KiboCUBE Academy

Lecture 21

Lessons Learned of CubeSat Missions

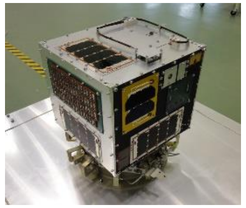
Kyushu Institute of Technology

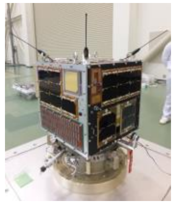
Laboratory of Lean Satellite Enterprises and In-Orbit Experiments

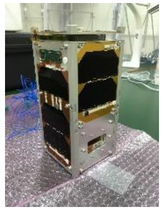
Professor Ph.D. Mengu Cho

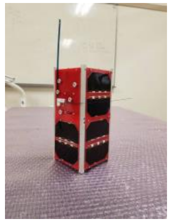
This lecture is NOT specifically about KiboCUBE and covers GENERAL engineering topics of space development and utilization for CubeSats.
The specific information and requirements for applying to KiboCUBE can be found at:
https://www.unoosa.org/oosa/en/ourwork/psa/hsti/kibocube.html

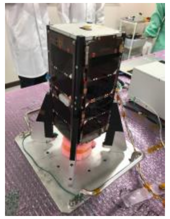
0. Lecturer introduction











Mengu Cho, Ph.D.

(*since 2018)
(**since 2020)

Position:

2004 - Professor, Department of Space Systems Engineering*
Director, Laboratory of Lean Satellite Enterprises and In-Orbit Experiments **
Kyushu Institute of Technology, Japan

2021 – Visiting Researcher, Chiba Institute of Technology, Japan

2014 - Visiting Professor, Nanyang Technological University, Singapore

2013 - Coordinator, Nations/Japan Long-term Fellowship Programme, Post-graduate study on Nano-Satellite Technologies (PNST)

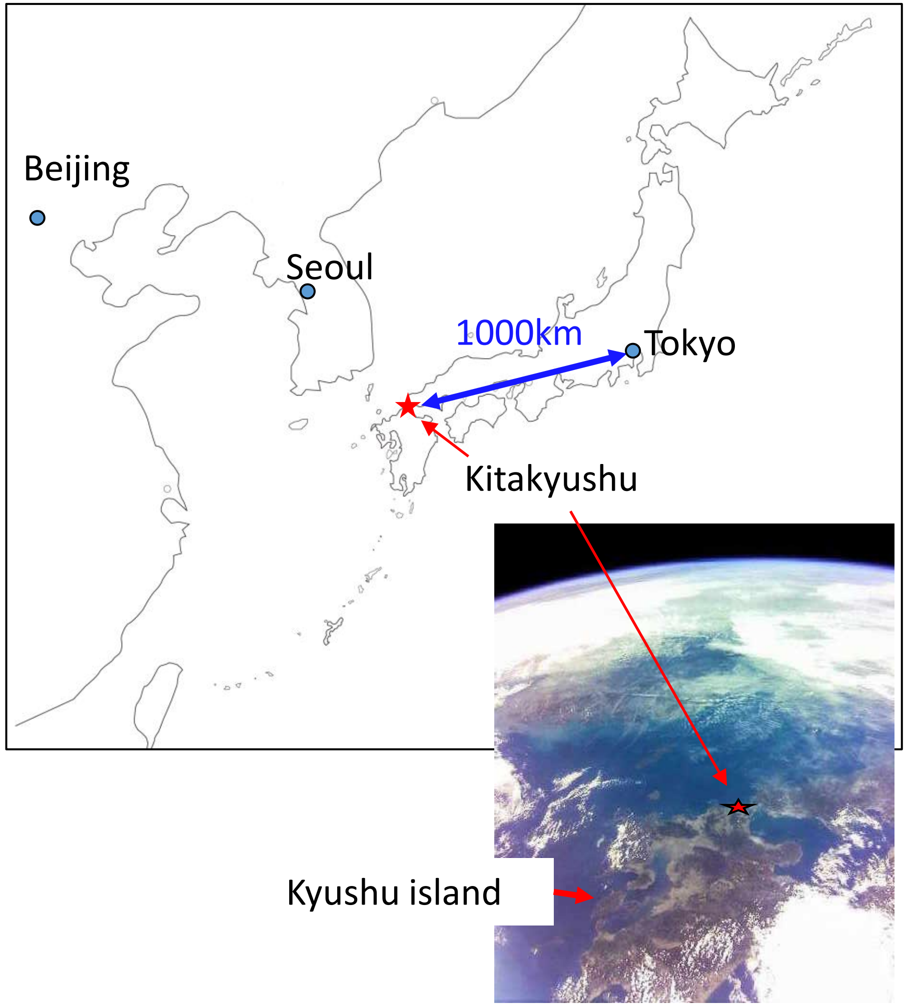
Research Topics:

Lean Satellite, Spacecraft Environment Interaction

0. Lecturer introduction

0.2 Kyushu Institute of Technology (Kyutech)

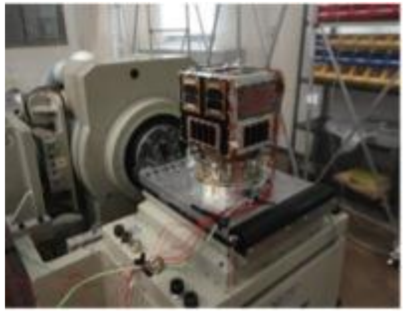
- A national university founded in 1909
  - 4,200 Undergraduate students
  - 1,300 Graduate students
  - 360 Faculty members
  - Engineering, Computer science, Life-science
- Located in the Kitakyushu region
  - Population of more than 1million



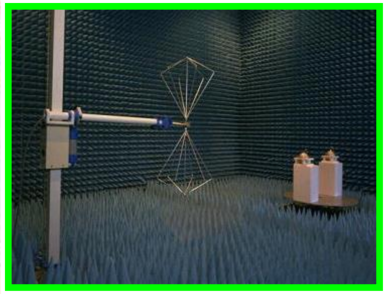
0. Introduction to Kyutech

0.3 Center for Nanosatellite Testing

To be capable of doing all the tests for a satellite up to 50cm, 50kg



Vibration



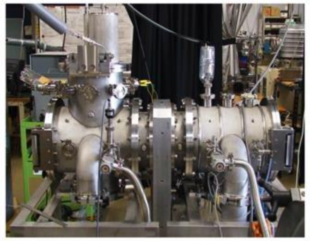
EMC & Antenna pattern

Pressure & Leak

Thermal vacuum

Assembly & Integration

α&ε measurement



Thermal vacuum

Thermal cycle

Shock

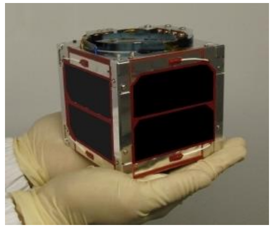
Outgas
(ASTM E595)

Tested more than 70 satellites since 2010 including satellites from overseas (e.g. Egypt, Costa Rica, Singapore, Malaysia, Vietnam, Thailand, etc.)

