Day #1 01.14 21:00~23:00 (JST)

KiboCUBE Academy

Lecture 1-2

Introduction to CubeSat Technologies

Tohoku University

Department of Aerospace Engineering

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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

JAXA

UNISEC JAPAN
University Space Engineering Consortium

United Nations Office for Outer Space Affairs ★ Japan Aerospace Exploration Agency
Kibo CUBE

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5. Launch Environment
6. Safety Design
7. Mission Assurance
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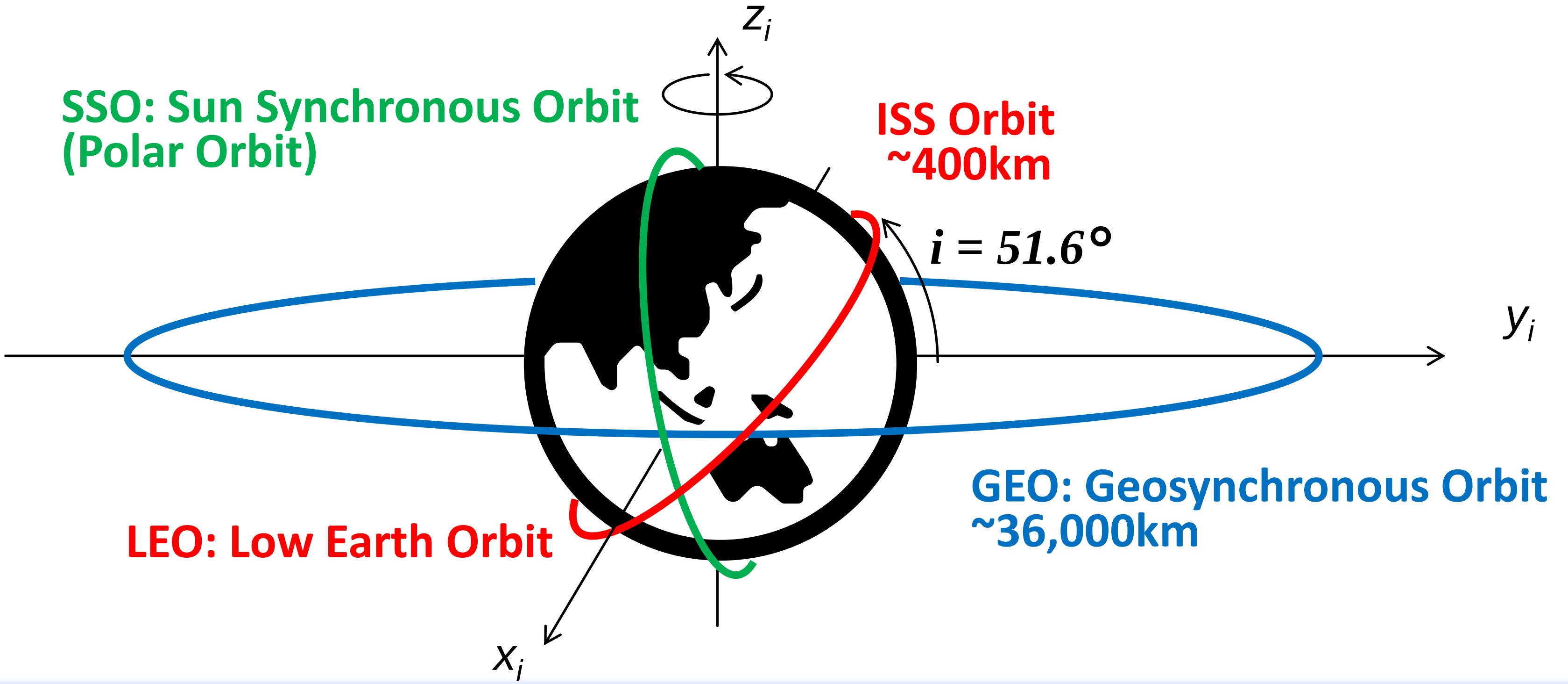
1. Introduction to Space Systems

Satellite Orbits

- There are many different types of satellite orbits.
- The most appropriate orbit for the mission needs to be selected.
  <-> Mission needs to be designed according to the available satellite orbits.

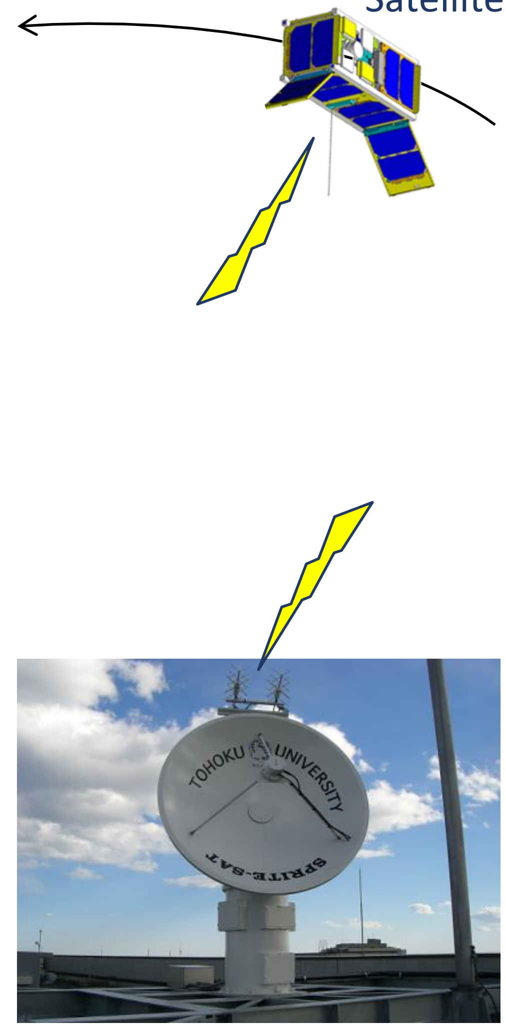


1. Introduction to Space Technologies and Utilization

Satellite Operation / Ground Station

- Satellites rotate around the Earth, about 16 times per day in the orbit of International Space Station (ISS).
- Earth also rotates once per day.
- Relative velocity between the ground station and the satellite is on the order of about 7.7 km/s.
- Satellite operator has a limited amount of time for communicating with the satellites (about 10 minutes or less per contact, several times a day).
- Satellite operator sends commands to satellites from the ground station and receives telemetry data from them.
- For satellite operation, following aspects must be considered:
  - Satellite Orbit and Mission Lifetime
  - Communication System
  - Ground Station
  - Link Budget Design
  - Operational Phase
  - Regulations

Satellite

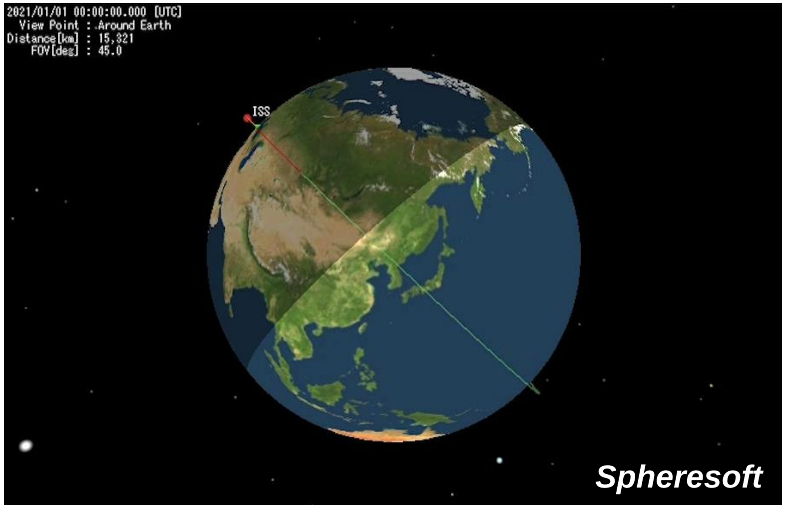


Ground Station

1. Introduction to Space Technologies and Utilization

Characteristics of Satellite Utilization

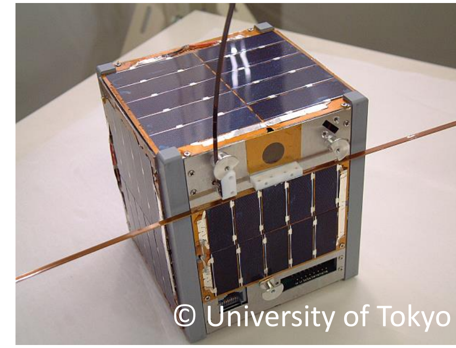
- Satellites orbiting in high-inclination orbits can cover a large portion of geographical area on Earth. This feature of global accessibility can be utilized for:
  - Earth observation: periodic, frequent observation of ground area under the satellite orbit.
  - Communication: can have communication contact with ground stations in the visible area.
  - Environmental measurement: can measure space environment, such as magnetic fields, radiations, etc.
- Higher orbit can have a wider field of view, and lower orbit can facilitate higher ground resolutions of Earth observation.
- Satellites are basically continuously "falling" toward the Earth. This free-fall micro-gravity environment can be utilized for experiments of material science, bioscience, medicine, etc.
- Space also provides unique environments such as vacuum, high radiation, strong ultraviolet light, cold and hot temperature, and existence of atomic oxygen and plasma, etc.



2. Introduction to CubeSat Systems

CubeSat Standards

- A 1U CubeSat is a 10 cm cube with a mass of up to 1.33kg.



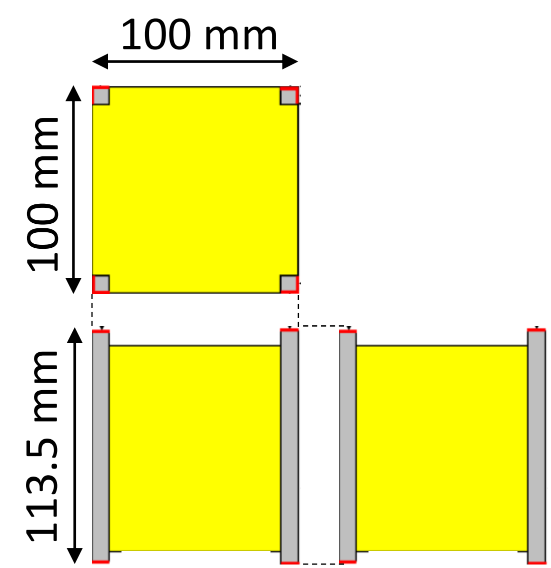
Some standards are available:

- CubeSat Design Specification rev.13
  - California Polytechnic State University (2014/2/20)
  (https://www.cubesat.org/)

- CubeSat System Interface Definition version 1.0
  - UNISEC Europe (2017/8/24)
  (http://unisec-europe.eu/wordpress/wp-content/uploads/CubeSat-Subsystem-Interface-Standard-V2.0.pdf)

- JEM* Payload Accommodation Handbook Vol.8 D (Japanese)
  - JAXA (2020/5/25)
  (https://iss.jaxa.jp/kibouser/provide/j-ssod/#sw-library)
  (https://iss.jaxa.jp/kibouser/library/item/jx-espc_8d.pdf)

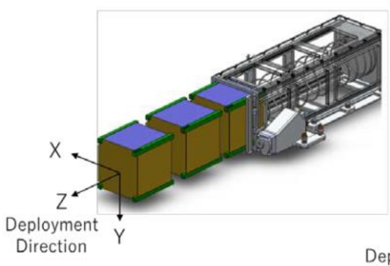
  JEM Payload Accommodation Handbook Vol.8 C (English)
  - JAXA (2018/11)
  (https://iss.jaxa.jp/kibouser/library/item/jx-espc_8c_en.pdf)
  rev. D (English) is to be released soon.

