Mission Assurance Handbook for University-based Lean Satellites

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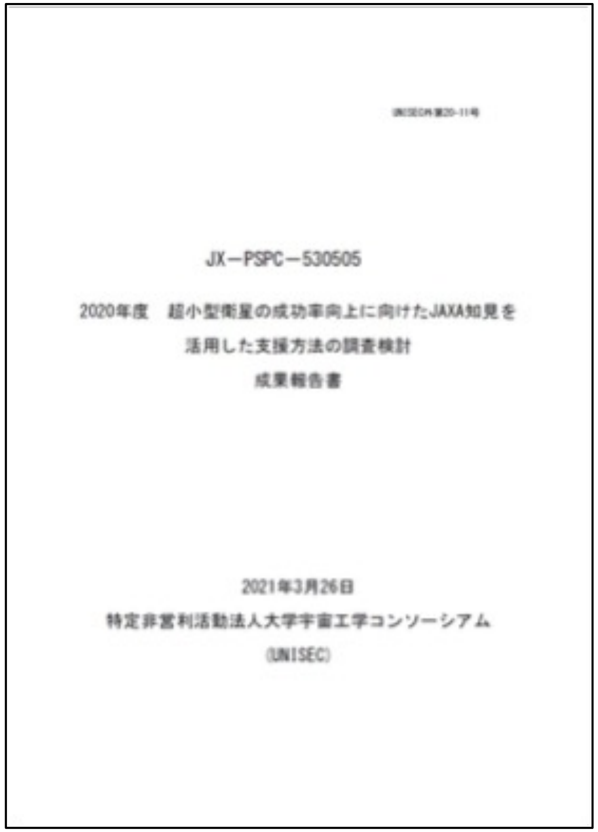
October 8, 2022

UNISEC Global Virtual Meeting

Introduction

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 and their causes.
    - Extraction of requirements for mission assurance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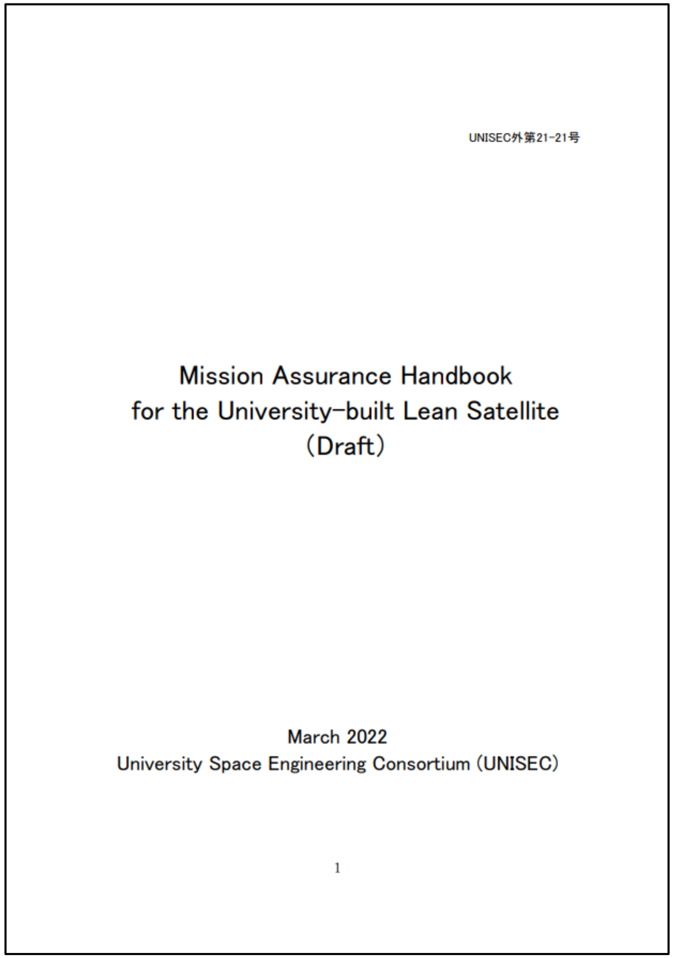
2020年度　超小型衛星の成功率向上に向けたJAXA知見を
活用した支援方法の調査検討
成果報告書

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)

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
  - Based on the activities, "Mission Assurance Handbook for the University-built Lean Satellite" was published in March 2022.



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Mission Assurance Handbook
for the University-built Lean Satellite
(Draft)

March 2022
University Space Engineering Consortium (UNISEC)

1

Examples of lessons learned and root causes

Lessons learned example (3U CubeSat)

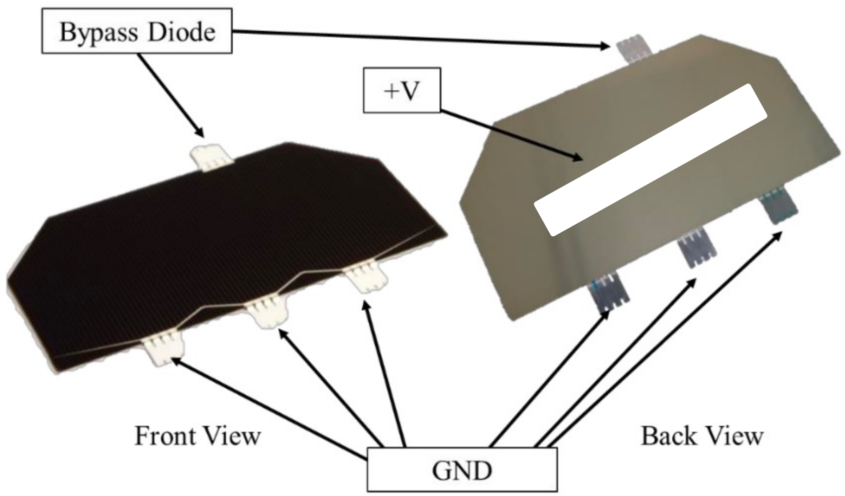
- Satellite was very difficult to assemble. Every time the satellite was assembled for testing, it suppressed the schedule significantly
  - During the safety review, the team promised to do 3D measurement each time the satellite is assembled
- Software development progress was far behind the hardware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

Root cause (3U CubeSat)

