Day #4 02.04 21:00~23:00 (JST)

KiboCUBE Academy

Lecture 4-1

Satellite Operation and Related Regulations

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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

Contents

1. Introduction to Satellite Operation

1. Introduction to Satellite Operation

What do you need to think about for the operation of YOUR satellite?

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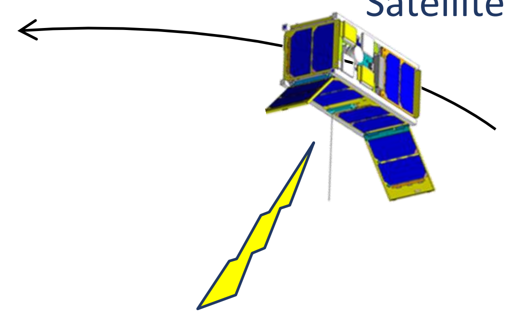
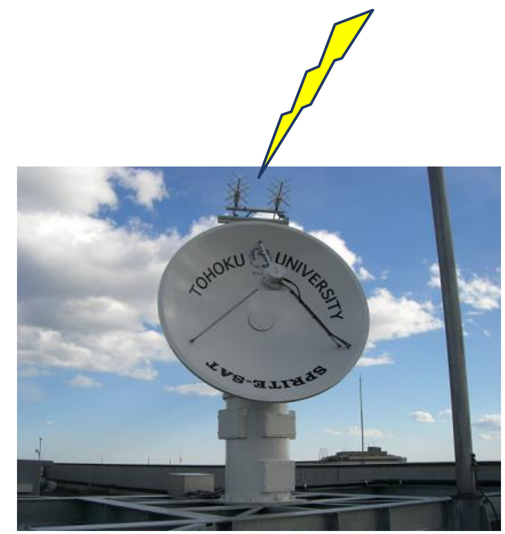
1. Introduction to Satellite Operation

Satellite Orbit and Related Aspects

- Satellites rotate around the Earth, typically about 16 times per day in LEO (Low Earth Orbit).
- 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 limited period of time for the communication 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, the following aspects must be considered:
  - Satellite Orbit and Mission Lifetime
  - Communication System
  - Ground Station
  - Link Budget Design
  - Operational Phase
  - Regulations

Satellite

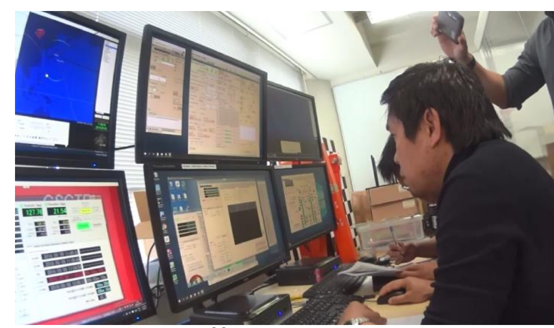




Ground Station

- Satellites cannot be repaired in orbit after they are launched. You can only communicate with them in order to conduct planned missions, solve unexpected problems, and even upgrade the functionalities.
- Satellites need to be self-sustaining in orbit.
  - Power generation, storage, and management
  - Thermal control
  - Communication
  - Attitude determination and control
  - Data handling
  - Mission control
- Thorough operational scenarios and procedures need to be developed and the satellite operators need to be well trained before the launch.

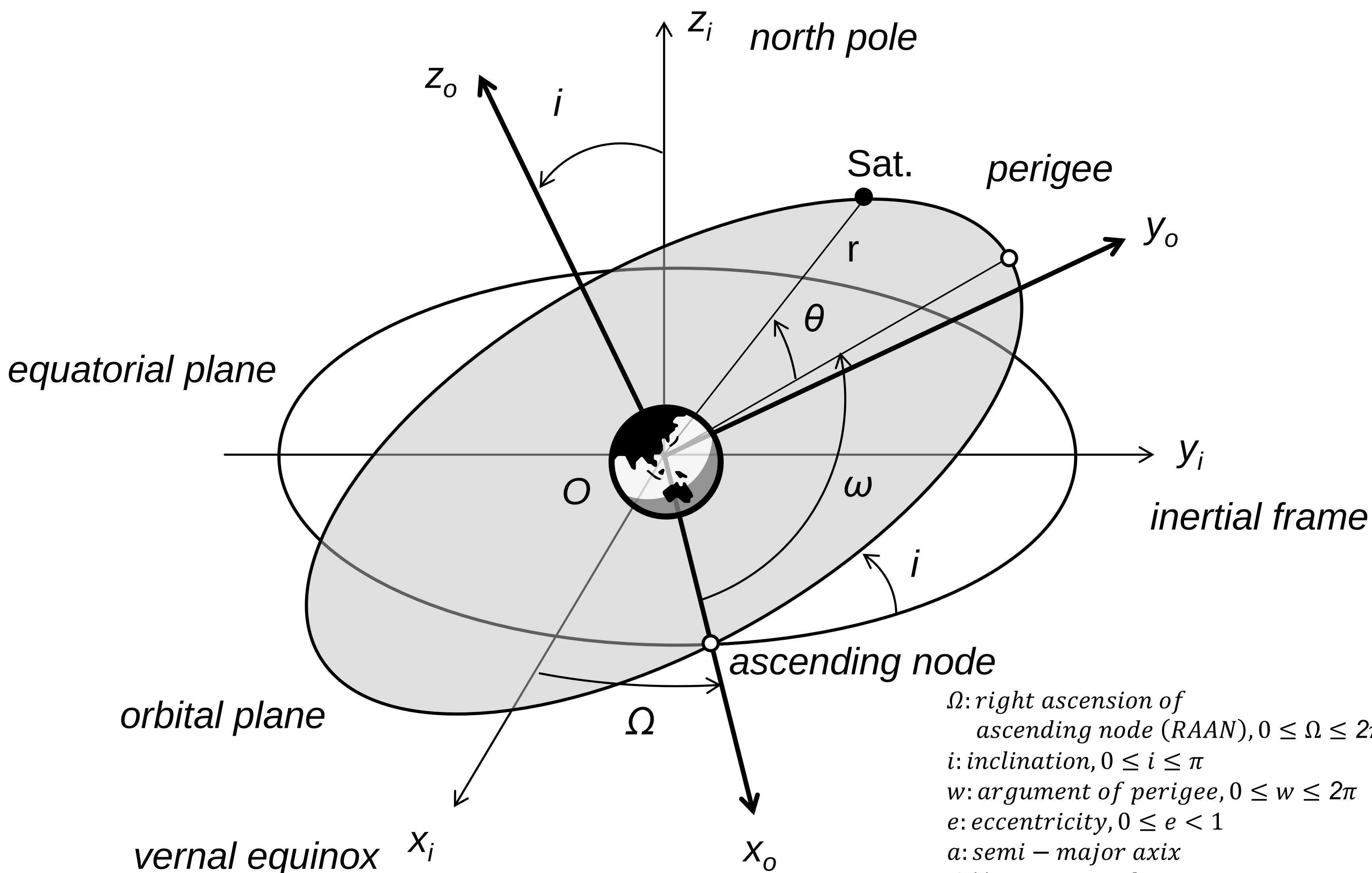
2U CubeSat RAIKO



Satellite Operators

2. Satellite Orbit and Mission Lifetime

Orbital Mechanics



Ω: right ascension of ascending node (RAAN), $0 \leq \Omega \leq 2\pi$

i: inclination, $0 \leq i \leq \pi$

w: argument of perigee, $0 \leq w \leq 2\pi$

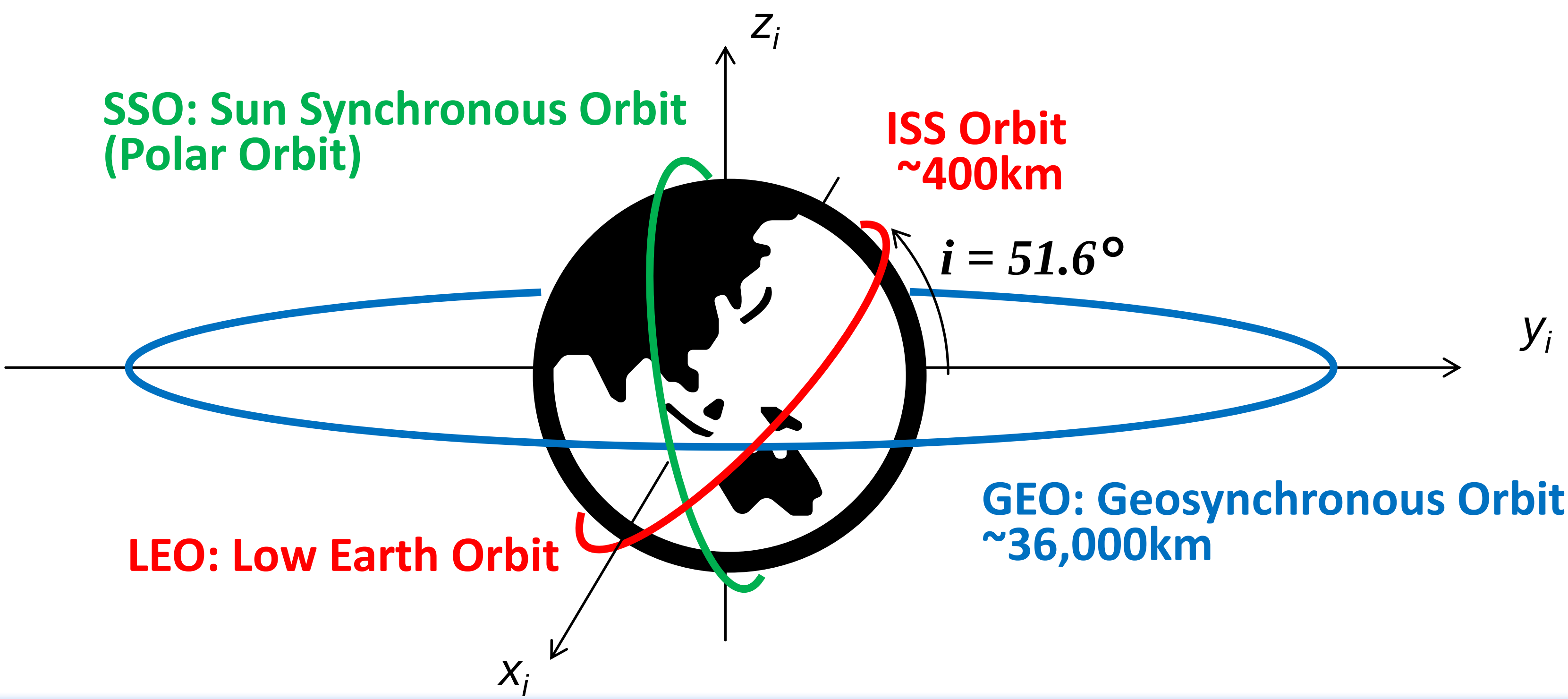
e: eccentricity, $0 \leq e < 1$

a: semi − major axix

$\theta(t)$: true anomaly

Type of Satellite Orbit

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

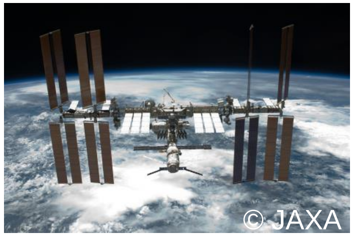


2. Satellite Orbit and Mission Lifetime

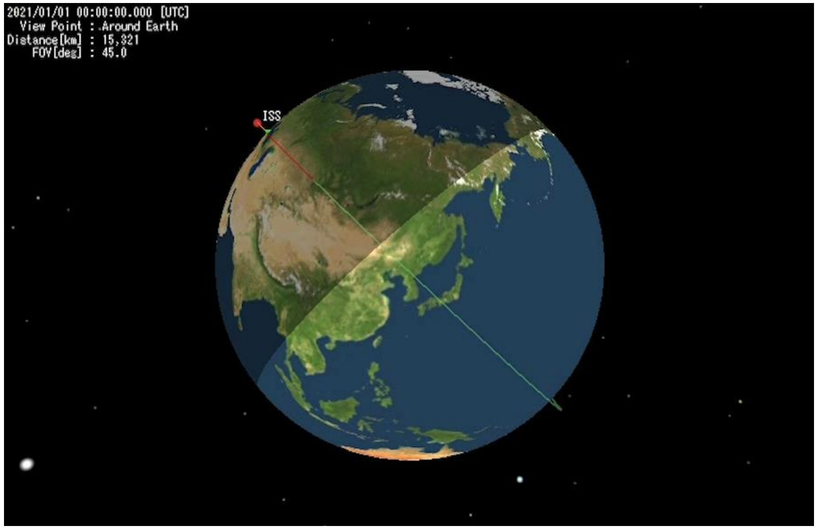
Orbit of International Space Station (ISS)