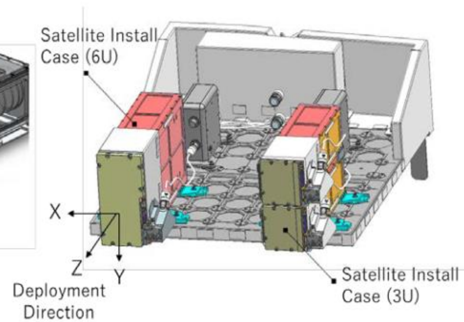


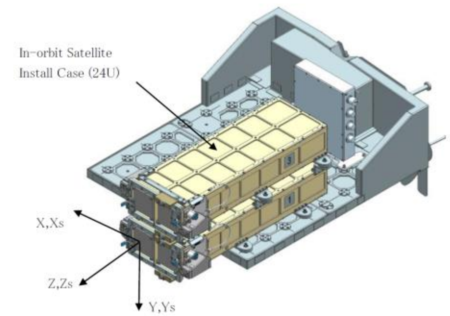
* Japanese Experiment Module (JEM) = Kibo

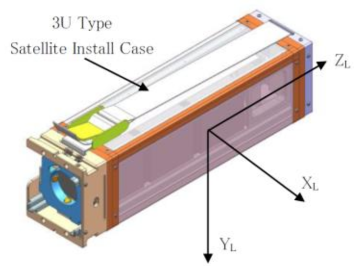
2. Introduction to CubeSat Systems

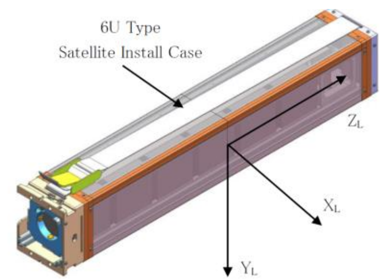
Kibo Release Opportunities











		Exterior Dimensions (*1)	Rail Dimension	CubeSat Installation	
10cm Class satellite	1U	X:100×Y:100×Z:113.5mm	More than 8.5mm squares	Ground / ISS	1U x 1U x 1U
	1.5U	X:100×Y:100×Z:170.2mm		ISS	1U x 1U x 1.5U
	2U	X:100×Y:100×Z:227.0mm		Ground / ISS	1U x 1U x 2U
	3U	X:100×Y:100×Z:340.5mm		Ground / ISS	1U x 1U x 3U
	4U	X:100×Y:100×Z:454.0mm		ISS	1U x 1U x 4U
	5U	X:100×Y:100×Z:567.5mm		ISS	1U x 1U x 5U
	6U	X:100×Y:100×Z:681.0mm		ISS	1U x 1U x 6U
	W6U	X:100×Y:226.3×Z:340.5 or 366.0mm		Ground	1U x 2U x 3U

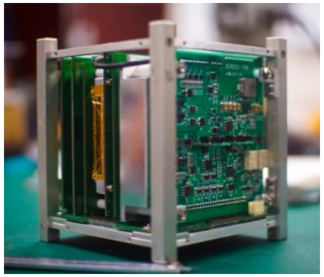
(*1) Nominal dimension including rails

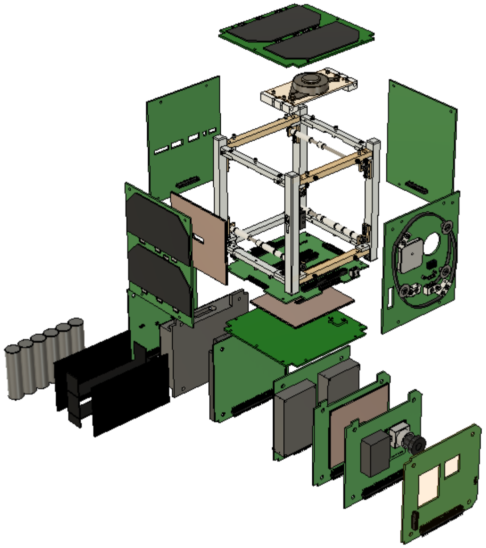
Reference: JEM Payload Accommodation Handbook Vol. 8 D (Japanese)
https://iss.jaxa.jp/kibouser/library/item/jx-espc_8d.pdf

2. Introduction to CubeSat Systems

1U CubeSat

- Best platform to learn essential engineering skills and technologies for satellite development and operation.
- A 1U CubeSat is the simplest implementation and larger formats can be selected depending on the technology level and mission requirements.
- Smaller format is mainly for fundamental functionalities and missions which require larger sensors, attitude control, and large amount of data transfer require larger formats.

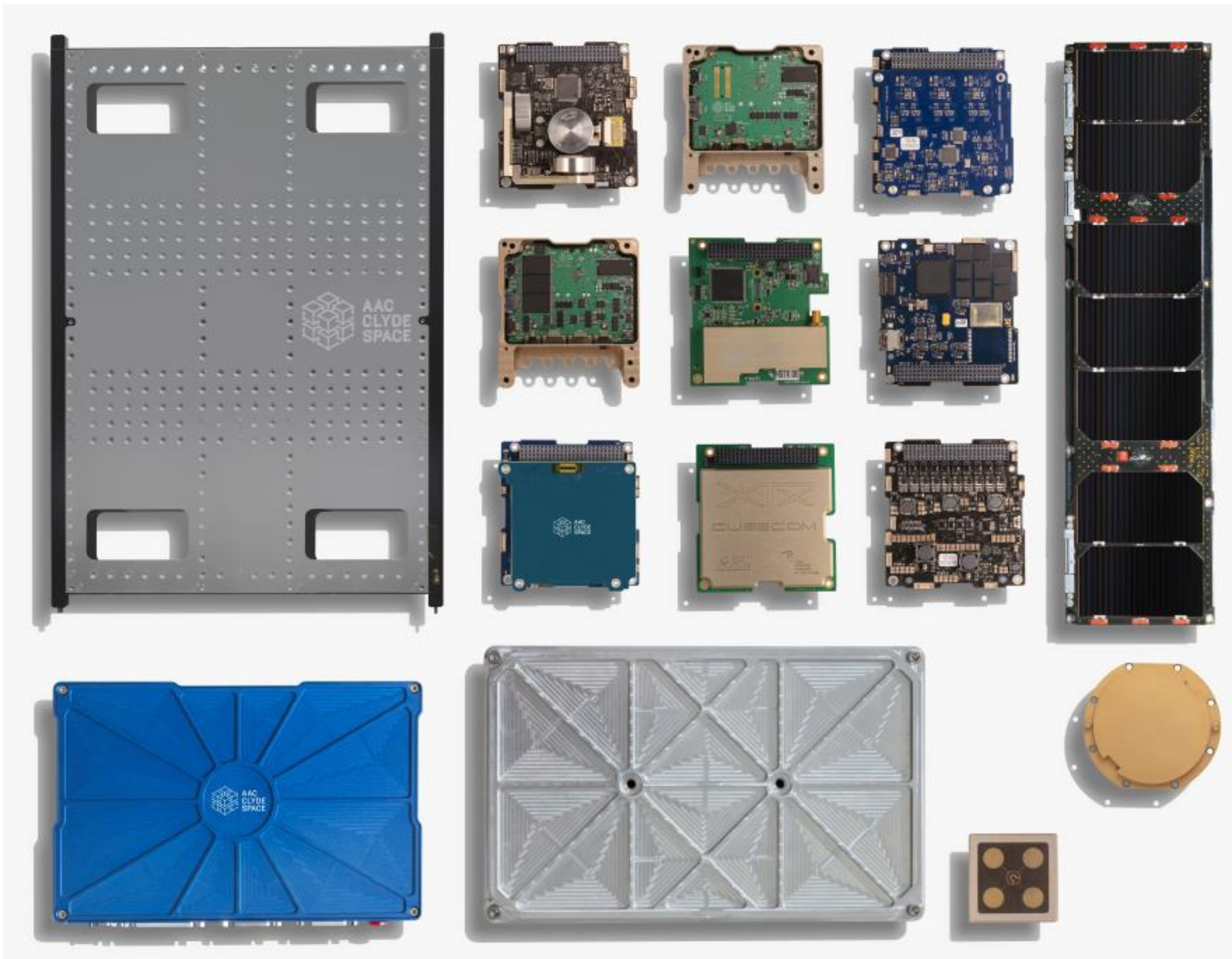




2. Introduction to CubeSat Systems

CubeSat Components

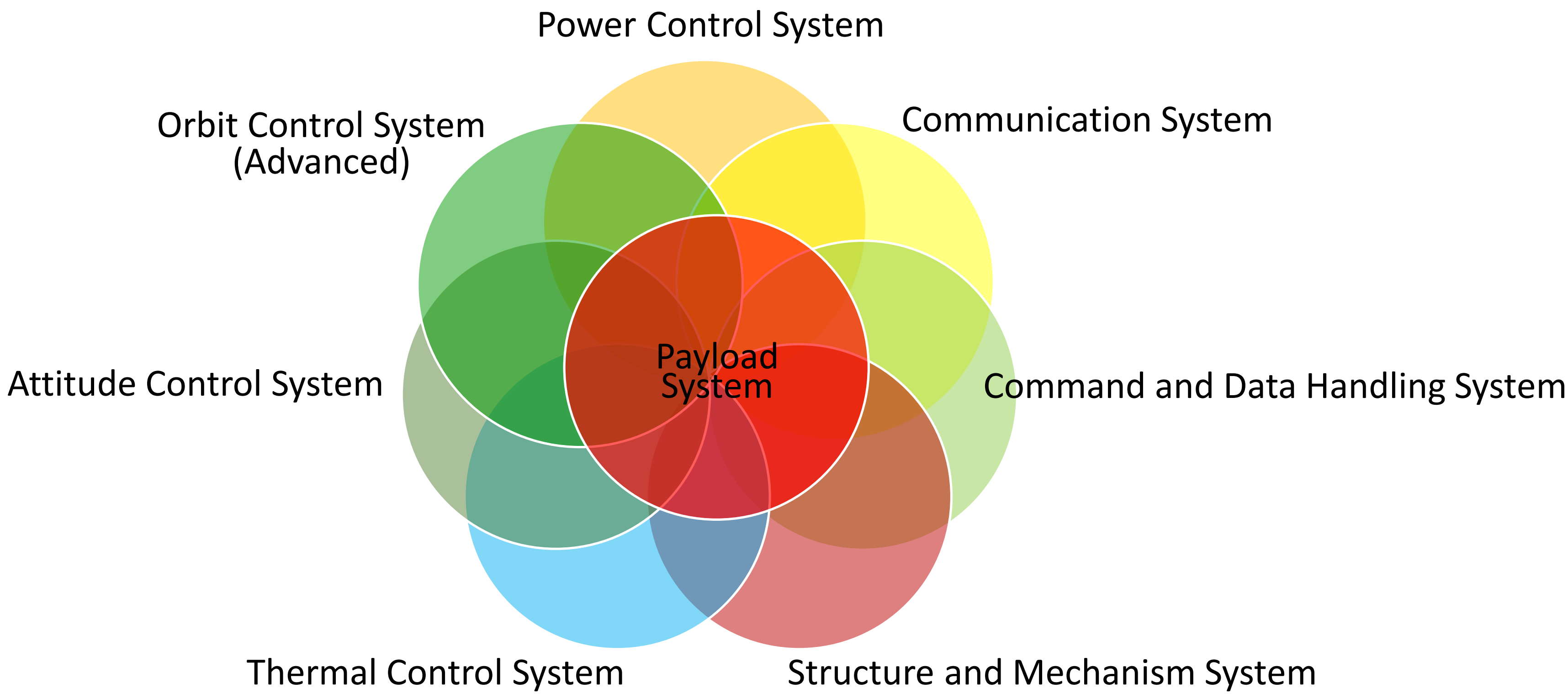
- Some CubeSat components are commercially available for quick access to space.