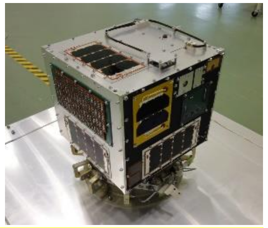
Space Development and Utilization Award (JAXA president award), 2022

0. Introduction to Kyutech

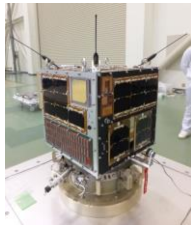
0.4 Kyutech Satellite Heritage



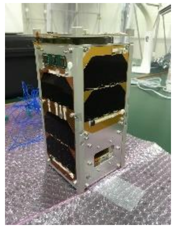
HORYU-1 (1U)
2006-2010
Not launched



HORYU-II
2010-2012
Launch 2012/5/18



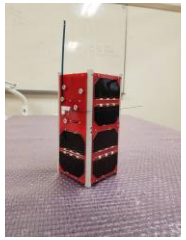
HORYU-IV
2013-2016
Launch 2016/02/17



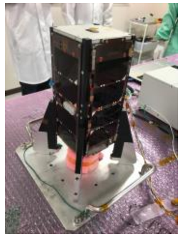
AOBA VELOX-III
2014-2016
ISS Release 2017/01/19

BIRDS-I constellation
2015-2017
ISS release 2017/07/07

BIRDS-II constellation
2016-2018
ISS release 2018/08/10



SPATIUM-I
2016-2018
ISS release 2018/10/06



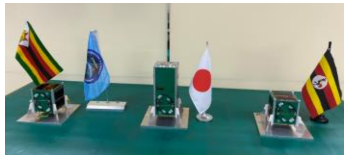
AOBA VELOX-IV
2016-2018
Launched 2019/01/18

BIRDS-III constellation
2017-2019
ISS release 2019/04/18

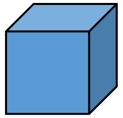
BIRDS-IV constellation
2018-2020
ISS release 2021/03/14

KITSUNE
2019-2021
ISS release 2022/03/24

FUTABA
2018~2021
Launch, 2022



BIRDS-5J, -5Z, -5U
Launch, 2022



MITSUBA
2022

Satellite name
Satellite development period
Launch/ISS release date

World's No.1 academic small satellite operator since 2018

(Bryce Space Technology report on SmallSats by the Numbers)

Contents

1. Introduction
2. Lessons Learned and Root Causes
3. Mission Assurance
4. Conclusion

1. Introduction

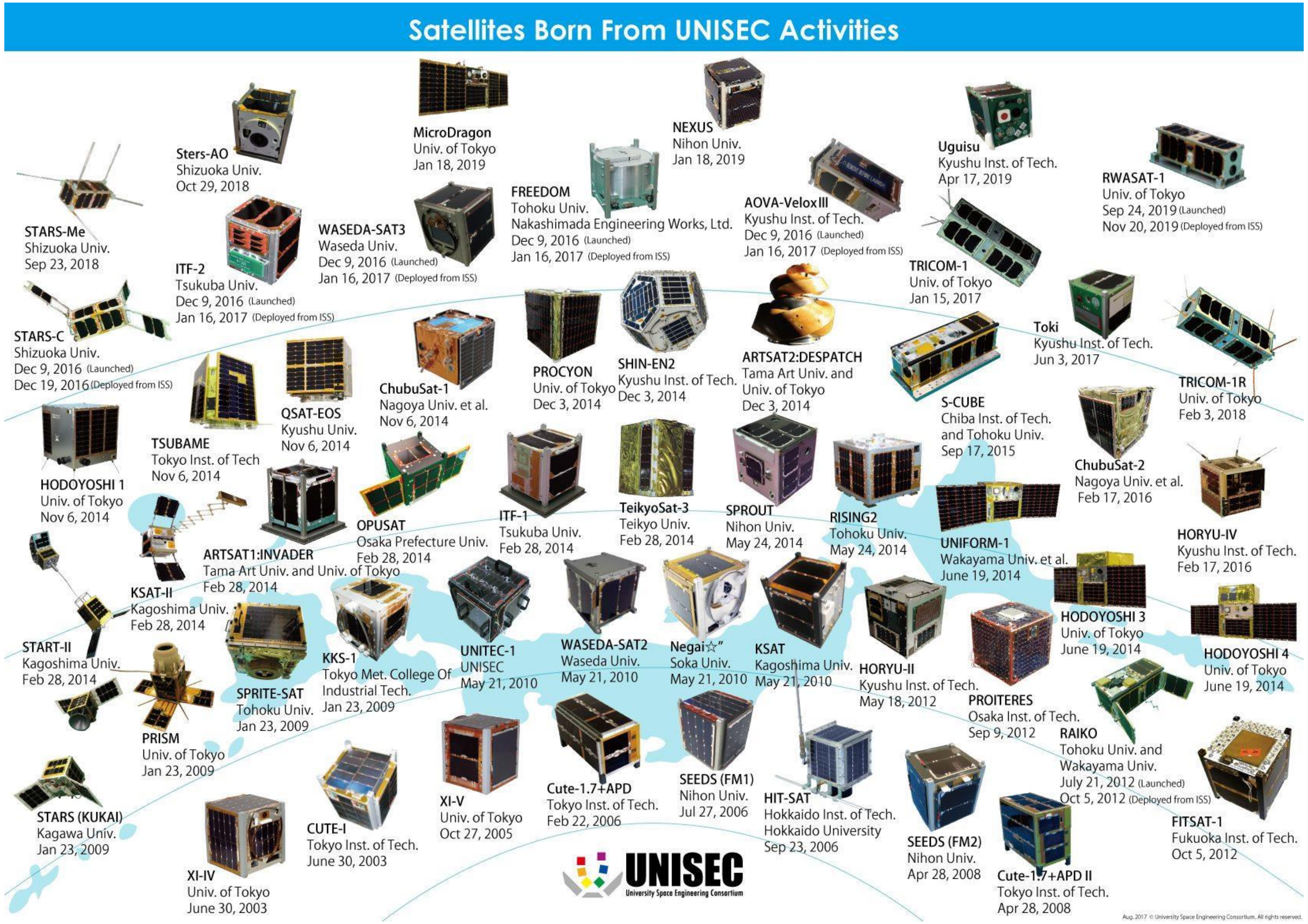
1. Introduction

1.1 University satellite projects in Japan

- UNISEC-Japan consists of
  - 36 Universities and research institutions
  - 49 organizations
  - 636 student members, and
  - 262 individual and 19 cooperate members, and
  - alumni members (based on Apr. 13, 2021).
- UNISEC-Japan members maintain cooperative relationships in conducting practical space development and utilization.

