. 18. External view of a BIRDS-3 satellite from the +Z axis

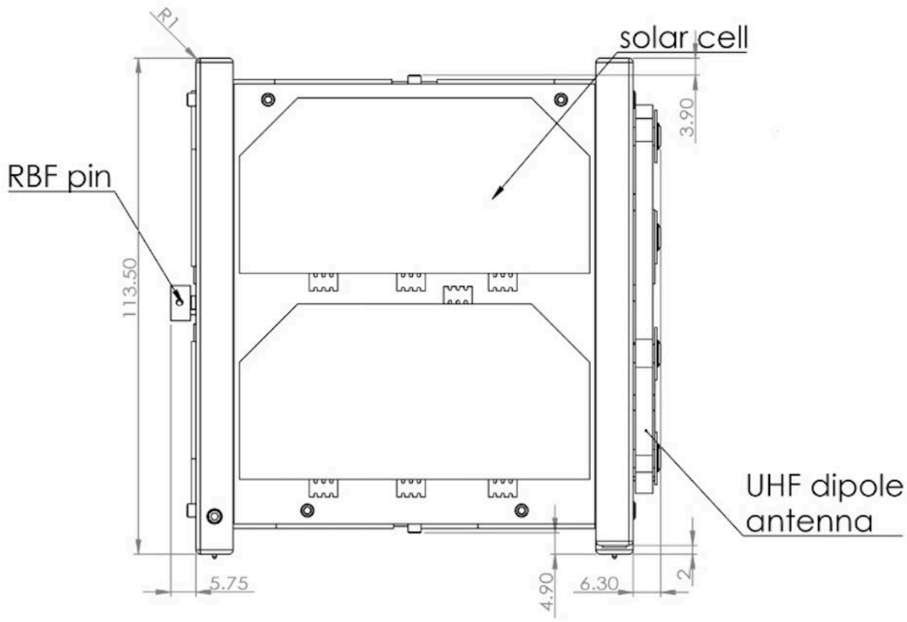

Fig. 19. External view of a BIRDS-3 satellite from the –Y axis

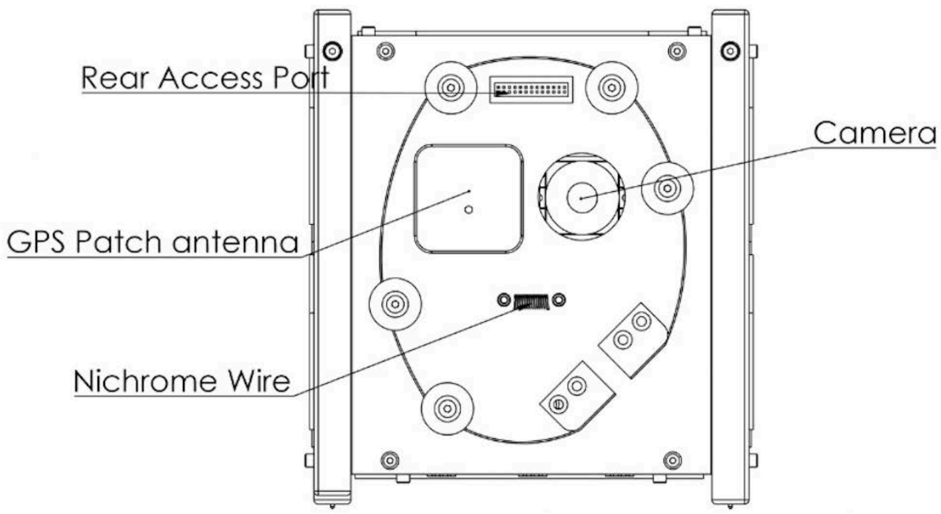

Fig. 20. External view of a BIRDS-3 satellite from the +X axis

The internal boards must keep their mechanical size to fit the board for the assembly work. The BPB must be 96 [mm] x 96 [mm], and must keep the holes positioned as in Fig. 21.

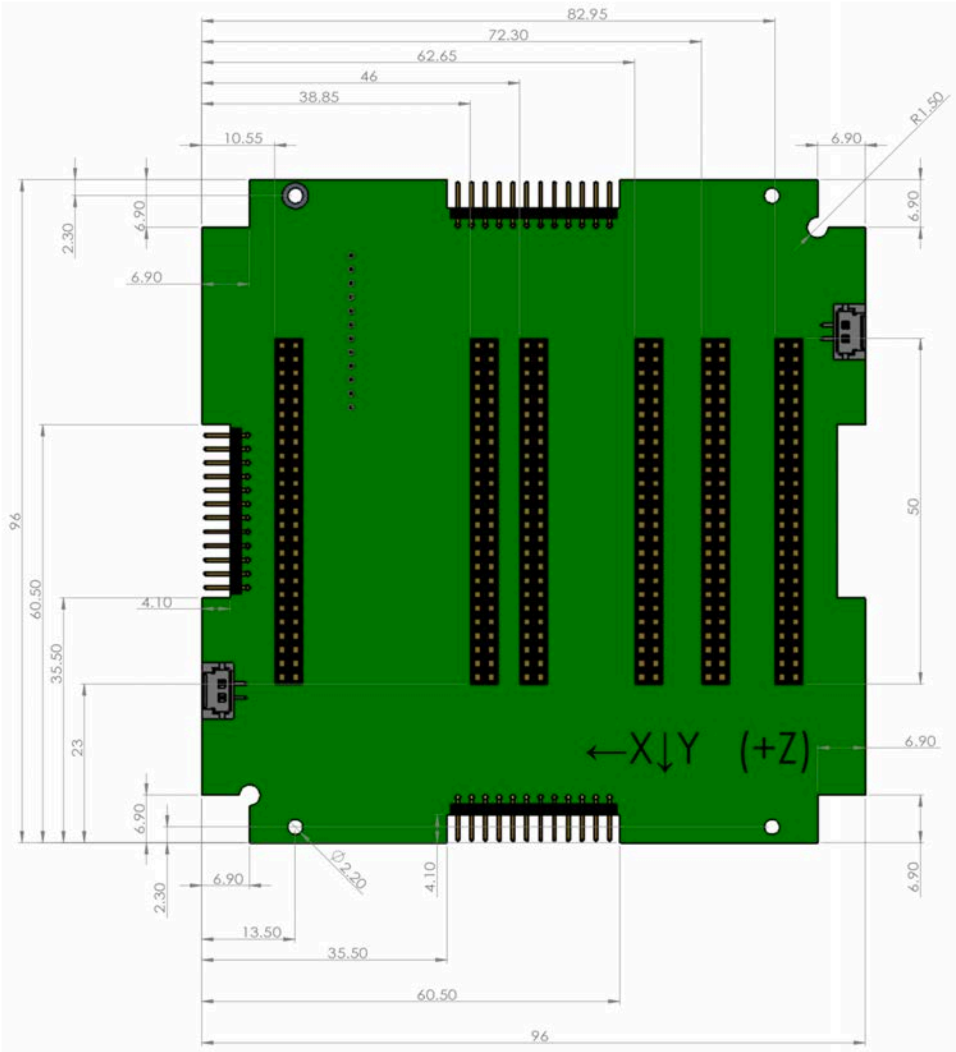

Fig. 21. BPB mechanical data

Other internal boards need to follow their mechanical size requirements too. In this text, FAB, OBC, and mission board data is introduced as an example. Users need to develop their mission boards smaller than example of mission board to avoid collision with frames. Actually, it is recommended to use same mechanical design of example for mission boards.

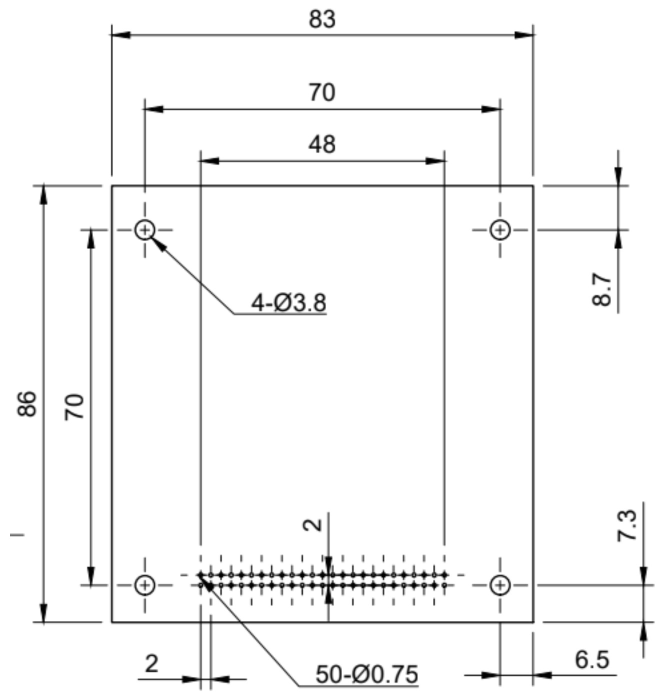

Fig. 22-1. FAB mechanical data

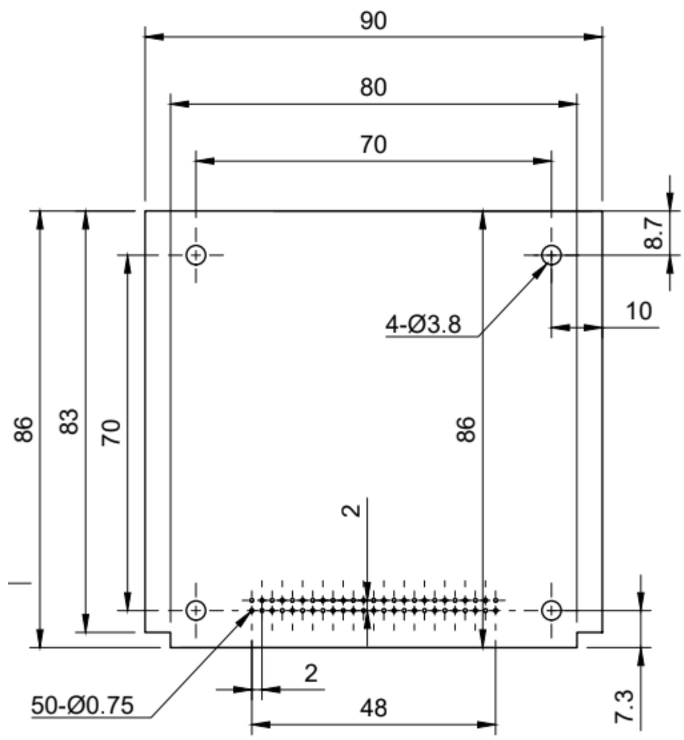

Fig. 22-2. OBC board mechanical data

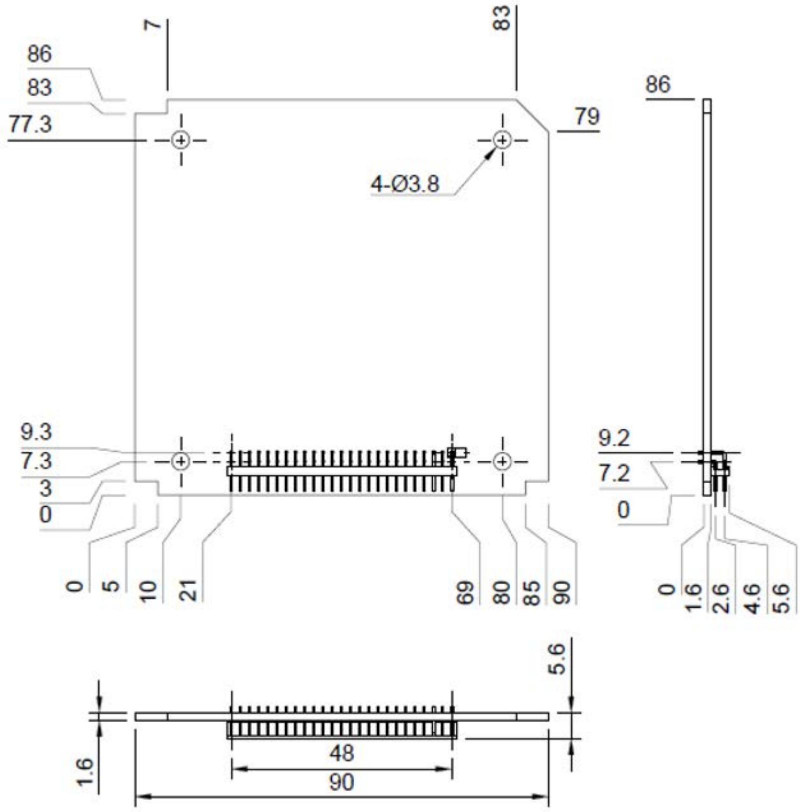

Fig. 22-3. Mission board mechanical data of example

c. Interface between satellite bus and satellite mission

The Bird BUS supports various interfaces between the bus system and the mission system. However, its transmission speed is not extremely fast. Only simple serial interfaces, shared flash memory, and digital input/output (DIO) signals are supported for the interfaces.

- Shared flash memory
  The shared flash memory is 1 [Gbit]. It is connected with a multiplexer for data sharing. The multiplexer is controlled by the bus system, the Main PIC, which changes the path to the mission system when the mission system needs to send a large amount of data. The shared flash memory has dedicated physical signal lines, and these signal lines cannot be used for other purposes.
- UART serial interface
  A simple UART serial interface can be configured between the bus system and the mission system. Eleven physical signal lines are assigned to the interface. If all signal lines are configured to the UART serial interface, 5 UART channels are available.
- SPI serial interface
  The 11 physical signal lines can be configured to a SPI serial interface too. If all signal lines are configured to a SPI serial interface, 2 SPI channels are available.
- Digital Input/Output (DIO)
  If all 11 physical signal lines are used for the DIO signals, 11 DIO channels are available.

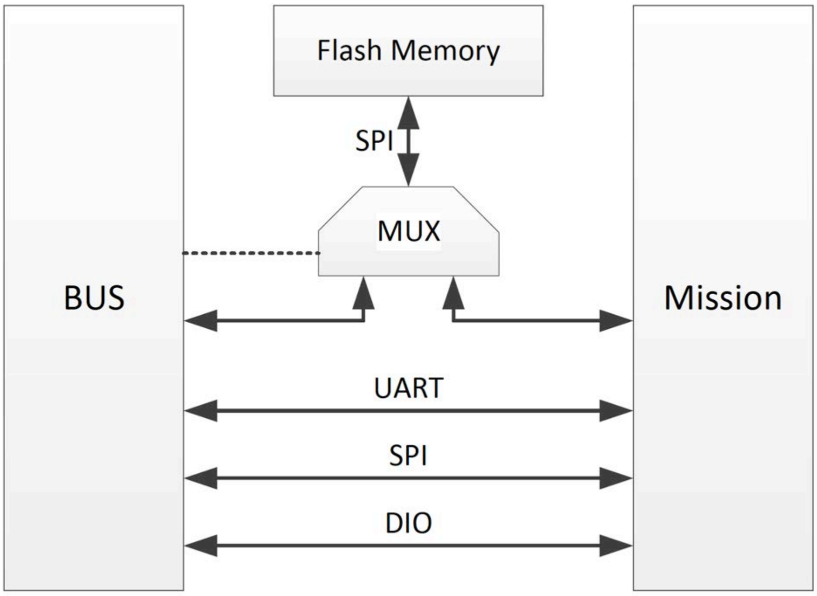

Fig. 23. Interface block diagram between bus system and mission system

d. System integration

In CubeSat projects, many problems arise when subsystems are integrated into a satellite system. Each subsystem may work properly during a stand-alone test. When the satellite is assembled and integrated, however, they may not work as a system. The following work is required to solve the problem of system integration:

- Have a clear interface design between subsystems
  Sometimes, subsystems have unclear interfaces with other subsystems. Subsystem development and testing often focuses on its own functionality. The interface should be checked at the design lever first, and should be tested before the subsystem goes to the Assembly, Integration and Testing (AIT) stage.
- Eliminate independent subsystem monitoring channels
  Many subsystems use their own monitoring channels, usually UART serial channels to monitor the subsystem interior even in the final moments of AIT. A subsystem with its own independent monitoring channel creates trouble after AIT in the flight model, because it is easy to forget actual operating conditions. A typical example would be a lack of monitoring function in the actual command and telemetry operation. As it is very convenient to keep the monitoring channels, subsystem developers are tempted to use them forever. The independent monitoring line is not, however, available after the CubeSat is deployed in orbit. Only telemetry data is available to monitor the satellite. Only uplink commands are available to probe the subsystem. Therefore, it is strongly recommended to cut all monitoring channels at the final moment of AIT, and use the COM to monitor the satellite in the same way as when the satellite is actually in orbit.
- Follow and create proper documentation for the work

All of the AIT work should follow strict procedures using a documented manual, not simply using the experience of some project members or unwritten rules. All test results should be documented and shared with all project members.

