KiboCUBE Academy

Lecture 14

Introduction to CubeSat Attitude Control System

Tohoku University

Department of Aerospace Engineering

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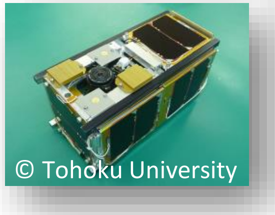
This lecture is NOT specifically about KiboCUBE and covers GENERAL engineering topics of space development and utilization for CubeSats.
The specific information and requirements for applying to KiboCUBE can be found at:
https://www.unoosa.org/oosa/en/ourwork/psa/hsti/kibocube.html

Lecturer Introduction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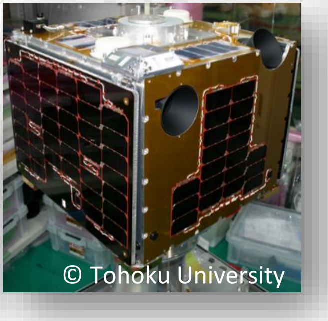
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Toshinori Kuwahara, Dr. –Ing.

Position:

2015 - Associate Professor, Department of Aerospace Engineering, Tohoku University
2017 - Technical Advisor, Nakashimada Engineering Works, Ltd.
2017 - Technical Advisor, ALE Co., Ltd.
2020 - Chairperson, University Space Engineering Consortium Japan (UNISEC)
2021 - Co-founder/CTO, ElevationSpace Inc.

Research Topics:

Space Development, Utilization, and Exploration by Small Spacecraft Technologies

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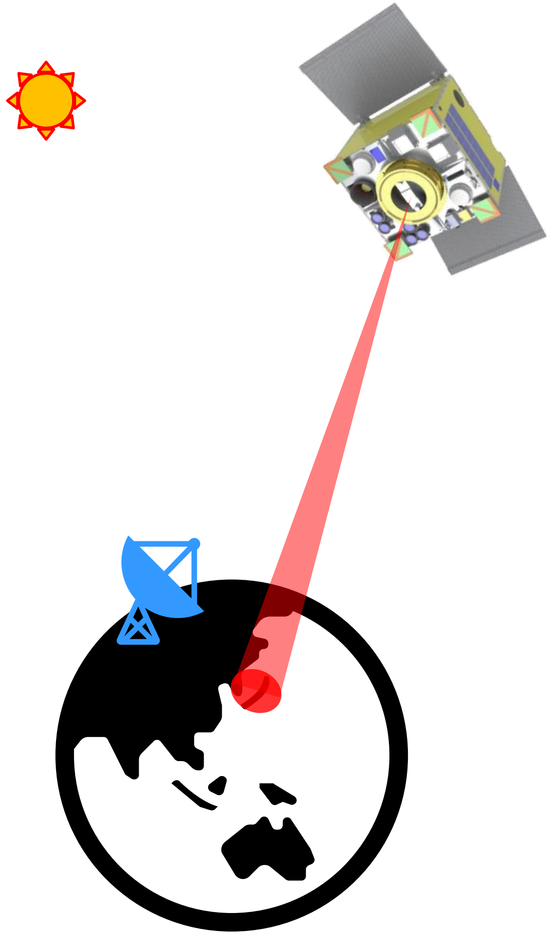
1. Introduction to Attitude Control System
2. CubeSat Attitude Control Mode
3. Hardware Components of Attitude Control System
4. Attitude Determination and Control Process
5. Attitude Determination and Control Algorithms
6. Functional Verification of Attitude Control System
7. Conclusion

1. Introduction to Attitude Control System

1. Introduction to Attitude Control System

1.1. Requirements of Satellite Attitude Control System

- Attitude Control System (ACS) is one of the satellite subsystems, which is responsible for attitude determination and control of the satellite body. ACS is sometimes denoted as Attitude Determination and Control System (ADCS).
- In general, attitude control of a satellite is required not only to achieve mission objectives, but also to survive in the space environment, mainly in terms of power generation and thermal control.
- Payload instruments of small satellites are usually mechanically fixed to the satellite body, and hence, the satellite attitude needs to be controlled in order to point those instruments to the desired directions.
- Attitude control types and accuracy depend on mission objectives.
- Typical attitude control requirements of satellites are:
  - Detumbling control – Detumble rotational rate
  - Pointing control – Point towards a certain direction for observation and/or communication
  - Spinning control – Spin-up around a specific direction



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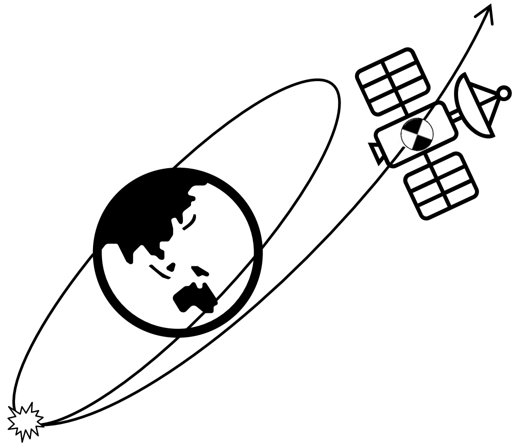
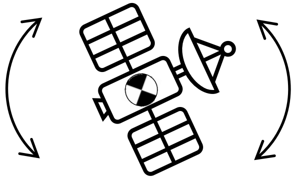
1. Introduction to Attitude Control System

1.1. CubeSat Dynamics and Control

Dynamic motion control of a CubeSat can be treated as the combination of translational motion control and rotational motion control. Dynamics problems of translational motion and rotational motion can be treated separately.