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

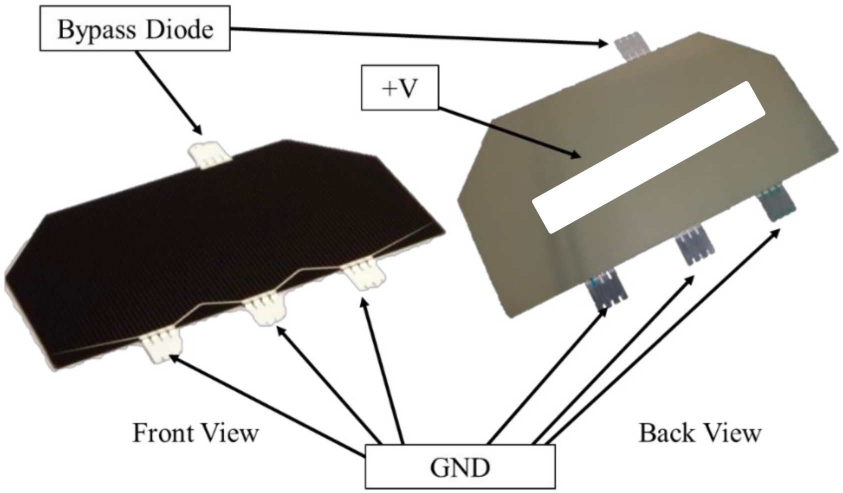
Lessons learned example (1U CubeSat)

- No signal was heard from the satellite (dead-on-arrival)
- Many single-points-of-failure in the satellite design
- Possibly connected the solar cells incorrectly
  - Mistook a bypass diode tab as an electrode
- The delivery date was fixed. The satellite had to be delivered regardless its condition



Root cause (1U CubeSat)

- 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



Lessons learned example (2U CubeSat)

- Ground station preparation was insufficient. Checking functionality was not done using other satellites in orbit
- The team was from the Mechanical Engineering Department, with little knowledge of communication.
  - Depended on external supporters regarding the communication system.
  - Difficult to point out problems by the system test done at the university.

Root cause (2U CubeSat)

- Dependent on the amateur radio experts outside the campus for the radio.
  - 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 (communication) for the satellite project.

Lessons learned example (50kg Earth Observation Satellite)

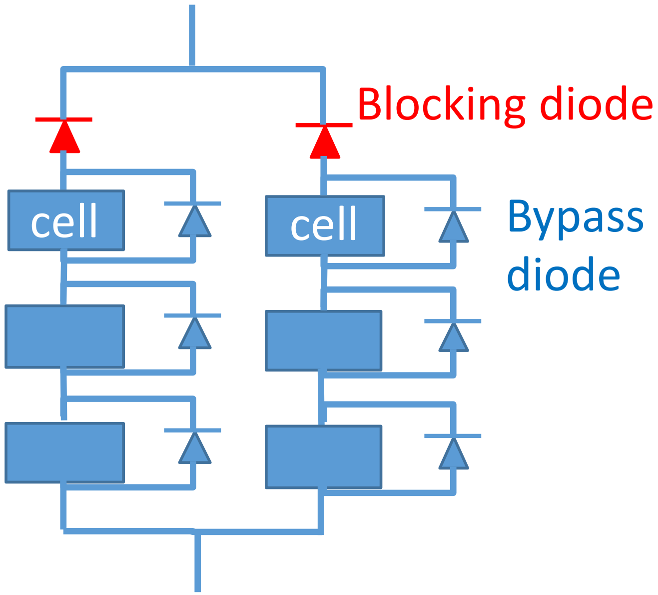
- Power budget did not have enough margin. Because of a power shortage frequent satellite resets occurred.
- Every time the reset occurred, the attitude control history was over-written and the complex attitude control had to be restarted once again.
  - Took too much time to establish the proper attitude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

Root cause
(50kg Earth Observation Satellite)

- 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"

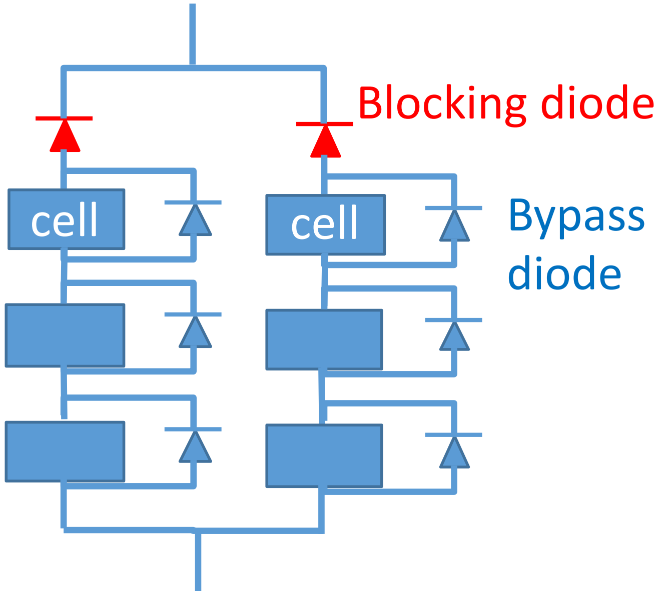
Lessons learned example (50kg Earth Observation Satellite)

- The battery was not designed to stop charging after full charging. Very delicate charging maneuver was needed.
- No bypass 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 reboot completely.



Root cause
(50kg Earth Observation Satellite)

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

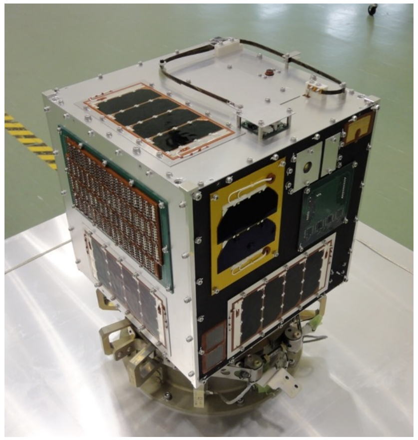


Lessons learned example (7kg Education/Tech-demo Satellite)

- 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 exit from the latch-up

didn’t work due to inadequate setting of the threshold current

  - Threshold value: 500mA
  - The actual latch-up current: 200mA.



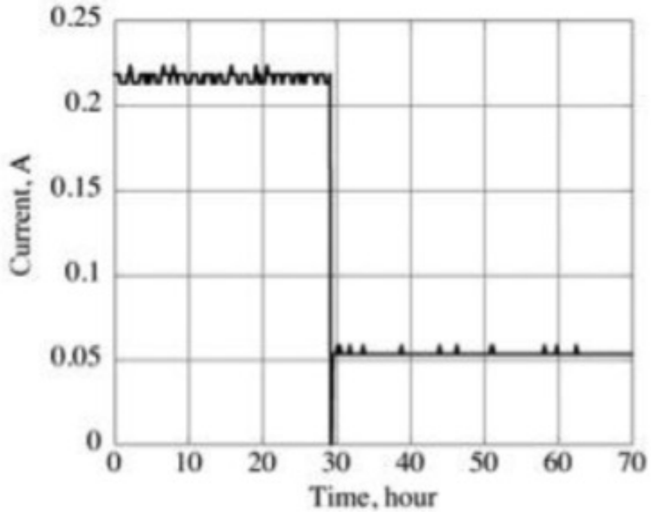
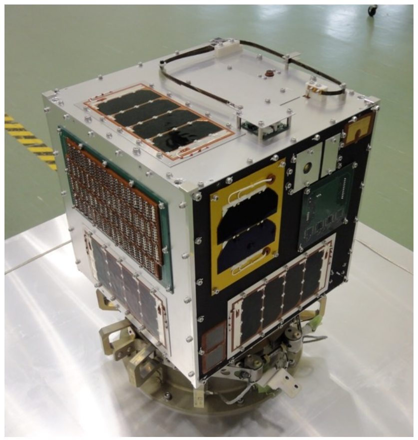