3. Definition of Satellite Subsystems

Satellite Subsystems

A satellite system consists of several subsystems. Typical categorization is as follows:



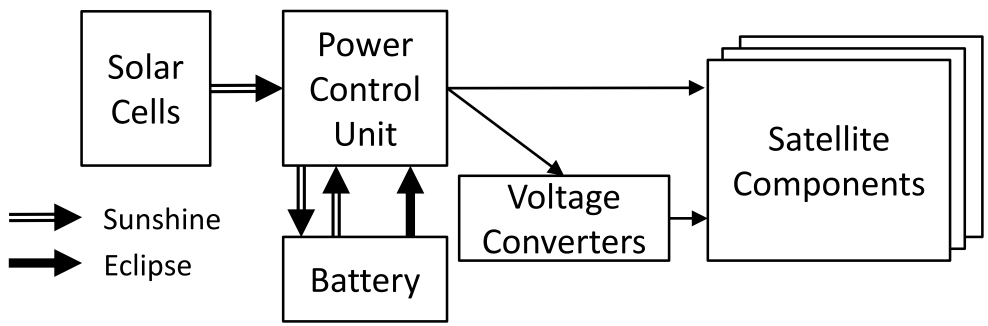
+ Harness System

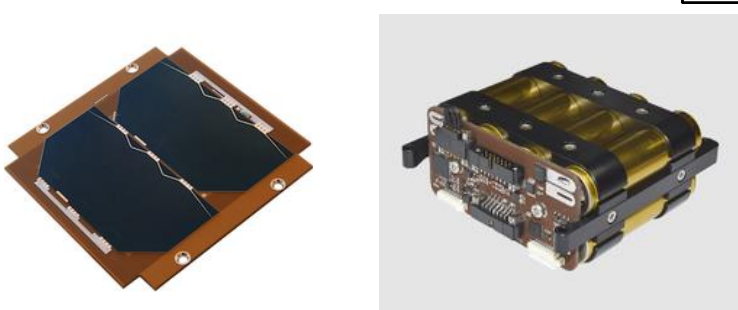
3. Definition of Satellite Subsystems

Power Control System

- Power control systems manage power generation by solar panels, storage into secondary batteries, and distribution to the satellite components.
- Power control systems shall be highly reliable, as compared to other on-board components.
- Size of solar cells and capacity of the battery shall be determined based on the power consumption requirements of the satellite mission.

Power Control System Block Diagram





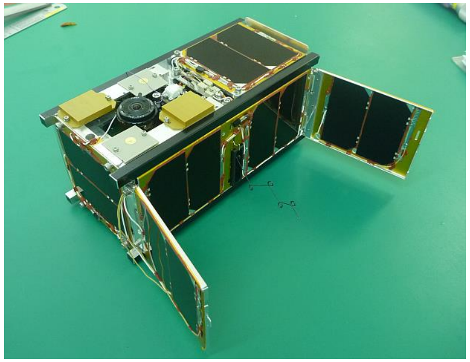
Solar Array and Battery ©GomSpace

Electrical Power Control System © AAC Clyde Space

Integrated Power management and communication system © Addnics corp.

- Example of 2U CubeSat "RAIKO"

Power		
	solar cells	ZTJ Photovoltaic Cell (>29.5% efficienty)
		2 series x 6 parallels (no paddle open)
		2 series x 10 parallels (paddle opened)
	batteries	8-cell NiMH (total 750mAH, 9.6V)
	power generation	3.19 W (avg. in sunshine, no paddle open)
		4.70 W (avg. in sunshine, paddle opened)
	power comsumption	4.90 W (communication mode)
		1.05 W (standby mode)

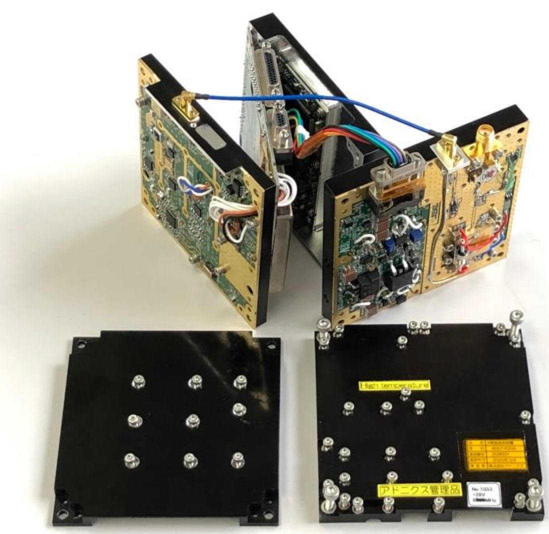


2U CubeSat RAIKO

3. Definition of Satellite Subsystems

Communication System – Transmitter/Receiver

- As the satellite operates remotely in space, information exchange through communication is indispensable to make the mission of the satellite meaningful.
- The communication throughput (amount of data), especially for the down-link, determines/limits the entire performance of the satellite system itself.
- For high-speed communication, higher electrical power is required, and the temperature of the transmitter increases. (Typically a ground contact lasts about 10 minutes or less.)
- Receiver shall be ideally powered on all the time so that the satellite doesn't miss any commands sent from the ground station. Transmitter can be turned on and off according to the ground contact schedule.
- The amount of mission data down-link can be increased by using more than one ground station if available. Collaborative satellite operation is very useful.

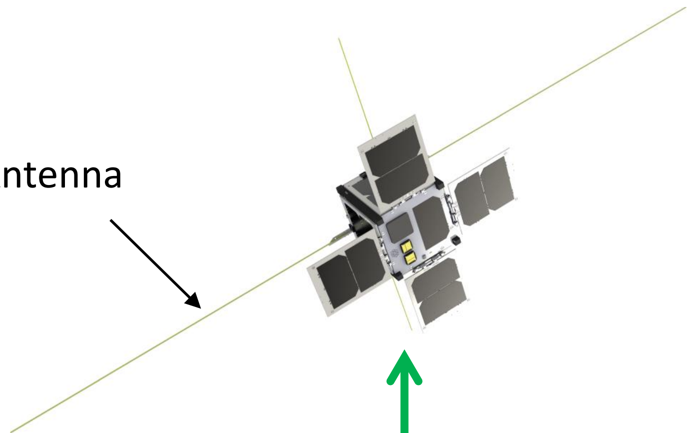


CubeSat S-band RF Transmitter and Receiver, X-band Transmitter, and inside of the X-band Transmitter (from left to right) © Addnics corp.

Communication System – Antenna

Low Frequency / Long Wavelength

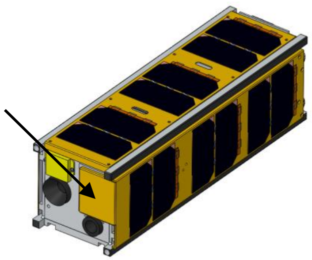
Antenna



Yagi-Antenna for VHF-band

High frequency / Short Wavelength

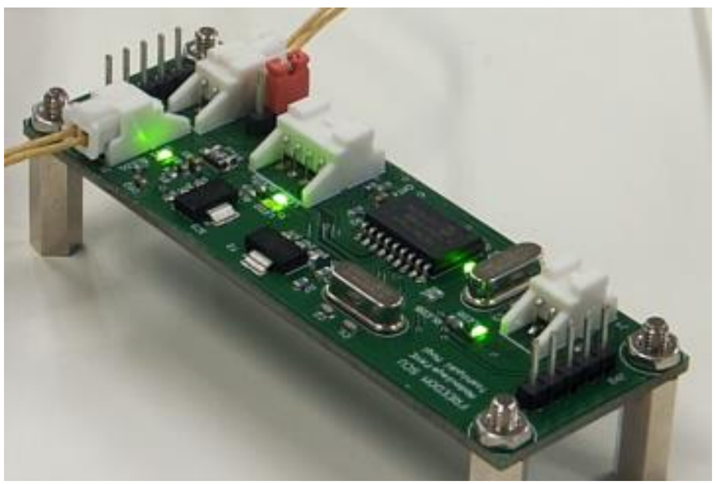
Antenna



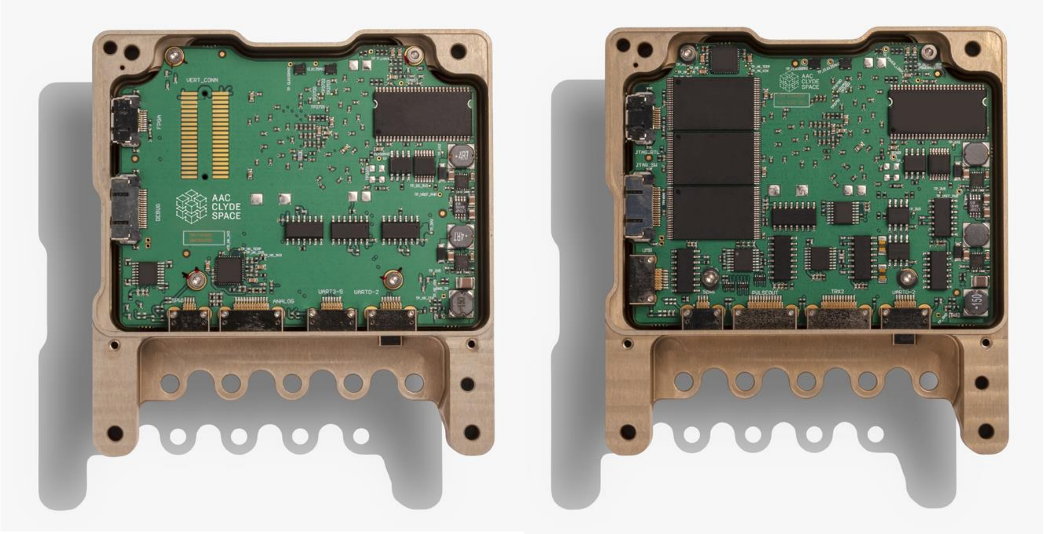
Dish-Antenna for S-Band

Command and Data Handling System

- Command and Data Handling System, often denoted as C&DH, manages data handling, components commanding/monitoring, data storage, signal processing (for communication), and error handling inside the satellite.
- Certain levels of autonomous functions need to be implemented in C&DH so that satellites can survive in the space environment.
- A high level of reliability is required for the C&DH computers. When errors occur, due to e.g. radiation effects, the power control system shall power cycle (power off and on) the computer either autonomously or by telecommand from the ground station.



PIC Computer



High-end CubeSat On-board Computers © AAC Clyde Space

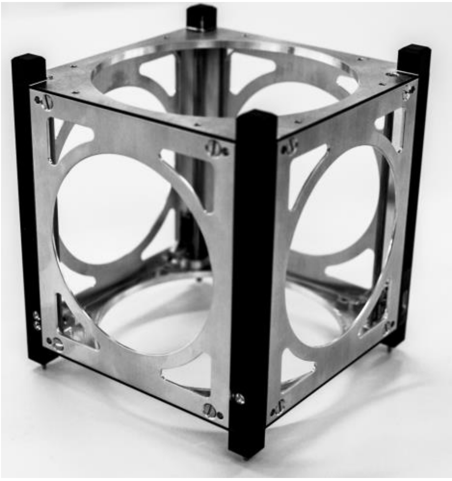
Structure and Mechanism System

Structure System

- Satellite structure system is the main interface with the launch vehicle. In case of CubeSats, the rails are the contact points between the satellite and the pod.
- The outer dimensions, surface area, and surface treatment of the rails and outer envelope of the entire satellite are specified.
- Structure system shall withstand launch environment, such as vibration, static acceleration, shock, (acoustic, air venting), etc.

Mechanical System

- Mechanical system includes separation switches, deployable antennas, deployable solar panels, shutters, booms, and any other mechanically moving elements on the satellite.
- Mechanical system shall be safely stowed during the launch to ensure the secure deployment of the CubeSat from the pod.



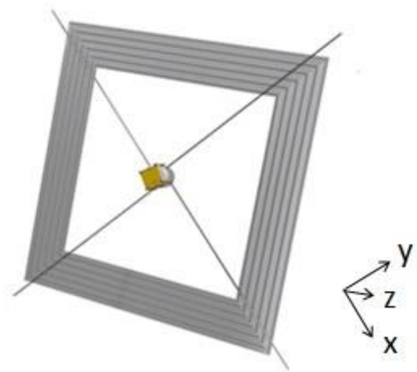
1U CubeSat Structure

Deployable Solar Panel for 3U CubeSat
© AAC Clyde Space

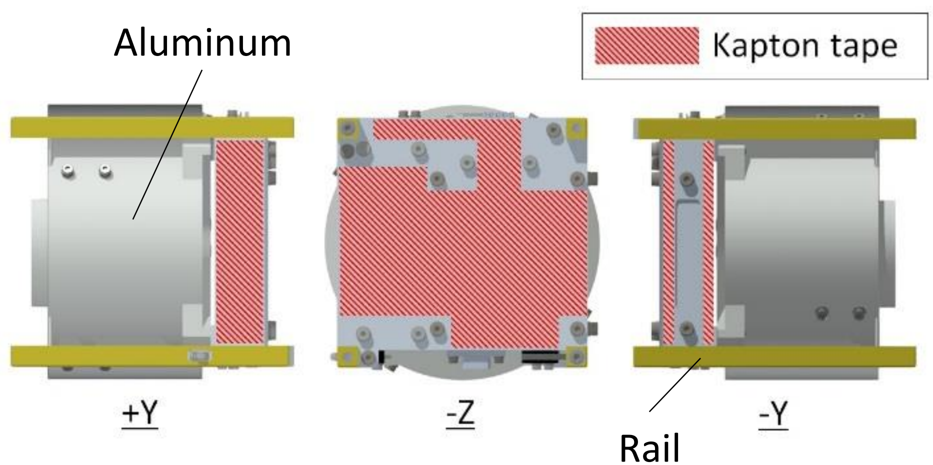
Thermal Control System

- Thermal control of a satellite can be achieved in two different ways:
  - Passive control
  - Active control
- As active control needs electrical power (heaters/coolers) in general, passive control is the usual thermal control concept of CubeSats.
- Passive thermal control utilizes different surface materials with different thermo-optical characteristics in order to adjust heat exchange between the deep space and the Earth.
- Aluminum surface contributes to warming up the temperature.
- Kapton surface contributes to cooling down the thermal condition.