- Translational Motion = Orbital Motion:
  - Satellite is regarded as a point of mass (motion of the center of mass of the satellite)
  - Orbital position needs to be determined by means of ground observation or on-board instruments
  - Satellite orbital motion can be propagated based on orbital mechanics
  - Perturbation effects need to be estimated for precise orbit propagation
  - Orbital parameters such as altitude, inclination, etc. need to be controlled through orbital maneuvers by means of thrusters, if required.
- Rotational Motion = Attitude Motion:
  - Satellite attitude around its center of mass is handled separately from the orbital motion
  - Satellite attitude needs to be determined by on-board sensor instruments
  - Satellite attitude needs to be controlled by on-board actuator instruments by generating attitude control torques.
  - Satellite attitude is controlled relative to the reference target attitude and/or reference target rotational rate.



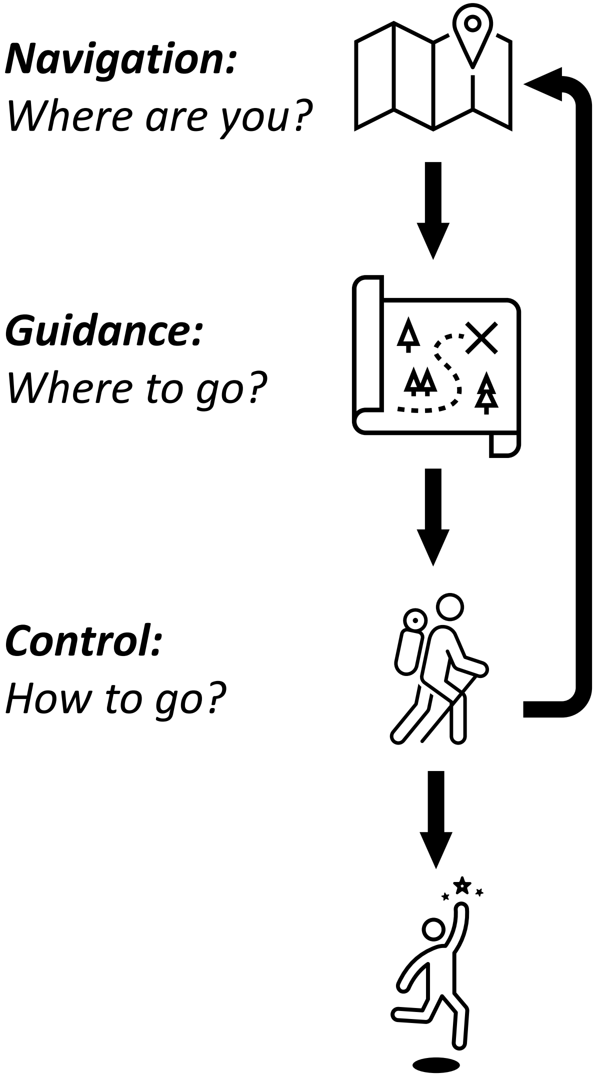
1. Introduction to Attitude Control System

1.3. CubeSat Dynamics and Control Process

The control process of spacecraft motion can be described in the following three steps:

1. ***Navigation***
    - Determine current satellite position and velocity (orbital motion), and satellite attitude and rotational rate (attitude motion).
2. ***Guidance***
    - Calculate desired target position and velocity (orbital motion), and target attitude and rotational rate (attitude motion), in order to achieve the objectives.
3. ***Control***
    - Make changes in satellite position and velocity (orbital motion), and satellite attitude and rotational rate (attitude motion), or keep them to certain fixed values, by means of actuators.

These processes are called GNC (Guidance, Navigation, and Control) and are conducted repeatedly and continuously. Attitude control accuracy is influenced by the accuracies in each of these steps.



Navigation:
Where are you?

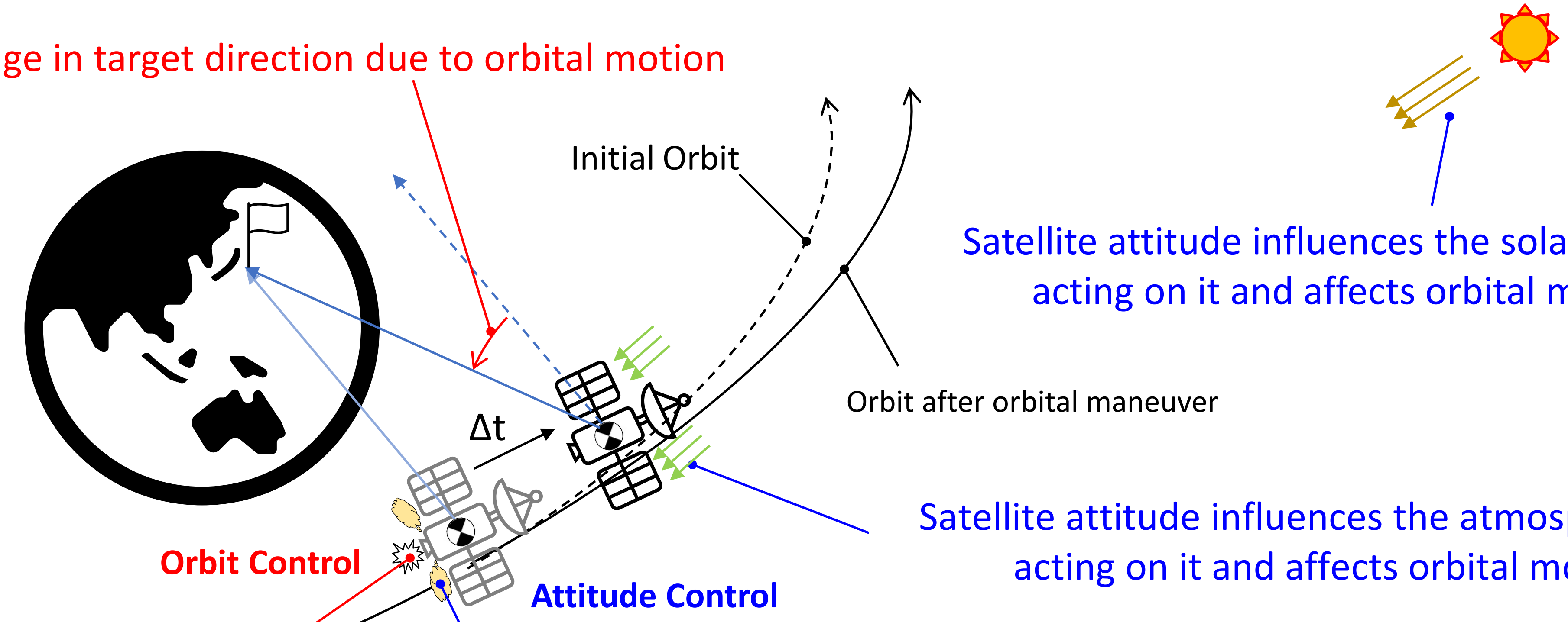
Guidance:
Where to go?