Fig. 4 Latch-up current acquired on orbit

Root cause (7kg Education/Tech-demo Satellite)

- Decided the OCP threshold value without any basis
  - “Perhaps this is good"
- SEL protection was designed but not verified
  - ”Maybe it will work”
- Should have done the main mission earlier



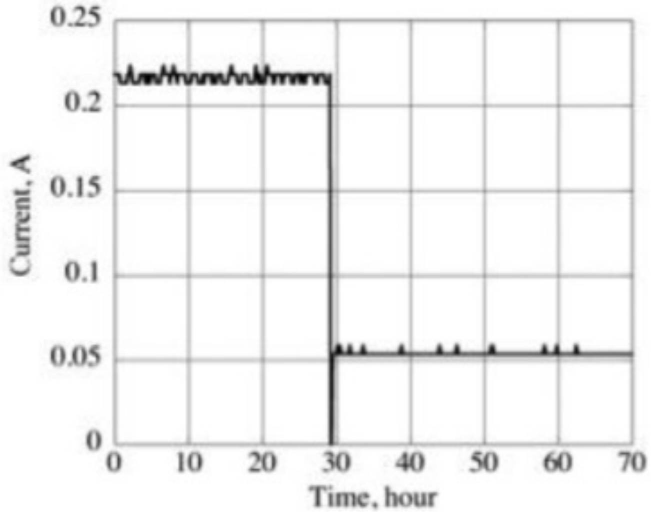
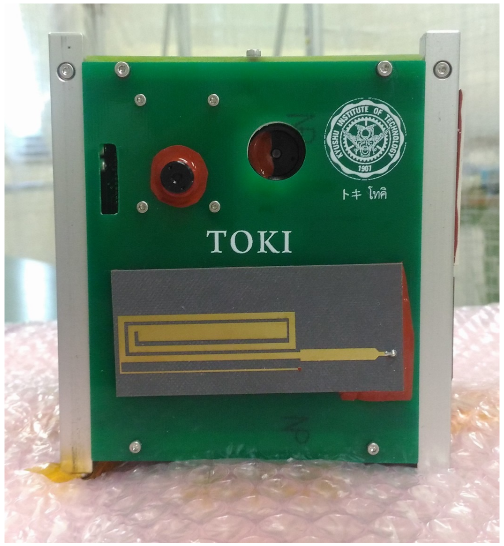


Fig. 4 Latch-up current acquired on orbit

Lessons learned example (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.



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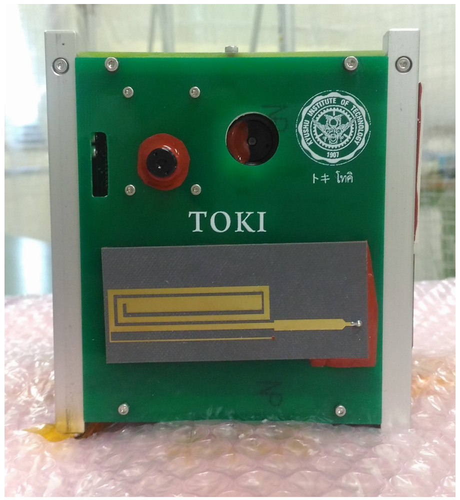
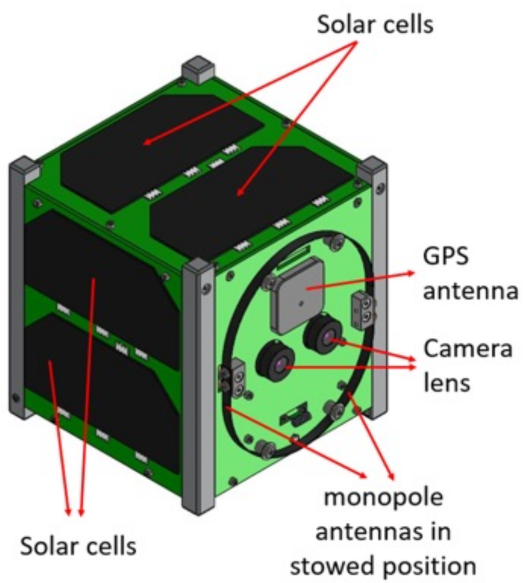
Root cause
(Constellation of five 1U CubeSats)

- 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.



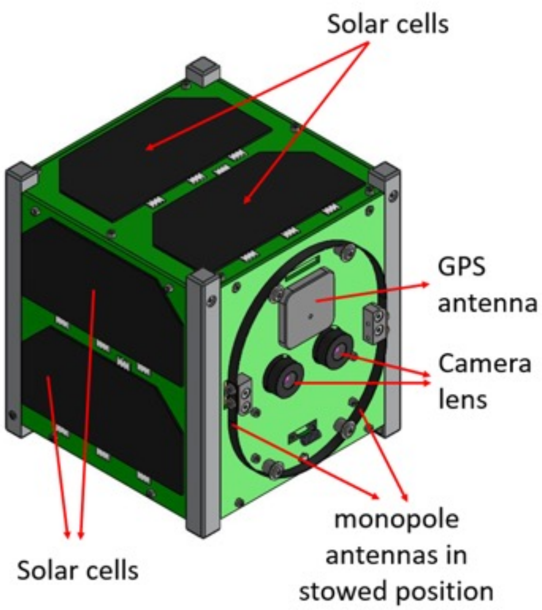
Lessons learned example (Constellation of three 1U CubeSats)

- 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.