1. Introduction

1.1 University satellite projects in Japan



1. Introduction

1.2 UNISEC’s Lean Satellite Mission Assurance Activities

- In 2020, members of UNISEC-Japan utilized the time that became available due to the pandemic in
  - Remote sessions on lessons learned from university satellite projects in UNISEC (University Space Engineering Consortium) JAPAN in 2020
  - Survey on the lessons learned of mission assurance
    - Sponsored by JAXA
  - Report (439 pages!) on
    - Analysis about the success and failure cases of domestic micro and nano-satellite projects and their causes.
    - Extraction of requirements for mission assurance of micro and nano-satellites.

JX−PSPC−530505

2020年度　超小型衛星の成功率向上に向けたJAXA知見を

活用した支援方法の調査検討

成果報告書

2021年3月26日

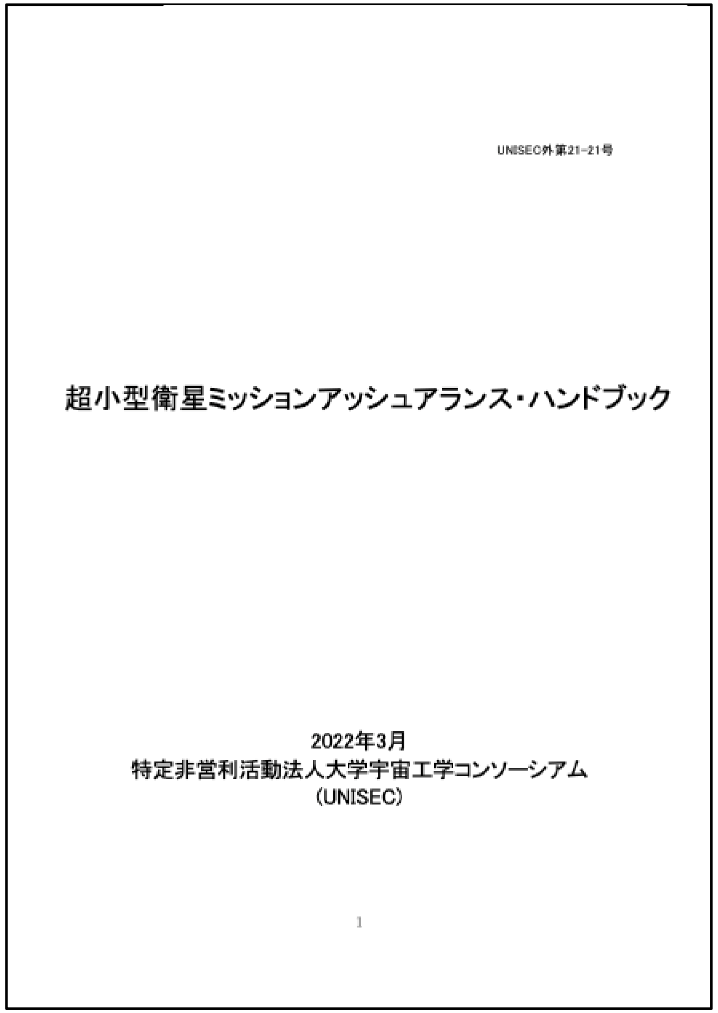
特定非営利活動法人大学宇宙工学コンソーシアム

(UNISEC)

1. Introduction

1.2 UNISEC's Lean Satellite Mission Assurance Activities

- Following the activities in 2020, in 2021 UNISEC members worked on
  - Mission assurance handbook for university-based lean satellites
    - Further analysis of the failure cause by Intensive interviews with the persons in charge of the projects.
  - Based on the activities, the "Mission Assurance Handbook for the University-built Lean Satellite" was published in March 2022.
- This lecture will provide examples of lessons learned cases, the failure root causes and how to improve the mission success rate.


UNISEC外第21-21号

超小型衛星ミッションアッシュアランス・ハンドブック

2022年3月
特定非営利活動法人大学宇宙工学コンソーシアム
(UNISEC)

1

2. Lessons Learned and Root Causes

2 .1 Case 1 (3U CubeSat)

- Satellite was very difficult to assemble. Every time the satellite was assembled for testing, it suppressed the schedule significantly
  - During the safety review, promised to do 3D measurement each time the satellite is assembled
- Software development progress was far behind the hardware development
- Due to collision of I2C, the satellite entered an infinite loop mode of resetting

2. Root cause

2 .1 Case 1 (3U CubeSat)

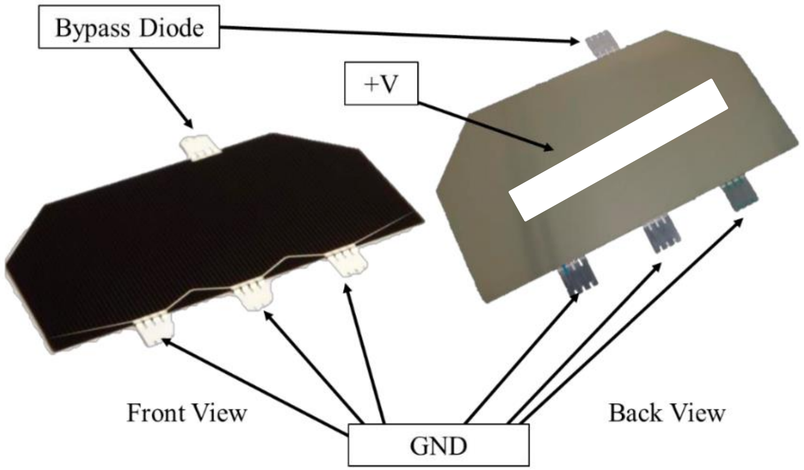
- Satellite was very difficult to assemble. Every time when the satellite was assembled due to testing, it suppressed the schedule significantly
  - During the safety review, promised to do 3D measurement each time the satellite is assembled
- Software development progress was far behind the hardware development
- Due to collision of I2C, the satellite entered a mode of infinite loop of resetting

- Promised more than enough for the safety requirement verification
- Only faculty members involved in the mission definition. Not enough student motivation
- Poor schedule management because it was the first satellite. Long-term end-to-end test was not done
- Satellite structure was too complicated (lack of experience in satellite design)

2. Lessons learned cases

2 .2 Case 2 (1U CubeSat)

- After deployment, no signal from the satellite was received by GS
- There were many single-points-of-failure in the satellite design
- Possibly connected the solar cells incorrectly
  - Mistake a bypass diode tab as an electrode
- The delivery date was fixed. The satellite had to be delivered regardless its condition