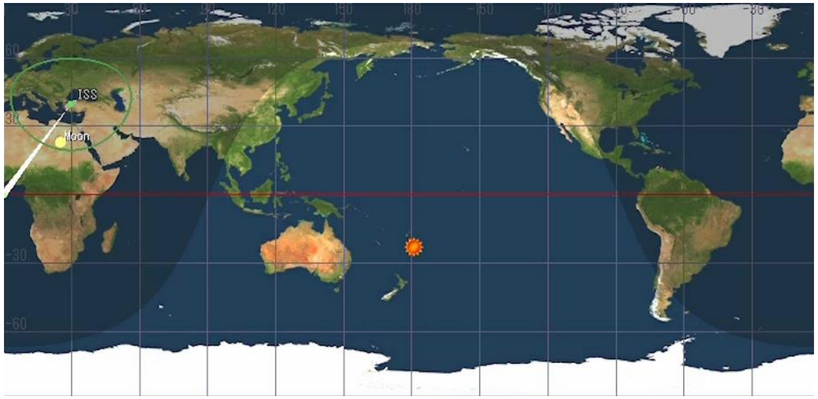
- Orbit of ISS:
  - Orbit altitude: ≃ 400km*
  - Inclination: ≃ 51.6 deg
  - Orbital period: ≃ 91 min

  * Orbit altitude changes for about ±20km



- CubeSats deployed from the ISS stay in almost the same orbit as the ISS.
- Slight differences in initial relative velocity and different mechanical characteristics, such as mass and shape (and hence, ballistic coefficient), make the CubeSats separate from each other into different orbits.
- ISS orbit covers the ground surface of regions with lower latitude (between ± 51.6 deg).
- ISS rotates around the Earth about 16 times a day, while the Earth rotates about 22.5 deg during the 1 orbital period of the ISS.

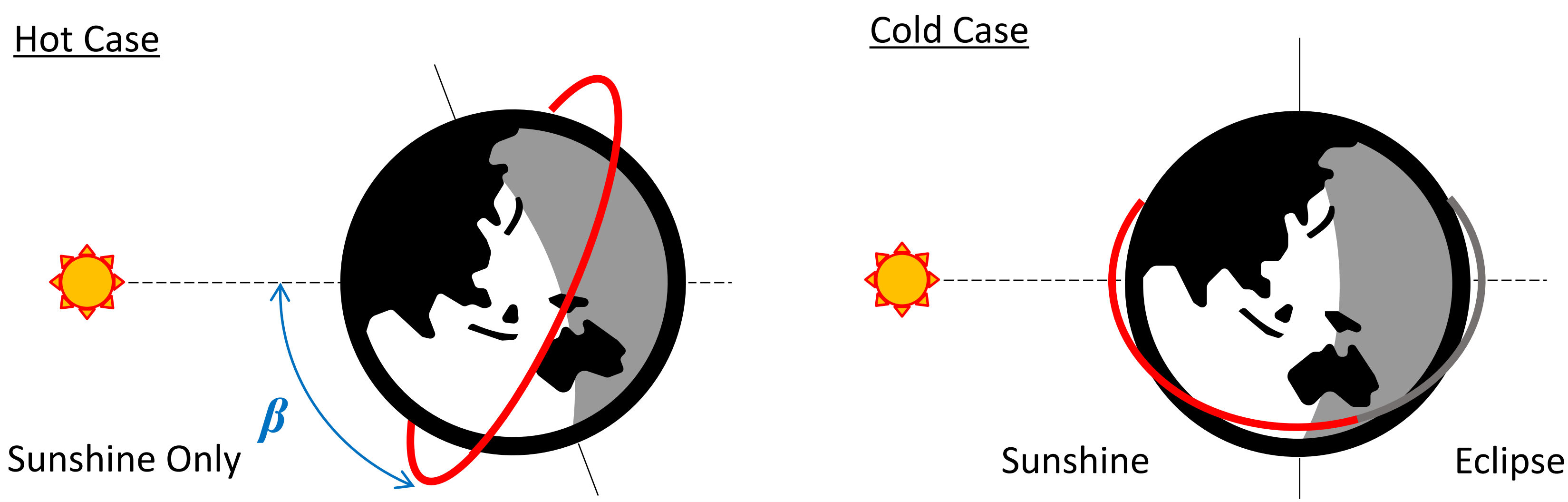




Spheresoft

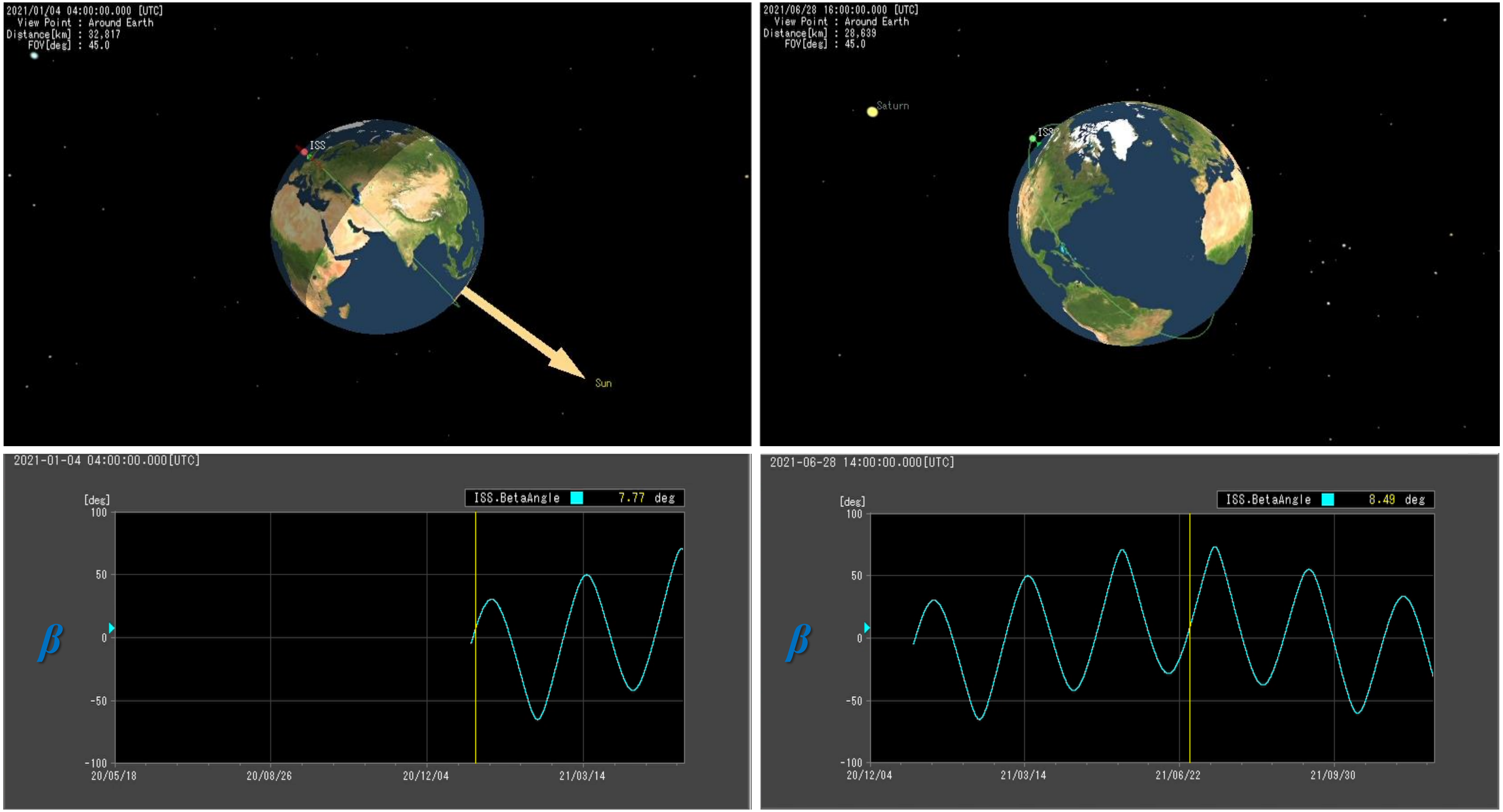
Influence of the Eclipse

- The illumination conditions in the ISS orbit change throughout the year, based on the following facts:
  - Earth rotates around the Sun once a year.
  - The rotational axis of the Earth is tilted by about 23.4 deg to the equatorial plane. (The Sun direction moves ±23.4 deg from the equatorial plane.)
- There are periods several times a year, when the ISS orbit experiences no eclipse for the entire orbit. This situation is good for electrical power generation, but is not ideal for thermal conditions (satellites become too hot).
- Satellite needs to have a battery to survive eclipse period (max. ≃ 35 min)



Influence of the Eclipse

- Transition of the β angle.