Root cause (1U CubeSat)

- 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



Common root causes for mission failure

- Poor schedule management
- Insufficient team talent and skill
- 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

Mission assurance handbook

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 low-cost and with short time to realize the satellite mission[1].
- Lean satellite tolerates a risk, 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*

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
- Published and available online
- Many of the content is still applicable to satellite projects in new space companies and/or non-Japanese organizations

Handbook download

Use your smartphone and capture the QR code below

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

If you missed the last page

2.1 Project management (schedule management)

- First project often fails. 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
CDR	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
PDR	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

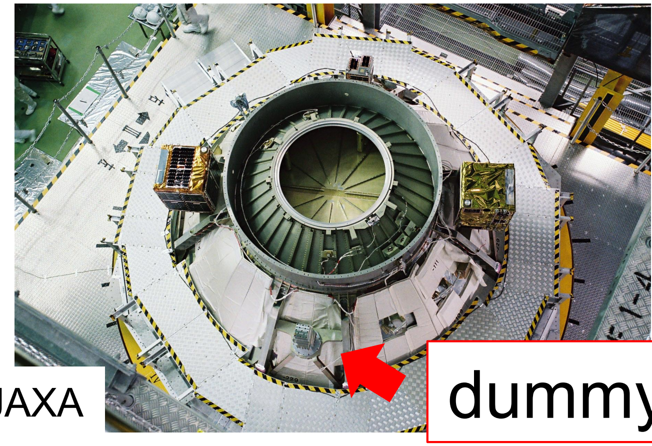
A* depends on each satellite project

2.2 Project management (project team organization)

- 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

2.5 Project management (Compliance with safety requirements)

- 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 **the minimum effort**
  - The safety verification is necessary, but non-value adding activity
  - Do more value-adding activities such as mission assurance



dummy mass

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Lean Philosophy

- Value added activity
  - Improve satellite reliability
  - Improve attitude accuracy
  - others
- Non-value added but necessary activity
  - Safety review
  - Radio license
  - Space activity law
  - others
- Waste
  - Looking for tools
  - others

Eliminate the waste and make the non-value added but necessary activity efficiently

3.1 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?

3.2 Mission definition phase (Mission Success Criteria)

- Minimum success
  - Things to be achieved even if the satellite has problems
- Full success
  - Things to be achieved when the satellite works as expected
- Extra success
  - Something more than expected in addition to the full success
- Use quantitative indicators as much as possible, especially for minimum and full success
- You may need to change the criteria as the project proceeds, but
  - Examine whether the meaning of the entire project can be achieved (i.e., Can we satisfy the project stakeholders?)
- When you discuss a design change
  - Examine whether the minimum success criteria can be achieved
- Try to achieve the minimum success criteria as soon as the satellite is deployed into orbit

4.1 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

4.4 Conceptual design phase (Verification plan)

- Do not use a design that cannot be verified
- Doable verification plan

List of minimum test items for an ISS-released CubeSat

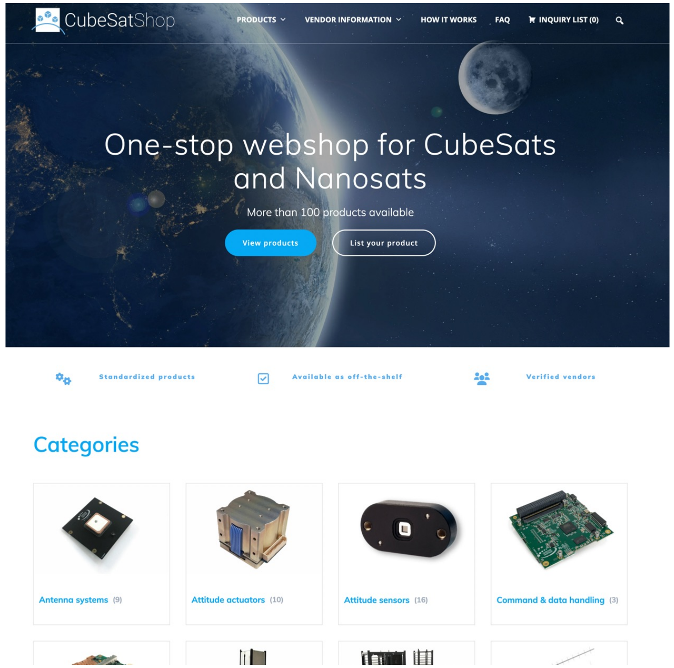
Test Item	EM(QT)	FM (AT)
Electromagnetic Compatibility	R	N*1
End-to-End mission simulation	R	N*1
Electrical interface	R	R
System function	R	R
End-to-End long-time operation	N	R
Deployment	R	R
Fit Check	R	R
Thermal	R	O*3
Random Vibration	O*2	R

*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

5.1 Detailed design phase (Selection of Parts and Components)

- When you select a vendor, price and performance may not be the key factor
  - Easy and quick to procure
  - Easy to handle (simple interface)
  - Good response to repair requests
  - More valuable than the size, price, and function.
- For a series of satellite project (i.e. program), change of bus component specifications should be minimized
  - Eliminate development work for the later projects
  - Slight change leads to increase of cost and delivery time
- When the component is developed jointly with the vendor, the design and knowhow should be transferred to the vendor
  - Sustainable supply chain

You can find many vendors, but be careful when you select the right one



https://www.cubesatshop.com/

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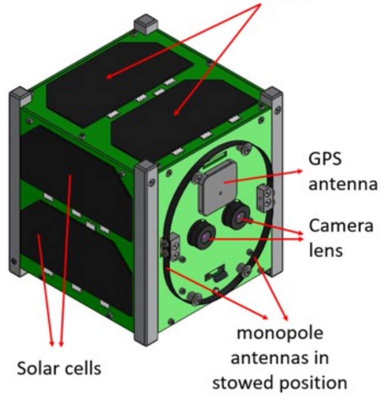
5.2 Detailed design phase (Risk Management, FTA, FMEA)

- Try to minimize the risks based on **priority**
- **External review** is effective to list up the risks with high priority along with the 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.)

5.3 Detailed design phase (Aiming for a Satellite that can Survive)

- Avoid complete failure (loss of communication with the ground)
- "God PIC", Micro Controller PIC16F877 for power reset
- Battery recharging from empty condition
- Satellite works w/o battery using solar panel only
- Redundant communication links
- Feasible power budget for the minimum function (communication with the ground) even with
  - Loss of attitude control
  - Solar paddle deployment failure
  - Loss of one solar panel
- Verify that the satellite can recover from the power reset
  - Avoid Zombie state

From Digikey®

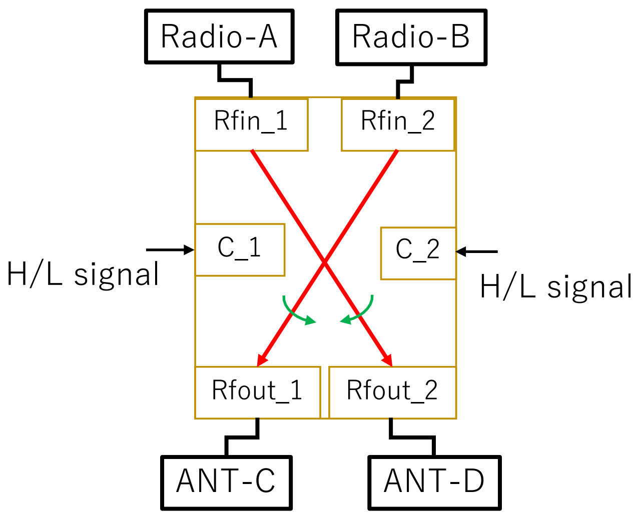


https://www.irasutoya.com/2013/04/blog-post_1022.html

5.5 Detailed design phase (Points to Note in Design Changes)

- When the design change is discussed, evaluate
  - Benefits obtained
  - New risks generated
- Use minimum success and full success as criteria