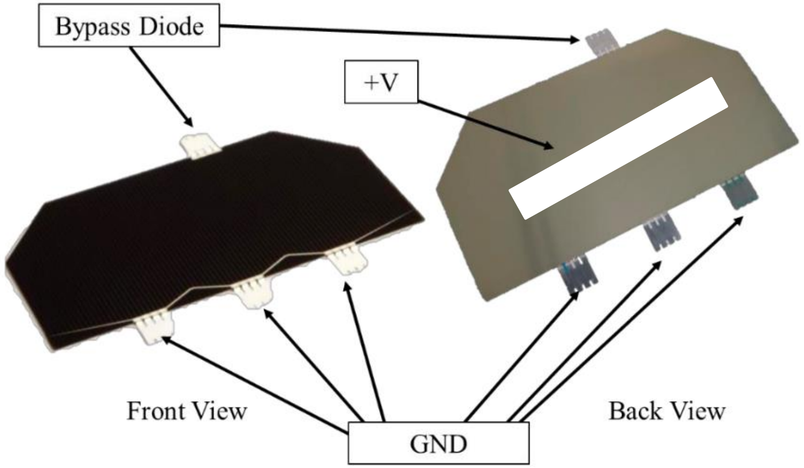


2. Lessons learned cases

2 .2 Case 2 (1U CubeSat)

- After deployment, no signal from the satellite was received by GS
- There were many single-point-of-failure in the satellite design
- A possibility of connecting solar cells in a wrong way
  - Mistake a bypass diode tab as an electrode
- The delivery date was fixed. The satellite had to be delivered regardless its condition

- It was the first satellite. Didn’t know what to do to build a satellite.
- Didn’t know who or where to ask questions if they had any



2. Lessons learned cases

2 .3 Case 3 (2U CubeSat)

- Ground station preparation was insufficient. Checking functionality was not done using other satellites in orbit
- The university team was from the Mechanical Engineering Department, lacked know-how of communication. The team depended on external supporters regarding the communication system. It was difficult to point out problems by the system test done at the university.

2. Lessons learned cases

2 .3 Case 3 (2U CubeSat)

- Ground station preparation was insufficient. Checking its functionality was not done using other satellites in orbit
- The university team was from Mechanical Engineering Department, lacked know-how of communication. The team depended on external supporters regarding the communication system. It was difficult to point out problems by the system test done at the university.

- Dependent on the amateur radio experts outside the campus for the radio. But the communication between the expert and the students was difficult due to physical distance. The principal faculty couldn’t take care of the gap properly.
- Lack of necessary expertise for the satellite project.

2. Lessons learned cases

2 .4 Case 4 (50kg Earth Observation Satellite)

- Satellite power budget did not have enough margin. Because of a power shortage frequent satellite resets occurred.
- Every time the reset occurred, the attitude control history was over-written and the complex attitude control had to be restarted once again. It took too much time to establish the proper attitude for the mission (camera capture and high-speed downlink).
- Because of the insufficient attitude control, no image data could be downlinked

2 .4 Case 4 (50kg Earth Observation Satellite)

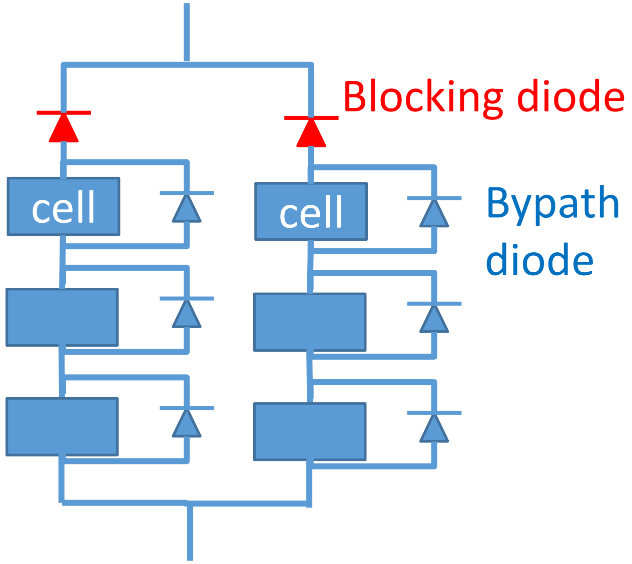
- Satellite power budget did not have enough margin. Because of power shortage frequent satellite reset occurred.
- Every time, the resent occurred, the attitude control history was over-written and the complex attitude control had to be restarted once again. It took too much time to establish the proper attitude for the mission (camera capture and high-speed downlink).
- Because of the insufficient attitude control, no image data could be downlinked

- It was the first satellite for the team. Lack of experience in satellite system design, development and operation.
- No time to do the full system test to check the power budget under the flight representative condition
  - Couldn’t do “Test as you fly”

2. Lessons learned cases

2 .5 Case 5 (50kg Earth Observation Satellite)

- The battery was not designed to stop charging once it was fully charged. It forced a very delicate charging maneuver in orbit.
- No bypath diode or blocking diode in solar cell circuit. A shadow on the solar panel circuit killed the entire solar array circuit on 50cmx50cm panel.
- When the voltage became low, the satellite computer entered “Zombie” state where it cannot function, nor be rebooted completely.



2. Lessons learned cases

2 .5 Case 5 (50kg Earth Observation Satellite)

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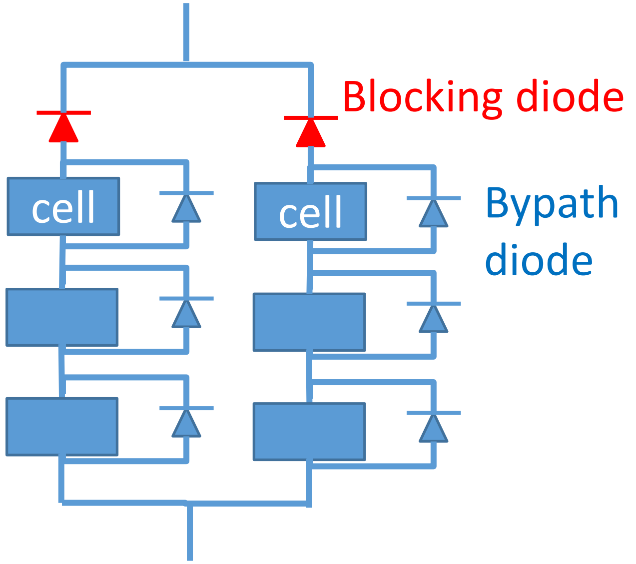
- No bypath diode or blocking diode in solar cell circuit. A shadow on solar panel circuit killed entire solar array circuit on 50cmx50cm panel.
- When the voltage became low, the satellite computer became Zombie state where it cannot function nor be rebooted completely.