1U CubeSat FREEDOM
Nakashimada Engineering Works, Ltd.

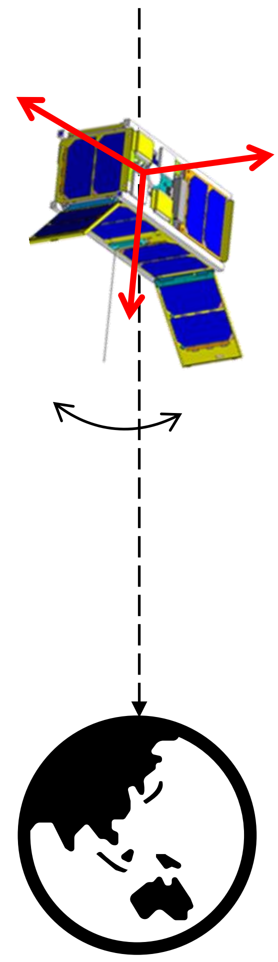


Example of 1U CubeSat "FREEDOM"



Attitude Control System

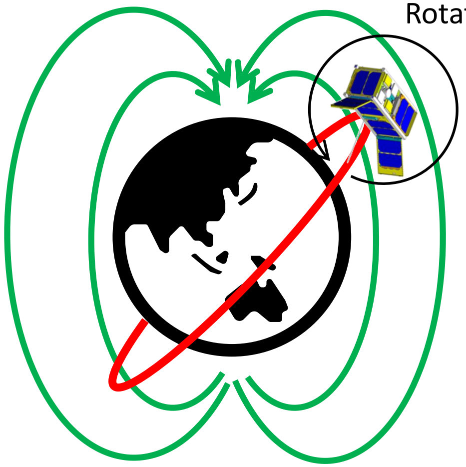
- Attitude control capability is required depending on the mission operation of the satellite, such as:
  - Pointing observation instruments toward the target
  - Pointing high-gain antenna toward the ground station for high-speed communication
  - Orienting solar panels toward the sun for larger power generation
- For the attitude control, attitude determination is also necessary beforehand, therefore attitude determination sensors and attitude control actuators are required.
- Type of attitude control
  - Passive control
  - Active control
- Attitude control modes
  - Detumbling control (after the separation from the launch vehicle or release from the ISS).
  - Pointing control: inertial, nadir, target, velocity direction, etc.



Attitude Control System – Detumbling Control

Detumbling Control

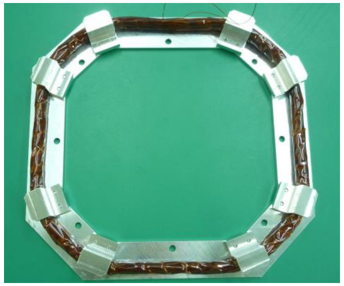
- Satellites can experience high rotational rate after the separation from the launch vehicle or deployment from the ISS.
- In general, satellites in high-speed rotation cannot communicate with the ground station properly.
- Satellites shall be able to detumble and reduce rotational speed down to about several degrees per second.



Earth Magnetic Field

Type of detumbling control

- Active control
  - Generate magnetic moment by means of magnetic torquers to interact with Earth magnetic field to actively slow down the rotational rate.
- Passive
  - Utilize permanent magnets and magnetic hysteresis dumpers to passively slow down the rotational rate.

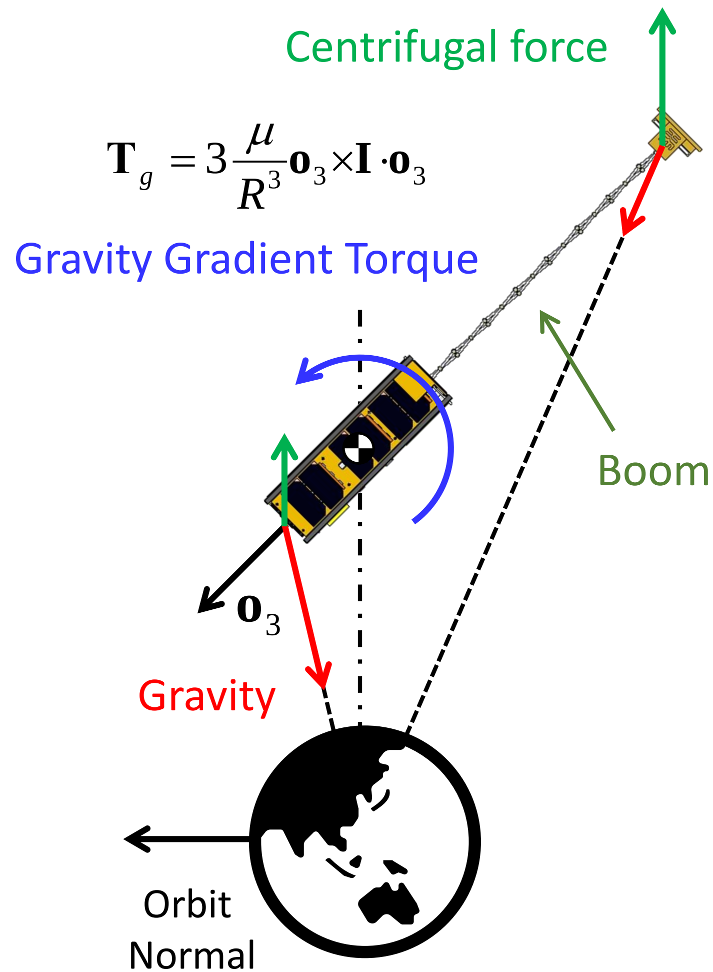


Magnetic Torquers
(Electrical Coil)

Attitude Control System – Gravity Gradient Control

Gravity Gradient Control (passive control)

- Satellites with long shapes and spread mass distribution experience gravity gradient torque such that the longitudinal direction points toward the Earth.
- Cameras, antennas, sensors can be pointed toward the Earth without additional electrical power for the attitude control.
- Pointing accuracy is relatively low.
- Can be combined with active attitude control with some attitude control actuators such as magnetic torquers and reaction wheels.



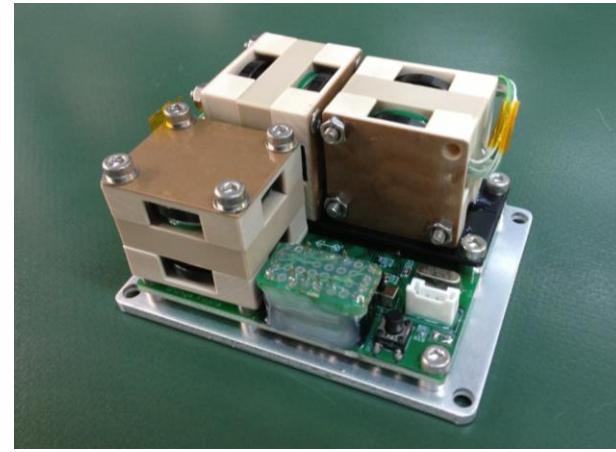
$$\mathbf{T}_g = 3\frac{\mu}{R^3}\mathbf{o}_3 \times \mathbf{I} \cdot \mathbf{o}_3$$

μ : gravitational constant, R : orbit radious

$\mathbf{o}_3$: observation vector (Z - axis)

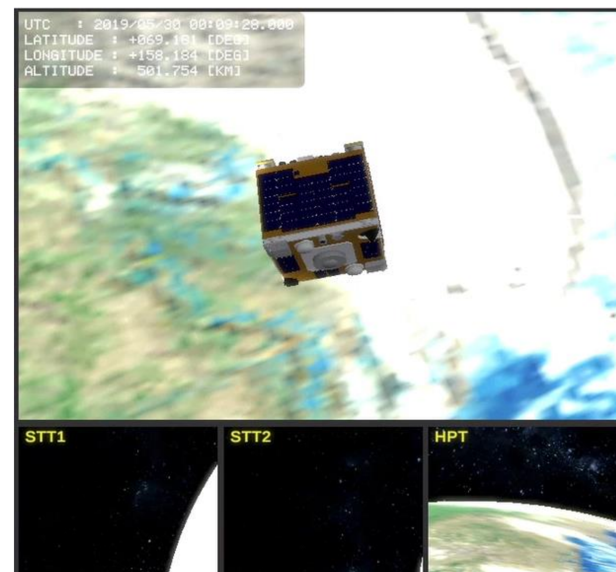
3. Definition of Satellite Subsystems

Attitude Control System – 3-axis Control



Active 3-axis Control

- Attitude control actuators such as magnetic torquers and reaction wheels are used for active 3-axis control.
- Reaction wheels can realize agile and stable attitude control.
- Disturbance torques acting on the satellite gradually accumulate as angular momentum stored in the reaction wheels. Reaction wheels cannot be operated for a long time without desaturation using magnetic torquers.
- Satellite attitude shall be determined precisely by means of a combination of attitude determination sensors.



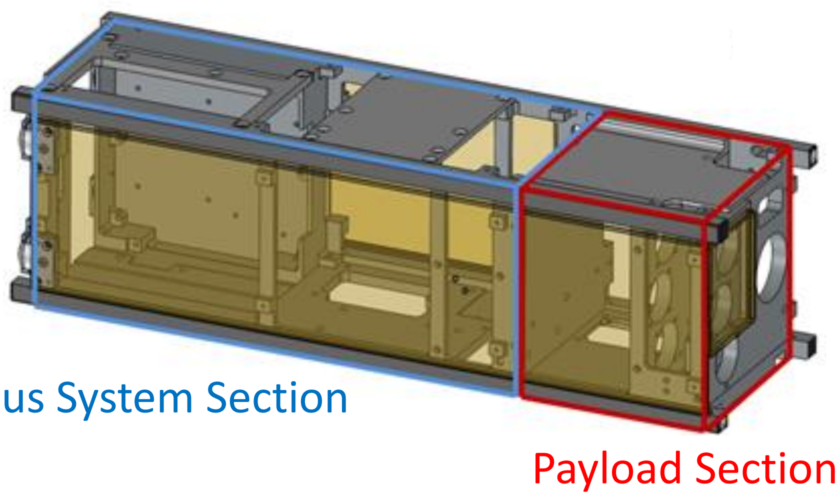
3. Definition of Satellite Subsystems

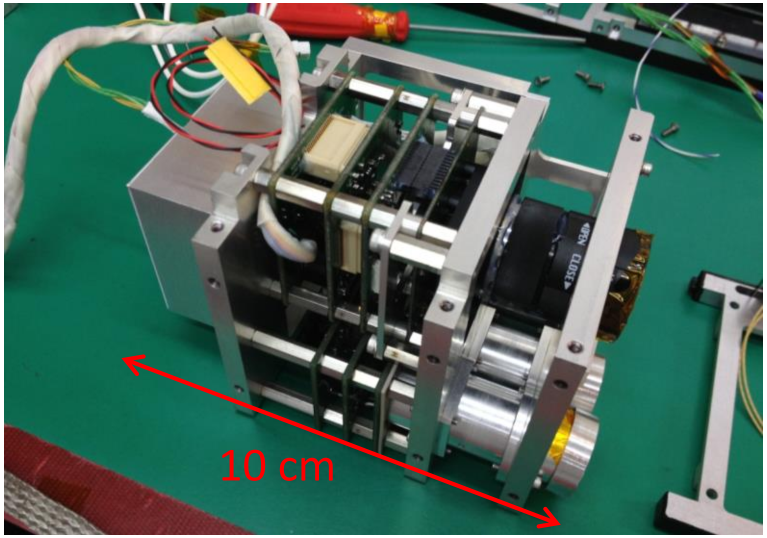
Payload System

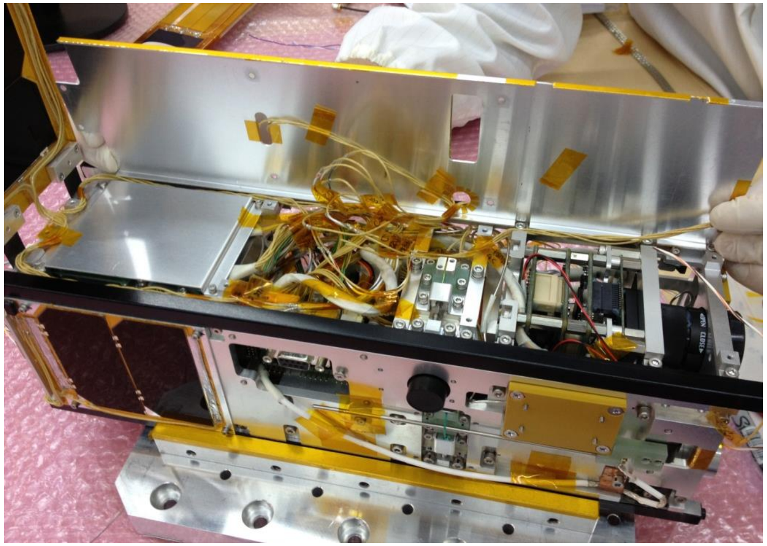
- Payload system is the on-board components dedicated to the satellite's missions.
- Good practice is to define clear interfaces (mechanical and electrical) with the bus system.