Example



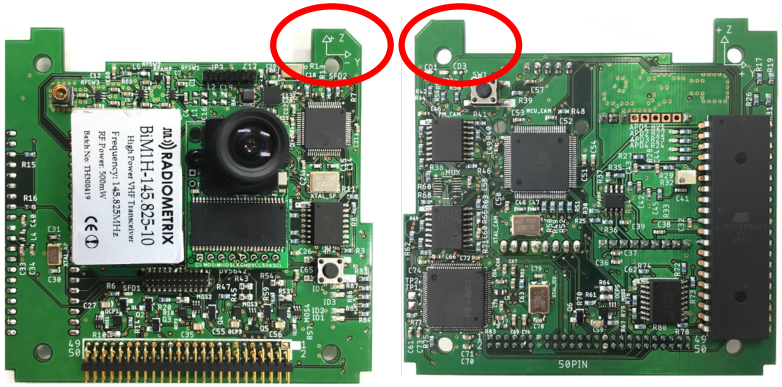
- Antennas and radios have no flight heritage
  - Improve the reliability of communication
- Risk of RF switch stuck in the intermediate position (no communication)
- Without the RF switch, communication is possible if one pair of radio and antenna survives

5.6 Detailed design phase (Easy operation)

- Image how to execute the mission
- Reflect the lessons learned from pervious operations
- Stored command (reserved command)
  - Make missions execution possible anywhere in the orbit
  - Do a series of operation
  - Increase the amount of data by downlink to GSs other than Japan
    - Be careful about frequency coordination
- Simple uplink commands
  - Small number of bytes to improve the uplink success rate
- GS software can adopt remote and automatic operation
  - The team size may be significantly smaller during operation due to graduation
- Keep housekeeping data history before power reset
- Keep important parameters before/after reset
  - Control gain of attitude control

5.7 Detailed design phase (Easy to Assemble, Integrate and Test)

- Reduce the number of fasteners (bolts), harness, connectors, as much as possible
  - Possible causes of workmanship error
- Implement the mitigation against mistake in the design
  - ”Being careful” is not a solution
- Save connectors
  - Frequent attach/remove may damage connector
- External ports to internal processors
- Physical inhibits against antenna deployment
  - You may want to work on the software until the last minutes. But deployment may not be allowed after the final safety review.
- Prepare jigs for the assembly, test, storage.
- Think how to carry a satellite
  - Do not carry a satellite by hands



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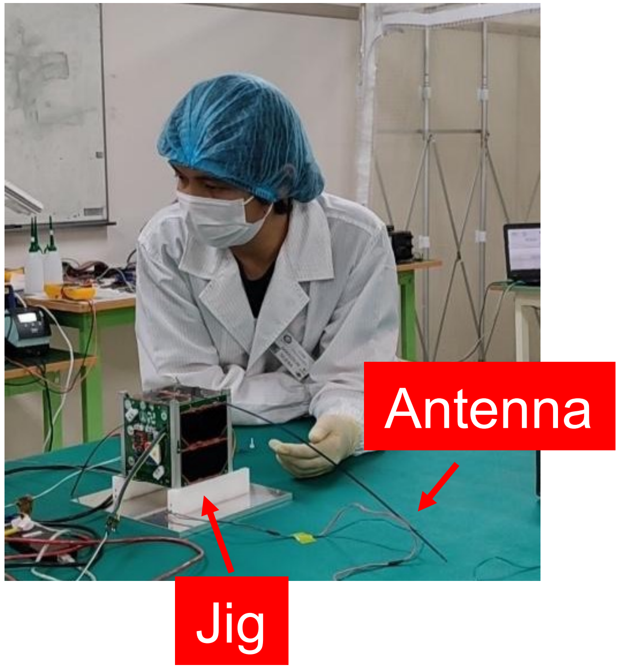
back



6.2 Production (inhouse vs outsourcing)

- The purpose of an education satellite
  - Practice systems engineering and project management
  - Not, acquiring handyman skills
- Do not try to save money by making inhouse
  - After all, it may end up in schedule delay and cost increase
- Buy quality and time with money
- Some students have good hand skills. But some not. Relying on student hand skills is risky

6.3 Production (Compliance with safety requirement)

- Verification of safety requirements in FM stage is critical to pass the safety review
- Agree on safety hazard control methods before FM assembly between the launcher and the satellite
- Need to verify that the control methods were implemented according to the agreement
- Before moving to FM assembly, the team members (especially AIT team) should be aware of what **procedures** they have to follow and what **documents** they need to make
- Good communication between safety officers and AIT team

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7.1 Testing phase (Electromagnetic Compatibility Test)

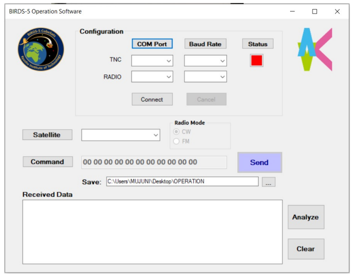
- Because of cold launch, EMC with launchers and other satellites are not important
- Live with **self-generated noise**
- Verify that the communication link has enough margin
  - Uplink signal level is much higher than the satellite-generated noise floor
  - Confirm before moving to FM

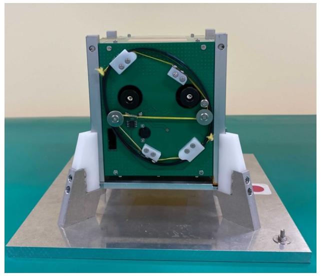
Sensitivity test for uplink success in a shield box