- It was the first satellite for the team. Lack of experience to check the design made by the EPS contractor.
- Lack of experience of doing system test



2 .6 Case 6 (7kg Education/Technology Demonstration Satellite)

- Satellite deployment was successful and housekeeping data was collected for an initial 3 weeks from the deployment before doing the mission. Communication with the satellite was suddenly lost due to single event latch-up (SEL)
- The satellite recovered with a power reset, but the operation time was limited due to a series of disruption caused by SEL.
- The over current protection (OCP) to exist from the latch-up didn't work due to inadequate setting of the threshold current
  - Threshold value: 500mA
  - The actual latch-up current: 200mA.

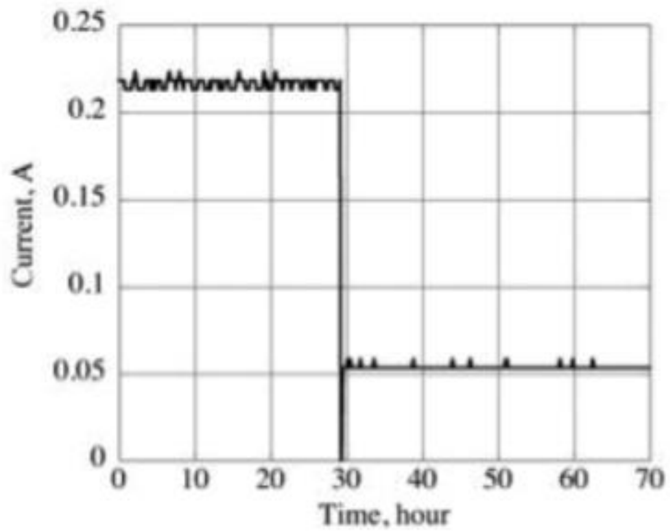


Fig. 4 Latch-up current acquired on orbit

2. Lessons learned cases

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  - Threshold value: 500mA
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- Decided the OCP threshold value without any basis
- SEL protection was designed but not verified
- Should have done the main mission earlier

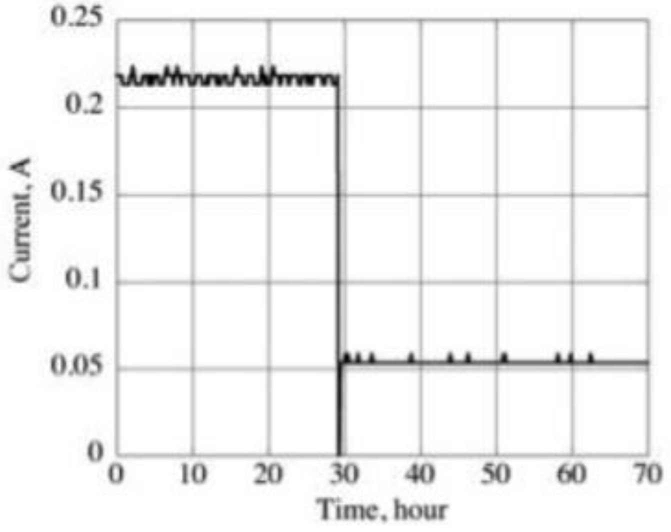
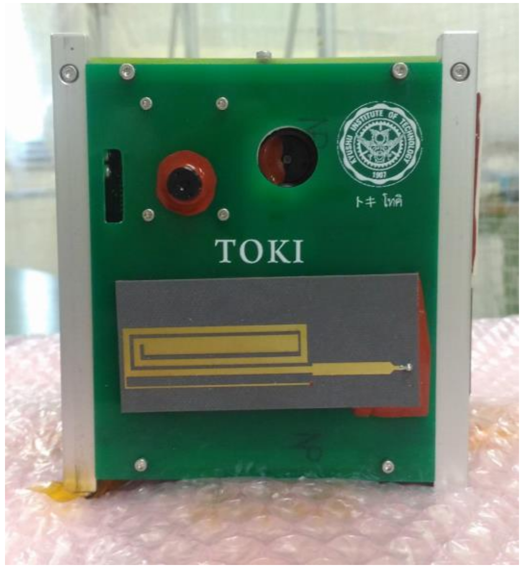


Fig. 4 Latch-up current acquired on orbit

2. Lessons learned cases

2 .7 Case 7 (Constellation of five 1U CubeSats)

- Experimental patch antenna for both UHF (downlink) and VHF (uplink) was used
- The gain of the patch antenna was not as good as expected. No uplink success for all the five satellites. CW beacon was very weak.
- The problem was not detected by the ground test because the flight model antenna arrived at the last minute and no system communication test was not done with the flight models.



2. Lessons learned cases

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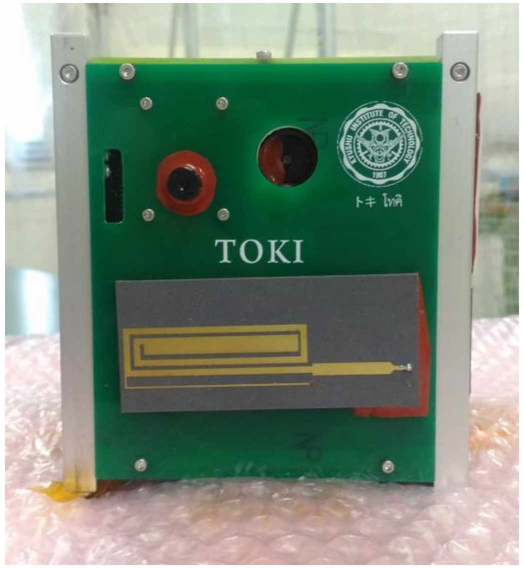
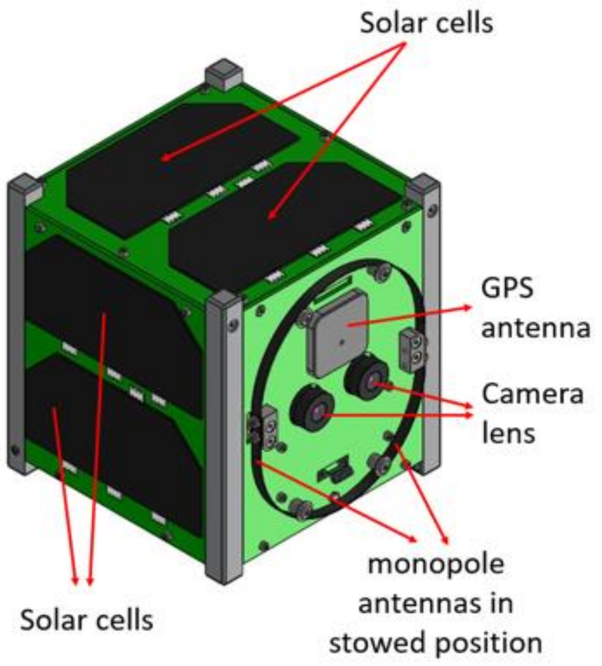
- The problem was not detected by the ground test because the flight model antenna arrived at the last minutes and no system communication test was not done with the flight models.