Control:
How to go?

1. Introduction to Attitude Control System

1.4. Relationship between Orbital Motion and Attitude Motion

1. Influence of Orbital Motion to Attitude Motion ⇨ Attitude analysis requires orbital information.
2. Influence of Attitude Motion to Orbital Motion ⇨ Orbital analysis requires attitude information.



Change in target direction due to orbital motion

Satellite attitude influences the solar pressure acting on it and affects orbital motion.

Satellite attitude influences the atmospheric drag acting on it and affects orbital motion.

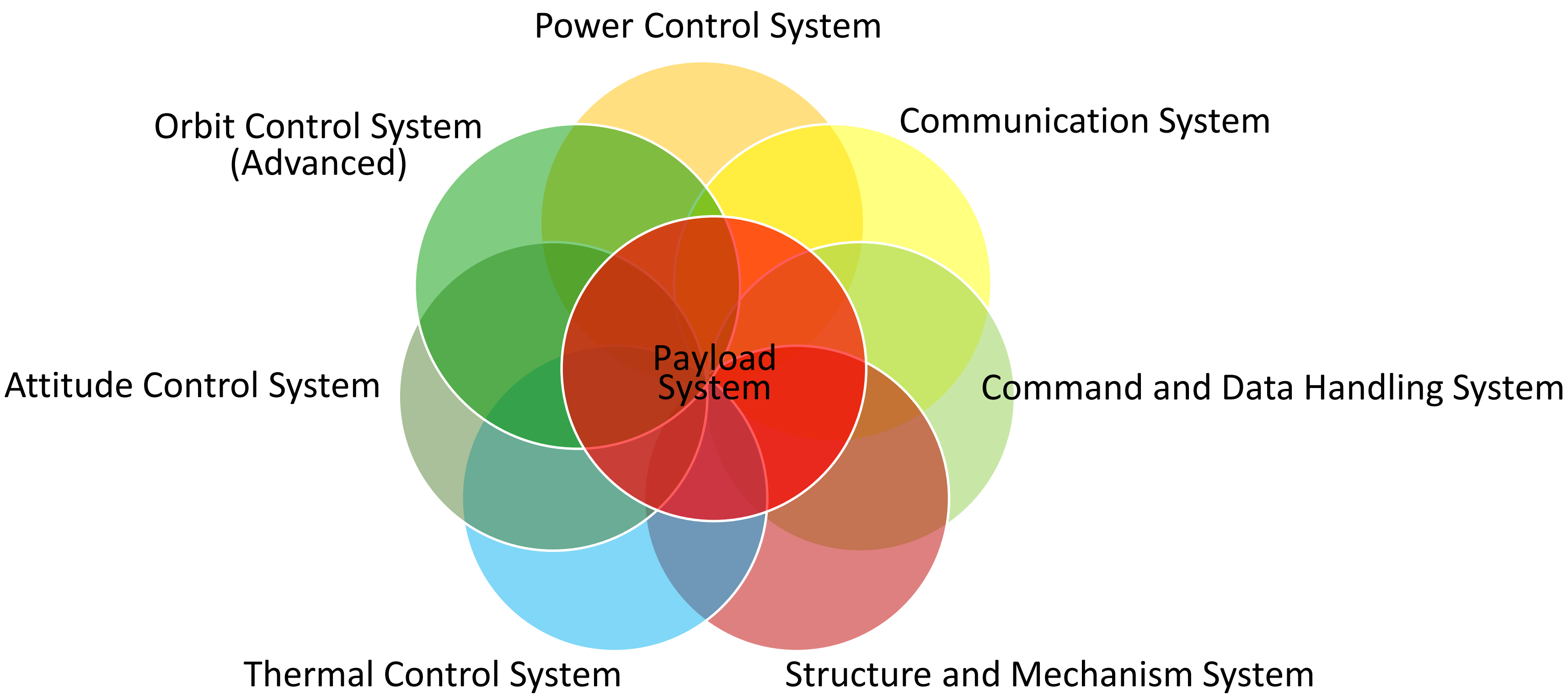
Thruster for orbital control also affects satellite attitude

Satellite attitude control using a reaction control system influences the orbital propagation.