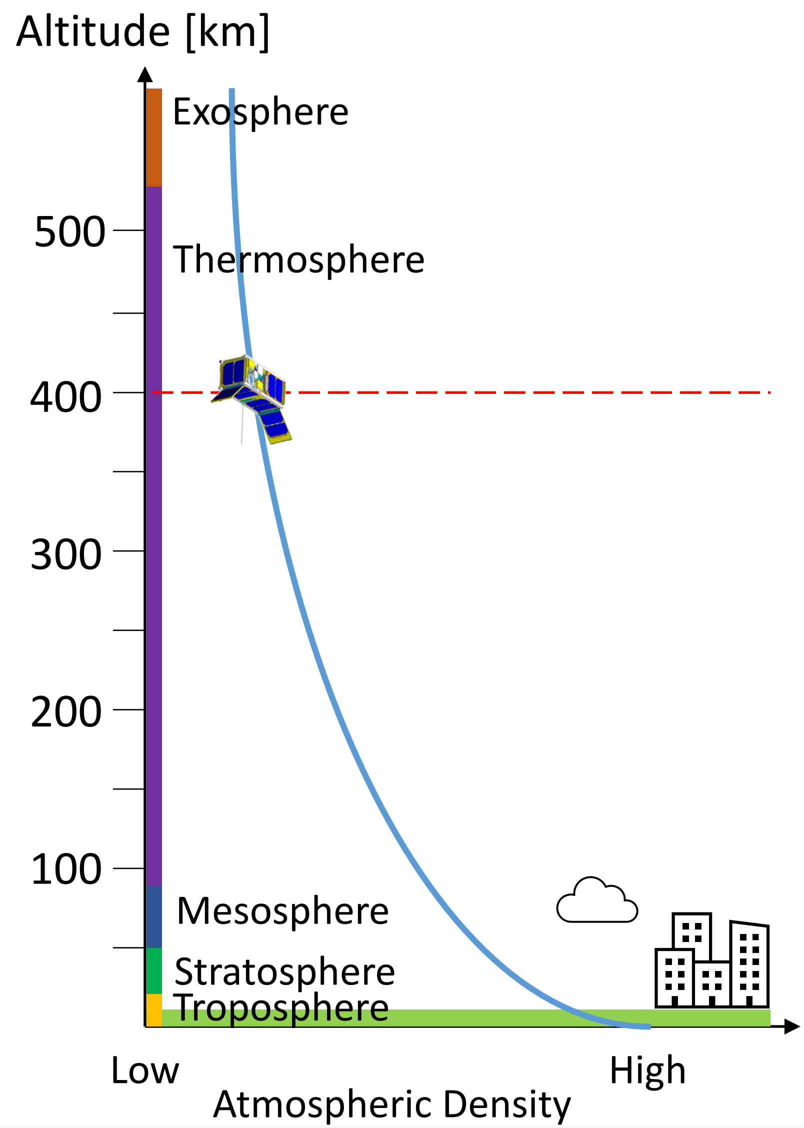


Spheresoft

2. Satellite Orbit and Mission Lifetime

Atmospheric Drag

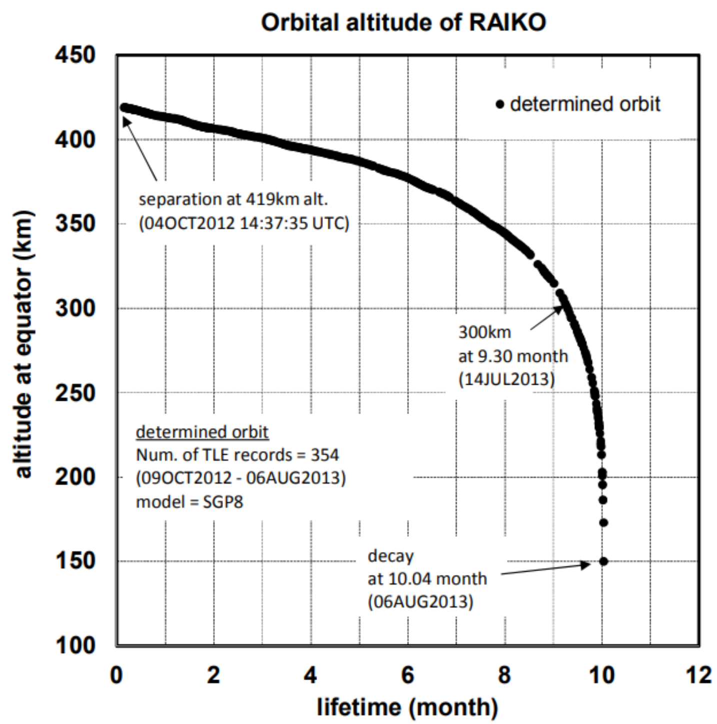
- Residual atmosphere in low Earth orbit causes atmospheric drag acting on satellites and the satellite orbit altitude decreases with time, eventually resulting in re-entry into the Earth’s lower atmosphere.
- Satellite materials must be selected in a way that they burn out and completely melt down by aerodynamic heating upon re-entry into the atmosphere.
- Atmospheric density in the upper atmosphere changes depending on solar activity (the higher the solar activity is, the denser the atmospheric density).
- De-orbiting time depends on the mass and projected area (size) of the satellite (the heavier and smaller, the longer).



2. Satellite Orbit and Mission Lifetime

2U CubeSat “RAIKO” (Oct. 4, 2012 ~ Aug. 6, 2013)

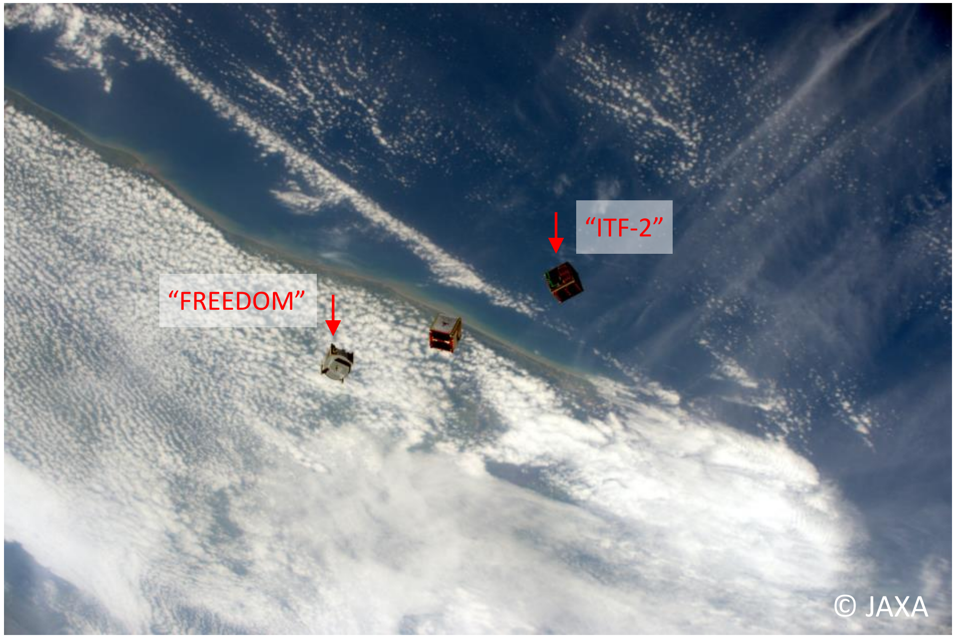
- Example of 2U CubeSat “RAIKO.”
  - Mission: Earth observation
  - Deployment: Oct. 4, 2012
  - Mass: 2.66 kg
  - Size: 2U with two deployable panels.
  - Initial altitude: ≃ 419 km
  - World-first CubeSat deployed from the ISS.
- The solar activity was relatively strong.
- The transition of the orbit was recorded based on the publicly available two-line element (TLE) information.
- The mission lifetime of the RAIKO was about 10 months.

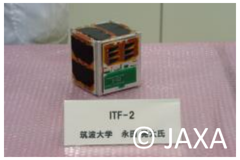


2U CubeSat RAIKO

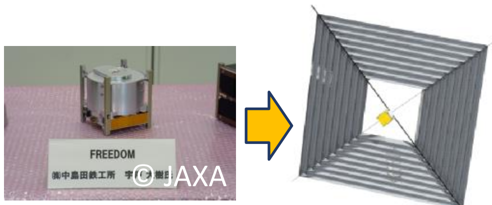
1U CubeSat "FREEDOM" (Jan. 16,2017 ~ Feb. 7, 2017)

- Example of 1U CubeSat "FREEDOM."
  - Mission: Demonstration of drag-sail
  - Deployment: Jan. 16, 2017
  - Mass: 1.33 kg
  - Size: 1U with deployable drag-sail.
  - Initial altitude: ≃ 410 km
  - Drag-sail: 1500 x 1500 mm
- The Drag-sail was deployed 30 minutes after the deployment of FREEDOM.
- The transition of the orbit was recorded based on the publicly available two-line element (TLE) information.
- The mission lifetime of the FREEDOM was 22 days (world record shortest).

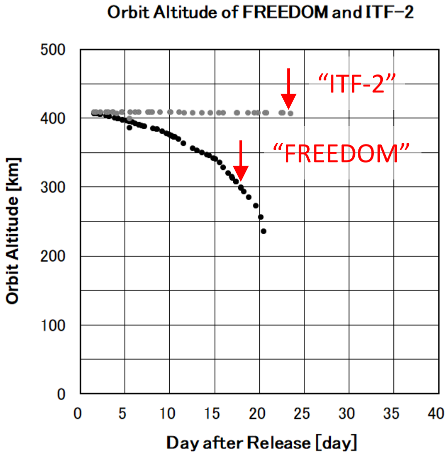




1U CubeSat "ITF-2"



1U CubeSat "FREEDOM"

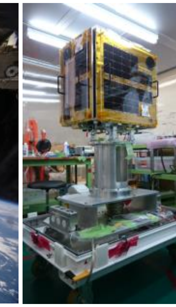


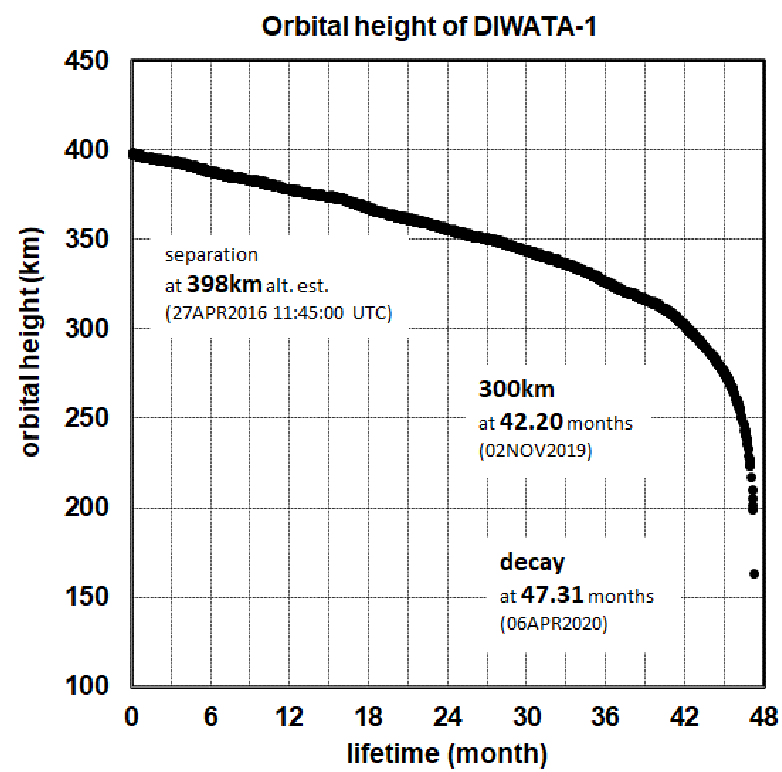
2. Satellite Orbit and Mission Lifetime

Micro-Sat. "DIWATA-1" (Apr. 27, 2016 ~ Apr. 6, 2020)

- Example of 50-kg-class Micro-sat. "DIWATA-1."*
  - Mission: Earth observation
  - Deployment: Apr. 27, 2016
  - Mass: ≃ 50 kg
  - Size: 550 x 350 x 550 mm
  - Initial altitude: ≃ 398 km
- The solar activity was relatively weak.
- The transition of the orbit was recorded based on the publicly available two-line element (TLE) information.
- The mission lifetime of the DIWATA-1 was about <u>47.3 months (≃ 4 years)</u>.