- Perform a long-term operation test

  There is no system without bugs, and debugging is inevitable in development work. For debugging, a long-term operation test is essential. It is strongly recommended to keep the CubeSat with actual condition in orbit. Simulating the first weeks after deployment. Debugging should be done following the operation schedule. The external power supply should follow the actual in-orbit power condition too.

Reference

[5-1] Turtogtokh Tumenjargal, Sangkyun Kim, Hirokazu Masui, Mengu Cho, "CubeSat bus interface with Complex Programmable Logic Device", *Acta Astronautica*, Vol. 160, July 2019, 331–342.

6. Ground segment

The ground segment or ground station is a terrestrial radio station designed for telecommunication with satellites. The stations communicate with satellites by transmitting and receiving radio waves, usually from the Very High Frequency (VHF) band to the X-band. When a ground segment successfully transmits radio waves to a satellite or vice versa, it establishes a telecommunication link. The CubeSat ground segment mostly uses the VHF or Ultra High Frequency (UHF) band with a Yagi-Uda antenna. If the satellite uses a frequency higher than the UHF band, such as the S-band, the principal antenna is a parabolic antenna. The ground station antenna needs a tracking function if the station needs to communicate with a satellite, with the exception of geosynchronous satellites. The primary objective of the ground segment is to operate the satellite by telemetry data and uplink command. And, the mission system payload data is also transmitted to the ground segment.

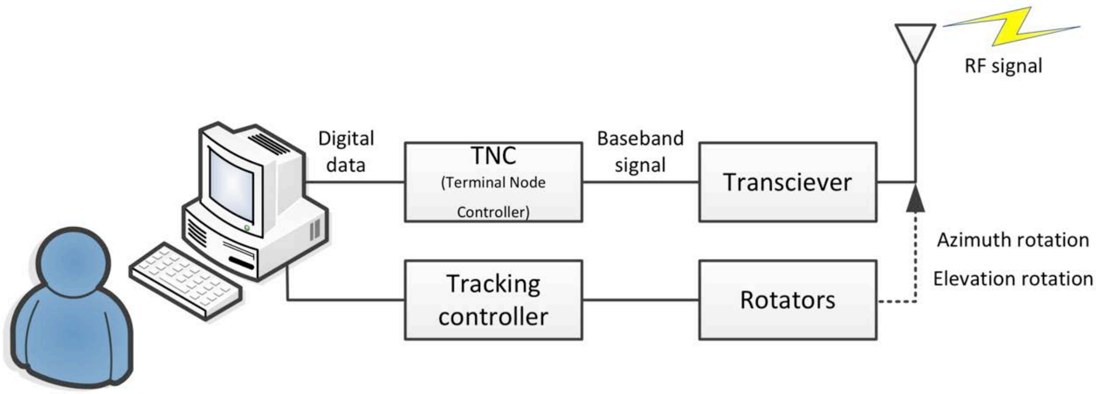

Fig. 24. Block diagram of a ground station for BIRDS projects

A typical CubeSat ground station is constructed as shown in Fig. 23. During the uplink process, the digital data goes to a Terminal Node Controller (TNC) first. The TNC acts as a modem. The data is modulated to a baseband signal by the TNC. The baseband signal is mixed with the carrier band signal at the radio transceiver. The mixed RF signal is transmitted to the satellite by antenna. The downlink process is just the reverse of the RF signal transmission. The received RF signal is collected by the antenna, and transmitted to the transceiver of the radio device. The received downconverted baseband signal goes to the TNC for demodulation. The TNC sends the demodulated digital data to the user.

Many ground stations use a directional antenna for higher gain. The direction antenna needs satellite tracking control to rotate the antenna for the azimuth and the elevation. The satellite position can be calculated by a Simplified Geneneral Perturbation satellite orbit model 4 (SGP4) algorithm using Two Line Elements (TLE) from NORAD. User software, such as Orbitron, calculates the azimuth angle and the elevation angle to point the antenna toward the satellite. The angle information goes to the tracking controller and moves the antenna to track the satellite.

Here, a typical CubeSat ground station is introduced using a BIRDS ground station as an example. A BIRDS ground station uses a KPC9612+ from Kantronix for the TNC, and an IC9100 from iCOM is used for the transceiver of the radio device. An ordinary Yagi-Uda antenna is used for the antenna, and it is installed on the rooftop of a building to avoid obstacles to the RF signal.

Fig. 25. KPC9612+, ©Kantronix

Table. 3 Specification of KPC9612+

Items		Specification
Radio Port 1	Data Rate	1200 [bps](Default), 300, 400, 600
	Modulation	1200 [bps] FSK full duplex CCITT
	Audio Output Level	Continuously adjustable from 1 [mV] p-p to 4 [V] p-p
	Output Impedance	600 [Ohm], AC coupled
	Audio Input Sensitivity	5 [mV] p-p
	Input Dynamic Range	> 70 [dB]
	Input Impedance	Unbalanced, 10 [kOhm]
	Max Audio Input	±12 [V] dc, 35 [V] p-p sinusoidal
Radio Port 2	Data Rate	4800, 9600, 19200, 38400 [bps]
	Modulation	Gaussian filtered DFSK with normal bandwidths of 0.3, 0.5 or full
	Audio Output Level	2 [mV] p-p – 100 [mV] p-p, J20 off 80 [mV] p-p – 4 [V] p-p, J20 on
	Output Impedance	600 [Ohm], AC or DC coupled
	Audio Input Sensitivity	Low: 15 [mV] – 200 [mV] p-p, J16 on High: 80 [mV] – 2.0 [V] p-p
	Input Dynamic Range	> 20 [dB], either range
	Input Impedance	Unbalanced, 10 [kOhm]
	Max Audio Input	±25 [V] dc, 25 [V] p-p sinusoidal
General	Operating Modes	Packet, KISS, XKISS, HOST, GPS, PAGING, MODEM
	Operating Protocols	AX.25 Levels 1 and 2 (User-selectable)

Fig. 26. IC-9100M, ©iCOM

Table. 4 Specification of IC-9100M

General	Frequency Ranges	500 [kHz] – 29.9999 [MHz] 50.000[MHz] – 54.000 [MHz] 144.000[MHz] – 146.000 [MHz] 430.000[MHz] – 440.000 [MHz] 1260.000[MHz] – 1300.000 [MHz]
	Modes	LSB/USB, CW, RTTY, AM, FM, DV
	Antenna Impedance	50 [Ohm]
	Antenna Connectors	Three Type-M connectors - Two HF/50-[MHz] connectors - One 144-[MHz] connector Two Type-N connectors - One 430-[MHz] connector - One 1200-[MHz] connector
	Stability of Frequency	±0.5 ppm
	Resolution of Frequency	1 [Hz]
Transmitter	Transmission Power	1.9 – 50 [MHz] range SSB/CW/RTTY/FM/DV: 100 – 2 [W] AM: 30 – 2 [W] 144/430 [MHz] range SSB/CW/RTTY/FM/DV: 50 – 2 [W] 1200 [MHz] range SSB/CW/RTTY/FM/DV: 10 – 1 [W]
	Modulations	SSB, AM, FM, DV
Receiver	Receiver Type	Double Super Heterodyne (1200-[MHz] band: Triple Super Heterodyne)
	Intermediate Frequency	1st IF: 64.455 [MHz] (HF/50-MHz band) 10.850 [MHz] (144-MHz band) 71.250 [MHz] (430-MHz band) 243.950 [MHz] (1200-MHz band) 2nd IF: 36 [kHz] 10.950 [MHz] (1200-MHz band) 3rd IF: 36 [kHz] (1200-MHz band)

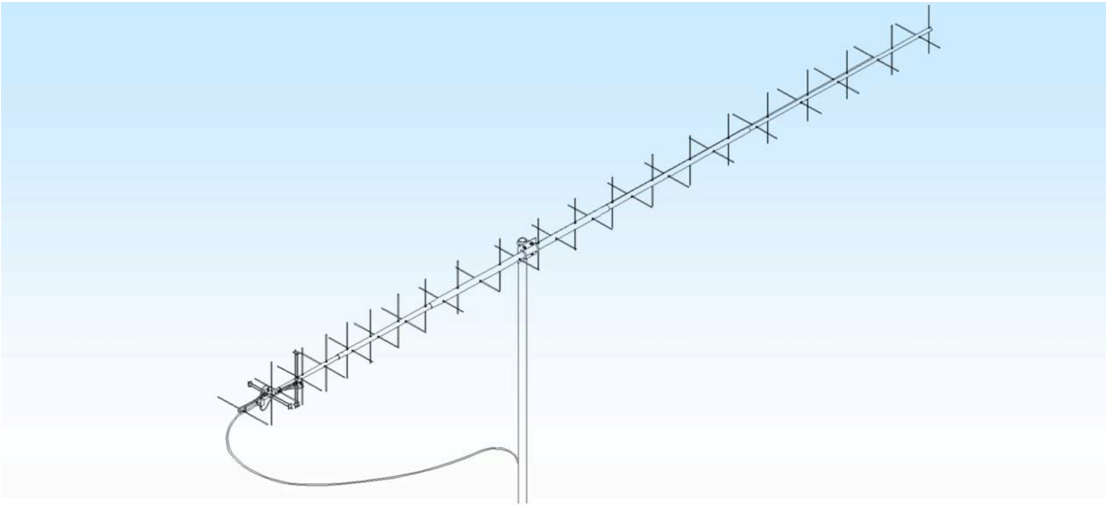

Fig. 27. Schematics of Yagi-Uda antenna for BIRDS ground station, 436CP42UG, ©M2

Table. 5 Specification of 436CP42UG

Items	Specification
Frequency Range	430 – 438 [MHz]
Gain	18.9 [dBic]
Beam Width	21° circular
Feed Type	Folded Dipole
Feed Impedance	50-[Ohm] unbalanced
Maximum VSWR	1.5 : 1
Input Connector	Type-N, Female
Power Handling	1 [kW]
Wind Area	0.19 [m^2]
Weight	3.4 [kg]
Polarization	Circular

A BIRDS ground station uses a PST2051 antenna rotator with its controller.

Fig. 28. PST2051 rotator and its controller, ©PRO.SIS.TEL

Table. 6 Specification of PST2051

Items	Specification
Max Wind Load Area	2.5 m^2
Braking Torque	294 [Nm]
Rotating Torque	196 [Nm]
Max. Vertical Load	650 [kg]
Motor Voltage	12 [V] dc
Rotating Range	500° (70 + 360 + 70)
Rotating Speed	- 90 [sec] for 360°
Reading Accuracy	- 1 [%] no backlash
Antenna Mast OD	48 – 50 [mm]
Operating Temperature Range	-40 – 60 [°C]

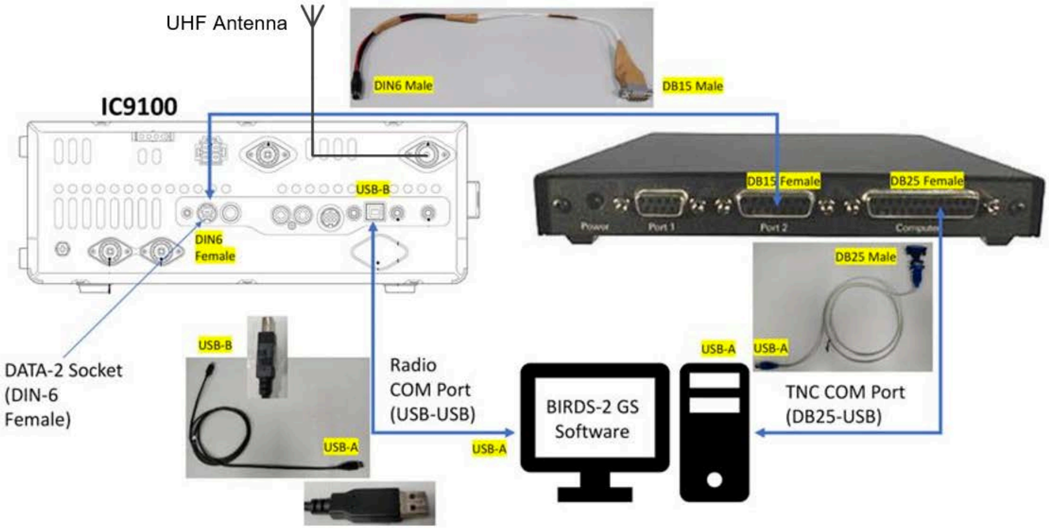

Fig. 29. Connection diagram for the BIRDS ground station

Figure 28 shows the connection diagram for the TNC, Transceiver, and PC. Both the IC9100 and KPC9612+ use the serial COM port to connect with the PC. However, the serial COM port is no longer an ordinary interface for a PC. Virtual COM ports are required for connection with physical USB connectors. BIRDS projects use the 430-MHz-band UHF frequency for both directions of communication, uplink and downlink. It uses a Type-N connector behind the IC9100 device and is connected to a rooftop antenna. The cable between the IC9100 and the antenna should be as short as possible to minimize signal loss.

Fig. 30. Rooftop antenna

7. Data analysis segment

The ground segment provides the payload data for the satellite mission system, but it is only raw data. CubeSats use a relatively slow data transmission link, and the data contains many errors. After the data analysis segment takes the payload data, the following process is required to extract valuable information for the mission object.

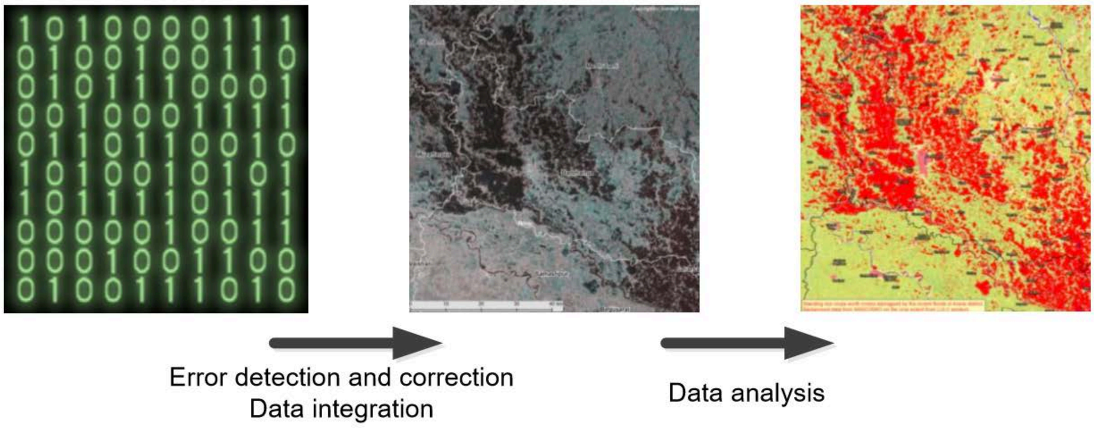

Fig. 31. Rough data analysis process, © reliefweb
https://reliefweb.int/map/india/india-mapping-inundation-extent-bihar-using-esa-sentinel-1-satellite-data-20-august-2017

Error detection and correction

Some data are missing parts or include contaminated data due to a data transmission error. The error needs to be detected and the data needs to be retransmitted. A Cyclic Redundancy Check CRC is a commonly used error detection code to detect accidental changes to raw data. A short check value is attached to the data block by the CRC code based on the remainder of polynomial division of its contents. Upon retrieval, the CRC code calculation is repeated, and if the two values do not match, data corruption can be confirmed. Another famous error correction method is the Reed–Solomon error correction codes.