- Satellite design (demonstration of new technology) was inconsistent with the satellite mission (education)
- Lack of expertise in communication. Couldn't understand the risk of a patch antenna
- Should have considered the advantage of a constellation more. Should have selected a strategy of making at least one satellite survive, rather than making all the satellites survive
- Key decision (use of patch antenna) was made only by the principal faculty. No other member could challenge the decision.



2 .8 Case 8 (Constellation of three 1U CubeSats)

- UHF beacon downlink signal was improved drastically
- The uplink suffered difficulty due to internal noise generated by the EPS board.
- The problem was not detected during the ground test because an internal attenuator of 10dB in the reference diploe antenna was overlooked, resulting in over-estimation of 10dB in the link budget.



2. Lessons learned cases

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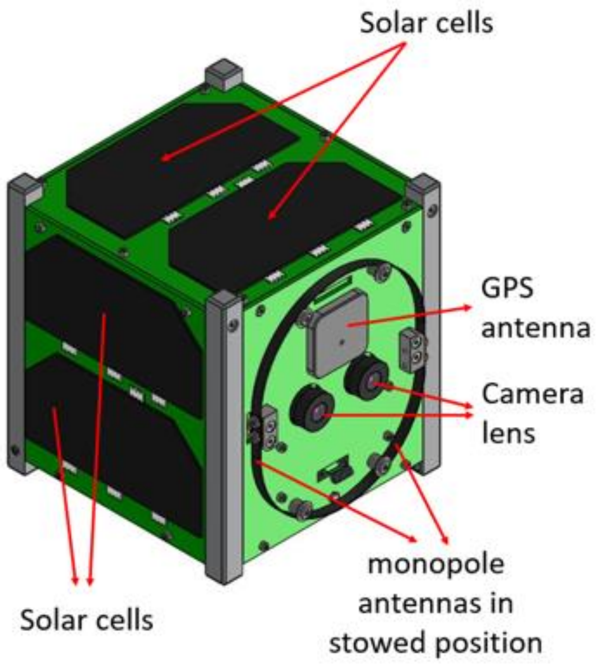


- Few expertise in communication. Couldn’t check the test set-up consistency.
- Lack of knowledge that the internal noise affects the uplink signal reception.
  - The background noise in the link budget was chosen without any basis

3. Mission Assurance

3. Mission assurance

3.1 Common root cause

- In the examples shown, there are many common causes among different cases
  - Poor schedule management
  - Team structure
  - Inconsistency in requirements
  - Improper verification planning
  - Wrong strategy to avoid total satellite loss
  - Insufficient full system end-to-end test
  - Difficulty in assembly, integration and testing
  - Poor understanding of the rationale behind the design
  - Others

3. Mission assurance

3 .2 What is mission assurance?

- Mission assurance
  - A series of activities to identify the factors in design, making, operation of the satellite, etc. that will hinder mission success and to eliminate or decrease the effects of such factors.
- University satellite is categorized as “Lean Satellite”
  - a satellite that utilizes non-traditional, risk-taking development and management approaches – with the aim to provide the satellite value to the customer and/or the stakeholder at a low-cost and with a short time to realize the satellite mission[1].
- Lean satellites tolerates risks, but still needs to achieve the mission success as much as possible
  - “Failure is not an option” nor “Failure is accepted”

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

3 .3 Mission Assurance Handbook for the University-built Lean Satellite

- Target satellite projects at universities and polytechnic-colleges in Japan
  - Not only the first project of the universities, but also the second and later projects
- Summary of points to be kept in mind of faculty members and students to improve the mission success rate
- Organized in the order of project life-cycle
- Final version to be published in late 2022
- Much of the content is still applicable to satellite projects in new space companies and/or non-Japanese organizations

Contents

1. Introduction
2. Project management
3. Mission definition
4. Conceptual design
5. Detail design
6. Production
7. Testing
8. Operation
9. Post-operation
10. Sustainability of university satellite program

Ordering according to project life-cycle

3. Mission assurance

3 .4 Project management (schedule management)

- First projects often fail. Improper schedule management due to lack of satellite project experience
- Very little time spent in system tests
- Guideline for the project milestones until satellite delivery

Time	Milestone
D	Satellite delivery
D-1 month	FM hardware and software complete. Finished hardware testing. Basic GS software is complete
D-3 month	All FM hardware components delivered and ready for FM system assembly
D-6 month	Finished EM testing and confirmed that the satellite functions as a system
D-10 month	All EM hardware components delivered and ready for EM system assembly
D-13 month	Finished proof of concepts. Confirmed that the missions are feasible. Finished EM design and start procurement
D-A* month	Determined what missions to be done

A* depends on each satellite project

3. Mission assurance

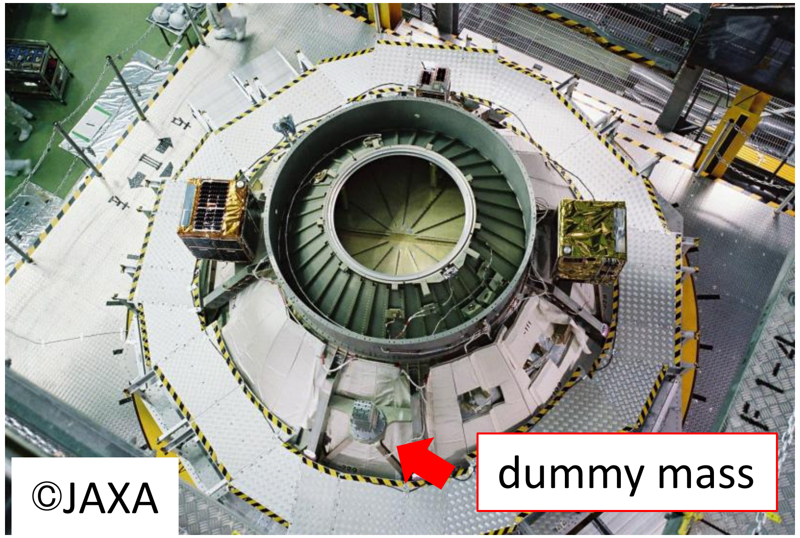
3 .5 Project management (team talents)

- Not possible to have all the talents necessary for the projects by students alone. Need to find solutions to fill the shortage,
    1. Procurement
    2. Collaboration with external people
    3. Expect students to grow
- Even for 1 or 2, the requirements for the procured or outsourced items must be made by the team
- Keep persons familiar with the satellite design for operation
    - Need to finish the project life cycle (from kick-off to operation) in 3 years
- The principal investigator (faculty member)
    - Responsible for keeping the student motivation
    - Responsible for securing the communication channels for the external assistance