*"DIWATA-1" project was a collaboration between the University of the Philippines, the Philippine DOST-Advanced Science and Technology Institute (DOST-ASTI), Japanese Tohoku University, and Hokkaido University.





3. Communication System

3. Communication System

Introduction to Communication System

- Communication architecture for a satellite consists of:
  - the satellite system,
  - ground station(s), and
  - communication links between them

  which transfer information for the satellite control, telemetry monitoring, and mission data acquisition.
- Selection of communication frequency bands is very important, as these influence:
  - frequency allocation process,
  - satellite and ground station hardware components,
  - satellite power management,
  - required antenna pointing accuracy, and
  - amount of communication data.
- For satellites without accurate antenna pointing capability, lower frequency (longer wavelength) is more appropriate.
- Communication frequency bands often used for CubeSats are VHF(30~300MHz), UHF(300M~3GHz), S(2~4GHz), and X(8~12GHz)-bands.

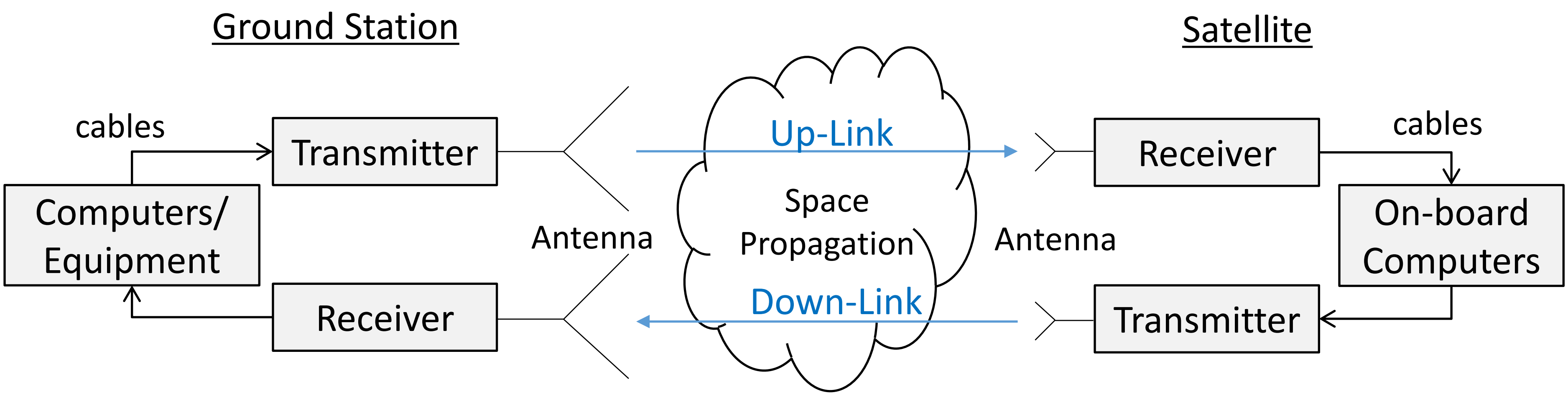
3. Communication System

Components of Communication System

- Communication systems usually involve the following components in both directions - command up-link and housekeeping (HK) data/mission data down-link:
  - Computers
  - Transmitter and transmitting antenna
  - Receiver and receiving antenna
  - Cables
  - Other components such as power amplifiers

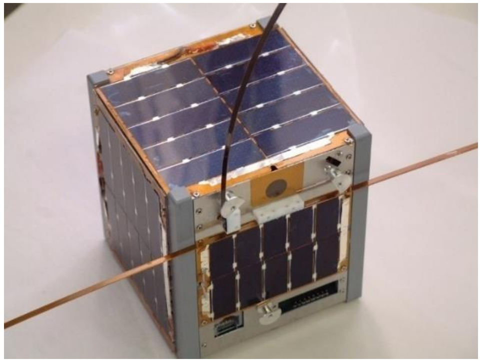
Typical CubeSat RF Transmitter and Receiver © Addnics corp.

- Radio frequency (RF) cables are thick and their connectors are relatively large.



Deployable Antenna

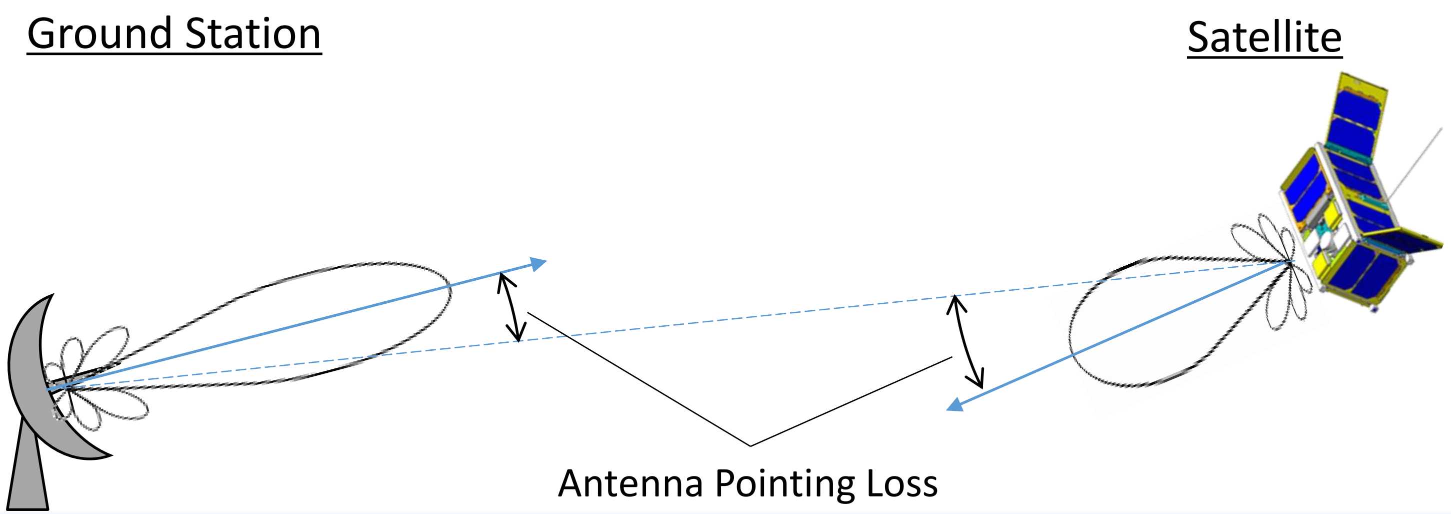
- In general, lower frequency bands (longer wavelength) necessitate larger antennas. CubeSats often use deployable flexible antennas for communication using VHF and UHF-bands.
- Longer wavelengths are less affected by satellite attitude, and therefore especially suitable for the command uplink, which needs secure communication independent of the satellite attitude.
- Possible data transfer rate is, however, lower than when using higher frequency bands.
- Deployment mechanisms are required to safely hold-down the antenna during launch and reliably release it after the deployment into orbit for the start of operation.



XI-IV © University of Tokyo

High Gain Antenna

- High gain antennas are required for high-speed data downlink.
- Antenna pointing requirements for higher frequency bands are stricter.
- Antenna gain matters for both transmitting and receiving signals.
- The direction of the high gain antenna shall be pointed toward the ground station, and the ground station antenna shall also be pointed toward the satellite.
- High gain antennas for CubeSats are usually hard-mounted to the satellite structure and the satellite controls its attitude such that the antenna points toward the ground station.



4. Ground Station

Types of Ground Station

- Types of Ground Station:
  - Yagi-antenna: often used for VHF and UHF-band communication.
  - Dish-antenna: often used for S-band and higher frequency communication.
- Satellite orbit shall be predicted beforehand so that the ground station antenna can be pointed toward the satellite.
- Satellite orbit (satellite position) is publicly available by CSpOC in the form of two-line elements (TLEs)*.


Yagi-Antenna for VHF-band

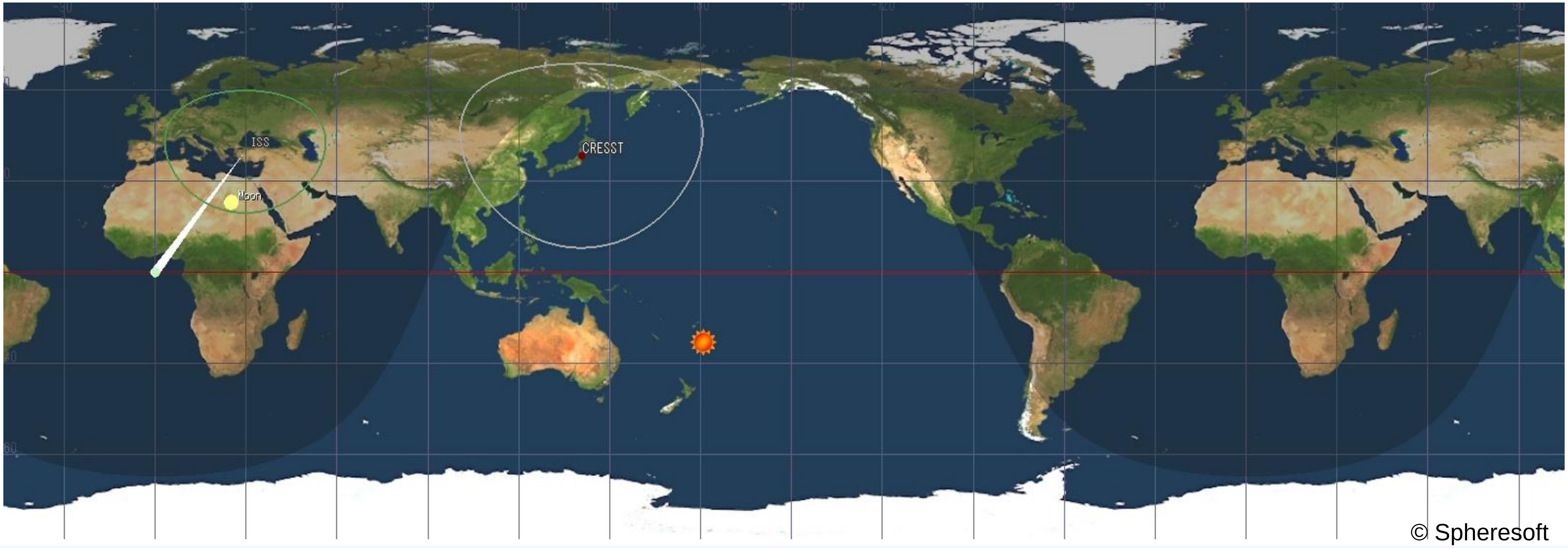
Dish-Antenna for S-Band

*TLE format: https://celestrak.com/columns/v04n03/ (last visited on 2020/12/28)

4. Ground Station

Geographical Position of the Ground Station

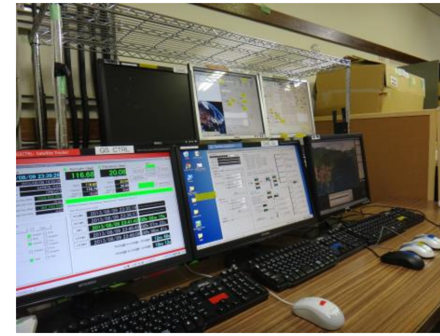
- The latitude of the ground track of the CubeSats deployed from the ISS is between about ±51.6 degrees. Therefore, their ground stations need to be located in that region.
- In low latitude region, CubeSats can approach to the ground station both from northwest and southwest. (different direction in day and night)
- The duration of the ground contact is the longest when the CubeSat flies just above the ground station. (However some ground station cannot track satellites around the vertical direction!)
- Ground contact time, i.e., the amount of communication data can be increased by using more than one ground stations, which are geographically separated.