Data integration

Mission data is usually downlinked in a packet. Each packet is just a part of the entire data set. Before analysis of the data, it must be reconstructed with the proper format. The downlinked data is often in a compressed format, such as JPEG, to save memory and transmission time. Even a small error in reconstruction can cause serious problems in later processes.

Data analysis

The transmitted data is just raw data for further analysis. Simple data analysis can be performed by users within a short time. However, if the amount of data is huge and the data is highly complex, specialized software must be developed. Actually, this data analysis part is the biggest bottleneck for the current CubeSat projects. Many projects have been carried out without a clear data analysis plan and do the work by trial and error. A clear and well-organized data analysis plan is inevitable for extracting valuable mission data in a limited time.

8. Satellite operation

A CubeSat passes over a ground station several times a day in the low-altitude-orbit condition, as shown in Fig. 32. The operational pass is determined by its maximum elevation angle because the communication becomes very difficult when the satellite has a very low elevation angle. Usually three to five operations a day are available for a low-orbit satellite.

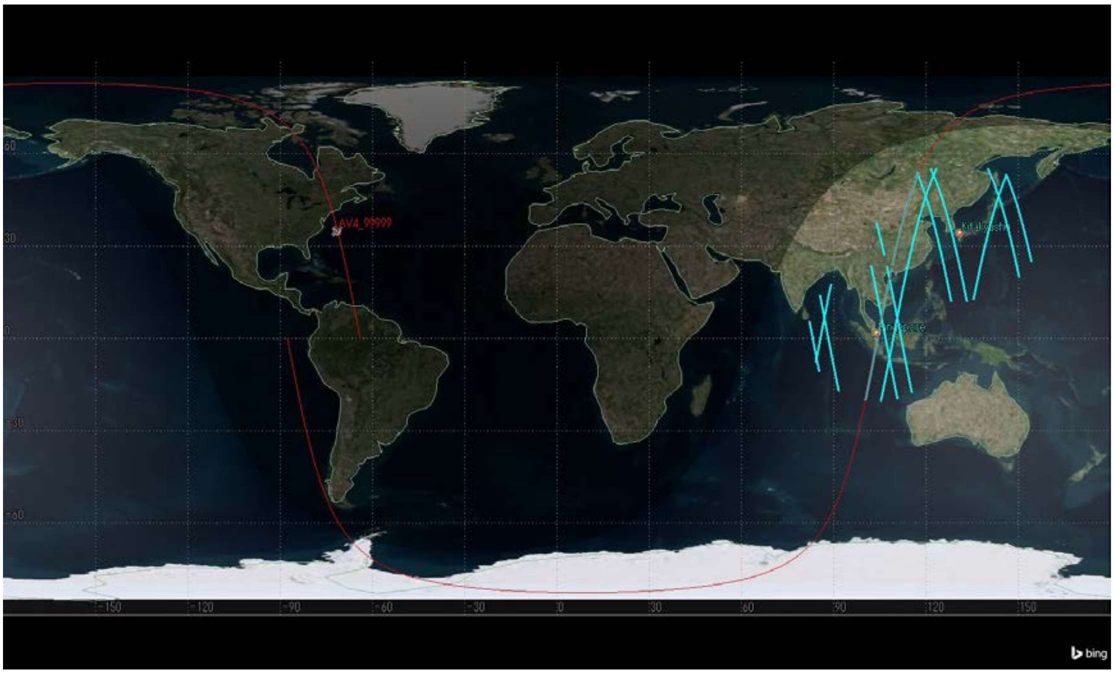

Fig. 32. Satellite passes for two ground stations

Each operation starts when a satellite appears from the horizon and signal acquisition is available. This is called Acquisition Of Signal (AOS). The operation is finished when the satellite passes beyond the horizon and signal acquisition is unavailable. This is called Loss Of Signal (LOS). For satellites in Low Earth Orbit (LEO), the operation time is from several minutes to less than 20 minutes. Within this short time, operators check the satellite signal first and take basic telemetry data to check the satellite condition. After that, the operators must get the payload data for the mission object and send commands to the satellite following the operation plans.

Basic knowledge of the satellite is required for the operators to detect any anomaly happening in the satellite during operation. Usually, satellites have a certain autonomous safety function, but that is not always sufficient. Proper actions are inevitable when the satellite is experiencing an anomaly by failure or malfunction of the onboard devices. An operation mistake can sometimes be fatal, leading to the loss of the satellite. Sufficient training and experience are required for the operators.

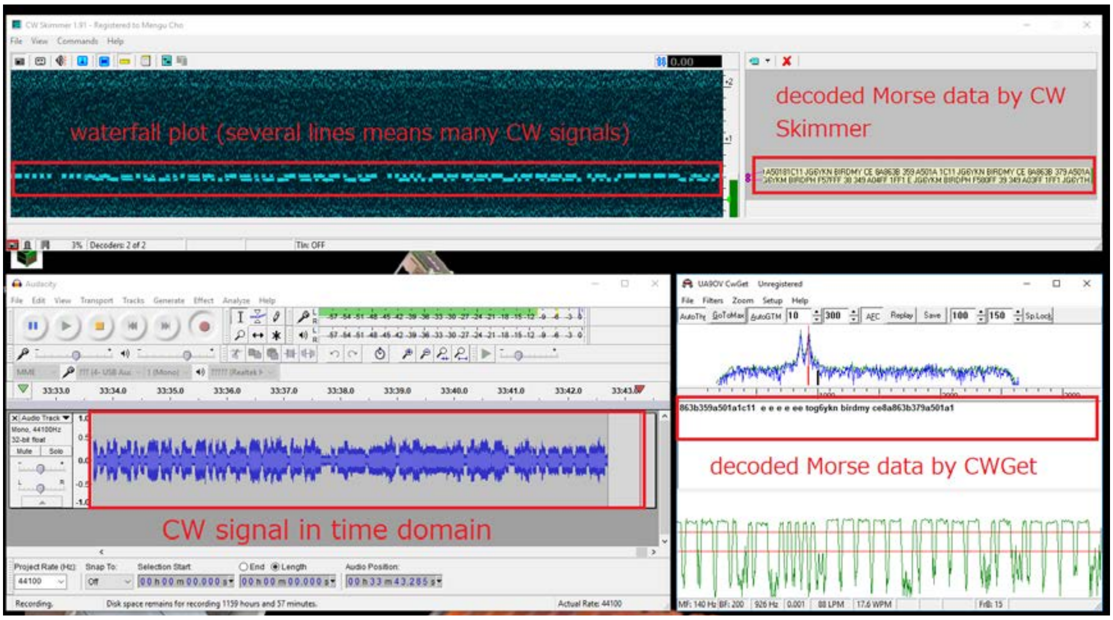

Fig. 33. CW processing software, CW Skimmer and CWGet

Many CubeSats use a Continuous Wave (CW) for the beacon signal to send basic satellite information. The CW is an electromagnetic wave of constant amplitude and frequency, almost always a sine wave. It is the name given to an early method of radio transmission, in which a sinusoidal carrier wave is switched on and off. Information is usually carried for the varying duration of the on and off periods of the signal by Morse code. A BIRDS ground station uses two types of software to catch CW information: CW Skimmer and CWGet. Usually, operation starts by catching the CW beacon, and moves to the next step of operation using Frequency Modulation (FM) communication.

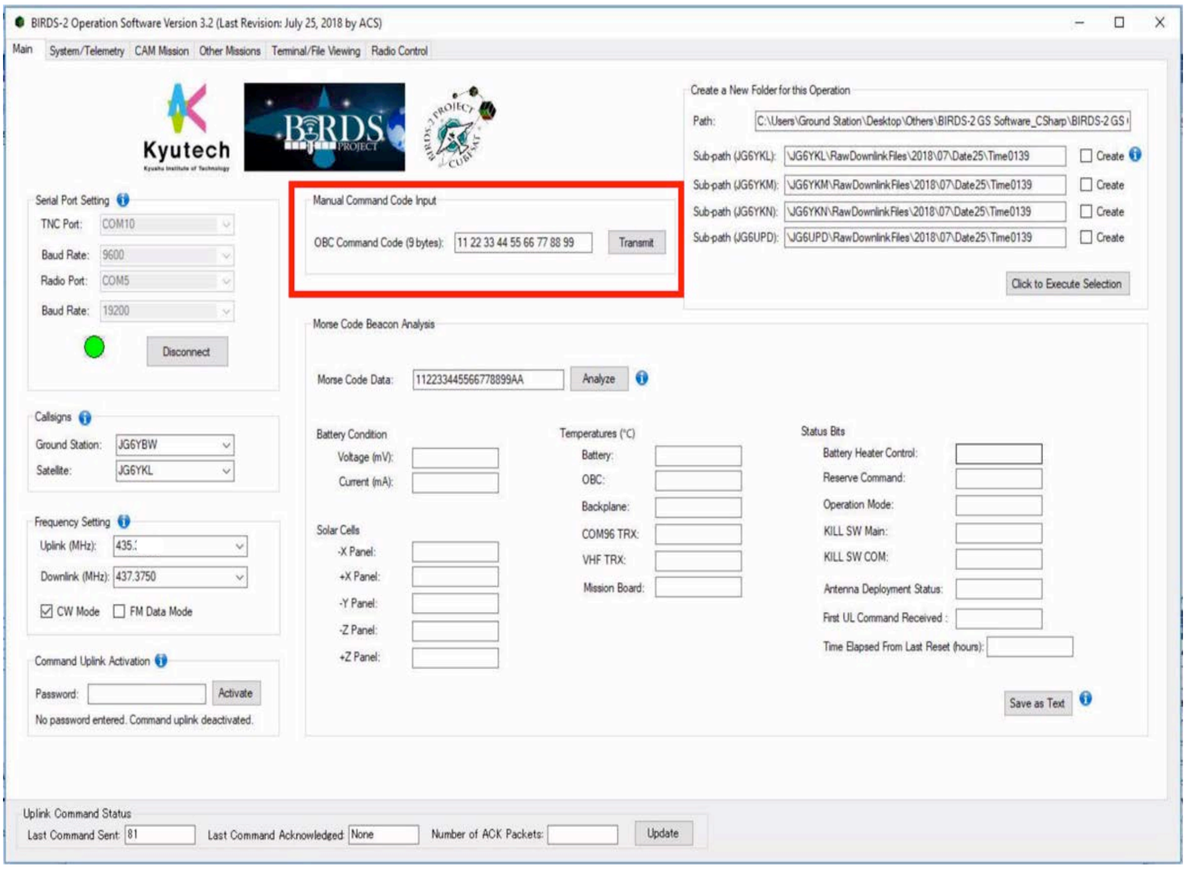

Fig. 34. Ground station software for a BIRDS project—uplink command

Basically, serial terminals are used to send commands to the satellite or get the data from the satellite through the TNC and the transceiver. However, using serial terminals for the operation is very inconvenient. Usually, specially made software is used to send the uplink command and get the data downlink. Figure 34 shows the ground station software of a BIRDS project for the uplink command. The same software can be used for the data downlink and basic data analysis, as shown in Fig. 35.

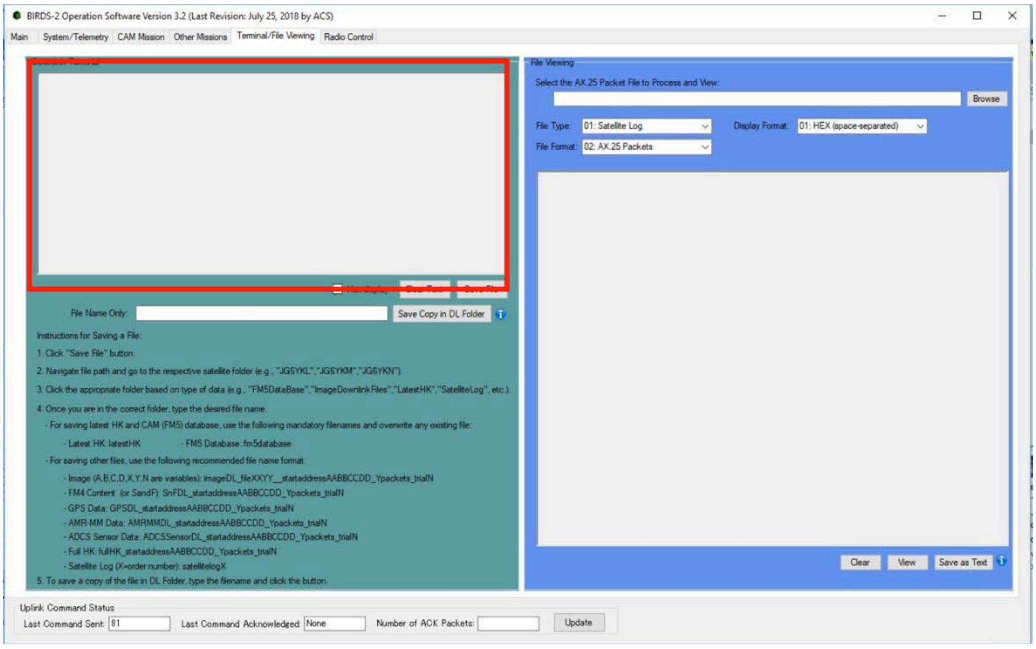

Fig. 35. Ground station software for a BIRDS project—data catching and basic analysis

Tacking a satellite also requires specific software. Many kinds of software are available for rotator control. SatPC32 software is used for a BIRDS ground station.

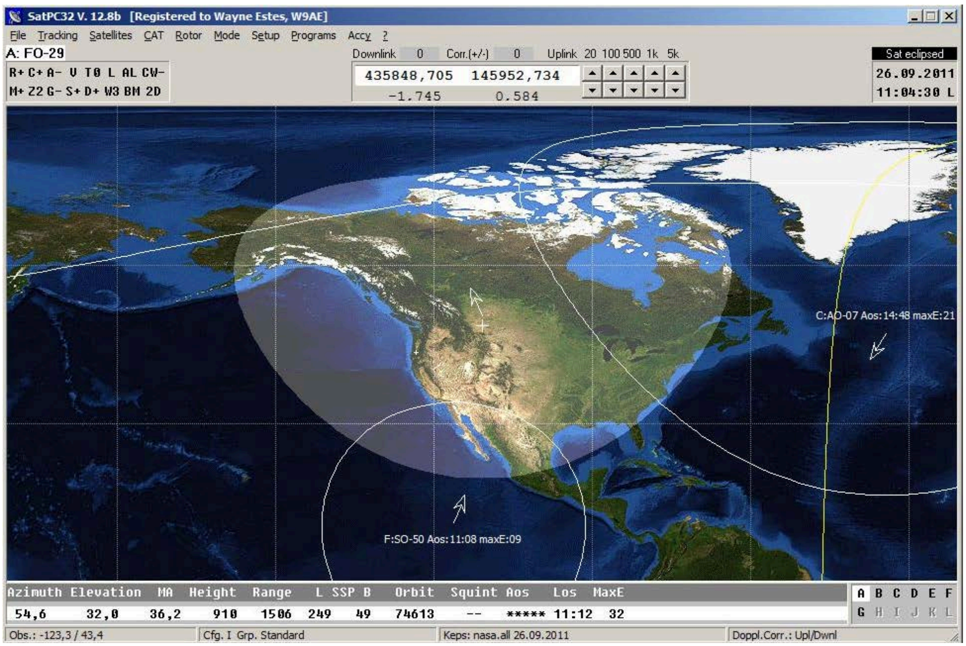

Fig. 36. SatPC32 for antenna tracking control

9. Frequency license

When a satellite uses a radio frequency for its communication, a proper license is required to use the frequency. Radio frequencies are a limited resource. The use of a radio frequency needs to be coordinated among the users through their governments. No frequency for satellite communication can be used freely. Even if the frequency is allowed for terrestrial communication, it does not mean that the use for satellite communication is allowed. Permission by an appropriate domestic authority is required for any frequency to be used for satellite communication. Satellite communication covers a wide area on the ground. Therefore, there is always a possibility of harmful interference beyond borders. Therefore, not only is it important to comply with domestic regulations, the use of a frequency must also have internationally approval.