1. Introduction to Attitude Control System

1.5. Attitude Control System and Orbit Control System

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



Power Control System

Orbit Control System
(Advanced)

Communication System

Attitude Control System

Payload
System

Command and Data Handling System

Thermal Control System

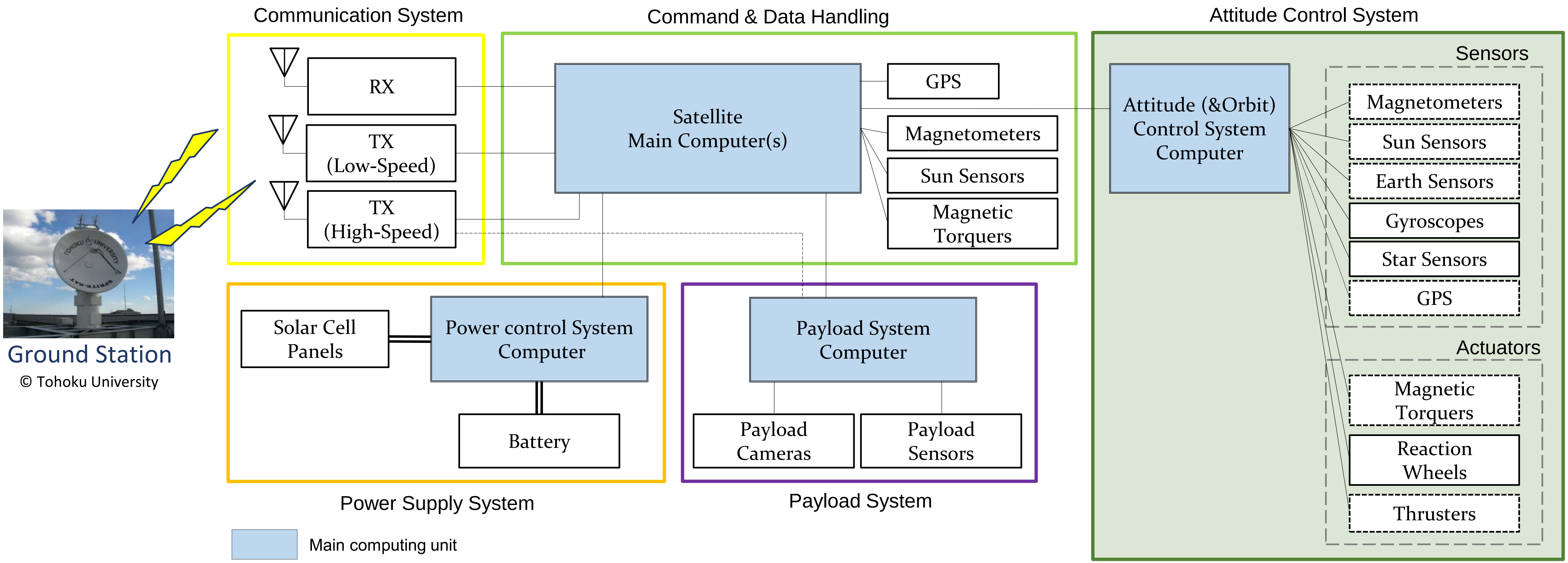
Structure and Mechanism System

+ Harness System

1. Introduction to Attitude Control System

1.6. Components of Attitude Control System

- Attitude control system (ACS) requires attitude determination sensors, attitude control actuators, and on-board computers. A satellite can have a dedicated computer for the ACS or ACS functionalities can be spread into several on-board computers.



Ground Station
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Communication System
RX
TX (Low-Speed)
TX (High-Speed)

Command & Data Handling
Satellite Main Computer(s)
GPS
Magnetometers
Sun Sensors
Magnetic Torquers

Attitude Control System
Attitude (&Orbit) Control System Computer
Sensors
Magnetometers
Sun Sensors
Earth Sensors
Gyroscopes
Star Sensors
GPS
Actuators
Magnetic Torquers
Reaction Wheels
Thrusters