4. Ground Station

Ground Station Setup

- Ground stations consists of:
  - antenna hardware
  - RF components
  - operation room
  - operation software
- Operation software consists of:
  - antenna controller
  - Satellite controller
  - Transmitter/Receiver controller

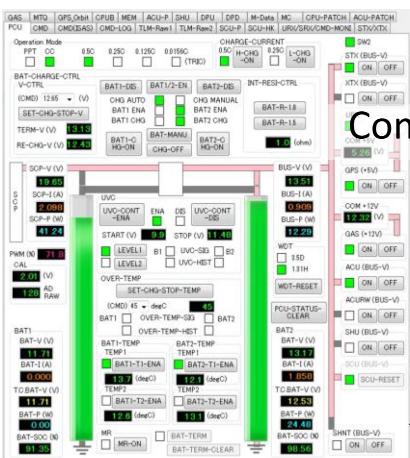


Operation Room

Up-link Signal

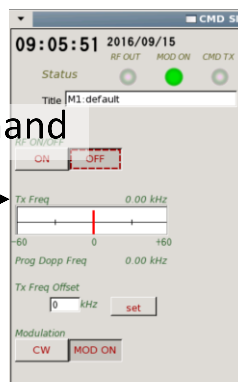
Down-link Signal

Antenna Control

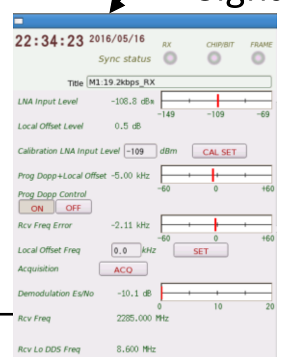


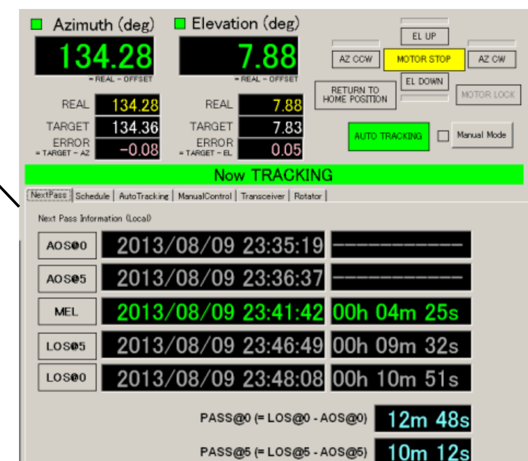
Satellite Control Software

Command



Telemetry





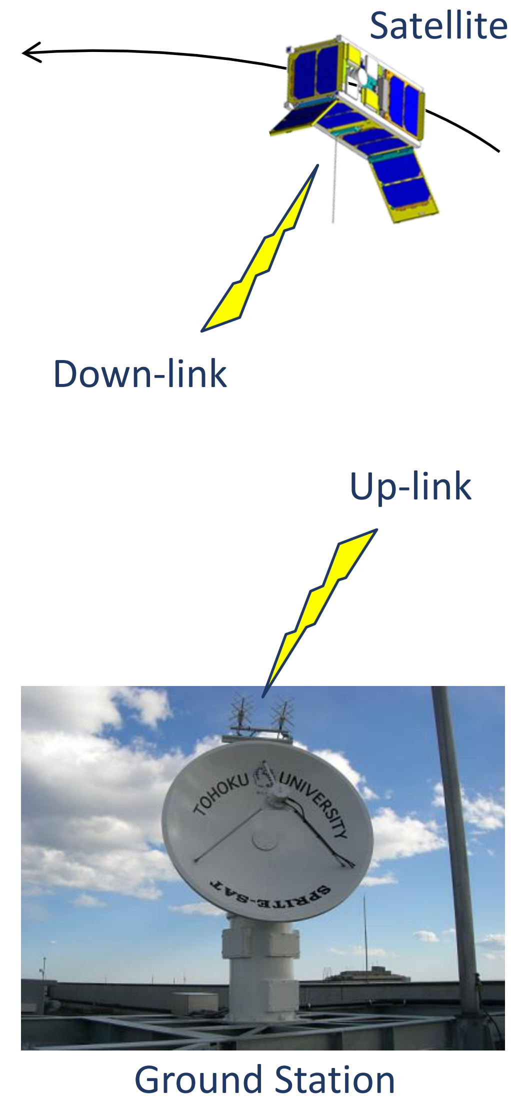
Dish-Antenna for S-Band

5. Link Budget Design

5. Link Budget Design

Communication Link

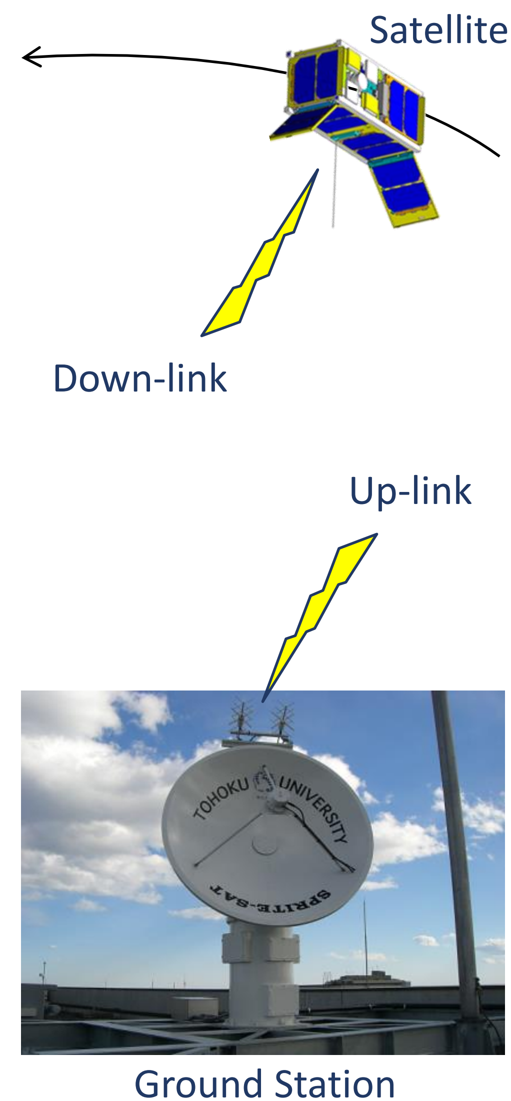
- For stable communication between the satellite and ground station, the received power at both receivers shall be strong enough relative to local noise signals so that the transmitted information can be decoded.
- Up-link signal:
  Communication from ground stations to the satellite. Satellite controlling commands, new software, and data for store-and-forward and/or relay are transmitted through this channel.
- Down-link signal:
  Telemetry / mission data from the satellite to ground stations are transmitted through this channel.
- Usually radio frequency (RF) signals are used for satellite communication, but optical communication is also utilized for high-speed communication in some applications.



5. Link Budget Design

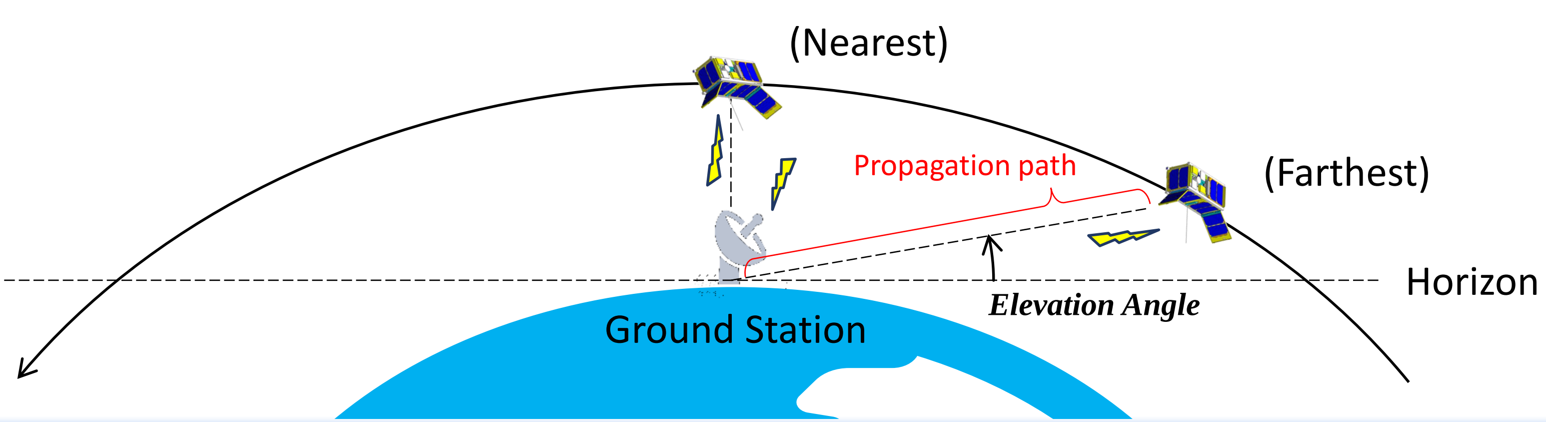
Communication Link Design Criteria

- Each satellite project shall design the communication architecture in accordance with the following criteria:
  - Data Rate – How much data is produced by the satellite and needs to be down-linked to the ground station?
  - Power consumption – How much power is available for communication?
    - Mainly driven by the satellite power generation and consumption constraints
  - Mass – How much weight can be allocated for the communication system?
  - Size – How large can the RF electronics and antenna be?
  - Orbit – What kind of orbit is planned?
    - This defines the typical time duration and frequency of the ground contact
  - RF spectrum – Which RF bands and how much bandwidth are available for the communication?



Link Budget Design

- The communication channel in both directions between the satellite and ground station need to be carefully designed.
- The received RF signal power at receivers shall be strong enough for a stable communication. (Ensure sufficient link margin!)
- The link budget is the relationship between data rate, antenna size, propagation path length, transmitter power, and losses through the communication channels.
- The propagation path between the satellite and the ground station is the longest at lower elevation angles (at the beginning and the end of the satellite contact), which is one of the design criteria for the link budget design.