3. Mission assurance

3 .6 Project management (Safety requirement verification)

- Non-compliance with the safety requirement may lead to serious delay of the schedule
- In the worst case, the satellite is not launched
  - Dummy mass will go instead of your satellite
- At the end of conceptual design and detailed design, list-up the issues related to safety requirements and confirm with the launch provider
- Agree with the launch provider on the safety requirement verification methods that can be done with minimum effort
  - The safety verification is necessary, but a non-value adding activity
  - Do more value-adding activities such as mission assurance



3 .7 Mission definition phase (feasibility)

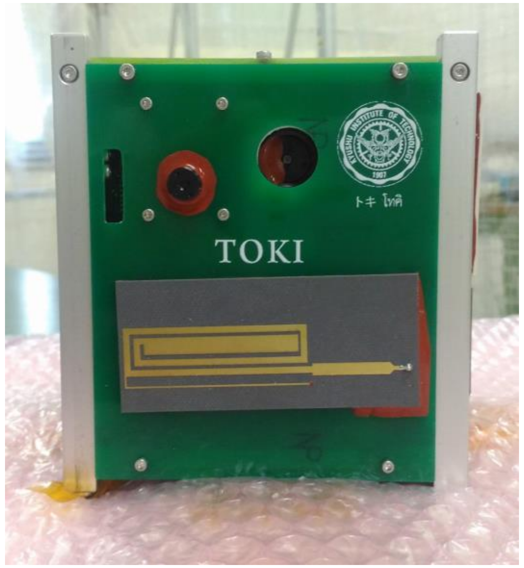
- **Know the limits** when you define the missions
  - Team talents and skills
  - Budget
- **A professor is not a God**
  - Doesn’t know everything to judge the mission feasibility
  - Open mind to suggestion/comments/assistance by others

- 3-axis stabilization from the first satellite?
- High-speed communication by mechanical students?

3. Mission assurance

3 .8 Conceptual design phase (requirement management)

- Check consistency between the mission requirements and the design requirements
  - Design should satisfy the mission requirements
  - No design requirement that doesn’t fit to the mission requirements
- External review by experienced experts is effective
- Open-mind to external suggestions



3 .9 Conceptual design phase (Verification plan)

- No use of a design that cannot be verified
- Doable verification plan

List of minimum test items for an ISS-released CubeSat

Test Item	EM(QT)	FM (AT)
Electromagnetic Compatibility	R	N*1
End-to-End mission simulation	R	N*1
Electrical interface	R	R
System function	R	R
End-to-End long-time operation	N	R
Deployment	R	R
Fit Check	R	R
Thermal	R	O*3
Random Vibration	O*2	R

*1 Included in End-to-End long-time operation test
*2 Depends on needs of each satellite
*3 The exposure to high/low temperature may be required for safety requirements verification

3 .10 Detailed design phase (Risk Management, FTA, FMEA)

- Try to minimize the risks based on **priority**
- **External review** is effective to list up the risks with high priority along with safety issues
- FTA/FMEA are not taught in school
  - Start from the levels students/professors can understand
  - List up single-point-of-failure and **prioritize** the risks
    - Not only part/components, but also works (wrong command, wrong assembly, etc.)

3. Mission assurance

3 .11 Testing phase (Electromagnetic Compatibility Test)

- Because of cold launch, EMC with launchers and other satellites are not important
- Live with self-generated noise
- Verify that the communication link has enough margin
  - Uplink signal level is much higher than the satellite-generated noise floor
  - Confirm before moving to FM

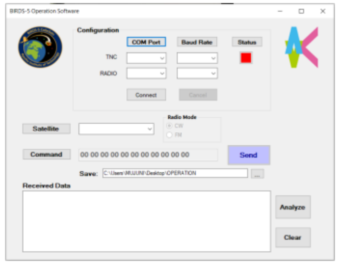
Sensitivity test for uplink success in a shield box

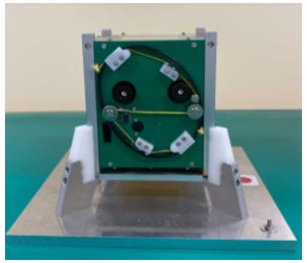
3. Mission assurance

3.12 Testing phase (End-to-End mission test)

- Verify the basic data flow of the main mission
  - Command uplink
  - Satellite mission
  - Data downlink
  - Confirmation of data on GS PC
- Make the details, after confirming that the basic mission can be done

GS PC → GS radio → Satellite → GS radio → GS PC





3. Mission assurance

3 .13 Testing phase (system function test)

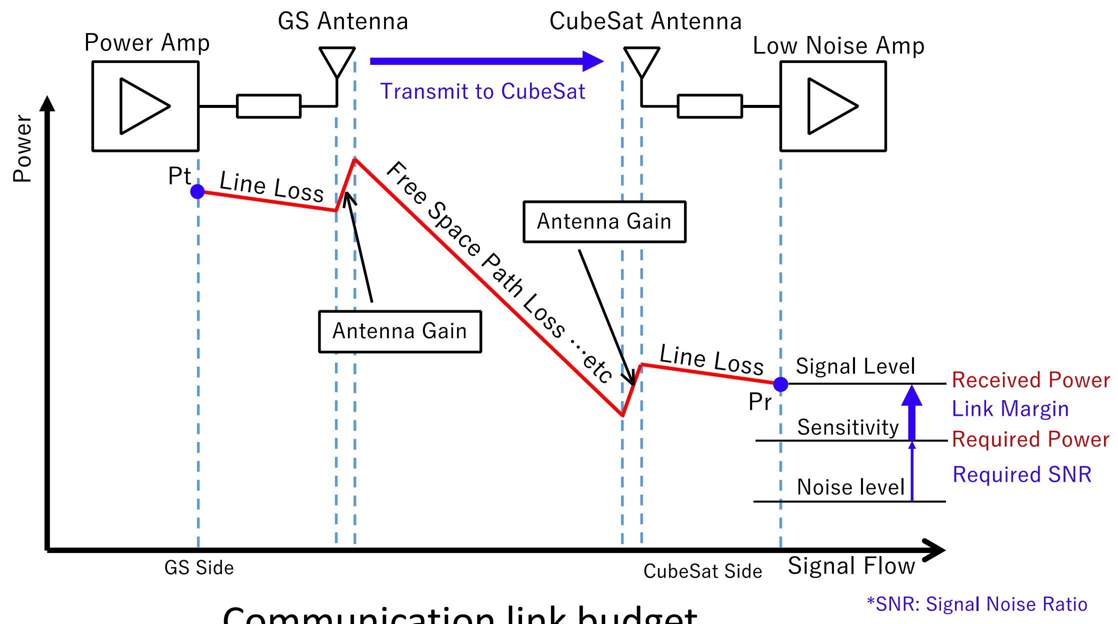
- Move to FM assembly as soon as FM components are delivered and start the function tests as an integrated system
- Check the consistency of data sent from the satellite
- Do not move to the environment tests (e.g. vibration, thermal vacuum), before you solve problems
  - Expect many problems to be found. Have enough schedule margin before moving to the environment tests