<u>Example of 3U CubeSat "S-CUBE"</u>

- 1U is assigned for the payload instruments
- 2U is assigned for satellite bus system





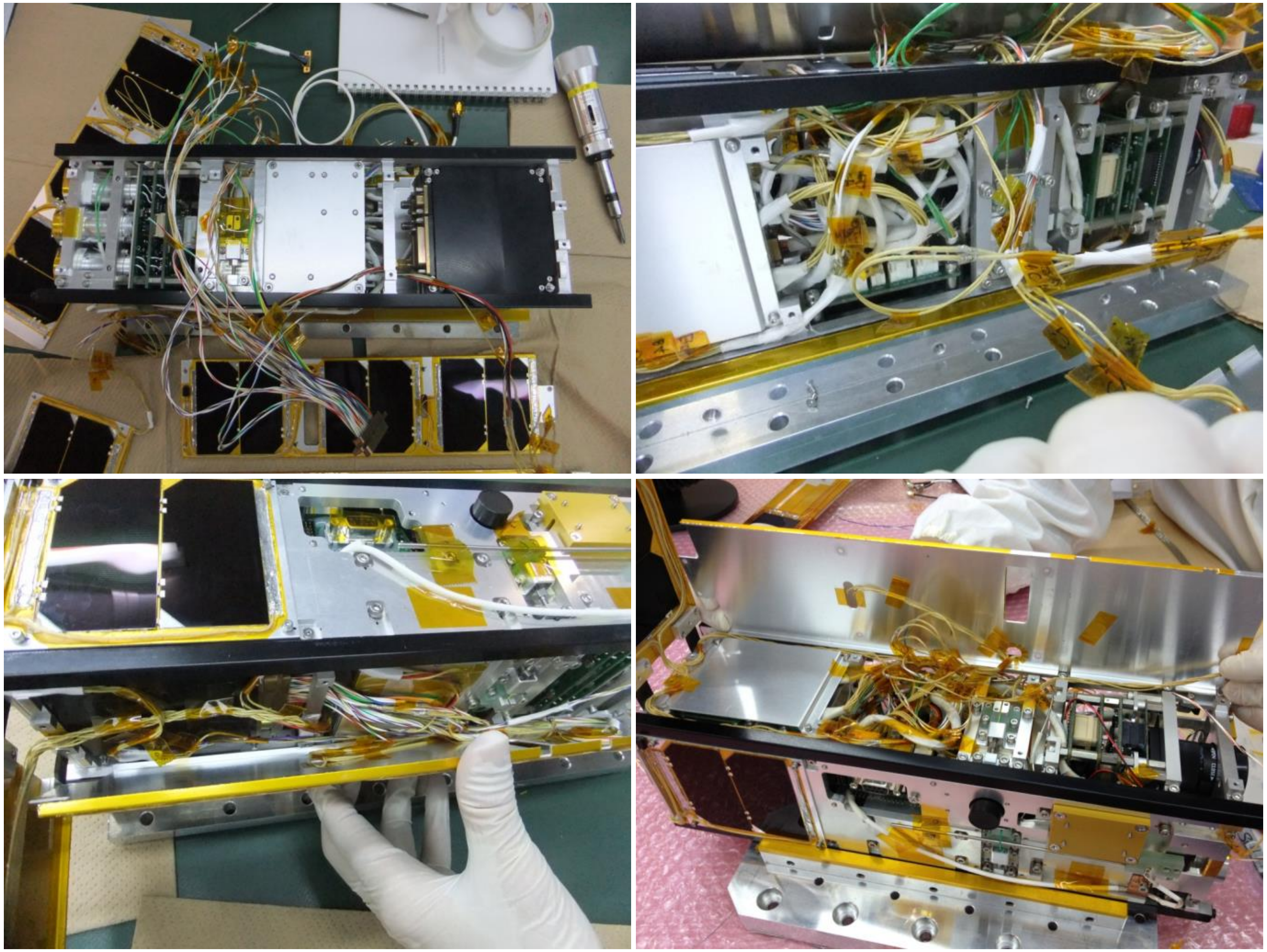


3U CubeSat S-CUBE © Chiba Institute of Technology / Tohoku University

3. Definition of Satellite Subsystems

Harness System

- Harness system is not negligible affecting the handling ability during integration.



3U CubeSat S-CUBE © Chiba Institute of Technology / Tohoku University

4. CubeSat Payload Systems

4. CubeSat Payload Systems

Types of Payload Systems

Each CubeSat has its own missions. The larger the CubeSat is, the more payload instruments can be carried and the more advanced missions can be conducted.

Examples of CubeSat payload instruments.

- Observation cameras (Earth, Planetary, Astronomy, etc.)
- In-situ space environment measurement sensors
- Meteor measurement sensors
- Communication instruments
- Engineering demonstrations
  - Deployment mechanisms
  - Advanced technologies (new sensors, electrodynamic tether, etc.)

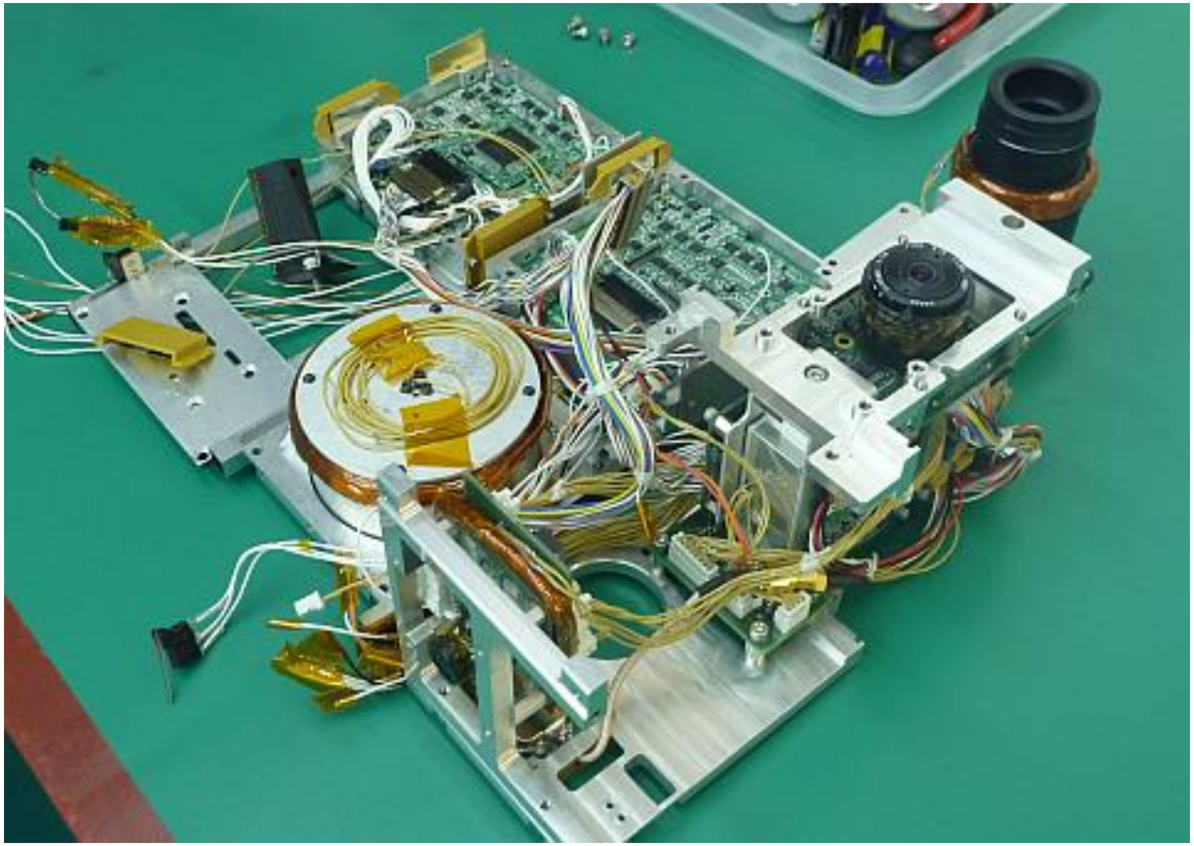
Some examples are illustrated in the following slides.

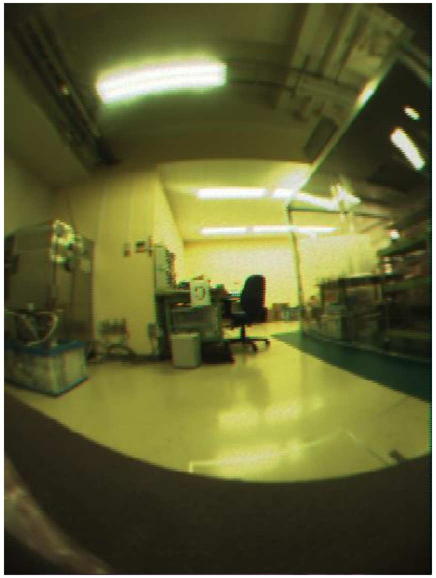
4. CubeSat Payload Systems

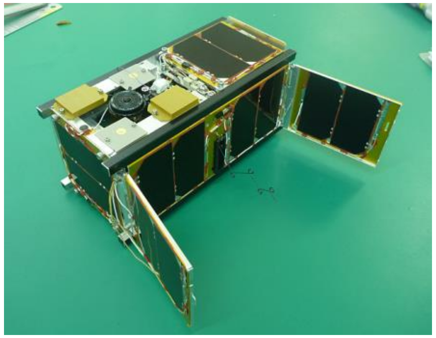
Earth Observation Camera System

Example of 2U CubeSat "RAIKO"