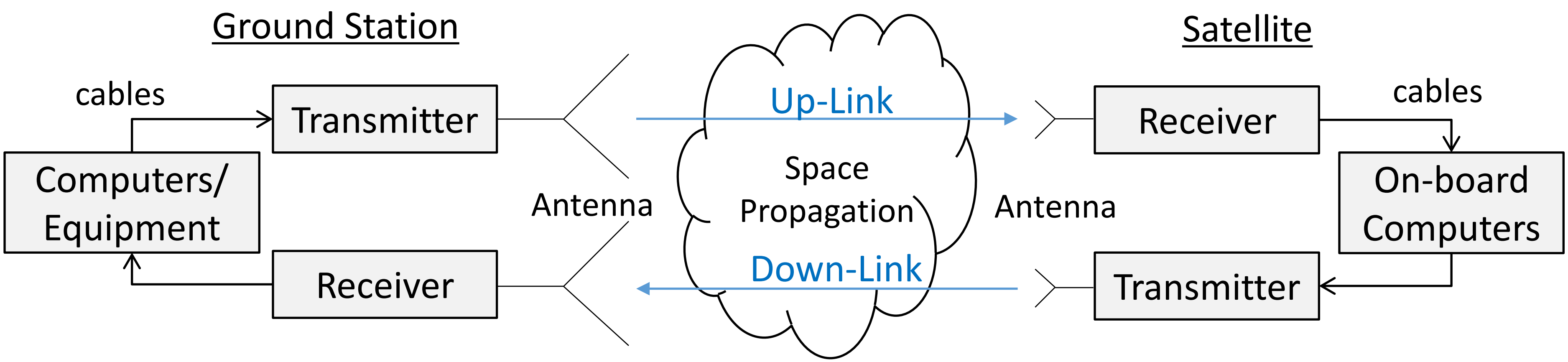
Link Equation

The RF energy per transmitting digital bit shall be stronger than noise-density of the environment.

Link Equation*: $$\frac{E_b}{N_0} = \frac{P L_l G_t L_s L_a G_r}{k T_s R}$$

Where:

- E_b/N_0 – Ratio of received energy-per-bit to noise-density (the larger the better)
- P – Transmitter power
- L_l – Transmitter-to-antenna line loss
- G_t, G_r – Transmitter antenna gain, receiver antenna gain (bigger antenna has larger antenna gain)
- L_s, L_a – Space loss, transmission path loss (rain attenuation, etc.)
- k – Boltzmann's constant
- T_s – System noise temperature
- R – Data rate



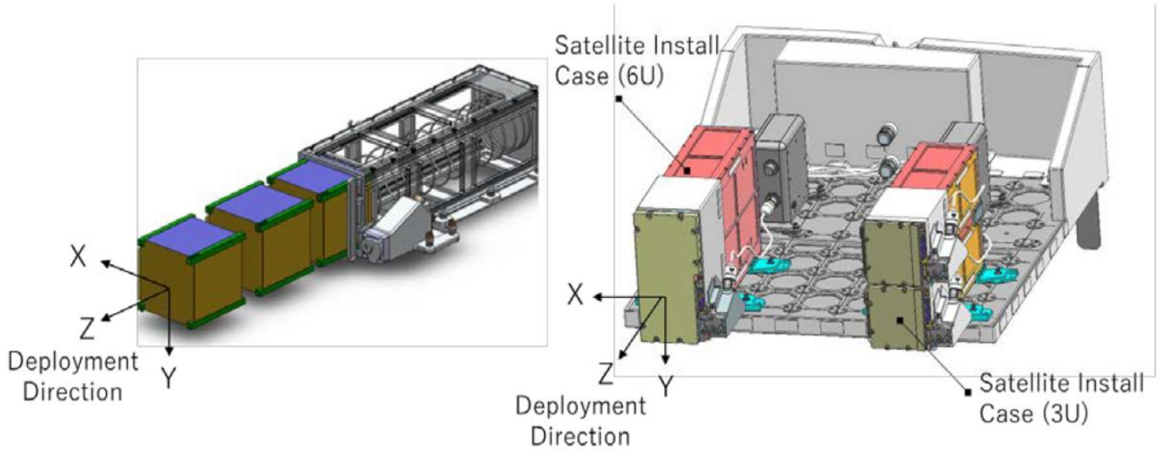
*Reference: J. R. Wertz and W. J. Larson, Space Mission Analysis and Design, Third Edition

6. Operational Phase

6. Operational Phase

Satellite Delivery

- Satellites are delivered to JAXA several months before the launch.
- CubeSats are assembled into the deployment mechanism called J-SSOD at the JAXA facility.
- Assembled J-SSOD and CubeSats are shipped to the launch site for further integration to the launch vehicle.
- CubeSats need to be non-hazardous against the launch vehicle and astronauts.



Appearance of J-SSOD © JAXA

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

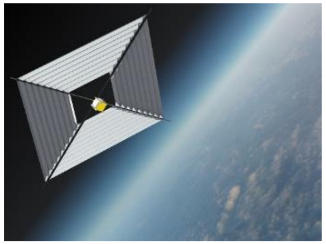
Satellite Delivery to JAXA

Operational Phase of CubeSat deployed from ISS

- Operational phase of the CubeSat to be deployed from the ISS can be categorized into several phases as follows.

Launch Phase → **Preparation Phase** → **Early Operation Phase** → **Mission Phase** → **Disposal Phase**

Launch Phase	Preparation Phase	Early Operation Phase	Mission Phase	Disposal Phase
• CubeSat is launched and delivered to the ISS.	• CubeSat is stored in the ISS and prepared for deployment into orbit.	• CubeSat is deployed from the ISS, communication link is established, and initial inspection is conducted.	• CubeSat conducts its missions.	• CubeSat is set to disposal mode and waits until the re-entry into Earth's atmosphere.



Example Case: HTV

- HTV is launched by the Japanese domestic launch vehicle H-IIB from the Tanegashima Space Center.
- HTV approaches and docks to the ISS after several days from the launch. J-SSOD and CubeSats are handled inside the ISS and prepared for the deployment by astronauts.
- CubeSats experience mechanical vibration and shock during the launch phase.
- The power supply systems of CubeSats are turned off at all times until they are deployed from the ISS.

Launch and Delivery to the ISS © JAXA

6. Operational Phase

Preparation Phase in the ISS

- CubeSats are prepared for deployment inside the ISS by astronauts.
- The deployment mechanism is transferred to outside the ISS and attached to the tip of the robotic arm of the Kibo.
- Astronaut (or ground crew) triggers the switch for the deployment.

Deployment preparation, and deployment from the ISS © JAXA

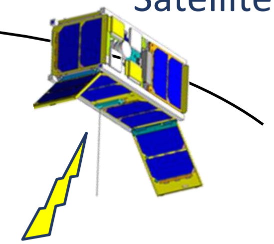
6. Operational Phase

Satellite Deployment from the ISS

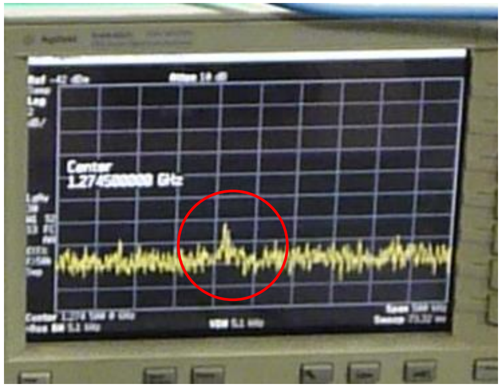
6. Operational Phase

Early Operation Phase

Satellite



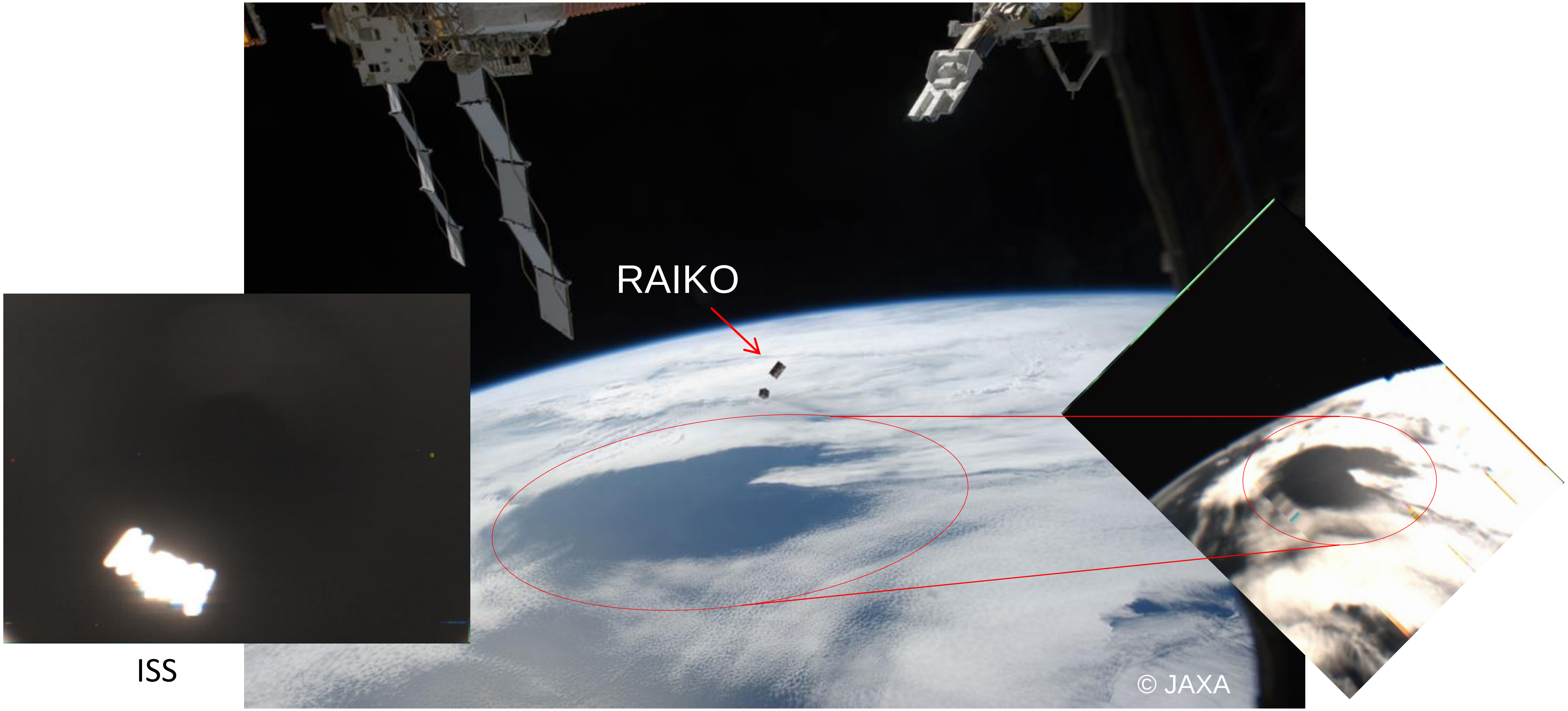
- After the deployment from the ISS, a CubeSat automatically starts functioning in space.
- The most exciting moment is the first communication contact between the satellite and the ground station.
- Health status of the satellite is checked, such as power generation, battery state-of-charge, temperature, signal strength, etc.