Power Supply System
Solar Cell Panels
Power control System Computer
Battery

Payload System
Payload System Computer
Payload Cameras
Payload Sensors

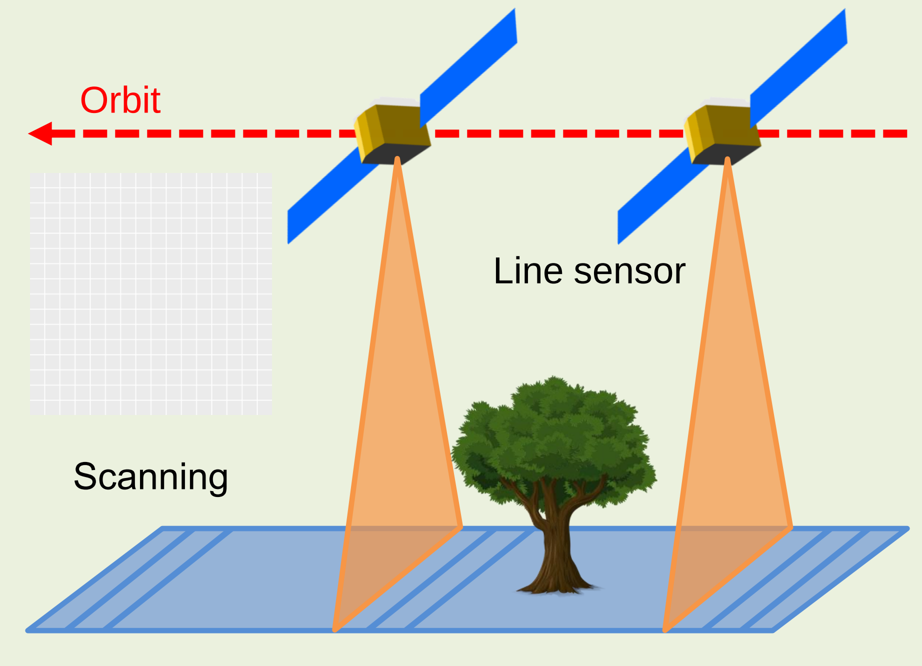
Main computing unit

1. Introduction to Attitude Control System

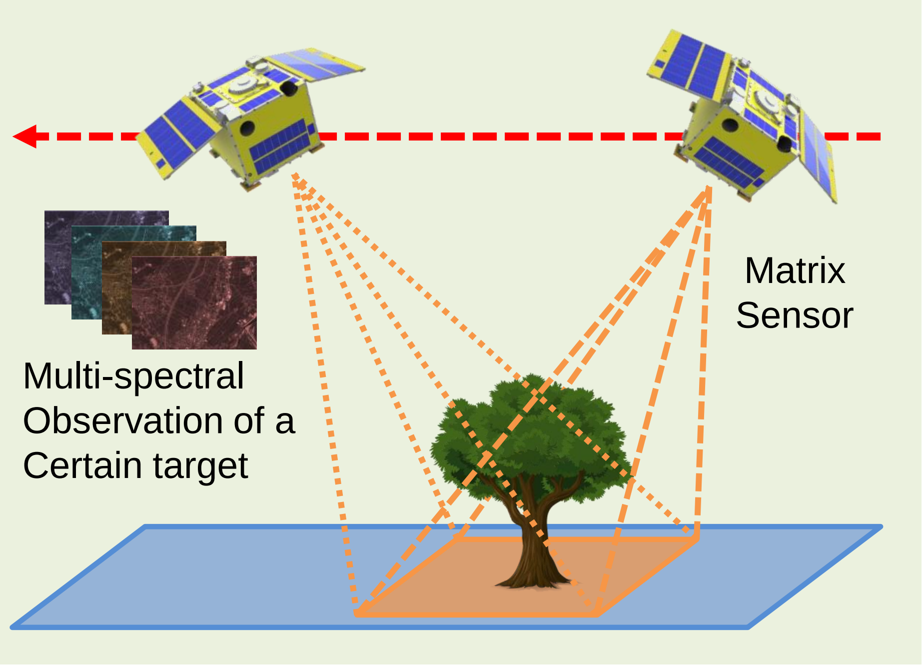
1.7. Attitude Control System Design Trade-off

Attitude control methods to achieve the mission objectives shall be selected by a careful engineering trade-off process.

Push-Bloom Observation



Step-Stare Observation



Merit: The attitude motion of the satellite can be kept slow
Observation area can be larger

Demerit: Exposure time tends to become short.

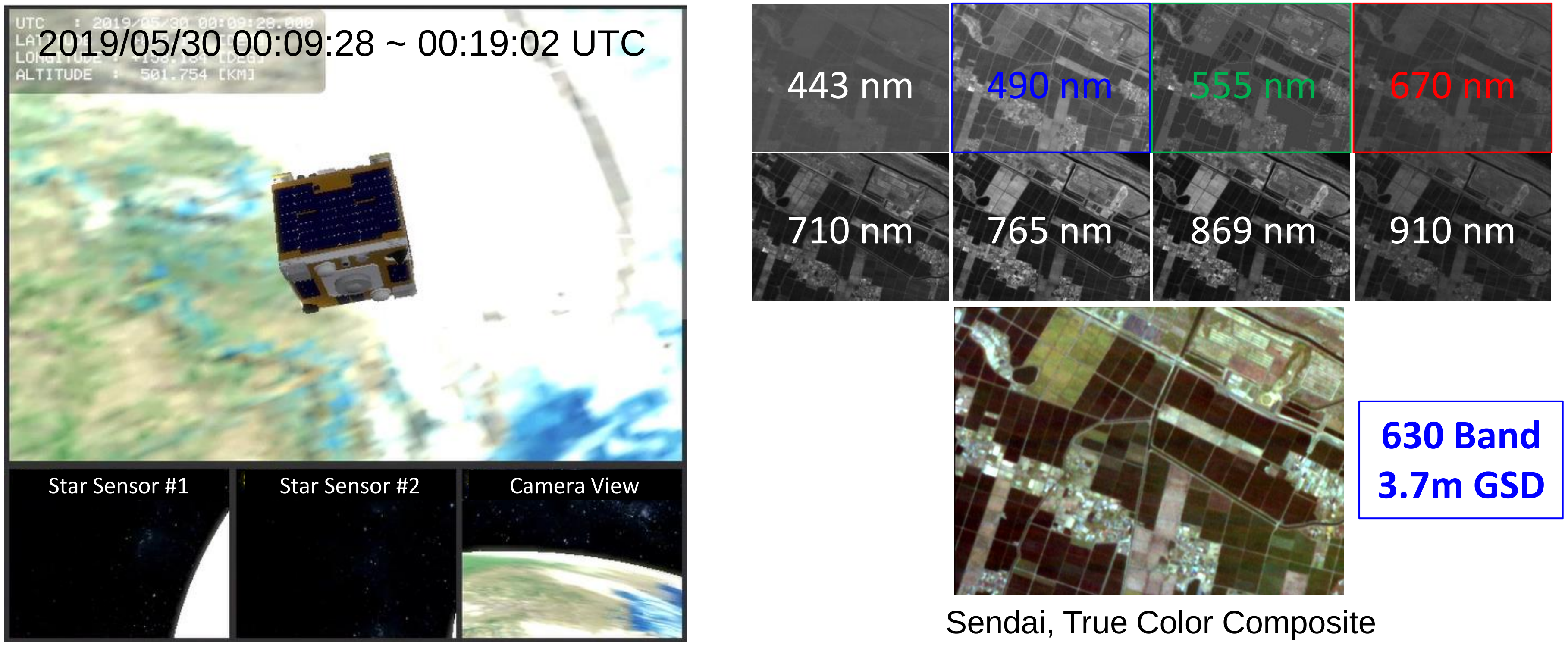
Merit: Exposure time can be long.