- Earth Observation Camera System
- New sensor: Star Tracker





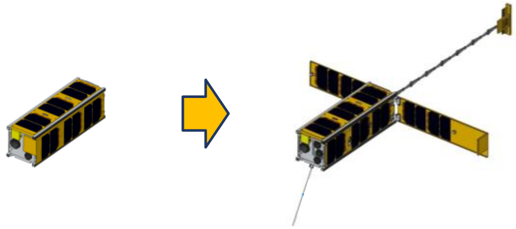


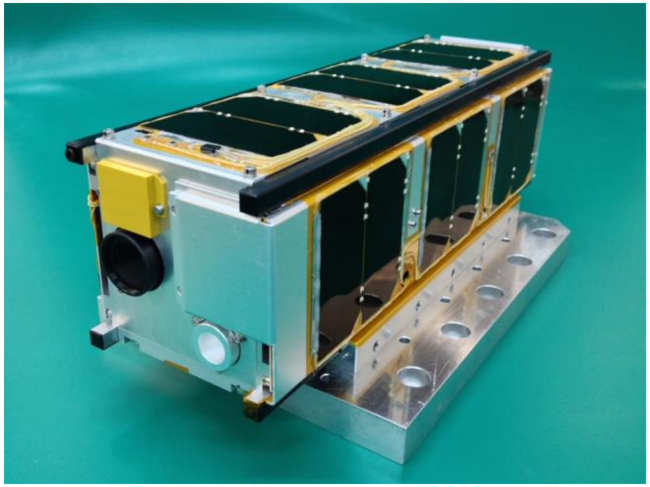
2U CubeSat RAIKO

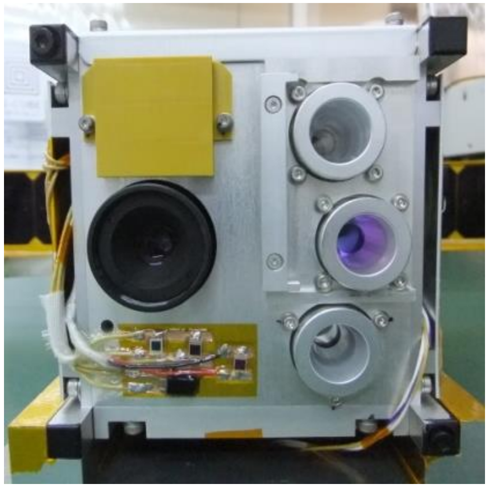
Example of 3U CubeSat “S-CUBE”

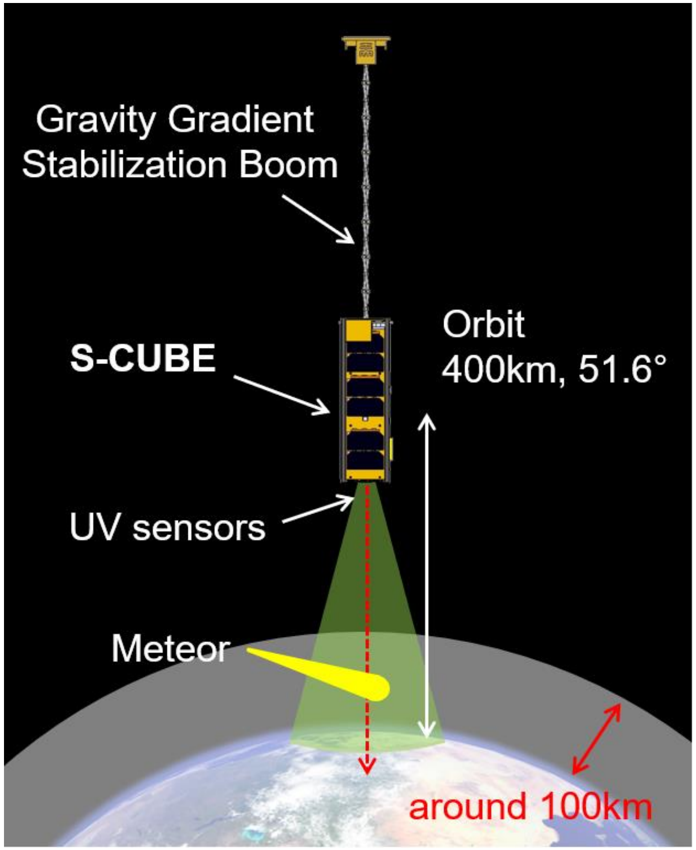
- Meteor Observation Camera System
- Gravity Gradient Boom
- Deployable Solar Panels

Gravity gradient boom was used to point the meteor observation camera toward the Earth’s atmosphere to detect incandescent meteors as they enter the atmosphere.









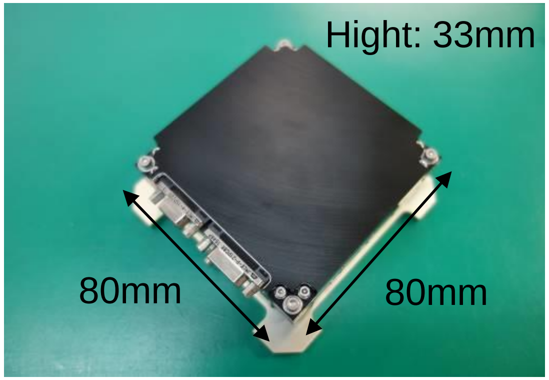
3U CubeSat S-CUBE © Chiba Institute of Technology / Tohoku University

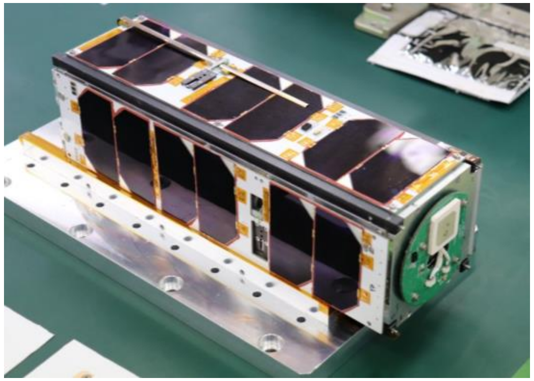
Signal Measurement Instrument

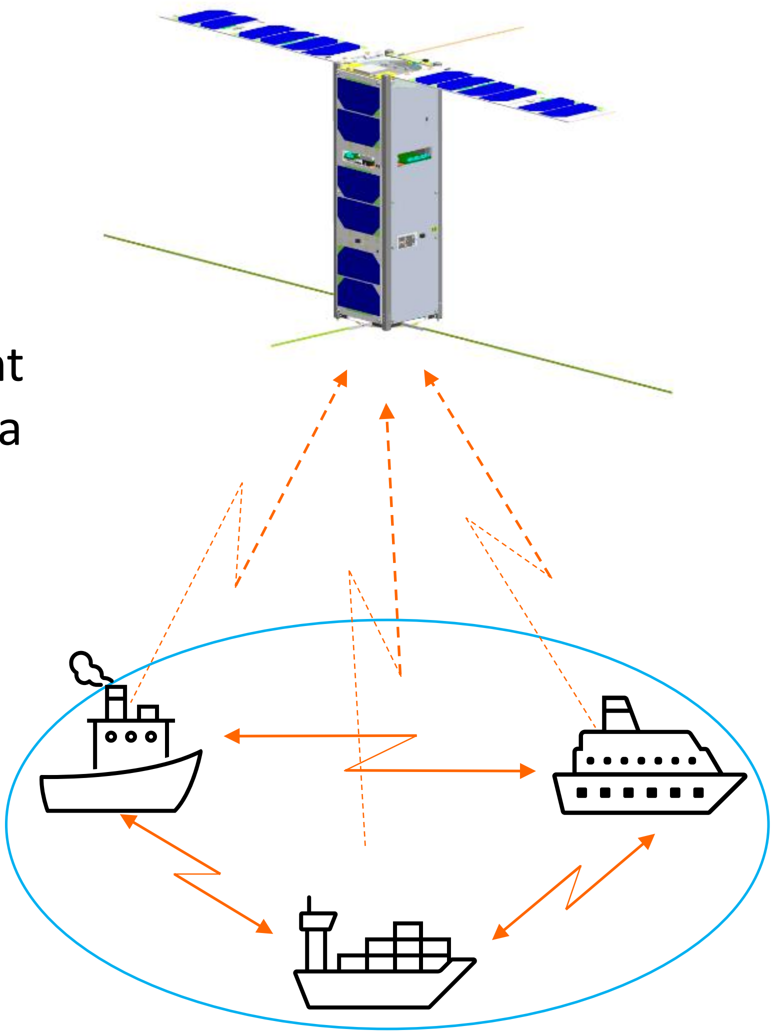
<u>Example of 3U CubeSat</u>

- AIS (Automatic Identification System) signal receiver
- Deployable directional antenna

3-axis attitude control was utilized to point the antenna toward the Earth to detect AIS signals sent from ships to track the positions of the ships with a higher geographical resolution.







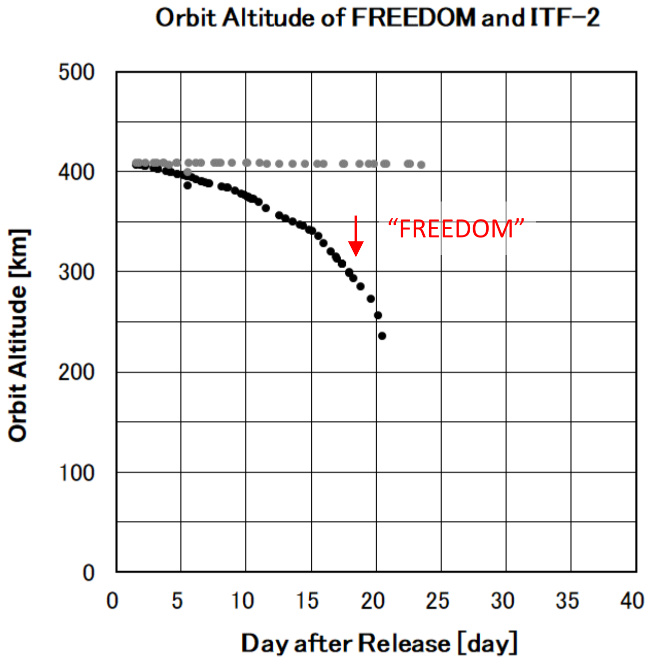
Deployment Mechanism – De-orbit Sail

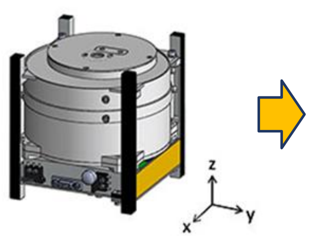
<u>Example of 1U CubeSat "FREEDOM"</u>

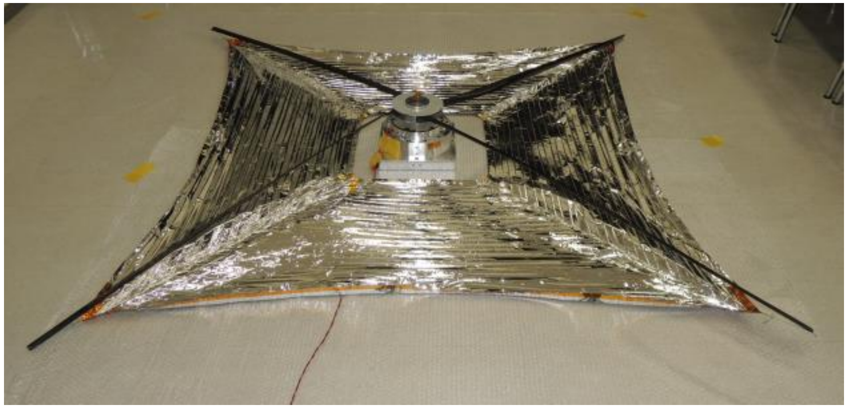
- De-orbit sail for fast de-orbiting and re-entry into Earth atmosphere from ISS orbit.
- No communication system, and solar cells.

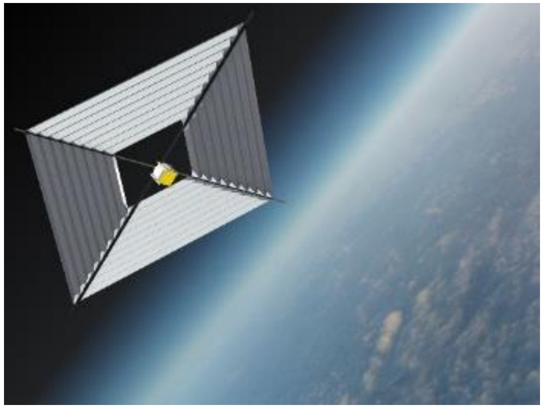
FREEDOM demonstrated on-orbit deployment of the thin-film based de-orbit sail, which can be utilized for space debris mitigation and prevention using atmospheric drag.

The successfully demonstrated device is now available for CubeSats and micro-satellites.