7.2 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





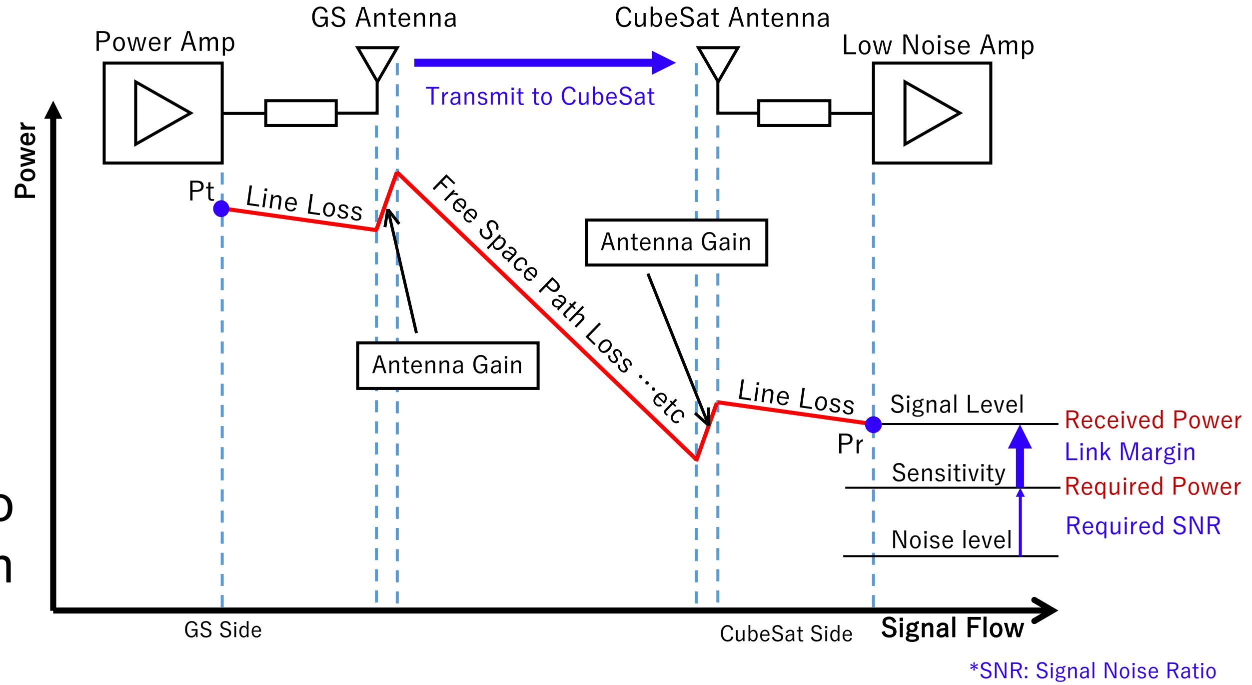
7.4 Testing phase (System functional test)

- 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

FM system function test

7.5 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

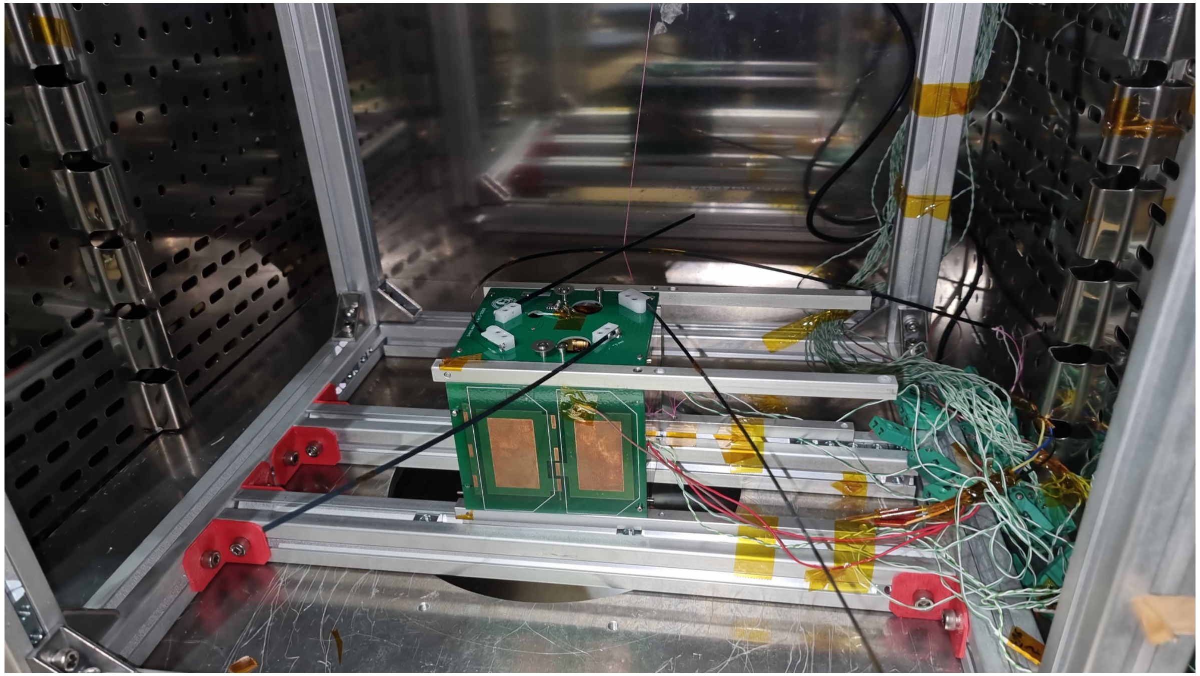


Line loss and noise level inside the satellite is hard to derive theoretically. Confirm the link budget by testing

Communication link budget

7.6 Testing phase (Deployment test)

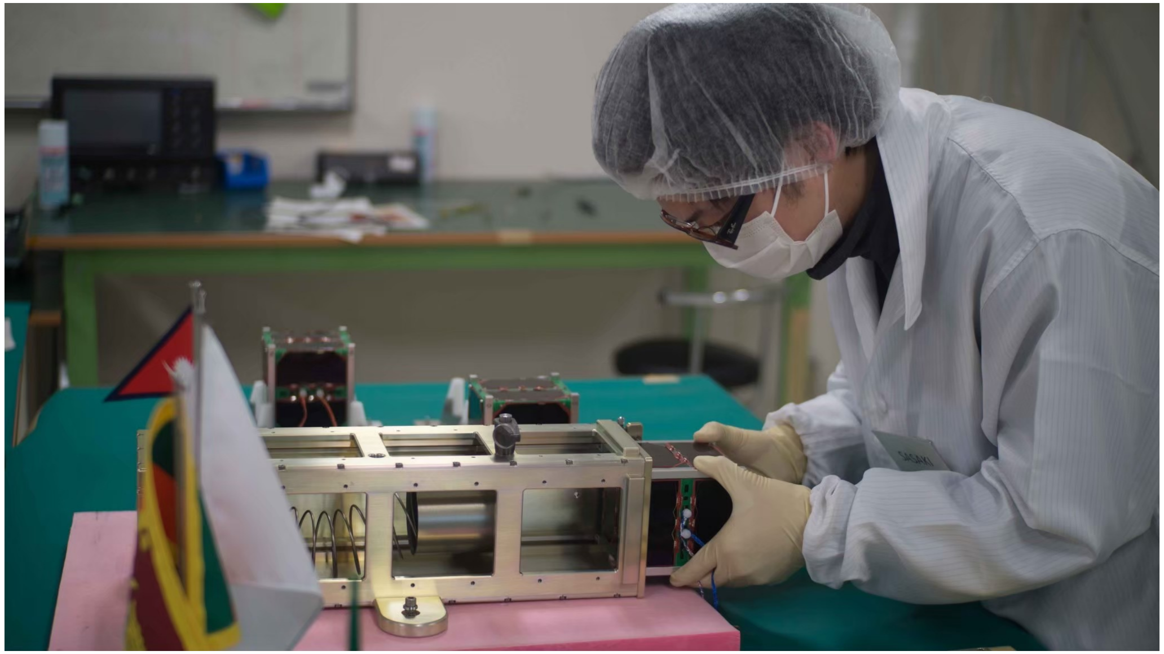
- 25% of university satellites end up DoA (Dead on Arrival)
  - Antenna deployment failure?
- Make sure the antenna can be deployed in the worst case
  - Cold, low-battery, etc.