Demerit: Attitude control needs to be accurate and agile .
Small observation area.

1. Introduction to Attitude Control System

1.8. Attitude Control System Example – Microsatellite RISESAT

- An example of multi-spectral observation with target pointing attitude control is illustrated below.



2019/05/30 00:09:28 ~ 00:19:02 UTC

630 Band
3.7m GSD

Sendai, True Color Composite

Multi-spectral observation with target pointing attitude control mode © JSASS

* Fujita, S., et al.: Development and Ground Evaluation of Ground-Target Tracking Control of Microsatellite RISESAT, Trans. JSASS ATJ, 17, 2 (2019), pp.120-126.
* Kurihara, J., Kuwahara, T., et al.,: A High Spatial Resolution Multispectral Sensor on the RISESAT Microsatellite, Trans. JSASS ATJ, 18, 5 (2020), pp.186-191.

2. CubeSat Attitude Control Mode

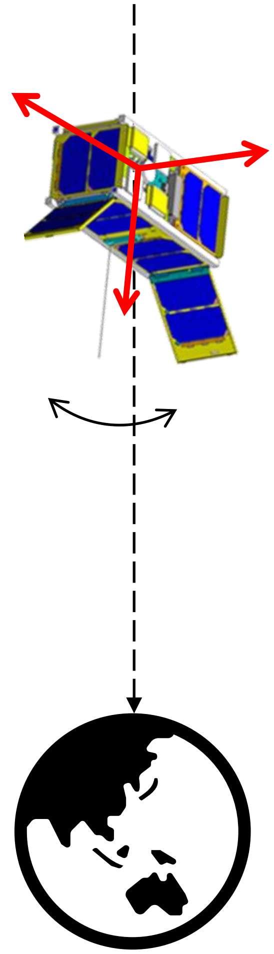
2. CubeSat Attitude Control Mode

2.1. Types of Attitude Control Mode

- It is often the case that satellites need to be capable of performing specific attitude control modes in order to achieve the mission objectives.
- There are a variety of possible attitude control modes for spacecraft.
- Usually, a spacecraft is equipped with several attitude control modes, and the mode transition between them is carefully designed in order to ensure safe and stable satellite operation.

- **Types of attitude control**
  1. Passive control
  2. Active control

- **Attitude control modes**
  - Detumbling control (after the separation from the launch vehicle or release from the ISS)
  - Gravity gradient control
  - Spin-stabilization control
  - 3-axis control (Pointing control): Inertial, Nadir, Target, Velocity Direction, etc.



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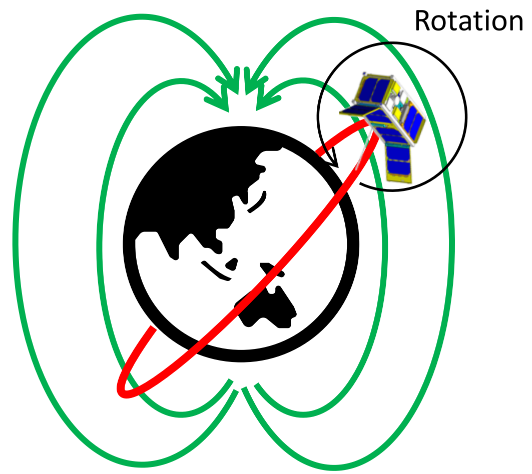
2. CubeSat Attitude Control Mode

2.2. Detumbling Control

Detumbling Control

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



Earth Magnetic Field

Type of detumbling control

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

Magnetic Torquers
(Electrical Coil)