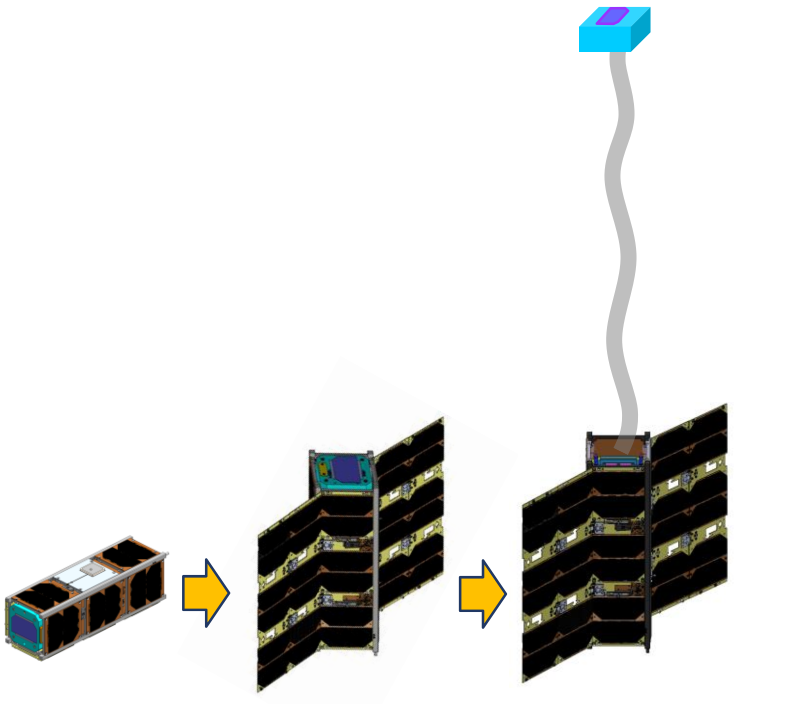


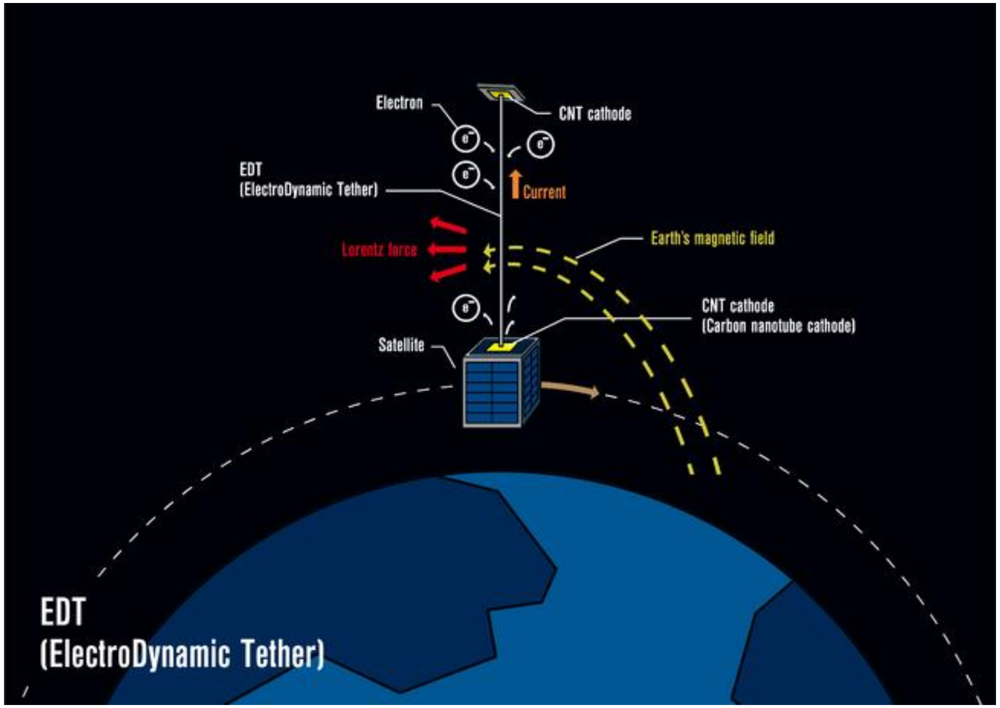
1U CubeSat FREEDOM © Nakashimada Engineering Works, Ltd. / Tohoku University

Example of 3U CubeSat "ALE-EDT"

- Electro-dynamic tether for de-orbiting and re-entry into Earth atmosphere.

3-axis attitude control is used to control the satellite attitude during the extension of the electrodynamic tether. The device will be useful for space debris mitigation and prevention in higher altitude orbits, as it can operate independent of atmospheric drag.





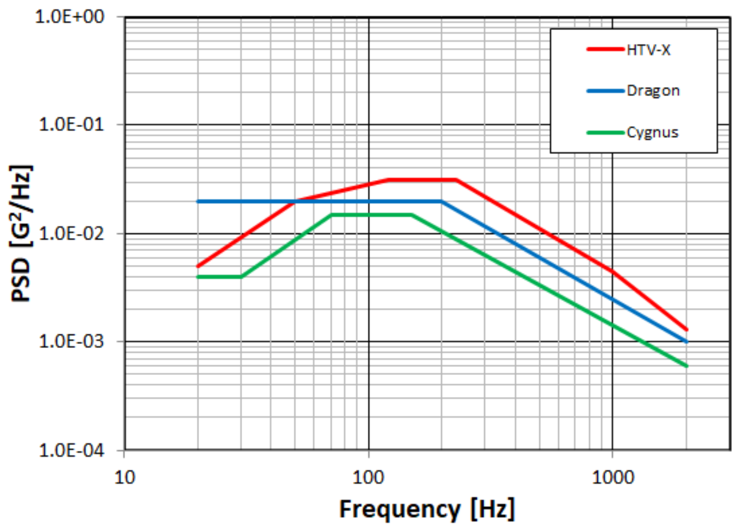
5. Launch Environment

Launch Conditions of KiboCUBE's Launch Vehicles

- Random vibration condition

Random vibration conditions of launch vehicles

HTV-X		Dragon		Cygnus	
Freq. (Hz)	PSD (g^2/Hz)	Freq. (Hz)	PSD (g^2/Hz)	Freq. (Hz)	PSD (g^2/Hz)
20	0.005	20	0.02	20	0.004
50	0.02	200	0.02	30	0.004
120	0.031	2000	0.001	70	0.015
230	0.031			150	0.015
1000	0.0045			2000	0.0006
2000	0.0013				
Overall (grms)	4.05	Overall (grms)	3.2	Overall (grms)	2.44
Duration (sec)	60	Duration (sec)	60	Duration (sec)	60



- Quasi-static acceleration condition
  - HTV-X: 6.0 [g]
  - SpaceX Dragon: 9.0 [g]
  - Orbital Cygnus: 9.0 [g]

- Shock condition
  - N/A

Reference: JEM Payload Accommodation Handbook Vol. 8 D (Japanese)
https://iss.jaxa.jp/kibouser/library/item/jx-espc_8d.pdf

5. Launch Environment

Environment Conditions: Launch and at the ISS

- Maximum Air pressures
  - HTV-X: 104.8 [kPa]
  - Dragon: 102.7 [kPa]
  - Cygnus: 104.8 [kPa]
  - Inside the ISS: 104.8 [kPa]
- Air pressure changing rates
  - HTV-X: 0.878 [kPa/sec]
  - Dragon: 0.891 [kPa/sec]
  - Cygnus: 0.891 [kPa/sec]
  - Inside the ISS: 0.878 [kPa/sec]
  - Inside the JEM Airlock: 1.0 [kPa/sec]
- Temperature conditions
  - HTV-X: +10 ~ +32 [deg C]
  - Dragon: +18.3 ~ +29.4 [deg C]
  - Cygnus: +10 ~ +46.1 [deg C]
  - Inside the ISS: +16.7 ~ +29.4 [deg C]
  - Outside the ISS: -15 ~ +60 [deg C]
- Humidity conditions (Dew Point, Relative Humidity)
  - HTV-X: -34 [deg C], N/A
  - Dragon: N/A, 25~75 [%]
  - Cygnus: +4.4 ~ +15.6 [deg C], 25~75 [%]
  - Inside the ISS: +4.4 ~ +15.6 [deg C], 25~75 [%]

Reference: JEM Payload Accommodation Handbook Vol. 8 D (Japanese)
https://iss.jaxa.jp/kibouser/library/item/jx-espc_8d.pdf

6. Safety Design

6. Safety Design

Safety Design of Satellite System

- Satellite development projects shall consider safety design aspects not only for the satellite launch phase, considering the launch vehicle and other satellites being launched by the same vehicle, but also for the development and handling on ground, considering the ground facilities, personnel, and equipment, and handling on the ISS by the astronauts and with other instruments.
- The safety design plan, implementation, and verification results shall be reviewed by the launch vehicle's safety board.
- For critical hazard sources, design requirement of "two fault tolerance = triple redundant inhibits" shall be applied, which ensures that the safety is guaranteed even if two faults occur at the same time.
- Safety design requirements can greatly affect the system design of the satellite, and hence they shall be considered from the very beginning of the satellite project.
- Safety design requirements depend on launch vehicles.
- JAXA provides management and engineering requirement documents for safety and mission assurance, called "JERG," linked below:

JERG: (https://sma.jaxa.jp/en/TechDoc/index.html)

6. Safety Design

Safety Design of Satellite System – Hazards Identification

- Safety design begins with identifying the possible sources of hazards.
- Hazards can be classified into "Standard Hazards," that are common for general satellite systems, and "Unique Hazards," that are unique for each satellite system.

Standard hazards:

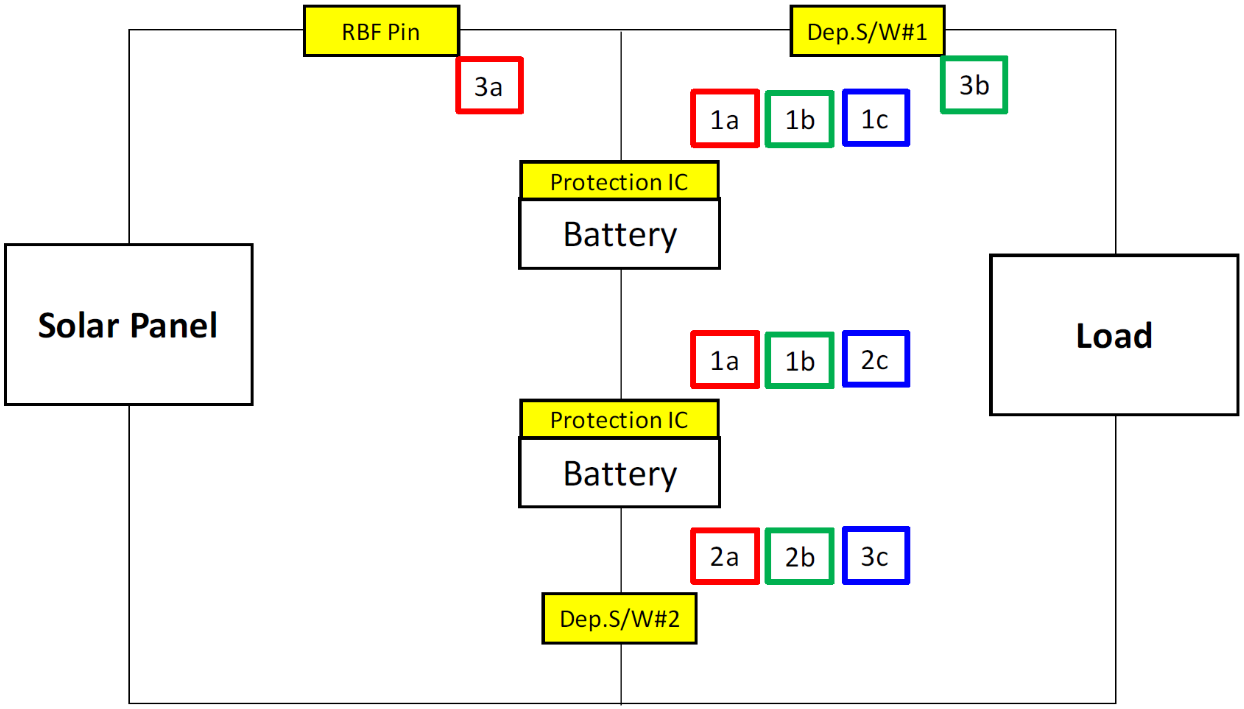
- Ignition of Flammable Material
- Material Offgassing
- Dust, Toxic, or Biological Hazardous Material
- Sharp Particles
- Mechanical Hazards and Translation Path Obstructions
- LASER
- Circuit Protection Devices
- Radio Frequency
- Rotating Equipment
- Sealed Container
- etc.

Unique hazards:

- Structure failure
- Deployment mechanisms
- Shatterable materials (glasses, etc.)
- Handling of heavy items, specifically utilized for the satellite, such as satellite itself, transport container, etc.
- Electrical short circuit of batteries.
- Unexpected radio frequency emission.