First ground contact with deployed CubeSat

Early Operation Phase

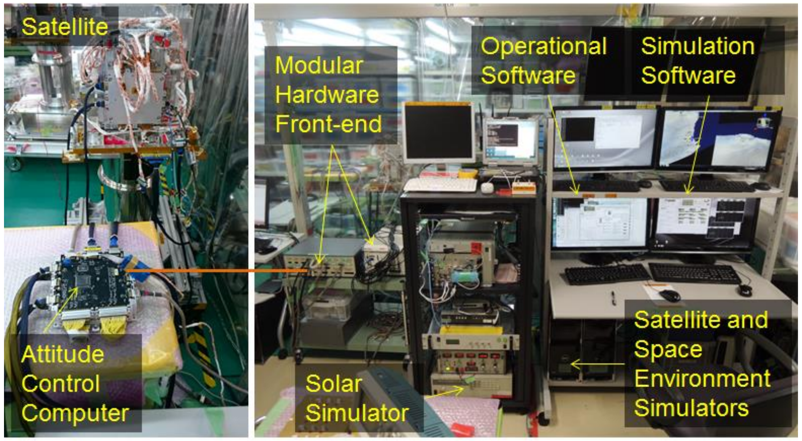
- After confirming that the satellite is in a healthy condition, preparation of the mission operation can be started, such as test picture acquisition (first light!) and instrument check-out and calibration.



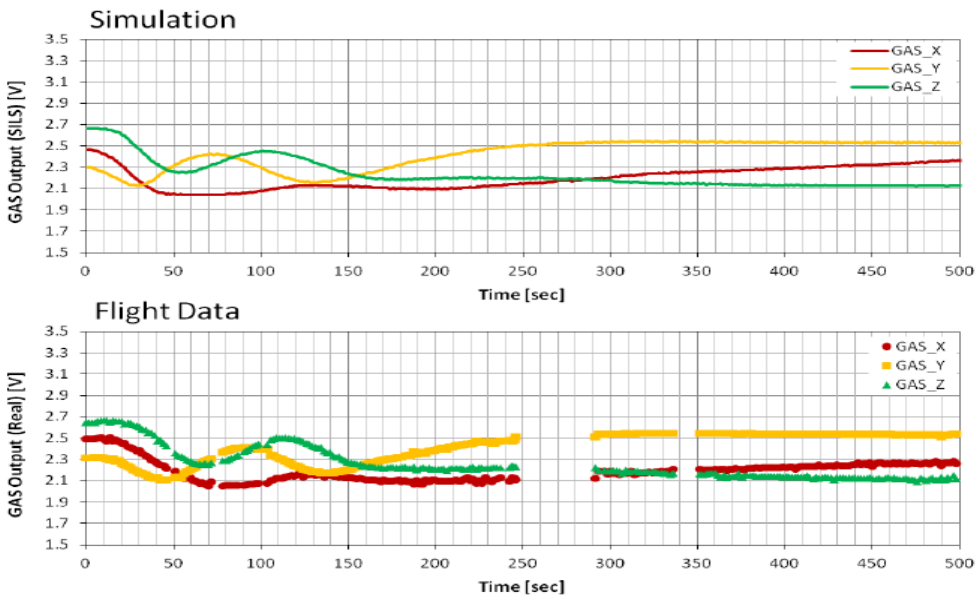
Images obtained by CubeSat RAIKO just after the deployment from the ISS

Ground Evaluation of Operational Scenario

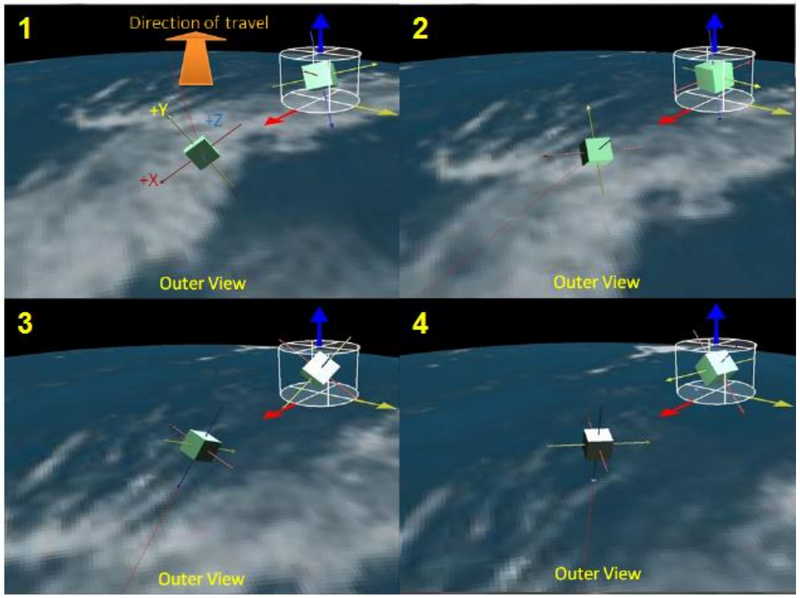
- Operational scenarios for the mission are planned and expected satellite behavior is carefully evaluated by ground simulations.
- According to the simulation and orbit calibration, software parameters of the satellite on-board computers are adjusted.



Ground Simulator



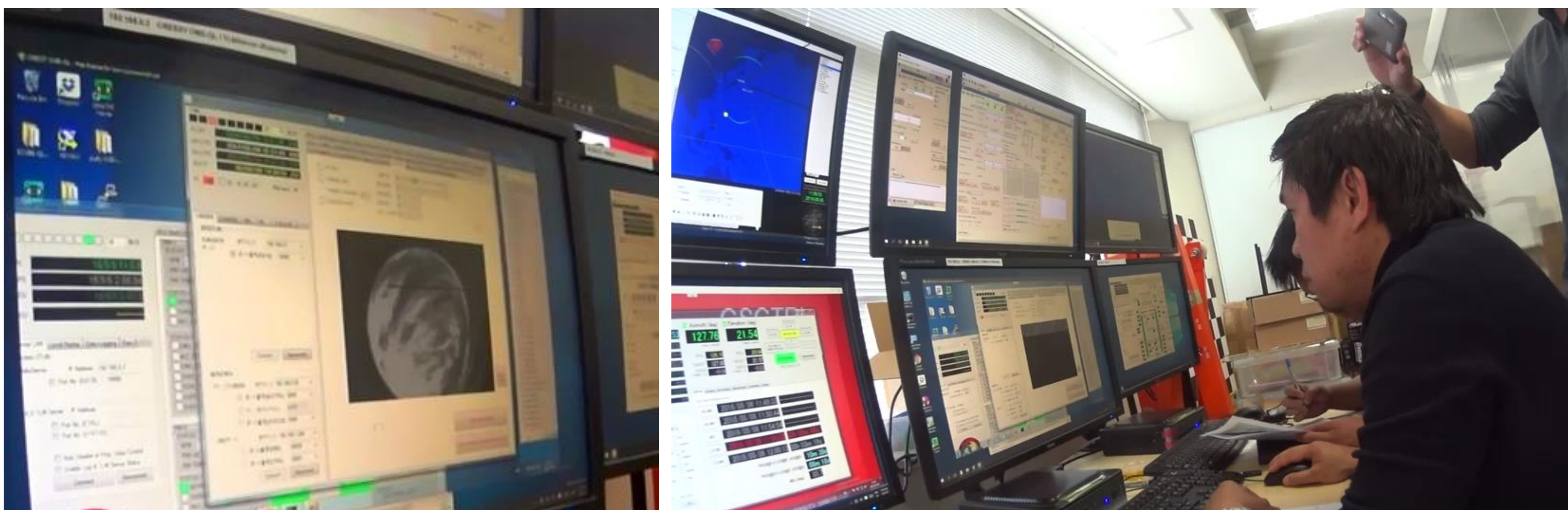
Analysis through comparison of simulation and flight data



Graphical Visualization

Mission Operation

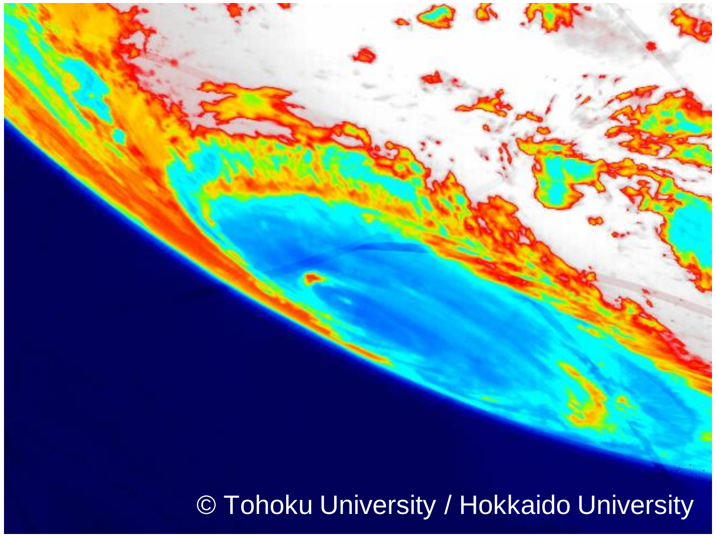
- The well-prepared command sets are up-linked to the satellite.
- Commands are usually classified into:
    - Realtime command: executed immediately after the up-link.
    - Stored command / Time-tagged command: stored in the on-board computer and executed at the pre-set execution time.
- A series of complex commands are prepared as a batch of commands with specified execution times.
- Each operational procedure is verified by investigating the behavior of the satellite.

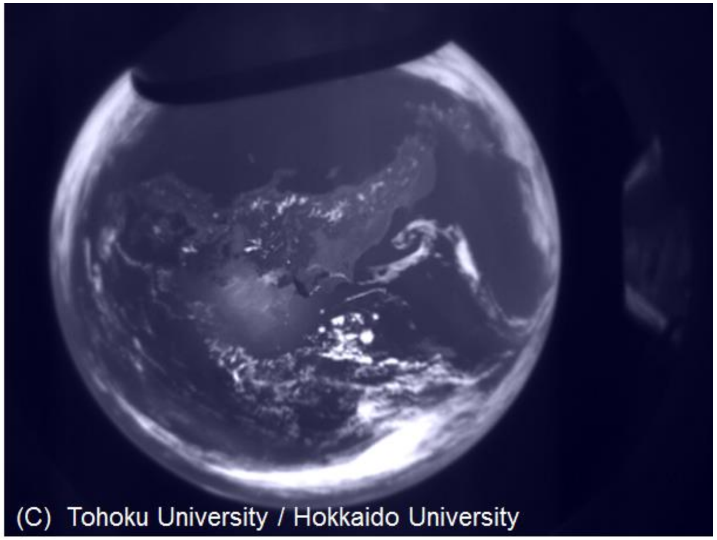


First-light obtained by the mission camera and downlinked to the ground station.