International frequency coordination activities are managed by the International Telecommunication Union (ITU). The ITU is a specialized agency of the United Nations (UN) that is responsible for issues that concern information and communication technologies. The ITU does not deal with individuals, companies, or any other unauthorized organization. Contact is limited to government bodies. In the case of Japan, the Ministry of Internal Affairs and Communications (MIC) is the government body in contact with the ITU. Figure 37 shows the rough procedures for international frequency coordination. For the case of international frequency coordination in Japan, the following material give the detail.

https://www.tele.soumu.go.jp/resource/j/freq/process/freqint/001.pdf

International coordination starts when Advance Publication Information (API) is submitted to the ITU. An API is a specific document that has satellite communication information in the ITU format. In Japan, the user (the one who build the satellite communication network) submits the API draft to the MIC first. In Japan, it is also possible to draft API with the support of a company introduced by MIC based on the information provided by the user. The MIC checks the API draft, then sends the API to the ITU. The ITU publishes the API. The administrations who think there may be harmful interference send comments to ITU. These comments are collected by the ITU and sent to the MIC. The user has to respond to the comments for further coordination and send their responses to the ITU again, through the MIC. After the coordination has finished, the frequency use is registered with the Master International Frequency Register (MIFR), and the information published by the ITU. These procedures require a significant amount of time, especially because it takes quite a long time for the ITU to process the comments from all over the world. Therefore, a frequency license application must be submitted in the initial stage of the project.

All documents for a frequency license already have their own format for each organization. An API requires a specific software to properly generate the document. The following URLs are useful for each step of the documentation work:

- JARL: http://www.jarl.org/
- IARU: http://www.iaru.org/
- JAMSAT: https://www.jamsat.or.jp/
- MIC: http://www.telesoumu.go.jp/
- ITU: https://www.itu.int/en/Pages/default.aspx

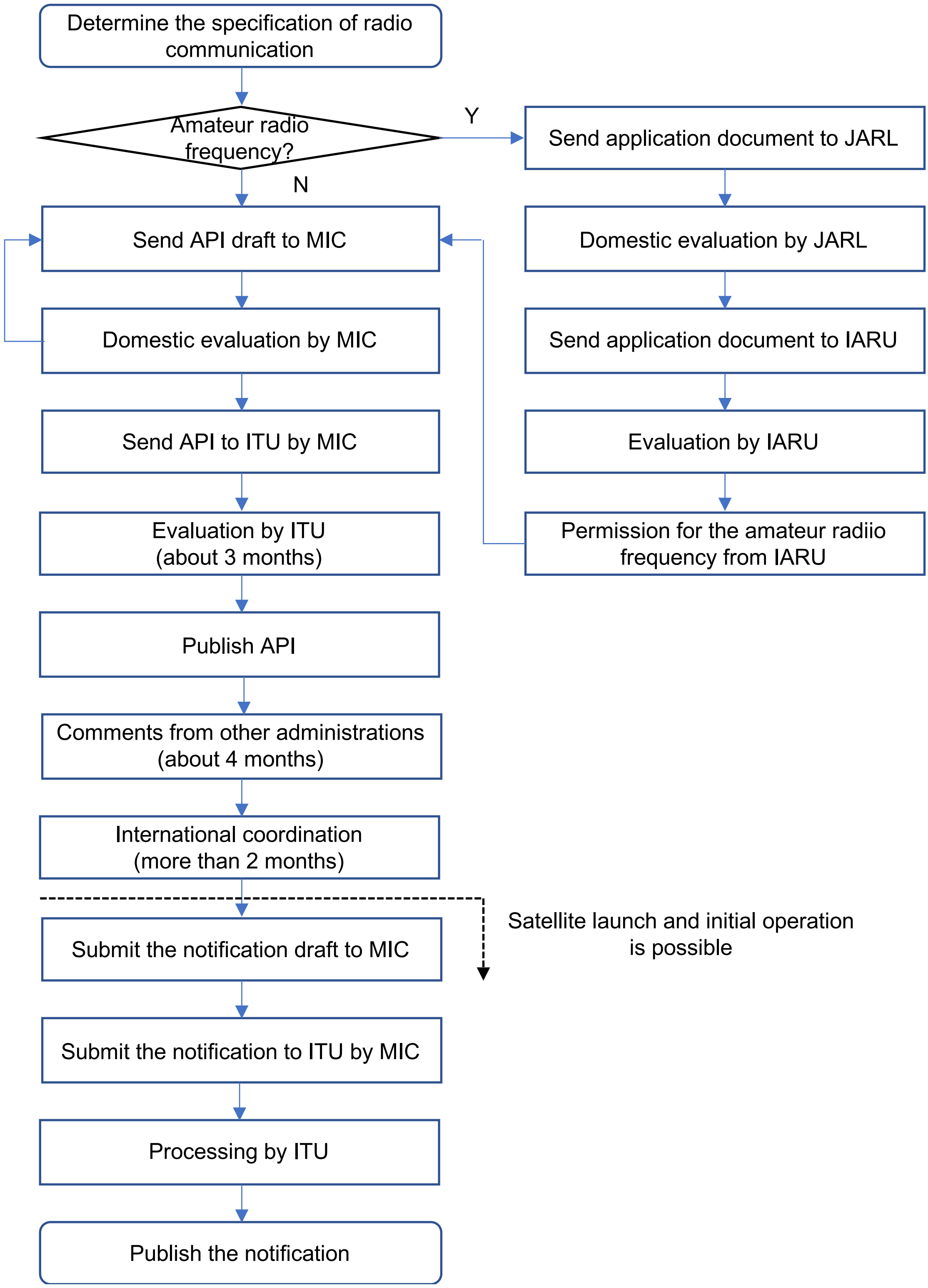

Fig. 37. Rough procedures for frequency coordination

Many CubeSat projects use the amateur radio frequency band (to be exact, the radio frequency band allocated for amateur radio satellite communication) in cooperation with the amateur radio community. In Japan, the amateur radio is defined by the law as follows, “The use of radio to do self-training, communication and technical research mostly for the personal interest in wireless communication, not for monetary purpose”. In order to do amateur radio communication, the user shall obtain the amateur radio license and the call sign from MIC. This is more or less the same in other countries too. We cannot use the amateur radio band beyond the scope defined by the law. Therefore, the usage of amateur radio band has the following restrictions. Please note that the items listed here do not cover all the restrictions.

- As long as the satellite uses the amateur radio band, a commercial mission is not allowed.
- The satellite missions have to follow the spirit of the amateur radio community and should contribute something positive to the community. Doing scientific experiments or being a university satellite does not justify the use of amateur radio band.
- Except the command uplink, encrypted communication is not allowed.
- When a satellite does both amateur radio missions and non-amateur radio missions, they must be clearly separated. For an example, receiving uplink communication from a ship via non-amateur radio and sending downlink via amateur radio is not allowed. Sending uplink command via amateur radio band to operate the satellite to do a non-amateur radio frequency mission or making downlink via amateur radio band to obtain the data of a non-amateur radio frequency mission. The opposite is also true.
- The specification of communication also has some restrictions. Use of a common radio communication method is recommended rather than a specialized device or communication specification, as other amateur radio operators participate in the communication experiment.

The following are typical procedures for obtaining a radio license for a CubeSat to use amateur radio frequencies. The frequency must be allocated first by the International Amateur Radio Union (IARU) before going to the ITU. The IARU has members in many countries. For an example, the Japan Amateur Radio League (JARL) is the Japanese member. Before sending application documents to the IARU, the local member needs to be consulted. In the case of Japan, in addition to the JARL, the Japan Amateur Satellite Association (JAMSAT) should be involved too.

The application to IARU needs to use a special IARU format, and additional documents are also required. The document needs to contains the information about the satellite mission, the frequencies to be used, the communication method, a CAD model, a block diagram of the communication system, a communication plan, a link budget, information on power consumption, and the antenna radiation pattern, etc. Once the JARL and JAMSAT agree with the content, the documents written in English will be sent to the IARU. Three months are usually needed to get a frequency allocation from the IARU at this stage.

After obtaining a frequency coordination letter from the IARU, an API must be submitted to the ITU through the government body (MIC for the case of Japan). The API requires specific software designated by the ITU-R. This software is supported by Windows only. This documentation should be done very carefully because, if the document is modified after the MIC submits the API to the ITU, the international coordination process must restart from the beginning.

Space networks and related software download:
https://www.itu.int/ITU-R/go/space-software/en

The following four software programs are used for API documentation:

GIMS (contour diagram)

https://www.itu.int/en/ITU-R/software/Pages/gims.aspx

SpaceCapture (API document)
https://www.itu.int/en/ITU-R/software/Pages/spacecap.aspx
https://www.itu.int/en/ITU-R/software/Pages/ap7capture.aspx

SpaceVal (API document)
https://www.itu.int/en/ITU-R/software/Pages/spaceval.aspx

SpacePub (API printing)
https://www.itu.int/en/ITU-R/software/Pages/spacepub.aspx

Within three months after receiving the API, the ITU publishes the API so that all other administrations can view the document. After going through the processes mentioned before Fig.37, the coordination ends. Once the coordination ends and the satellite is launched, users must submit the final communication specifications of the satellites and Earth stations, along with satellite orbit information. Notifying the ITU is done through the MIC. When the notification document passes evaluation by the ITU, the frequency usage is registered to the MIFR and the notification material is made public. When the satellite information is registered with the MIFR, a Bringing Into Use (BIU) notification must be sent to the ITU through the MIC. The BIU is usually the date when the satellite is launched. The frequency use registered on the MIFR has higher priority to the next coordination. This can be a basis of refusing the request of using the same frequency by other users in specific countries (service area). If the user refuses, it jeopardizes the relationship with the others and enhances the risk of being refused when the position is reversed.

Acquisition of a domestic license proceeds in parallel with the ITU frequency coordination. In Japan, before a satellite is launched, a preliminary license is issued based on the content of license application. The transmitters are then inspected based on the specification in the preliminary license. After the satellite is launched, it first goes through test operation under that preliminary license. Once it has been confirmed that the uplink and downlink communication link is established, an official radio license is issued. Official satellite operation is possible only after the official domestic radio license has been obtained. It is important to keep the flow of “test operation -> official license -> mission operation”. For an example, if you make a news release of “the satellite successfully captured the Earth image” before the official license is obtained, you are violating the regulation.

10. Launch environment and space environment

Launch environment

A satellite has to survive an environment of severe vibration and shock during the launch phase because rocket launch is the only way to orbit at present. The launch vehicle and the satellites onboard receive intense acoustic pressure during launch, which induce high levels of vibration in structural elements and equipment. In addition, elastic structural interactions with propulsion systems and flight control systems can produce low-frequency, high-deflection flight instabilities. Here, examples of launch environments are introduced using the two sample cases of Falcon 9 and Dnepr rocket boosters.

Figure 38 and Table 7 show a sample of a Dnepr rocket flight sequence. The entire launch sequence may last several hours, depending on the final orbit. Major vibration and shock occur within several minutes from lift-off as they are caused by the acoustic pressure, transonic disturbance, engine ignitions, stage separation, and fairing jettison.

During the launch phase, satellites are exposed to the following mechanical load. The load levels differ among different launch vehicles.

- Static
- Vibration
- Shocks
- Acoustic

In mechanical testing, vibration is further divided into sinusoidal vibration and random vibration. After all, the two vibrations both occur through the interface between the POD and the rocket structure. Sinusoidal vibration results from natural vibration modes of the rocket body to a disturbance such as engine firing, etc. Random vibration results from excitation of the rocket body by acoustic force from outside the rocket body. In the case of CubeSats, the acoustic load can be neglected as the surface size of the POD is so small that the acoustic load on the POD can be neglected compared to the vibration load applied directly through the interface between the POD and the rocket structure. Table 8 to 11 list the levels of static acceleration, sinusoidal vibration, random vibration and shocks, respectively.

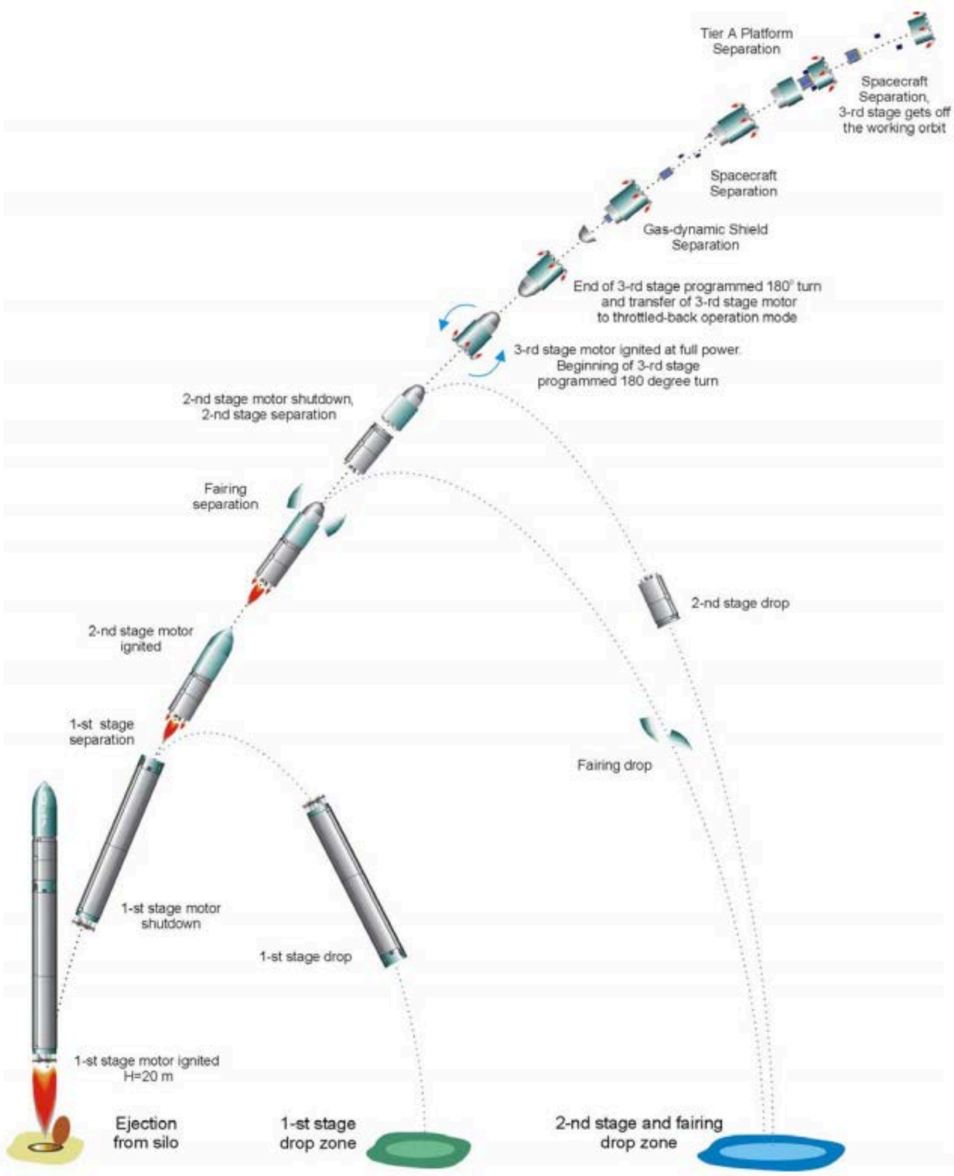

Fig. 38. Rocket launch profile in the case of a Dnepr Rocket, ©Yuzhnoye

Table 7. Dnepr Rocket Flight Event Example

Sequence	Event
0	Liftoff by hot gas generator
1	First stage ignition at 20-m altitude
2	End of first stage burning
3	First stage separation; ignition of second stage
4	Fairing separation; end of second stage burning
5	Second stage separation
6	Third stage ignition; start of 180-degree turn
7	End of 180-degree turn
8	Gas dynamic shield separation
9	Spacecraft separation

Table. 8 Acceleration Load of Dnepr Rocket Booster

Load Source	Longitudinal Acceleration [g]	Lateral Acceleration [g]
1st stage burn	7.5	0.5
2nd stage burn	7.8	0.2
3rd stage burn	-0.3 – -0.5	0.25