FM system function test

3 .14 Testing phase (End-to-End Long-term operation)

- Finding and fixing bugs of flight software
- Operation rehearsal
  - Critical modes (release, recovery from reset, etc.)
  - Nominal modes (HK data collection)
  - Mission modes
- Link budget confirmation
  - Compatibility with ground station

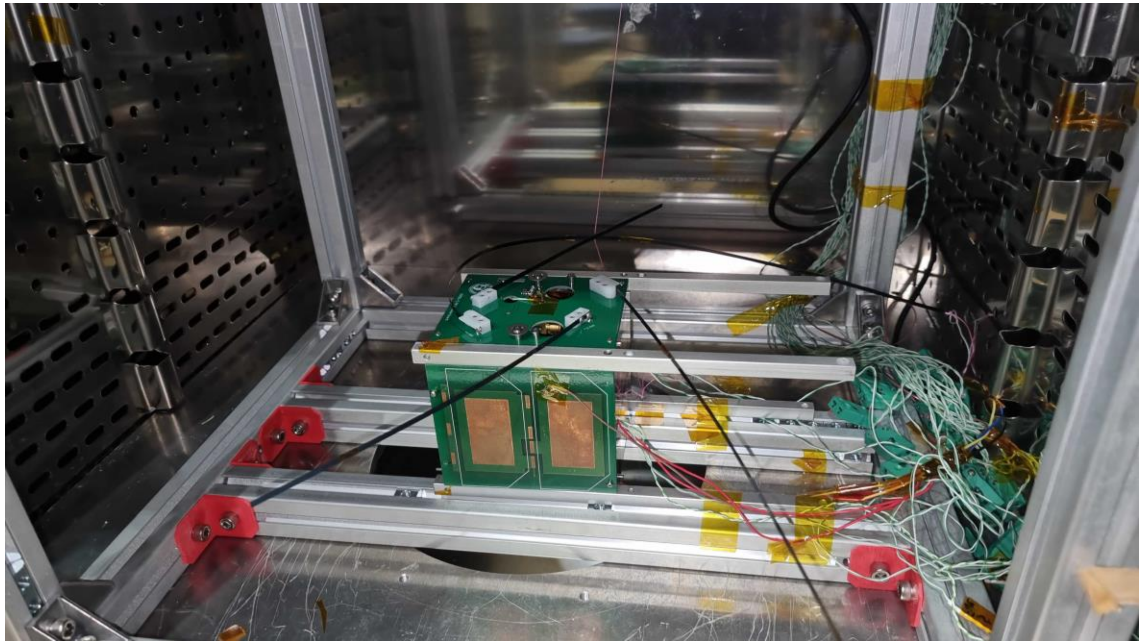
Line loss and noise level inside the satellite is hard to derive theoretically. Confirm the link budget by testing



Communication link budget

3 .15 Testing phase (Deployment test)

- 25% of university satellites end up DoA (Dead on Arrival)
  - Antenna deployment failure?
- Make sure the antenna can be deployed in the worst case
  - Cold, low-battery, etc.

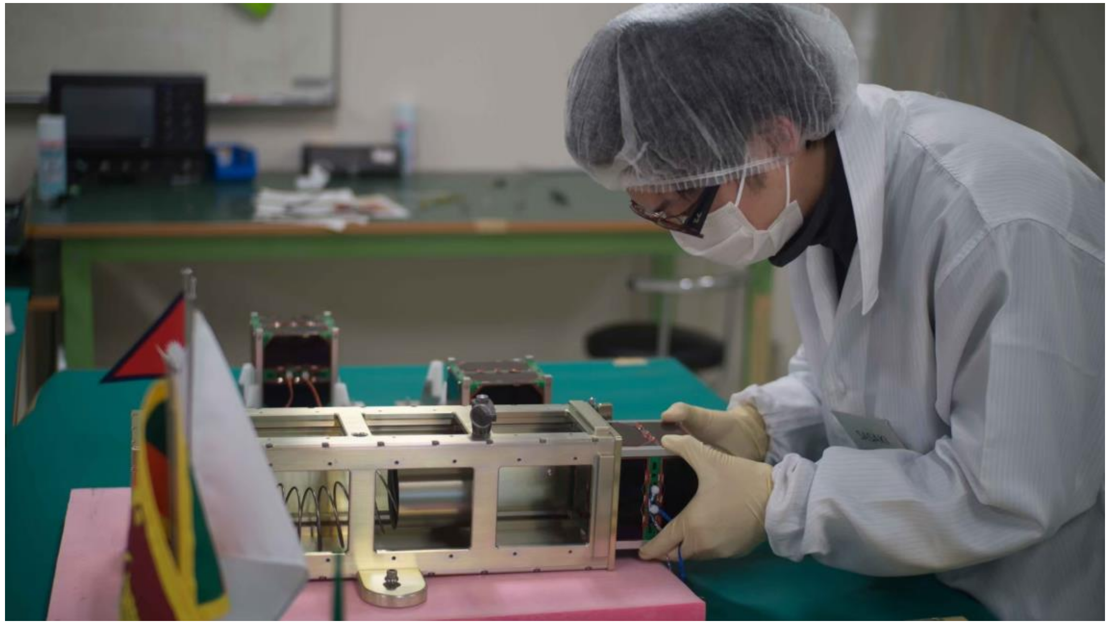


Antenna deployment test in low temperature

3. Mission assurance

3 .16 Testing phase (Fit check)

- CubeSats may not fit into a POD at satellite delivery
- The best and simplest way is to do fit-check with an *official* POD borrowed from the launch provider
  - Both for EM and FM



Fit-chek

3. Mission assurance

3 .17 Operation phase

- Ground station preparation and maintenance
- Operation plan
  - Obtain the frequency license asap
    - In Japan, we get only a “preliminary license” before launch. Need a full license to operate the satellite officially and publish the results
  - Do the main mission first. Achieve the minimum success criteria as soon as possible
- Anomaly investigation
  - Never give up
  - P/I (faculty) should keep the motivation of the team
  - Do thorough FTAs for the next project

4. Conclusion

4. Conclusion

- CubeSat mission success rate is low
  - Especially for the first satellite
- We can take risks in CubeSat, but this does not mean “failure is accepted”
- There are many lessons learned
- Sharing the lessons and the root causes among the community is important
- The mission assurance handbook has been developed
  - Waiting for the official release in 2022
  - Need to revise it by taking inputs and new lessons from the CubeSat community worldwide

Thank you very much.

[Disclaimer]
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