6. Operational Phase

Mission Data Acquisition



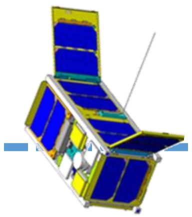


Exemplary Satellite Mission Data

Mission Phase – Nominal Operation Planning (Example)

M = Manned Operations
U = Unmanned Operations

Can be remote ground stations

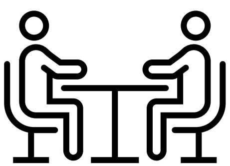


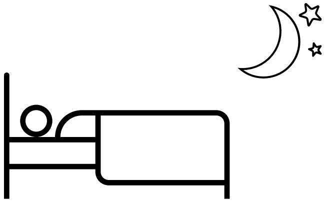
M | M | M | U | U | U

Command

Telemetry

Mission Data





Make Operation Plan

Upload Command List

Evaluate Status

Unmanned Mission Data Download

Daytime | Night

7. Regulations

7.1. Frequency Allocation

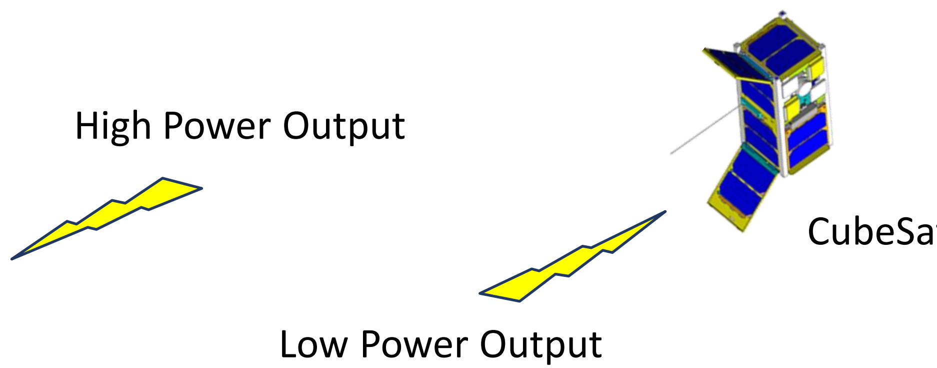
7.2. Space Object Registration

7.3. Space Debris

7.1. Frequency Allocation – Influence of RF Signal

- Radio frequencies are limited resources.
  - Communication with satellites can affect ground communications
  - Communication with one satellite can affect other satellites
- Typical communication output powers for CubeSat operations are:
  - Satellite to Ground: ~ 1 [W]
  - Ground to Satellite: ~ 50 [W]
- Ground to Satellite communications will have a greater effect on other communications.

Ground Station



7.1. Frequency Allocation – ITU Registration

- Satellites are space mobile radio stations.
- Specifications of transmitting radio signals must be informed to the world:
  - frequency band
  - from where? (ground location, or satellite orbit)
  - strength of the signal, etc.
- Transmitting signal from satellite can affect other communications internationally.
- Radio frequencies to be used by satellites need to be registered to the Master International Frequency Register (MIFR) maintained by the International Telecommunication Union (ITU).
- The ITU is one of the specialized agencies of the United Nations responsible for information and communication technologies. It promotes shared global use of the radio spectrum and facilitates international cooperation in assigning satellite orbits.
- Radio frequency allocation process requires international coordination and needs to be started well before (1 year earlier or more) the satellite launch.

7.1. Frequency Allocation – Domestic RF License

- After the international coordination of the radio frequency through ITU, satellite operators need to apply for domestic radio frequency licenses as well.
- The rules of domestic radio frequencies for satellite communication vary for each nation. If the satellite is the first satellite of the nation, the licensing process itself may also need to be defined.
- The radio frequency coordination process between the nation and the ITU needs to be conducted through the corresponding representative of the nation, such as ministry for communication related matters.
- In Japan, the Ministry of International Affairs and Communications (MIC) is responsible for the international radio frequency coordination. In Japan it is recommended that you inform MIC about the plan for frequency application 2 years earlier than the planned satellite launch.
- In Japan, a preliminary license is issued to the satellite before the launch, and an operational license is issued only if the demonstration of the communication between the ground station and satellite is successful after the launch.
- Ground stations also need radio frequency licenses!

7.1. Frequency Allocation – Amateur Radio License

- Satellites which use amateur radio frequencies shall apply for the frequency allocation through the IARU (International Amateur Radio Union) before the application to the ITU.
- If there exists a local amateur radio union in the nation, one shall also inform the union about the use of the amateur radio band for the satellite.
  In case of Japan, JARL (The Japan Amateur Radio League) is the first contact institution for the application.
- When using amateur radio frequencies, the mission purpose of the satellite and usage of the frequency shall be within the scope of amateur radio services, such as amateur radio communication.
- Satellites using amateur radio frequencies will be assigned a call sign as an amateur radio station.

7. Regulations

7.2. Space Object Registration

- In 1961, the United Nations has established a Register of Objects Launched into Outer Space, which was originally established as a mechanism to aid the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) in its discussions on the political, legal and technical issues concerning outer space.
- The evolution of international space law resulted in space object registration becoming a means of identifying which states bear international responsibility and liability for space objects.
- The Convention on Registration of Objects Launched into Outer Space entered into force in 1976.

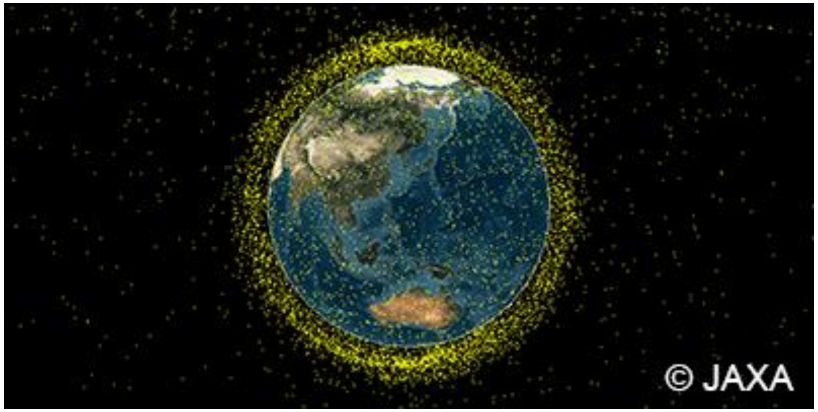
  https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/registration-convention.html

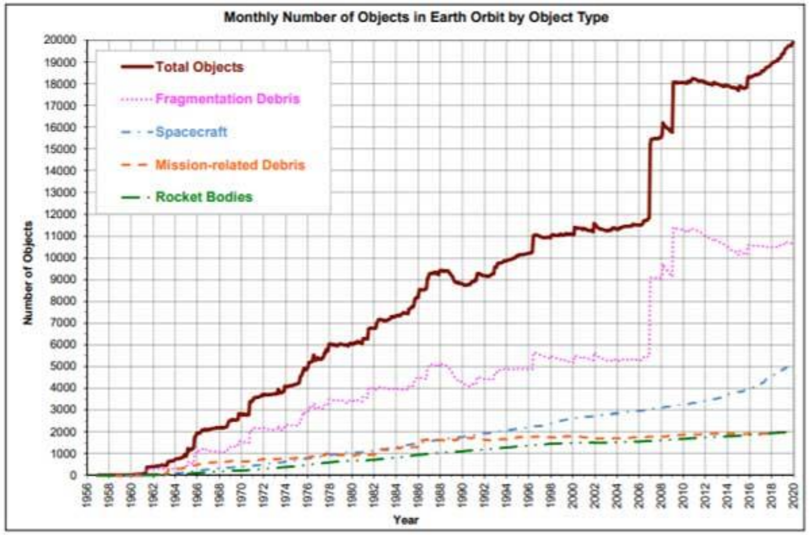
- To date over 86% of all satellites, probes, landers, crewed spacecraft and space station flight elements launched into Earth orbit or beyond have been registered with the Secretary-General.

  https://www.unoosa.org/oosa/en/spaceobjectregister/index.html

7.3. Space Debris – International Guidelines

- Space debris has been increasing year by year and in the future, it is expected to interfere with human space activities.
- To ensure the safety of space activities and promote sustainable space development, research and development of space debris mitigation and prevention methods are conducted worldwide.
- The United Nations General Assembly endorsed the COPUOS Space Debris Mitigation Guidelines discussed in COPUOS, which specify that rockets and satellites should be designed to produce no debris, and that satellites in low Earth orbit should re-enter the atmosphere within 25 years of ending their mission.





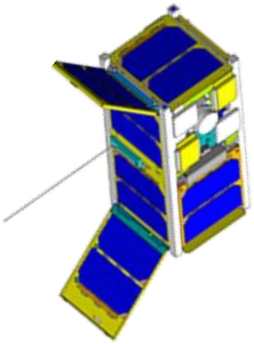
Source: The Orbital Debris Quarterly News, NASA, January 2020, Volume 24 Issue 1

7.3. Space Debris – Mitigation Methods

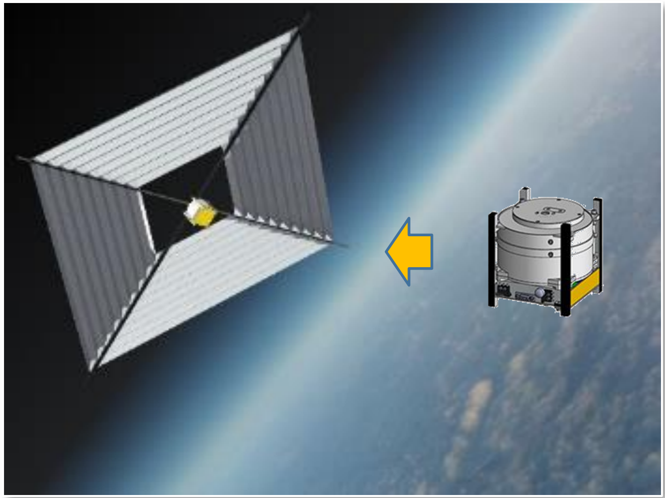
- There are two major debris mitigation and prevention methods.

- <u>PMD: Post Mission Disposal</u>
  - Spacecraft terminating their operational phase in LEO (Low Earth Orbit) region should be de-orbited with an expected residual orbital lifetime of 25 years or shorter.
  - Projection area of the spacecraft in the velocity direction needs to be large enough to catch sufficient atmospheric drag for re-entry.

- <u>ADR: Active Debris Removal</u>
  - Debris-removing spacecraft actively approaches and removes non-cooperative space debris.



2U CubeSat RAIKO
Natural De-orbit by Design



1U CubeSat FREEDOM
Utilization of Active De-orbit Devices
to Increase Atmospheric Drag

7. Regulations

7.3. Space Debris – Design Requirements

- CubeSats to be deployed from the ISS need to fulfil the following requirements
  - They need to be designed in such a way that their expected lifetime is no longer than 25 years.
  - They need to have appropriate area-to-mass ratio so that their de-orbit speeds are faster than that of the ISS, i.e., their surface area needs to be large enough, and their mass needs to be small enough.
  - If some parts of the CubeSat are separated during operation in space (which is not recommended), all parts need to follow debris mitigation guidelines individually.

Reference:

- Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space
  https://www.unoosa.org/pdf/publications/st_space_49E.pdf
- Guidance on Space Object Registration and Frequency Management for Small and Very Small Satellites
  https://www.unoosa.org/documents/pdf/psa/bsti/2015_Handout-on-Small-SatellitesE.pdf
- A Handbook for Post-Mission Disposal of Satellites Less Then 100 kg.
  http://www.unisec-global.org/pdf/sg423finalreport.pdf
  (http://www.unisec-global.org/whatwedo.html)

7. Conclusion

7. Conclusion

- CubeSats deployed from the ISS will follow similar orbits as the ISS. These orbits experience different illumination conditions of the sun throughout the year. CubeSats shall be designed in a way that they can survive the space environment.
- Mission duration of a CubeSat depends on the mechanical characteristics, such as mass and size, and the magnitude of solar activity.
- Link budget between the CubeSat and the ground station shall be carefully designed for steady communication in both directions: Up-link and Down-link.
- Each activity of operational phases is described with examples. Thorough mission planning, ground evaluation, stepwise orbit verification, and efficient operation framework are important.
- CubeSat projects also need to pay attention to related regulations, such as frequency allocation, space object registration, space debris mitigation guidelines.

Thank you very much.