Table. 9 Amplitude of Harmonic Oscillations of Dnepr Rocket

Longitudinal	Frequency [Hz]	5 – 10	10 – 15	15 – 20
	Amplitude [g]	0.5	0.6	0.5
	Duration [sec]	10	30	60
Lateral	Frequency [Hz]	2 – 5	5 – 10	10 – 15
	Amplitude [g]	0.2 – 0.5	0.5	0.5 – 1.0
	Duration [sec]	100	100	100

Table. 10 Power Spectral Density of Random Vibration of Dnepr Rocket Booster

Frequency [Hz]	Spectral Density Liftoff [g^2/Hz]	Spectral Density State Burn [g^2/Hz]
20 – 40	0.007	0.007
40 – 80	0.007	0.007
80 – 160	0.007 – 0.022	0.007
160 – 320	0.022 – 0.035	0.007 – 0.009
320 – 640	0.035	0.009
640 – 1280	0.035 – 0.017	0.009 – 0.0045
1280 – 2000	0.017 – 0.005	0.0045
RMS [g]	6.5	3.6
Duration [sec]	35	831

Table. 11 Shock Response Spectrum of Dnerpr Rocket

Load Source	Frequency [Hz]							Number Of Shock
	30 - 50	50 - 100	100 - 200	200 - 500	500 - 1000	1000 - 2000	2000 - 5000	
	Shock Spectrum Values [g]							
Separation of Fairing 3rd Stage Separation	5 - 10	10 - 25	25 - 100	100 - 350	350 - 1000	1000	1000	a)
Separation of Craft	5 - 10	10 - 25	25 - 100	100 - 350	350 - 1000	1000	1000 - 3000	1

a) Number of shock impacts is contingent upon number of spacecraft installed in the SHM

Orbit environment

Here, the Low Earth Orbit (LEO) environment is introduced because CubeSats are mainly launched into LEO. The typical LEO has an altitude range from 200 [km] to 1000 [km]. This LEO has the following characteristics:

- Ultra-high vacuum: 6×10^{-8} [Pa] at 960 [km] altitude
- Temperature range: ±100 [°C]
- Radiation: electromagnetic radiation, heavy particles are dominated by protons except the polar region
- Vacuum UV: 10^{-6} [W/m^2]
- Atomic Oxygen: 10^{13} – 10^{15} AO/(cm^2 sec) at altitude of 300 [km] – 500 [m], around 5 [eV]

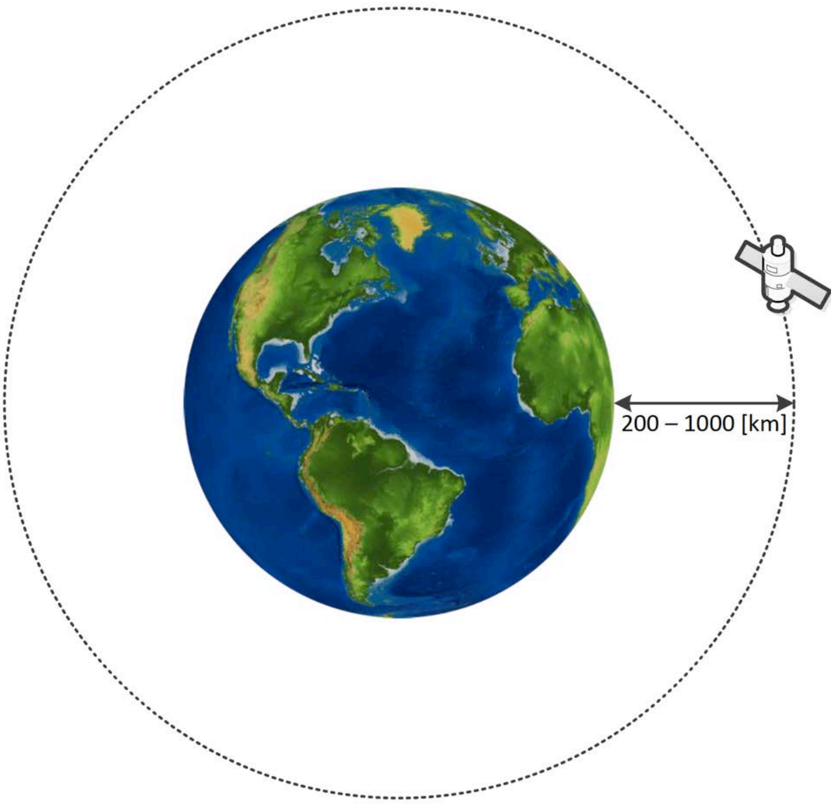

Fig. 39. Typical Low Earth Orbit

The most important environmental factors for CubeSat are thermal environment and radiation environment.

In LEO, the distance to the Earth surface is relatively short. Then the view angle of the Earth from the satellite is big. Therefore, due to infra-red thermal emission from the Earth, the temperature does not drop to a very cold temperature, such as -100oC even during the eclipse. It is also because the eclipse time in LEO is limited to 20 ~ 30 minutes. At the ISS orbit, these facts appear more and the low temperature is not a significant issue. On the other hand, during the daytime, the satellite tends to reach higher temperature. Especially, in a high-inclination orbit, such as ISS, there is possibility of high beta angle where the eclipse time is reduced even to zero. Then, the temperature does not decrease. We should be careful about the payloads that are operated constantly, such as a radio, for that case.

Regarding the radiation environment, the long-term cumulative damage, such as total ionization dose, displacement damage, radiation-induced damage of material, etc. is not a strong concern for CubeSats as their mission duration is mostly several years. Single event effects due to heavy particles, especially protons, are important. Especially, single-even-latch-up needs a special attention as it may lead to hardware destruction due to the over-current or computer hang-up.

11. Assembly, Integration and Testing

Assembly, Integration and Testing (AIT) activities are strongly interrelated and have a deep relationship with the quality assurance for a CubeSat. CubeSat development success is determined by the AIT activities. The ultimate goal of AIT is to achieve a target of confidence that the CubeSat will fulfill its mission in orbit.

a. Assembly

CubeSat hardware should be assembled into a system. Sometimes, people underestimate the role of the assembly work, but that determines the reliability of a CubeSat. CubeSat assembly needs the following for confidence in its quality:

- Well-trained team

  Assembly work requires sufficient experience, and only training provides experience. The assembly team needs to train themselves using a test model (such as an engineering model) multiple times before they start assembling the actual flight model.

- Assembly procedure

  Sometimes, assembly work is done without any memo or document. It may look time saving at first. Later, however, it leads to a huge time loss and very serious problems. The assembly work must be done following assembly procedure documents and checklist. The documents should be updated following the assembly work, and the they should be immediately shared with all members. Workmanship error during the assembly, such as a loose connector, a mistake in harness connection, a loose bolt due to under-torque, deformation due to over-torque, etc., may manifest later during critical phases, such as the final vibration test or even the launch. If that occurs, it could lead to not only mission failure but also catastrophic safety hazards. The checklist is an important piece of evidence to assure that the assembly was done according to the procedure. It must be written by a person who is NOT involved in assembling the satellite. The checklist may sometimes be required as evidence in the final safety review to show that the satellite was properly assembled. The assembly procedure itself is a living document. Through practice using a test model, the procedure document needs to be assessed to determine whether it is clear to everybody, easy to understand, reflects the real procedure, etc.

- Clean room

  A clean room or a clean booth is necessary for CubeSat assembly work. The room or the booth must have enough space for the work. The flight model must be protected from dust. On the ground, dust particles attach to a surface by gravity. They, however, levitate in orbit. They can attach anywhere on the satellite and can cause damage to sensitive devices, or they may cause a short circuit if electrically conductive. Compared to other industries, such as the semiconductor industry, the cleanliness requirement is not so severe. ISO Class 8 (Class 100,000) is the minimum requirement for general assembly work. Such a low-class cleanliness can be achieved with a clean booth. Even though the cleanliness requirement is not very high, care should be taken by wearing masks and gloves to prevent human saliva or sweat from contaminating the flight model.

- Well organized tools

  All tools have to be well organized and have to be kept clean for the efficiency of the work. Guaranteeing the safety of the working field is also very important to. And demagnetizing the tools regularly is also strongly recommended to minimize the residual magnetic moment of the CubeSat.

b. Integration

Integration is for combining multiple subsystems, which have been developed separately, into a working system. This has to be done not only with hardware but also with software. Integration is one of the most critical parts of CubeSat development, and perhaps the most difficult part in the entire development process. In many cases, each subsystem satisfies performance specifications without trouble in stand-alone; however, it may not when it has to work with other subsystems after integration. Then a process of trial and error is used to find the problems. The following items are required to minimize time loss in the integration work:

- System engineers

  It is strongly recommended to have at least one person dedicated to looking at the entire CubeSat system with a systematic point of view. This is difficult for CubeSat projects, as they are always short on human resources. For university CubeSat projects, a project manager often also acts as the system engineer. But the project manager is often occupied with many tasks. It is recommended to allow enough time for the system engineer to think about, review, and monitor system integration. The system engineer needs to know what is required of them.

- Interface control document

  The Interface Control Document (ICD) serves as a key technical document to specify the interfaces among the subsystems. As CubeSat subsystems are not so complex compared to bigger satellites, it is still possible to develop a subsystem without an ICD. It is however very risky to do integration without one. An important role of the system engineer is to keep track of the ICD. It serves as an important technical document to track the technical details during satellite operation when the students who designed the subsystem may have already graduated.

- Multiple integration

  Student teams often underestimate the difficulty of integration work and allocate an optimistic schedule for the integration. When the team is composed of inexperienced members who have little experience with system integration, doing the system integration work multiple times is recommended. The AIT of the engineering model before Critical Design Review (CDR) is very good practice for the team members. They learn many things from the experience and then allocate the proper amount of time to the flight model AIT.

- Integrate as you fly

The system needs to be integrated to a state similar to that for the flight condition. Many subsystem engineers want to include monitoring or diagnosis wires in their subsystem during the integration work. That is necessary at an early stage, but should be removed in later stages. The CubeSat cannot be launched with monitoring wires. That is why the system should be integrated to the same conditions that exist in orbit.

c. Testing strategy

Once a satellite is launched, it cannot be repaired. Usually just after the launch, many anomalies or failures are observed. Those events decrease with time in orbit and eventually occur only occasionally at a random pace. The initial anomalies and failures are due to mismatches of the system to the operational environment, as they are overlooked before the launch. The later anomalies and failures are due to random causes, such as single-event effects. Testing of the CubeSat on the ground should be focused on decreasing the initial anomalies and failures by finding them before the launch when the cause can be fixed, so that those events do not lead to the fatal loss of the satellite. The more testing done, the more lives in orbit. It is, however, unrealistic to do testing forever. More testing also means more time and more money. There right balance must be found between desired reliability and the efforts spent in testing.

ISO-19683, “Space systems — Design qualification and acceptance tests of small spacecraft and units”, describes the **minimum** test requirements for commercial satellites. ISO-19683 can be further tailored to fit into the scope of university CubeSat projects, but it serves as a good starting point for considering a testing strategy. From the experience of BIRDS programs, the following tests are truly essential:

1. Electrical interface, functionality and mission test
2. Electromagnetic Compatibility (EMC) test
3. Deployment test
4. Antenna pattern test
5. Launcher/Spacecraft interface test
6. Mechanical test
7. Thermal test
8. Long-range test
9. End-to-end mission simulation test

The electrical interface and functionality test are carried out during the integration processes. The satellite must work at least on a table so that all the subsystems can work together before the team starts the series of environment tests. Otherwise, they cannot distinguish whether the defect found during the environment test is due to the nature of the satellite design or due to environmental stress. In the mission test, if taking a picture with a camera is one of the mission objects, the team needs to confirm that an image can be reconstructed on a PC connected to the ground station equipment after the ground station sends a command to the satellite. The command uplink and the data downlink can be done either by RF or a cable, although RF is preferred.

The EMC test is important when the noise generated by the internal components affects the other onboard components, especially the satellite receiver. The uplink signal is already very weak when it reaches the satellite. When the background noise level is high, the signal-to-noise ratio may be below the threshold. The sensitivity level of the satellite receiver needs to be characterized first in a controlled situation, perhaps by connecting the receiver and a ground station radio (or a signal generator) with a variable attenuator between. Then the uplink is given to the satellite after it is fully assembled. Sending the uplink by RF in an anechoic chamber is recommended.

As many CubeSats use a deployable antenna, failure of the deployment leads to the loss of the satellite. Many antenna deployment systems employ nichrome wire to cut the holding string by heat. The deployment test should be carried out many times, especially assuming the worst conditions, the lowest temperature, and the lowest battery state. If mechanical parts such as hinges are used, testing in vacuum provides a severe condition for the mechanical parts. If there is no mechanical device, testing in a thermal cycle chamber may give the worst condition, as the atmosphere further prevents heating of the nichrome wire.

The antenna pattern test characterizes the antenna radiation pattern. Measuring the antenna gain of the flight model antenna is strongly recommended. The characteristics of CubeSat antennas, such as deployable dipole or monopole antenna, or a patch antenna, strongly depend on the final workmanship. Even if it looks the same, let the antenna radiate the radio wave and confirm that the antenna is properly manufactured and attached to the satellite.

For CubeSats, the launcher/spacecraft interface test means a fit check with the POD. For the case of the JAXA POD, the tolerance of the satellite external dimension is 0.1 [mm]. It is not difficult to manufacture structural parts with a precision of 0.1 [mm] or better. The satellite after assembly may, however, have been distorted. Doing the fit check at an early stage of the project, such as STM or EM, is recommended. Once it is confirmed that the satellite can enter and leave the POD smoothly, the structural design, the manufacturer, and the assembly procedure should be fixed. It is a tragedy if the satellite flight model does not fit into the POD at the final stage. If that happens, very little can be done. The flight may have to be cancelled.

Mechanical tests, especially random vibration tests, are required as a verification method to show compliance with the safety requirements. In the case of a rocket launch, it is to show that the satellite has sufficient structural strength for the mechanical load during launch. In this case, quasi-static load and sinusoidal vibration tests are also often required. For the case of the ISS, it is to show that no shatterable material, i.e., solar cell, comes out due to vibration during launch to the ISS. The test levels and conditions differ depending on the launcher. If the launch method is not yet fixed during the engineering model phase, Table 5 of ISO-19683 may be used. Although the table lists the unit qualification test requirements, we can regard a CubeSat inside a POD as a unit of a bigger satellite, i.e., the POD. The test levels and conditions of sinusoidal vibration and random vibration are listed in Table. 12. Figure 40 shows the vibration shaker at Kyutech. Vibration shakers are not very unique. They can be found in testing centers offering test services for automobiles, electronics, and other industries.

Table. 12 Test level and duration of vibration test

Test	Items	Specifications
Sinusoidal vibration	Vibration amplitude	8.4 [g] p-p or higher
	Frequency	5 – 100 [Hz]
	Sweep rate	4 [Oct/min], up and down
	Number of applications	Once for each axis
Random vibration	Root mean square	13.3 [g] rms or higher
	Lower tolerance limit on PSD	0 [dB]
	Duration	1 [min] for each orthogonal axis
	Frequency	20 to 2000 [Hz]
	Number of applications	Once in each axis


Fig. 40. Vibration shaker

Another part of the mechanical test is the shock test. Whether the shock test is required or not depends on the launcher. If one chooses ISS deployment, a shock test is not required. If one chooses rocket launch, it is sometimes required. A launch vehicle generates a pyro-shock several times during the launch phase, due to separations of SRB, stages, fairing and main satellites. For a CubeSat, pyro-shocks due to separation of its own does not exist. Perhaps the fairing separation will provide the highest shock level. The test levels and conditions differ depending on the launcher. If the launcher is not fixed during the engineering model phase, Table 5 of ISO-19683 may be used. The test levels and conditions of the shock test are listed in Table. 13. Figure 41 shows the shock test machine at Kyutech. Generally, shock test machines used for other industries are not appropriate for CubeSats as the method of shock acceleration is different. For example, the drop test, which is often used for electronics such as mobile phones, is not adequate, as the satellite does not release translational kinetic energy. The hammering type—hitting the baseplate where the POD is attached—is the most flight-representative test.