6. Safety Design

Example of "Two Fault Tolerance" Design



Hazard	Inhibit #1	Inhibit #2	Inhibit #3
Overcharge	Protection IC[1a]	Dep.S/W#2 [2a]	RBF Pin [3a]
Overdischarge	Protection IC[1b]	Dep.S/W#2 [2b]	Dep.S/W#1 [3b]
External Short	Protection IC [1c]	Protection IC[2c]	Dep.S/W#2 [3c]

Note：Safety design depends on each satellite.

Reference: JEM Payload Accommodation Handbook Vol. 8 D (Japanese)
https://iss.jaxa.jp/kibouser/library/item/jx-espc_8d.pdf

6. Safety Design

Safety and Design Reviews

Satellite projects experience several design reviews.

- JAXA Safety Review (Phase 0/I/II/III)
  - Phase 0/I: preliminary design review (not mandatory)
  - Phase II: detailed design phase (design and verification plan)
  - Phase III: acceptance test phase (verification results)

  *SAR (Safety Assessment Report) shall be submitted to JAXA for the reviews

- JAXA Compatibility Verification Review
  - Confirmation of the compatibility of the satellite verification results with the requirements from JAXA before the delivery.

- Japanese Cabinet Office Safety Review
  - Satellites with Japanese nationalities and or operated from Japan needs to be safety reviewed by the Japanese Cabinet Office.

7. Mission Assurance

7. Mission Assurance

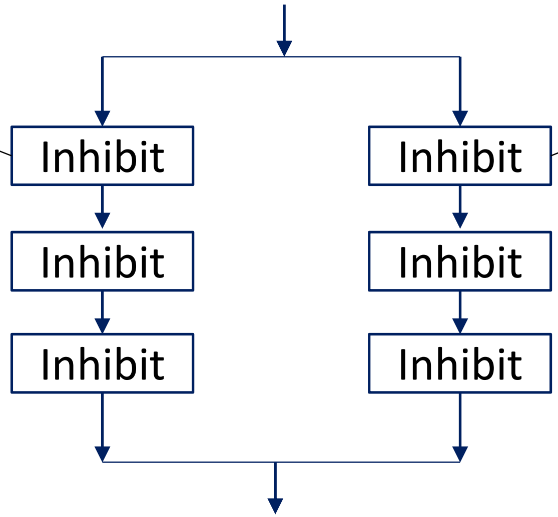
System Reliability

- Satellite projects shall conduct activities to maximize the probabilities of mission success, by mitigating any risks that threaten mission success, such as design failure, production failure, test and verification failures, etc.
- Safety design requirements necessitate satellite systems to be equipped with redundant inhibits for the safety of the surrounding environment of the satellite, which could result in excess restriction of the satellite functionalities.
- Satellite project shall find the best balance between the safety design and mission assurance within the limited resources of the satellite system, as well as the project.

Two Fault Tolerance against the hazard

All three components shall function properly for mission success

Mission reliability Is decreased!



Redundant Implementation can increase mission reliability

System trade-off is important!

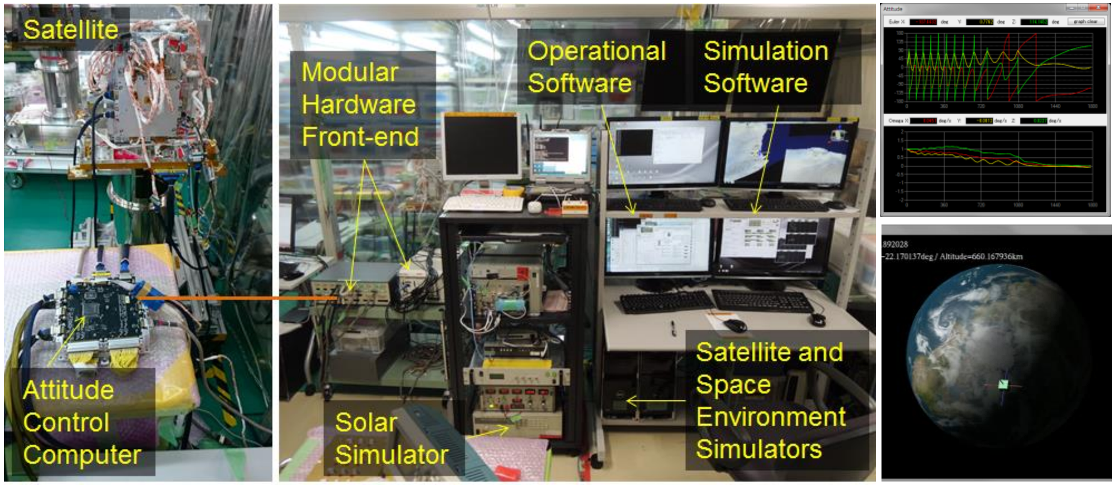
7. Mission Assurance

Importance of Ground Evaluation

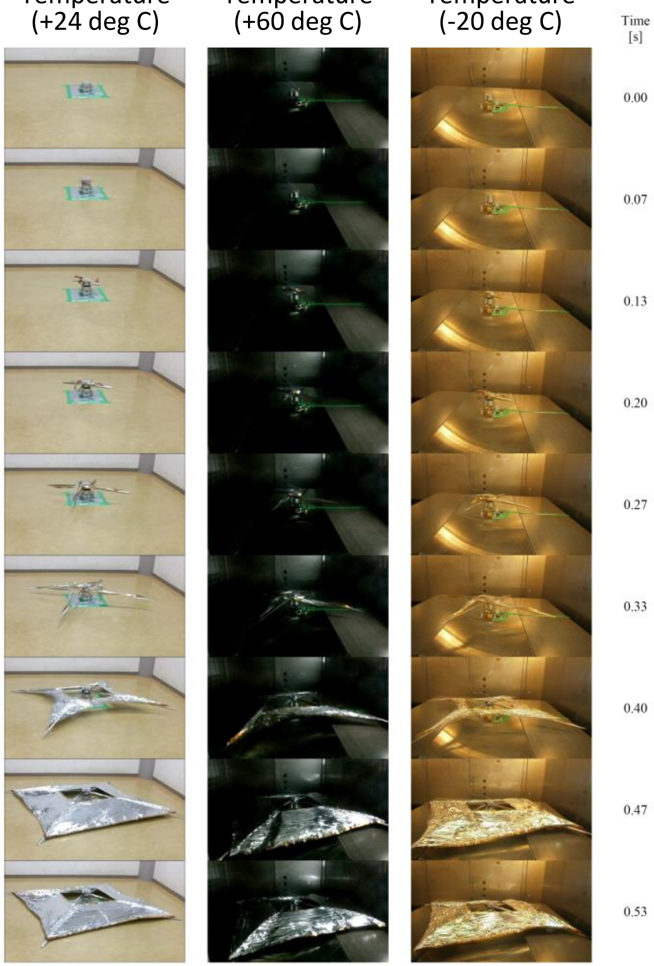
For mission assurance, ground evaluation through tests is very important.

- Electrical test
- Functional test
- Deployment test
- Environmental test
- End-to-end test
- Software simulations
- etc.

Ground Simulation Environment



Deployment Test of Drag-Sail



7. Mission Assurance

Sharing Lessons Learned is Important!

University Space Engineering Consortium, since 2003

UNISEC-Global – Worldwide Space Engineering Community

- Non-Governmental Organization consisting of University Consortiums around the world.
- Established in 2013.
- Permanent observer status of UNCOPUOS (The United Nations committee on the Peaceful Uses of Outer Space) since 2017
- Aim to create a world where space science and technology is used by individuals and institutions in every country and offers opportunities across the whole structure of society for peaceful purposes and for the benefit of humankind.

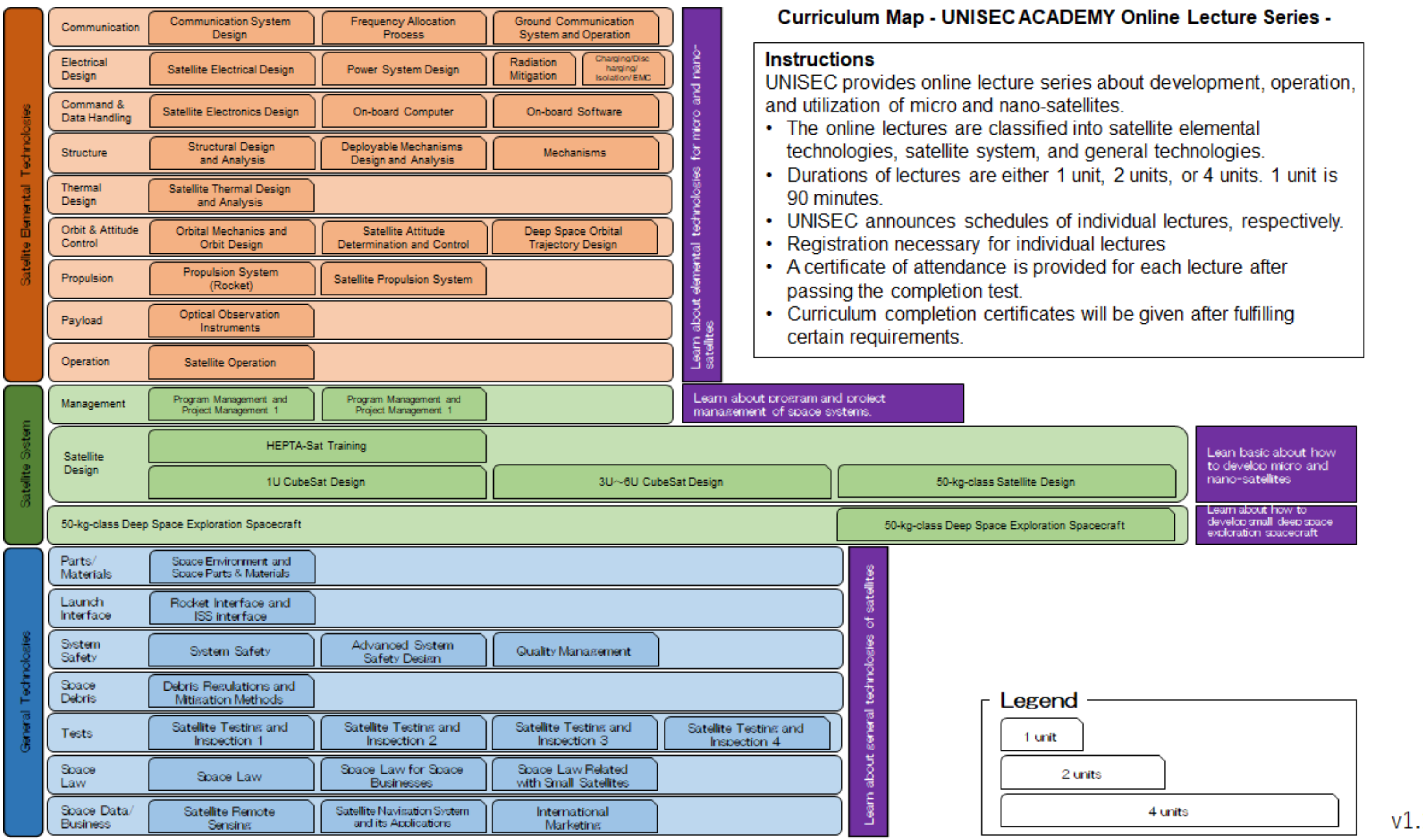
19 Local Chapters with 54 POC.

Vision 2030-All

"By the end of 2030, let's create a world where university students can participate in practical space projects in all countries."

Unisec Academy – Curriculum for Space Development/Utilization

- UNISEC is offering a series of lectures for space development and utilization in Japanese. English curriculum is coming soon.



7. Conclusion

7. Conclusion

- Characteristics of Satellite technologies and CubeSat systems are described and available CubeSat standards are introduced.
- The functionalities of each satellite subsystem, including the payload system, are described in detail.
- Some examples of CubeSat payload devices are provided together with real satellite projects.
- Environmental conditions during launch and at the ISS are summarized.
- Necessity and importance of the safety design activity for satellite projects are described and the required review processes and an example of "two fault tolerance" design are explained.
- Importance of mission assurance and necessary trade-offs are explained. Space engineering and education activities of UNISEC, as well as its space engineering curriculum are introduced.

Thank you very much.