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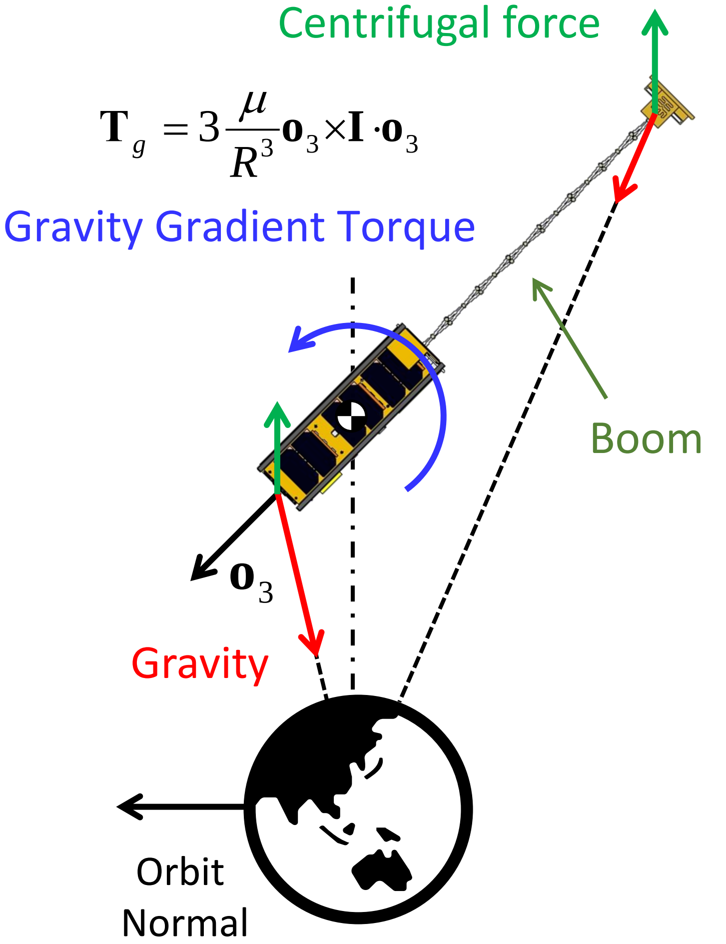
2. CubeSat Attitude Control Mode

2.3. Gravity Gradient Control

Gravity Gradient Control (passive control)

- Satellites with long shapes and spread mass distribution experience a gravity gradient torque such that the longitudinal direction points toward the Earth.
- Cameras, antennas, and 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)

2. CubeSat Attitude Control Mode

2.4. 3-axis Control (Pointing 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.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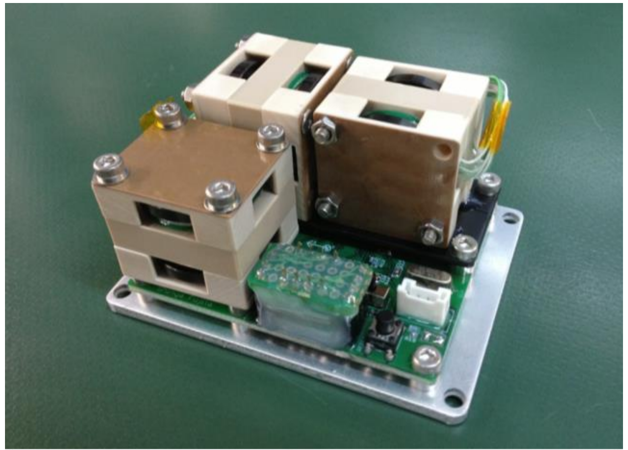