Table. 13 Test level and duration of shock test

Test	Items	Specification
Shock	SRS	100 [Hz]: 600 [g] 2500 [Hz]: 4000 [g] 5000 [Hz]: 4000 [g] * This PDS may be tailored according to the test requirements of launch vehicle

	Number of shocks	Once in each axis
	Q factor	10

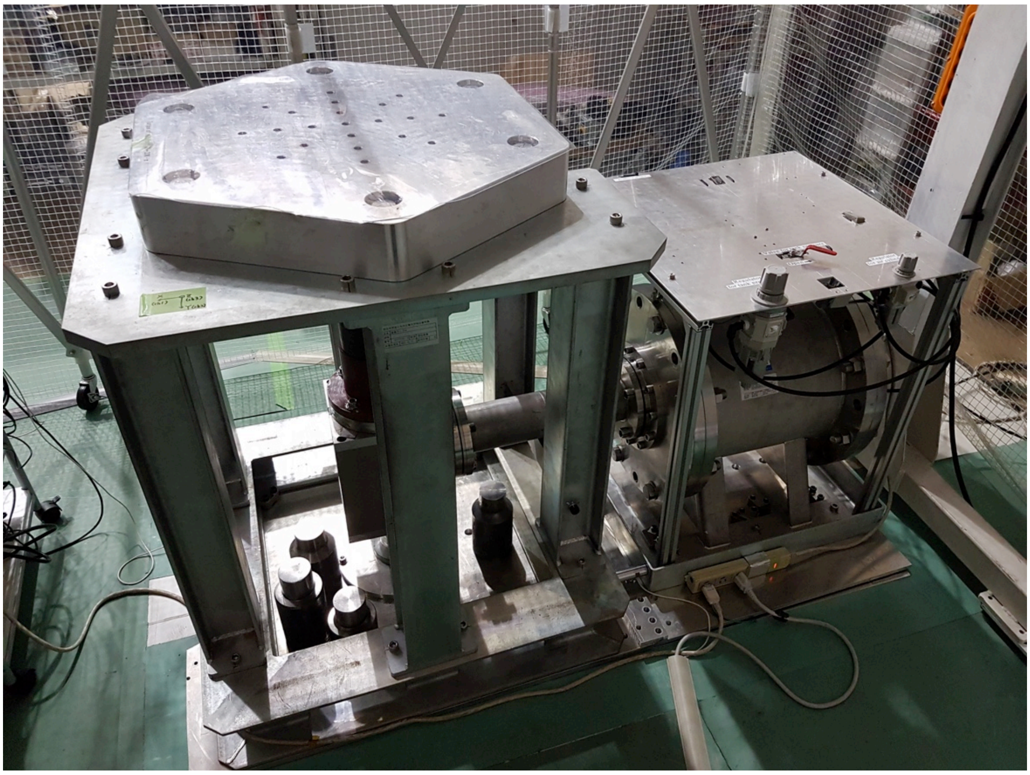

Fig. 41. Shock test equipment

The thermal test is used to verify that the satellite can withstand the temperature cycles in orbit and can function normally within the temperature range expected in orbit. If a thermal vacuum chamber is available, the thermal vacuum test is recommended, as it is more flight representative compared to a combination of thermal cycle functional test and functional test in vacuum. Either way, the satellite needs to be operated at least once in a vacuum environment to make sure that the temperature gradient inside the satellite does not cause any problems and no leakage of sealed parts such as a battery occurs. During the thermal vacuum test or the thermal cycle functional test, the cold start and hot start test should also be carried out to verify that the satellite can be turned on even in extremely cold or hot temperatures just after deployment from the POD.

The temperature range of the thermal vacuum test depends on the satellite's thermal design, its orbit, and the operational modes. The temperature range needs to be defined before the thermal vacuum test starts. One way of defining the temperature range is to look for the flight data of similar satellites flying in the same orbit. Notably, many CubeSats have already flown in the ISS orbit. The external surface of a CubeSat is covered by solar cells. Therefore, the thermal radiation properties of a CubeSat are more or less the same. If one is not sure about the accuracy of the thermal analysis, data taken from past flights are more reliable. At least the thermal analysis model should be validated by analyzing the flight conditions of previous satellites. Table 5 of ISO-19683 lists the test levels and conditions of the thermal vacuum test. If one has no clue about the temperature range in orbit, this may be a good starting point. It should be noted that the temperature is the one for internal components. If the CubeSat does not work well at this test level and these conditions, it is very likely that the satellite will not function in orbit.

Figure 42 shows a picture of a thermal vacuum chamber at Kyutech. It is big enough for up to a 3U CubeSat and is equipped with a liquid nitrogen cooling shroud. Unfortunately, there is no catalogued thermal vacuum chamber product; it is always custom made. Therefore, if one wants to buy a thermal vacuum chamber, the required specifications need to be understood very well.

Table. 14 Test level and duration of thermal vacuum test

Test	Items	Specification
Thermal vacuum	Temperature range	-15°C – +50°C
	Number of cycles	2 or more
	Operational soak duration	1 [h] or longer
	Thermal dwell	1 [h] or longer
	Tolerance limit	3°C
	Temperature ramp rate	±5°C/[min] or slower
	Chamber pressure	1.0 x 10^{-3} Pa or lower

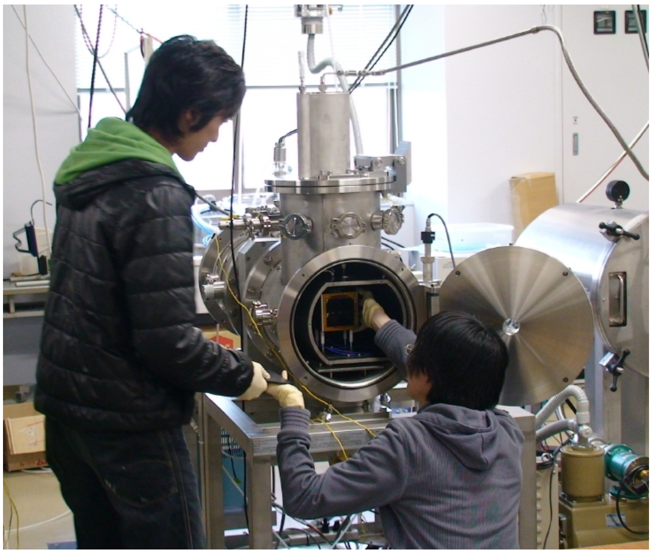

Fig. 42 Thermal vacuum test equipment

If the device must be tested for its temperature cycle only, the thermal cycle test can be used. Examples are solar panels and antennas. These tests shall be done during the development stage to verify the design and manufacturing process. Table 5 of ISO-19683 lists the test levels and conditions of the thermal cycle test. The temperature range is from -70°C to +100°C. ISO-19683 says 24 cycles or more; however, checking the test article after 10 cycles is recommended, as poorly made solar panels often show defects after a few cycles. Figure 43 shows a thermal cycle chamber at Kyutech. It is an industrial oven modified to achieve -190°C. For a -70°C requirement, however, an off-the-shelf product may be available on the market.

Fig. 43 Thermal cycle chamber at Kyutech

The long-range test verifies that communication between the satellite and the ground station has a sufficient margin in the link budget. Many communication functions are tested in an anechoic chamber avoiding external disturbance, but a long-range communication test is required for its final confirmation. In this communication test, a fully assembled satellite is moved to a remote place from the ground station. It is better to avoid obstacles to the RF signal path. A location high on a mountain is usually chosen. Even if the satellite is placed in that remote location, the distance is very small compared to the actual distance between the ground station and the satellite in orbit. Additional RF signal attenuators are installed on the ground station side or on the satellite side. Confirming the attenuation value by measurement is highly recommended, as a loose connection may drastically change the attenuation value.

Figures 44 and 45 show a schematic of a typical long-range communication test for a CubeSat when it uses the amateur UHF frequency for the uplink and downlink. In the sample case, the distance between the ground station and the satellite is around 6.3 [km], much shorter than the actual distance. A variable attenuator is installed on the ground station side to compensate for the difference in distance and increase the attenuation value to find the maximum attenuation for successful communication. The advantage of this long-range communication test is that the test configuration is very close to the actual flight conditions, except Doppler shift. This test needs a frequency license of temporary permission for the radio frequency emission on the ground.

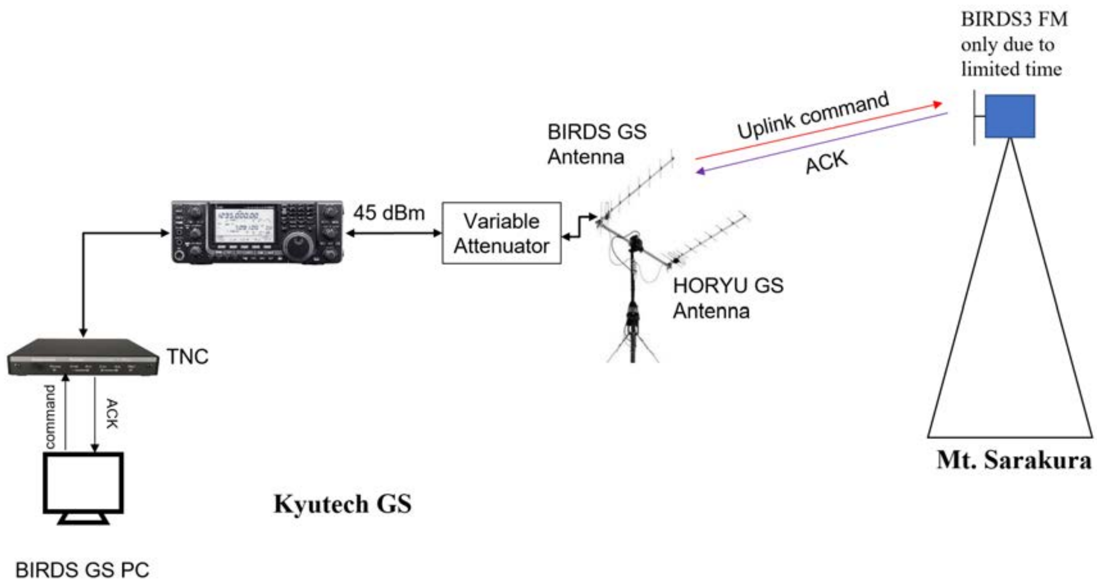

Fig. 44 Schematic of typical long-range test configuration

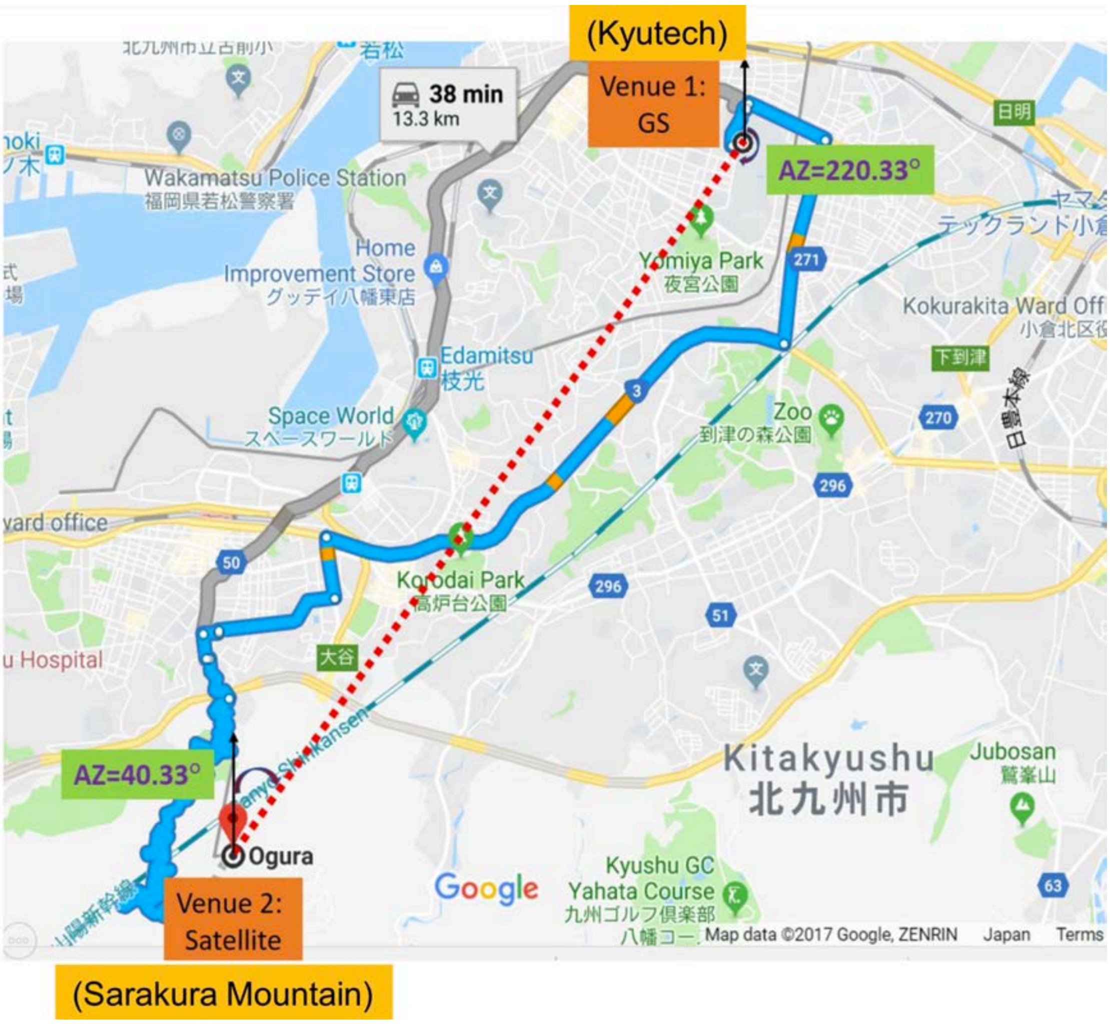

Fig. 45 Example of long-range test locations

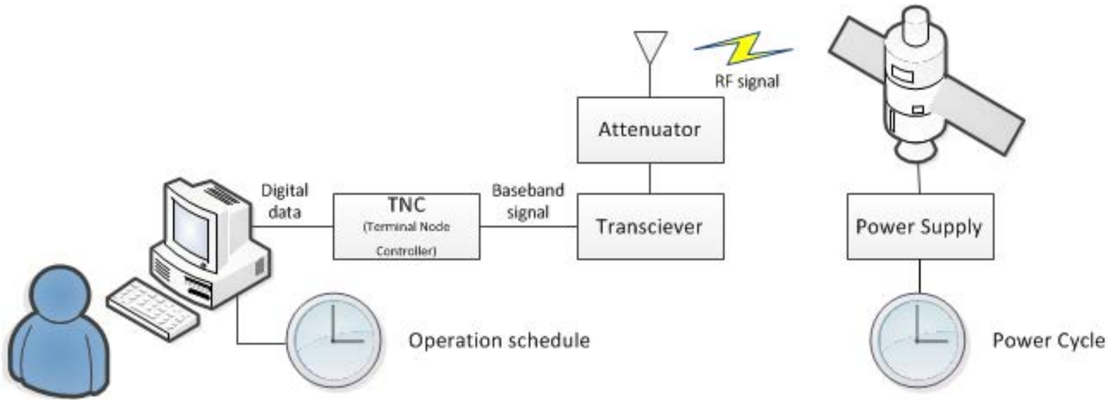

Fig. 46 Example of end-to-end test configuration

The above image shows a typical example of an end-to-end test configuration with a satellite flight model at a location close to the ground station. Because the distance is not large, an attenuator is required to reduce the RF signal power and antenna rotation control is not required. However, other operation systems are needed to keep the same actual operation configuration.