Antenna deployment test in low temperature

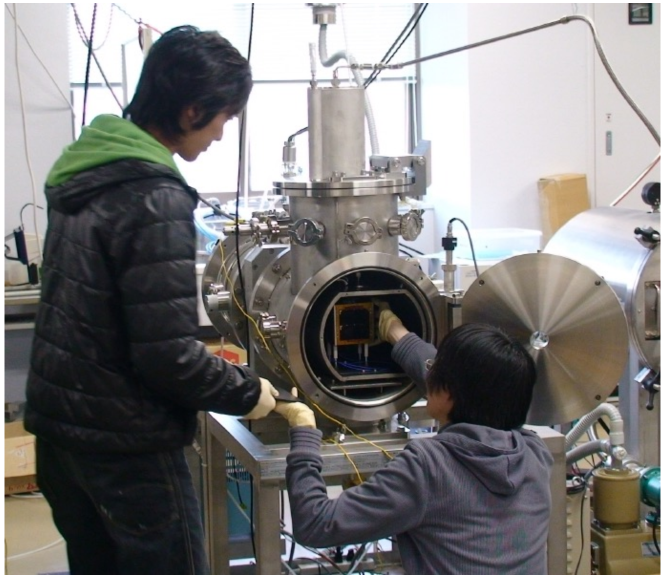
7.7 Testing phase (Fit check)

- 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

7.8 Testing phase (Thermal vacuum)



- Thermal vacuum is thermal vacuum. Size doesn't matter
- Temperature condition (high/low)
  - Use flight data of similar satellites flown in the same orbit
    - Many CubeSats flown already in ISS orbit
      - Use high beta angle data for high temperature
  - More accurate than thermal analysis

7.12 Testing phase (Evaluation of test results)

- Check the consistency of the test results.
- The pass/fail criteria should be established before the test
- If the results deviate from the tolerance limit, try to explain why
- If something hard to understand occurs randomly, record the observation
- Don’t be optimistic (fight against normalcy bias)
  - “Perhaps it won’t happen in orbit”
  - “It was just a random noise”
  - ”We just saw illusion”
  - “Let’s forget about it”
- Confirm that the test equipment is used properly
  - Often wrong usage of RF equipment
  - Need to be checked by multiple persons

“I didn’t see it”

From illust AC

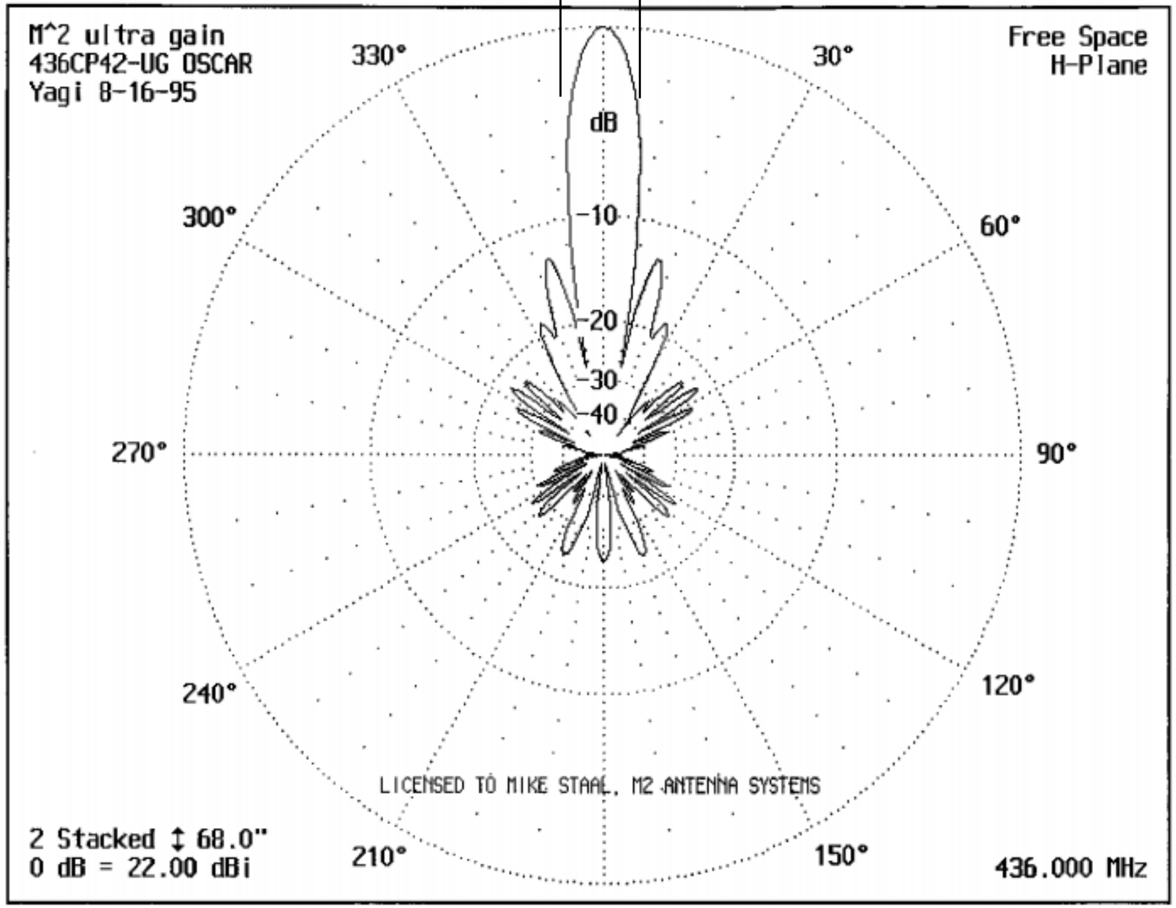
8.1 Operation phase (Preparation and Maintenance of Ground Systems)