The purpose of an end-to-end test is to confirm the satellite system at the final stage with conditions very close to those of actual operation. Satellite power is controlled by a power supply with a timer function by on-off control. The on-off power control emulates the actual power generation in orbit, and its output power and time should be controlled by the orbit condition. The electrical power status should be checked to confirm its effectiveness for the power budget, and the battery voltage provides very important information. However, the satellite status cannot be checked with any monitoring line attached to the satellite. The satellite needs to be free from any external harness to avoid any conduction noise from the outside. The status should be checked by telemetry data. The operation is also done according to the operation schedule with the orbit conditions. If the satellite has LEO conditions, satellite operation is usually possible four times a day. Its operation time is also calculated with the orbit conditions, usually 5 to 15 [min]. The following table shows an example of satellite operation when the satellite uses a 500-[km] altitude Sun Synchronous Orbit (SSO). Access to the satellite is critically limited in this end-to-end test. All commands should be tested in this test. If a command is not tested in this test, it should not be used in real operation because the command safety is not guaranteed. The end-to-end test is a nice rehearsal and training opportunity for the team before real operation.

Table. 14 Example of satellite operation schedule, SSO case

Pass	AOS(JST)	LOS(JST)	Max. Elevation [deg]
1	17 Jan 2019 11:24:39	17 Jan 2019 11:32:46	8
2	17 Jan 2019 20:24:21	17 Jan 2019 20:33:41	12
3	17 Jan 2019 21:56:46	17 Jan 2019 22:07:55	32
4	18 Jan 2019 09:28:56	18 Jan 2019 09:39:38	24
5	18 Jan 2019 11:02:50	18 Jan 2019 11:12:35	15
6	18 Jan 2019 20:04:23	18 Jan 2019 20:11:44	6
7	18 Jan 2019 21:35:22	18 Jan 2019 21:46:51	65

12. Safety

Every satellite, regardless of its size, mission, value, capability or any other nature, must comply with safety requirements [12-1]. This statement applies even to a 1U or smaller CubeSat. CubeSats are good examples of lean satellites that utilize non-traditional, risk-taking development and management approaches to achieve a low cost and fast delivery [12-2]. This lean satellite development philosophy has been adopted by almost all university CubeSat projects and by the CubeSat projects in non-space-faring nations, especially when they are making their nation's first satellite, because their resources are very limited.

System safety begins with identifying hazards. A hazard is "a state or a set of conditions, internal or external to a system, that has the potential to cause harm" [12-3]. The risk of each hazard is evaluated by the product of the likelihood of occurrence and the seriousness of the consequences. Hazards are divided into those common to all satellites (standard hazards) and those specific to individual satellites (unique hazards). Hazards need to be controlled by reducing the risk to a tolerable level. Safety requirements are given in order to control hazards. In other words, if part of a satellite design is not regarded as a hazard item, there is no need to do anything from a safety point of view. If it is regarded as a hazard item, the satellite developer needs to show how they will control the hazard and verify that the control is properly applied to the flight model. If there is a misunderstanding between the satellite developer and the launcher about whether an item is a hazard or not, satellite delivery is delayed until the issue is solved, causing a significant delay in the satellite project. For the case of lean satellites relying on a piggy-back with a particular launch vehicle, there is even a possibility of the worst case where a dummy mass is launched instead of the satellite. There have been two such cases in Japan since 2016.

Even if a satellite is confined to a POD, the satellite still needs to comply with the safety requirements specific to each launch vehicle. Nowadays, CubeSats are often built by combining COTS components purchased on the market (Internet). The components do not satisfy the safety requirements for ISS release. Even for an ISS release, interpretation of the safety requirements differs depending on which country is asked for the launch. Modifying COTS components is risky and time-consuming. The component manufacturers often refuse to modify products, which is understandable considering the cost and time necessary to modify the product is often very expensive. Therefore, the satellite developers often have to modify at their own risk, which requires additional verification to convince the launcher that the modification is safe. The satellite developers need to consider how to adapt their design to various safety requirements and how to verify their compliance from the early stages of satellite development, even before they decide on a launch option.

The major differences for ISS safety requirements compared with rocket launches are the following:

1. For ISS release, there is no requirement preventing ignition in an explosive hazardous atmosphere, which is required in most rocket launch cases, because CubeSats are launched inside a package. If that requirement exists, suppression of chattering for mechanical switches is required and three inhibits against chattering is required.
2. Electromagnetic radiation, i.e., radio emission, is allowed only 30 [min] after deployment. Inspection of a timer function is required.
3. Material flammability must be verified by the Material Identification Usage List (MIUL).
4. Material off-gassing must be verified by the MIUL.

5. If a satellite has shatterable materials, such as solar cell coverglasses, lenses, etc., exposed, then their integrity must be confirmed after a vibration test.

Points 3 to 5 are unique to the ISS, because a satellite will be brought into a pressurized module at the ISS. Other key safety related items are listed in Table 15.

Table 15. Key safety-related items for ISS release

Safety item	Requirement
Structure verification	• Structural requirement (main structure, rail strength, stiffness) is **verified by structural analysis only**
Battery and EPS	• Need to characterize battery cells before/after **each environment test** • Even if the battery has UL certification, testing battery protection functions is **required**
Separation switch	• **No need** to verify chattering because of no explosive environment • Need to verify the inhibit function
RF emission	• During ground operation, the hazard level varies • RF emission strength is evaluated at **1 [m]** from the satellite
Antenna deployment in POD	• If the surface thickness in contact with the POD inner wall is more than 1 [mm], it is not a hazard • If the satellite is demonstrated to not get stuck inside the POD due to accidental deployment, **fixing by one string** is acceptable • If demonstration is not possible, need more than two fixations **(two strings)** for one deployment

There are significant differences between a rocket launch and ISS release, which often make switching between the two launch options at the last minute very difficult. Only a random vibration test is required for ISS release. Among the items listed in Table 15, battery and antenna deployment are the most critical items that may significantly affect the satellite development schedule. Those two items are often procured from the market and are difficult to modify to comply with safety requirements.

For antenna deployment, many CubeSats use a burning wire mechanism, where string (fishing line is the most popular) is burned by a nichrome wire whose activation is controlled either by a timer circuit or a software timer. Most CubeSats have a deployable UHF/VHF antenna. Accidental deployment in a POD may lead to a situation where the satellite is stuck inside the POD. For ISS release, the POD will be retrieved, and it enters the ISS again from the airlock. If the satellite remains inside the POD, it may pose a safety risk to an astronaut or the ISS. Therefore, a satellite is expected not to remain inside a POD. There is another concern that the satellite may be released in the wrong direction and hit the ISS if the satellite is released from the POD with its antenna deployed.

Because the antenna deployment mechanism is one of the critical items that determine the fate of the satellite, CubeSat developers often buy deployable antennas from known manufacturers. Mostly, those antennas are held by only one string. It is extremely difficult to modify the commercial product to have a second string. Therefore, it is recommended to design the satellite so that antenna deployment inside a POD does not become a hazard. The easiest thing is to make the antenna more than 1 [mm] thick. The second is to design the satellite in a way that it is deployed even if the antenna is deployed inside the POD. One idea is to confine the antennas to a +/- Y or -X surface because the access window cover is in a +X surface only.

The battery safety requirements impose a significant amount of verification activities. Individual battery cells need to be evaluated for whether they can survive vacuum exposure and vibration. Cell characteristics such as capacity, over-circuit voltage and mass usually need to be measured by going through one cycle of charging and discharging. The measurement is required before or after each environment test, such as those for vacuum and vibration.

CubeSat developers procure batteries from the market. They are either single cells or a battery pack that is often integrated into the electrical power system. When the developers buy single cells, it is not difficult to comply with safety requirements as they can test individual cells and design the battery pack by themselves. But if battery packs are procured, it is impossible to test the individual cells. The satellite developer asks the vendor for information regarding the test results of individual cells. The vendor can provide that information for the cells used in the battery pack purchased by the customer, but the information is about the other cells of the same lot. Therefore, if the launcher asks for information about how the cells are screened, usually it is very difficult to obtain. Then, the safety verification reaches a standstill, starting a very long chain of email exchanges. This does not mean that buying individual cells and having the screening done by the satellite developers themselves is better. It is difficult to procure Li-ion batteries through the same channel officially acknowledged by the cell manufacturer. Therefore, it is difficult to obtain information about the battery protection circuit, which is often required. Finding a battery vendor who can supply that information is also a challenge.

Figure 47 shows the BIRDS-2EPS circuit. BIRDS-2 employed two mechanical separation switches (Dep. SW) and one RBF pin as inhibits. They control the MOSFET switches (Sep. SW). The current from the battery to the load is blocked by Sep. SW2, Sep. SW3 and Sep. SW4. The current from the solar array to the load is blocked by Sep. SW1, Sep. SW2, Sep. SW3 and Sep. SW4. Because Sep. SW1 and Sep. SW2 are controlled by the same RBF pin, the two are regarded as one inhibit. Therefore, the current from the solar array to the load has only three inhibits. In addition to an accidental power-on of the satellite, overcharging and overdischarging of the battery during ground handling and the launch phase need to be prevented. In Fig. 47, the inhibits against those two are also shown. They are made by a combination of protection or regulation circuits and switches.

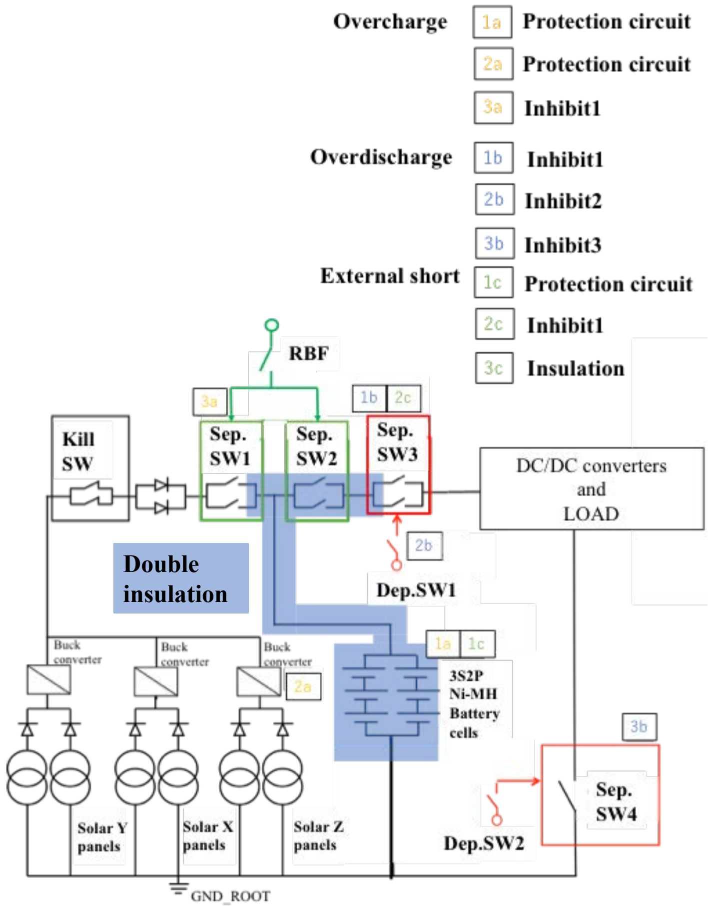

Fig. 47. BIRDS-2 EPS circuit diagram

External short-circuit of the battery is categorized as a catastrophic hazard which should be prevented by three inhibits. Proper insulation and two devices preventing the short circuit (which can be substituted by inhibit switches) are necessary. In the external short-circuit, the short-circuit itself is regarded as one fault. Therefore, two more inhibits become necessary to be two-fault tolerant.

In BIRDS-2, as the short-circuit protection device, Positive Temperature Coefficient (PTC) circuits inside the battery and Sep. SW2 were counted as two inhibits. When a short-circuit occurs between the battery and the inhibits, however, only the PTC works as a protection. Therefore, one more protection mechanism became necessary and double insulation was added between the battery and Sep. SW3. The reason the double insulation was extended to Sep. SW3 was that we needed to consider a case where a MOSFET used in Sep. SW2 suffers a short-circuit. If Sep. SW2 was made of a mechanical switch, double insulation would be necessary only up to Sep. SW2. Figure 48 indicates where the double insulation was added.

Insulation is counted as one inhibit when the distance between two points is more than 1 [mm]. To have double-insulation, we need to add one more layer of insulation. In BIRDS-2, a harness welded to the battery was connected to the PCB via a connector. The cable jacket between the battery and the connector was covered by Kapton tape. On the PCB, the HOT and GND lines were separated by a distance of more than 1 [mm]. Moreover, they were laid down on separate layers with an insulator layer between them. The terminals on the PCB were separated by more than 1 [mm]. Double insulation was achieved by covering the PCB surface with Kapton tape, as shown in Fig. 48.

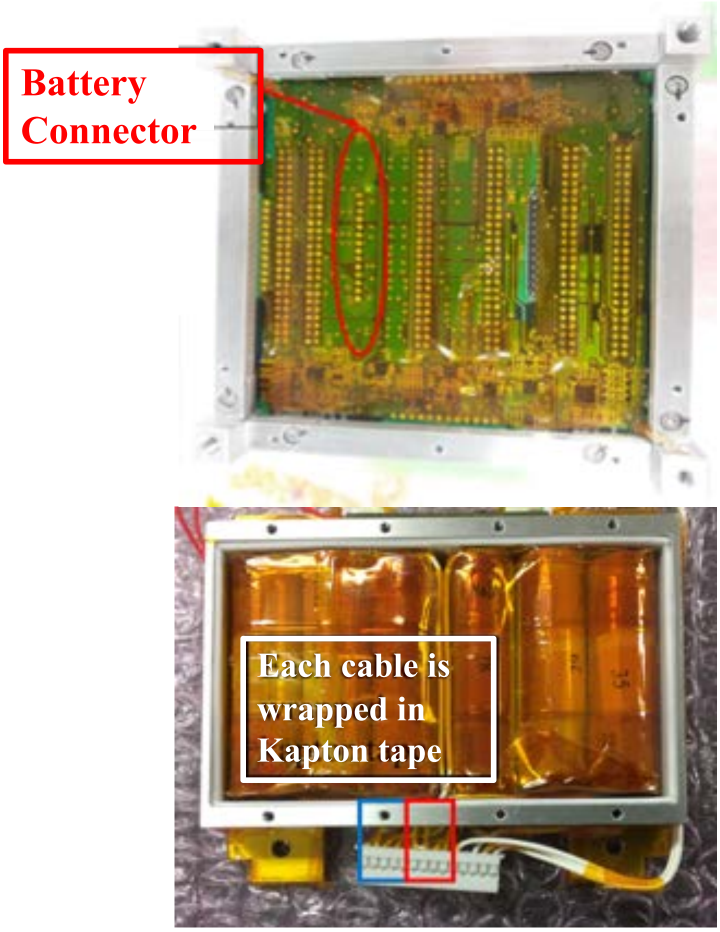

Fig. 48. Double insulation in BIRDS-2 EPS (upper: PCB; lower: battery box)

In addition to an external short-circuit, an internal short-circuit within the battery itself needs to be prevented. Basically, we need to measure the characteristics of each battery cell before and after each environment test and confirm that there is no significant change.

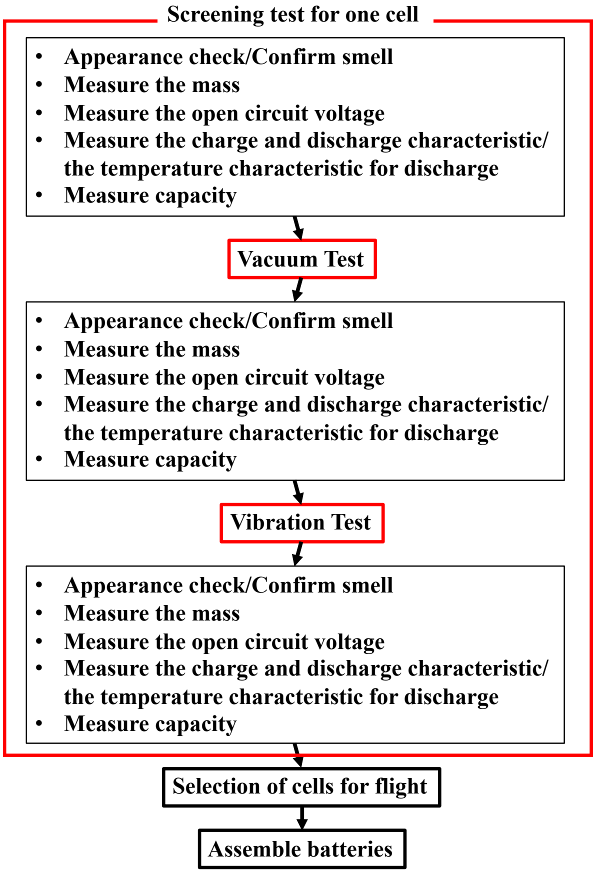

Fig. 49. Flow of battery screening for BIRDS-2

BIRDS-2 used a NiMH battery (Eneloop, HR-3UPT). To verify the individual cells, we followed the flow in Fig. 49. After the first characteristics measurement (open voltage, battery capacity, mass, visual inspection and odor), the batteries were exposed to $1x10^{-3}$ [Pa] vacuum for 6 [h]. Then the characteristic measurement was done again to verify the change of open circuit voltage (less than 0.1%), the battery capacity (less than 5%), and the mass (less than 0.1%) to be within an acceptable range. Then, a random vibration of 6.1 [Grms] was applied for 1 [min] to each axis. Cells whose characteristics (open circuit voltage, capacity and mass) change was within the acceptable range were selected as flight batteries and assembled into a battery pack. The storage temperature rating of the battery cells used for BIRDS-2 was between 0 and +40°C. The temperature requirement of the ISS was between -15 and +60°C. In order to show that the batteries can survive in this extended temperature range, a cell from the same lot of the flight batteries was exposed to the temperature range for 90 [min] in a thermal chamber. Before and after the temperature test, the charging and discharging characteristics were measured to verify those did not change.

REFERENCE

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[12-2] M. Cho and F. Graziani, ed., "Definition and Requirements of Small Satellites Seeking Low-Cost and Fast-Delivery", International Academy of Astronautics, February 2017.
[12-3] NASA System Safety Handbook, Volume 1, "System Safety Framework and Concepts for Implementation", NASA/SP-2010-580, November 2011.

13. Cross-cultural and capacity building aspects

Although an international capacity building project such as BIRDS can be structured in several possible ways, we have structured our projects following a special pattern due to particular constraints. These constraints are outlined below. They establish the structure of the two-year BIRDS education system.

First of all, we are able to bundle several BIRDS stakeholders into one project cycle (e.g., five stakeholders were involved in the BIRDS-1 project, 2015–2017) but to make it financially practical and viable, one stakeholder must be responsible for bearing the cost of one satellite; there can be no sharing of costs between stakeholders because this gets too complicated. Hence, a single stakeholder and Kyutech sign a contract (called a “Cooperative Research Agreement”, (CRA)) that spells out the obligations for each party. The BIRDS CRA states the sum of money the stakeholder must pay to Kyutech to cover the cost of the hardware of the satellite and the cost of launching it into space using an agreed method. The CRA goes into some detail of what Kyutech will provide in terms of advice, consultancy, training, services, supervision, educational support, and other forms of information needed to implement the project from start through to completion. The CRA also spells out all the obligations for the stakeholder. For example, there are regulatory tasks that the stakeholder must perform (registration of the satellite with the UN authorities in Vienna).

Fig. 50. ANUC of Ghana was the first BIRDS stakeholder to sign the CRA; this signing ceremony took place at Kyutech on 6 Jan. 2016

From experience, the stakeholder usually represents one nation. For example, in the BIRDS-1 Project, a private university by the name of All Nations University College represented the country of Ghana. This university signed the BIRDS-1 CRA with Kyutech for the implementation of Ghana’s BIRDS-1 satellite—which was Ghana’s first satellite into orbit around the earth (see Fig. 50). Accordingly, the stakeholder normally selects the students who build its satellite at the facilities of Kyutech. The stakeholder creates the satellite-building team, which is usually two or three students. These students are usually citizens of the stakeholder’s nation.

Another significant constraint to consider is *time*. The BIRDS paradigm (the way of doing things) is unique. Around the world, most universities are not super strict with satellite project timelines because it is assumed that delays cannot be avoided. However, BIRDS is extremely strict. This is where and why we are unique. We do not allow project delays (schedule slips) for the following two reasons:

1. Most of the students are master’s degree program students (the others are Phd students). The Kyutech master’s degree program is 24 months, strictly. BIRDS

students must finish their degree requirements and their satellite project (including orbital flight time) within this absolute constraint. When they graduate from Kyutech, their satellite must be operating in space; this is an important goal. Therefore, for BIRDS projects, satellites are always designed, built, tested, launched, and operated *on time*. If their satellite is not in space, there is no one else around to finish the project for them. Moreover, their stakeholder fully paid for the satellite—so it must be completed and launched because it is a contractual agreement.

2. BIRDS satellites become payloads to the ISS. Kyutech works with JAXA to arrange a suitable launch to the ISS using a JAXA rocket or some third-party rocket, such as a SpaceX rocket. There are several rocket options for a ride to the ISS; the exact rocket to be used is established case by case each time. In any case, this "launch arrangement" with JAXA is of course a signed contract. Once signed, the members of the BIRDS project are committed to delivery on time because the contracted rocket often has several signed customers—the rocket cannot wait for a tardy customer. If a BIRDS satellite misses its launch, then the next available rocket will not be suitable for the project. The next launch will be too late. In conclusion, BIRDS satellites cannot be delivered late. This is one defining trait of the BIRDS paradigm. It creates a lot of pressure on the participating students, but this situation is not avoidable because of the factors outlined above.

Another major constraint to consider is that *BIRDS is mainly capacity building*—it is not mainly an application project nor is it a technology demonstration project. Moreover, the members of BIRDS (aside from academic supervisors of the students) do not have any satellite development experience. *They are purely beginners.* As such, they make many mistakes while designing, building, and testing, their spacecraft. This is effective education because you learn a lot from making mistakes. But the hard part is that time is lost with the occurrence of errors. The lost time must be recovered as the satellite must be shipped on time. This creates a great deal of stress for all members involved. Your own work can fall behind because of a disaster that occurred somewhere else in the project. Tempers can flare and friction can develop among the team members.

Fig. 51. BIRDS team cooking contest

To improve team performance and harmony, we have a lot of social events. Figure 51 shows a BIRDS-1 cooking contest held in May 2016. The competing teams were from Ghana, Nigeria, Mongolia, Japan, and Bangladesh. The winner was the Bangladeshi team.

Another huge constraint is the language barrier. It should be noted that nearly no one is using his or her mother tongue in the BIRDS environment. Kyutech is a Japanese university with staff and students who use Japanese. We are located in Japan. Most of the hardware vendors are companies in Japan; they speak Japanese too. But most BIRDS students are from overseas—and they do not speak Japanese. So daily communication becomes a difficult "cross-cultural" situation that has no easy solution. Many Japanese students volunteer to be translators for the overseas students. It should be mentioned that Japanese students who do volunteer for translation tasks end up becoming much more confident with their command of English; it is a huge learning plus for them in the long term. Some overseas students also make the effort to learn Japanese; but two years is not really enough time to master Japanese.

A major cross-cultural result of BIRDS is the propagation of information. When overseas news organizations discover that their nation is building its first satellite, they arrange for many interviews with their nation's students via Skype, telephone, etc. Hence, information is collected and then distributed within their homelands.

There are challenges and constraints with the BIRDS education program. Constraints come in the form of the following: (1) budget, (2) time, (3) technical skills of the students, and (4) interpersonal communication skills (language barriers). The challenge for the Kyutech faculty is to help the students overcome these big hurdles. Teaching this effectively is crucial because if not successful then the BIRDS graduates will not be able to return to their home nations and repeat the process for the second satellite on home turf. After all, the real meaningful test is not building the first satellite at Kyutech under supervision; *the real meaningful test is building the second satellite on home turf without Kyutech supervision*. BIRDS can be claimed to be "a sustainable enterprise" if BIRDS graduates continue to design, build, and test satellites on their home turf using domestic ideas and resources. For Kyutech, this sustainability is a highly important strategic goal. To attain it requires much imagination.

BIRDS is a constellation of satellites. This is an interesting fact. It means that each satellite should have the same design. So even if we have Country A, Country B, and Country C involved as primary stakeholders, their satellites will be the same. Hence, the first step in development is for all the participants (stakeholders and their students) to sit down for a series of meetings to establish what the satellite system should do. This is not an easy process. Everyone has their own ideas. Each party is investing cash in the project. Each party has a say. *However, the process to determine what the constellation should perform for the stakeholders is an extremely important educational experience for all concerned.* It forces each person to think about the constraints that were outlined above: total budget, total development time, and the skill levels of the students. If the missions are too easy, then external observers will scoff and stakeholders will object. If the missions are too difficult, the students will suffer later on because they have to implement the missions in hardware and in software. A balance must be struck.

<u>BIRDS International Workshops</u>

Making BIRDS a "sustainable educational program" is a challenging proposition. In the world of university consortiums, projects come and go. There is project cohesion until the project is finished, but after that dispersal usually occurs. This is a loss of resources and opportunities. At an early stage, the BIRDS Project realized that it should conduct an annual event to bring together all BIRDS stakeholders for brainstorming to discuss results, problems, solutions, future plans, and new areas of collaboration. Accordingly, the following workshops (involving BIRDS stakeholders) have been conducted so far:

2016 - 1st BIRDS International Workshop, Kyutech, Japan
2017 - 2nd BIRDS International Workshop, ANUC, Ghana
2018 - 3rd BIRDS International Workshop, NUM, Mongolia, and next,
2019 - 4th BIRDS International Workshop, BRAC, Bangladesh

Fig. 52. Group photo of the *3rd BIRDS International Workshop* held in Mongolia in 2018. It brought together various BIRDS stakeholders for 3 days of meetings and socializing.

The aforementioned workshops have been documented in the following issues of the *BIRDS Project Newsletter:*

1st BIRDS International Workshop (Kyutech, Japan)
Pages 4–18, Issue **No. 6**, BIRDS Project Newsletter

2nd BIRDS International Workshop (ANUC, Ghana)
Pages 58–99, Issue **No. 23**, BIRDS Project Newsletter

3rd BIRDS International Workshop (NUM, Mongolia)
Pages 104–149, Issue **No. 31**, BIRDS Project Newsletter

All issues can be accessed from this website:
http://birds1.birds-project.com/newsletter.html

The primary function of this newsletter is to keep all stakeholders informed about the BIRDS Project. It is issued once a month as a PowerPoint document in pdf. It is archived at the website mentioned above. Each month, many things happen because of the activities of BIRDS-1, BIRDS-2, BIRDS-3, and BIRDS-4. All of these things are summarized and presented in the newsletter. This documentation also serves as a permanent record of all project achievements, events and milestones. This information is also useful for attracting future BIRDS stakeholders (e.g., BIRDS-5).

Moreover, this newsletter is also useful for informing a wider audience. Academic institutions, news organizations, private companies, government agencies, NGOs, United Nation agencies, and so on, all over the world take interest in how BIRDS develops.

The way to make BIRDS a sustainable educational program is to ensure that graduates continue to work on CubeSats after they leave Kyutech. This means we need to help these countries establish national space programs. For example, the countries can (1) create a space agency, (2) create a new space laboratory inside a national university, and (3) create an NPO for space activities.

One interesting development is the sprouting of BIRDS-like programs inside countries. In the Philippines, there is a program called “BIRDS-2S.” Different domestic universities join this UPD-led program and build their own CubeSat—in a manner similar to the Kyutech BIRDS program. A similar program is starting inside Malaysia; it is being led by UiTM.

A major contribution of the BIRDS paradigm is that it has shown to the developing world (Asia, Africa, Latin America) that designing, building, and operating CubeSats as part of a master degree program in space engineering is feasible. Building with one’s hands is important if you want to learn how to build satellites. Reading books will not be sufficient for that know-how.

14. Implementation as a sustainable educational program

The BIRDS projects described in the present book require significant amounts of financial, human and infrastructure resources. The financial contribution of each BIRDS partner (those who will own the satellite) has supported the program. Five faculty and research staff members are involved in the projects; though none of them spend 100% of their time on them, the do commit a significant portion of their time to them. The state-of-the-art CubeSat research/development/testing facility at Kyutech, especially the Centre for Nanosatellite testing, has contributed a lot to making each project finish in two years. The question is now how do we sustain ourselves?

We aim to make an educational satellite project like the BIRDS project doable and sustainable by other universities without heavy investment of faculty resources or budget. If the satellite project is a one-time project, it is rather easy for many universities to do because the university management will most likely support the project, considering the return gained in terms of publicity. Faculty members are also willing to help, if it is only one time. However, if we plan to implement a satellite project as a routine educational project, we need to find a way to finance it and reduce faculty involvement.

To offer the satellite project as a part of an educational curriculum, however, the following two points are necessary: 1. The project finishes on time. The biggest unknown in the satellite project schedule is launch. Therefore, securing a slot for ISS release by paying a fee is the best way. It guarantees a launch opportunity once every three months. 2. The students need to be graded. Therefore, involvement of faculty members, even at a minimum level, is essential. At the same time, we need to reduce the burden on the faculty members.

In terms of financing, two things must be done in parallel: Reduce the project cost and find external funding. First of all, because it is an educational satellite, the satellite should be a 1U CubeSat and the cheapest launch method should be targeted. Trying for a free launch is not recommended, though, because free launch slots can be delayed for reasons on the launcher side. Currently, the ISS release is the cheapest way to launch a CubeSat. Using standard satellite bus components not only saves time but also money, because we do not have to spend money and time on in-house development. Finding external funding may be difficult, but an opportunity to do experiments in orbit may be attractive to some parties outside the university—those who are not interested in making a satellite but do want data. If the university sets up a system to call for sponsorship from industry partners, a constant revenue stream from industry partners may financially support part of the project.

In order to reduce faculty involvement, making knowledge transfer between student generations systematic may help. In the BIRDS-3 and BIRDS-4 projects, we hired a teaching assistant from the members of the former generation, i.e., BIRDS-1 and BIRDS-2. They were a great help to the students who are beginners in satellite making. In typical Japanese engineering universities, one student spends their time in non-lecturing activity for three years, one year in senior undergraduate and two years in the master's program. If one generation of satellite project finishes in two years, the students who worked on the project can serve as TAs during their third years. To do so, we need to have one satellite project start every year.

If we can keep the total cost (hardware, launch, operation) of one satellite project to less than 8~10M JPY, where 50% is covered by external funding and faculty involvement is equivalent to 1/2 to 1 full-time person, the project can be sustainable.

15. Conclusion

There is increasing demand for small satellites, especially CubeSats for educational capacity building projects. This textbook introduced a standard CubeSat bus system in Chapter 4 for the electrical design. The standard bus has been developed to support BIRDS projects. It is a very simple bus system for quick training and easy development by its simple design and unified device selection. Its power system has been improved to solve issues encountered by previous BIRDS generations, and provides higher efficiency. The data-handling system has been designed to support beginners who have no experience with CubeSat development.

The effectiveness of BIRDS BUS has been verified with the actual BIRDS-3 CubeSat development work. Three BIRDS-3 CubeSats were launched to the ISS in April 2019. Using this standard BIRDS BUS, the development time of BIRDS-3 was much shorter than previous BIRDS-1 and BIRDS-2generations, and the schedule management has been simplified. Besides the time saving of project, the simple and standardized bus system is more reliable with quick training, and frees up resources for the mission system of BIRDS-3 and other technical issues. BIRDS-3 was deployed from ISS in June 2019. For a nearly one year since then, the three satellites are carrying out missions without having any anomaly in orbit. BIRDS-4 started in October 2018, and reused the exact same BIRDS BUS for its design. The BIRDS BUS is not a universal standard for a CubeSat. It has a very specific target as an educational CubeSat bus for fast delivery for an annual project. It can, however, also support many other educational CubeSat projects because it has scalability up to 3U and has compatibility with various launch services without any design modifications.

This textbook presents other basic CubeSat system information to help beginners with CubeSat projects. We tried to cover the overall CubeSat system, not just satellite development. Actually, CubeSat development does not mean building the CubeSat itself; the project requires a ground segment to operate the satellite, and a data analysis segment to extract valuable information from the mission data. And CubeSat projects involve other important aspects, such as satellite operation, frequency license acquisition, and so on.

It is challenging to make a satellite program sustainable as part of a regular educational curriculum. There is a way, however, by properly designing the program structure, to make the satellite project feasible for any ordinary university.