- Good location for a ground station
  1. No high buildings around the site
  2. No electromagnetic noise emission source nearby
  3. Short distance between the antenna and the radios
  4. Comfortable environment in the radio room which is **near to an office and 24-hours access**
  5. **Easy access to the antenna** for inspection and maintenance
- Periodic maintenance of antenna pointing
  – Track a known and reliable satellite
- Do not use a compass to find the north
  – The magnetic north ≠ Geographic north

Antenna is often broken

Very narrow (~10deg)

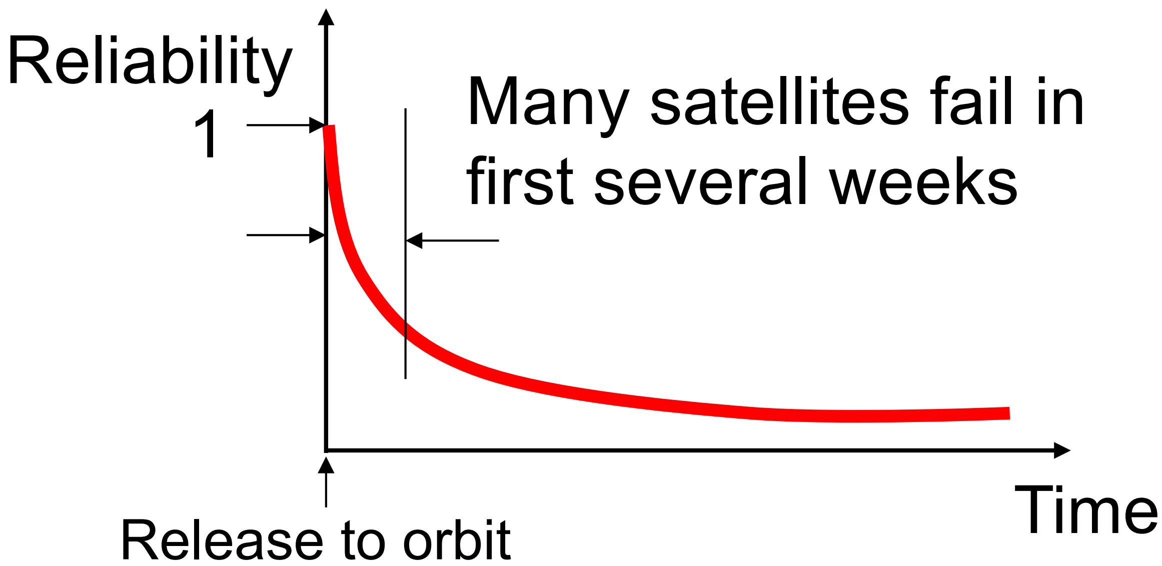
Misalignment of 10 deg matters seriously



Antenna pattern of UHF Yagi Antenna

8.2 Operation phase (Operation plan)

- Obtain the frequency license as soon as possible
  - In Japan, we get only "preliminary license" before launch. Need 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
  - Don't be relaxed with the beacon signal



8.3 Operation phase (Handling Anomaly and Failures)

- Anomaly investigation
  - Never give up
  - P/I (faculty) should keep the motivation of the team

Keep motivation

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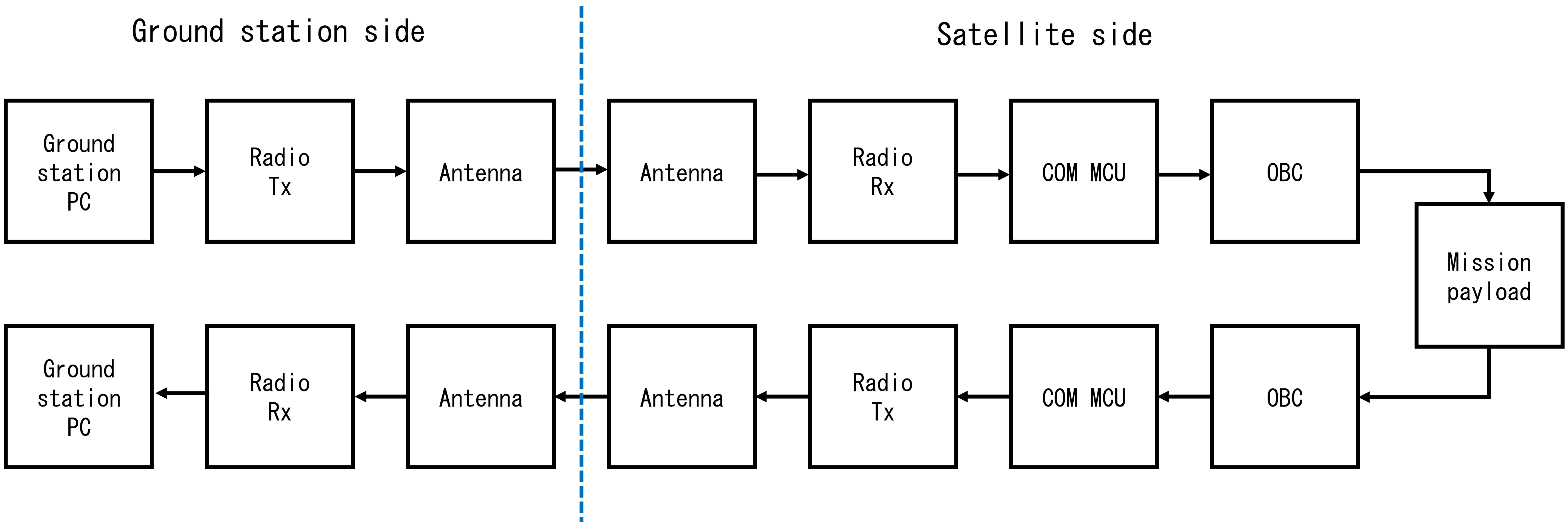
8.3 Operation phase (Handling Anomaly and Failures)

- Do thorough FTAs for the next project
- Check along the information flow



Information flow diagram

9. After Satellite Operation

Lessons Learned

Documentation

Sharing know-hows

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10. Sustainability of University Built Satellite Program

- View as a program
  - Professor engaged as a program director
  - Academic career of junior researchers
- Build and strengthen the base in university
  - Support from the university management
    - Give something to university
    - Get something from university
  - From ***a project of Professor A*** to ***a program of Professors A, B, C***, and more.
- Funding
  - Efforts by individual professors
  - No miracle
    - Money won't come from the heaven. Do something.

Conclusion

- A mission assurance handbook for university-based lean satellites published in 2022.
- Summary of points to be kept in mind by faculty members and students to improve the mission success rate.
- Many of them apply to non-Japanese universities & new space companies.
- The handbook is open to comments by the lean satellite community worldwide
- To be reviewed globally and the comments will be reflected in the next version.

Please give us your feedback!