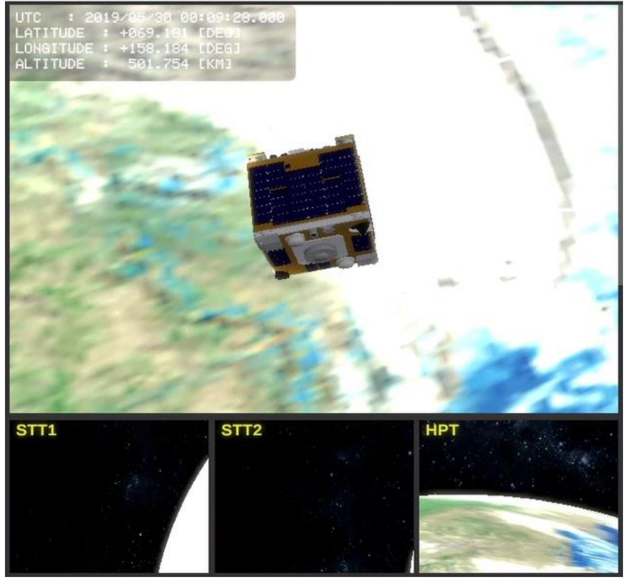

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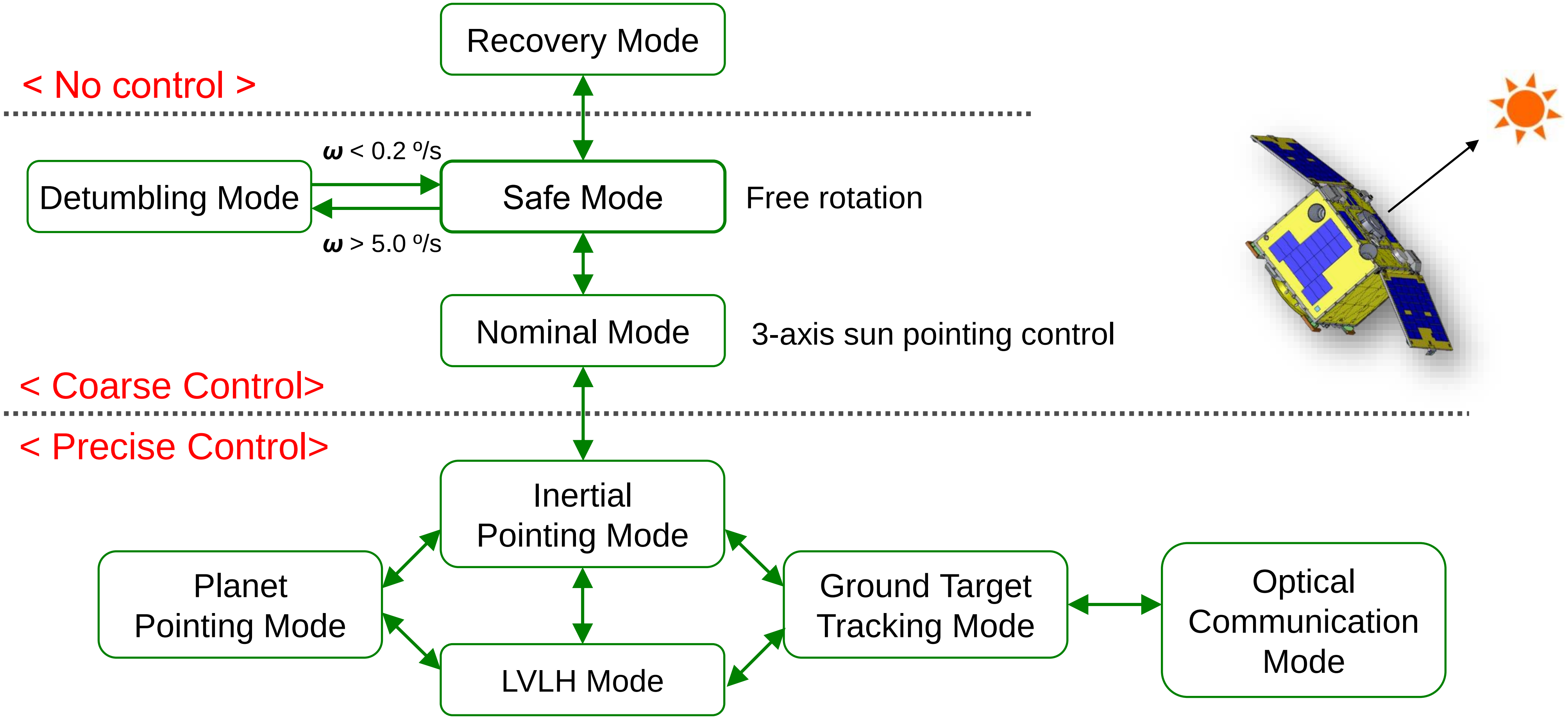
2. CubeSat Attitude Control Mode

2.5. Mode Transition between Attitude Control Modes

Example of Mode Transition State-Machine of a microsatellite, RISESAT.



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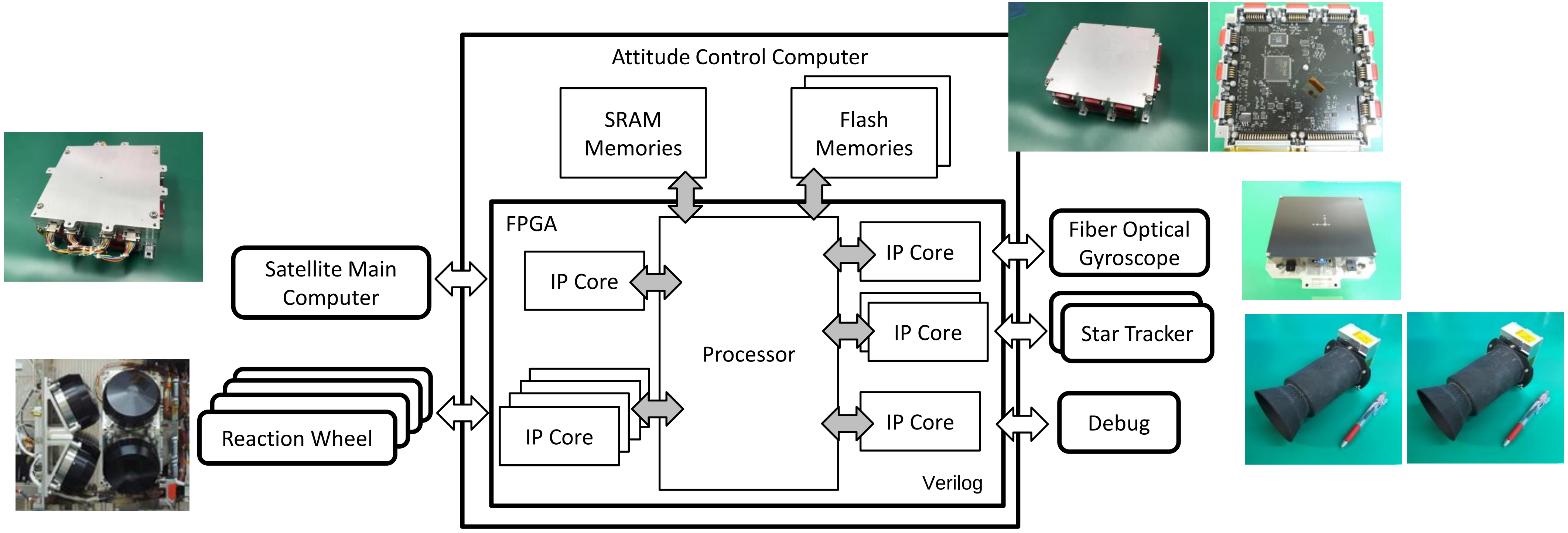
3. Hardware Components of Attitude Control System

3. Hardware Components of Attitude Control System

3.1. Introduction to Hardware Components of Attitude Control System

- Attitude control system (ACS) requires attitude determination sensors, attitude control actuators, and on-board computers. A satellite can have a dedicated computer for the ACS or ACS functionalities can be spread into several on-board computers.
- ACS requires a lot of on-board components and significant efforts are needed for their verification. Definition of their requirements and “make or buy” decisions have considerable impacts on project progress and mission successes.



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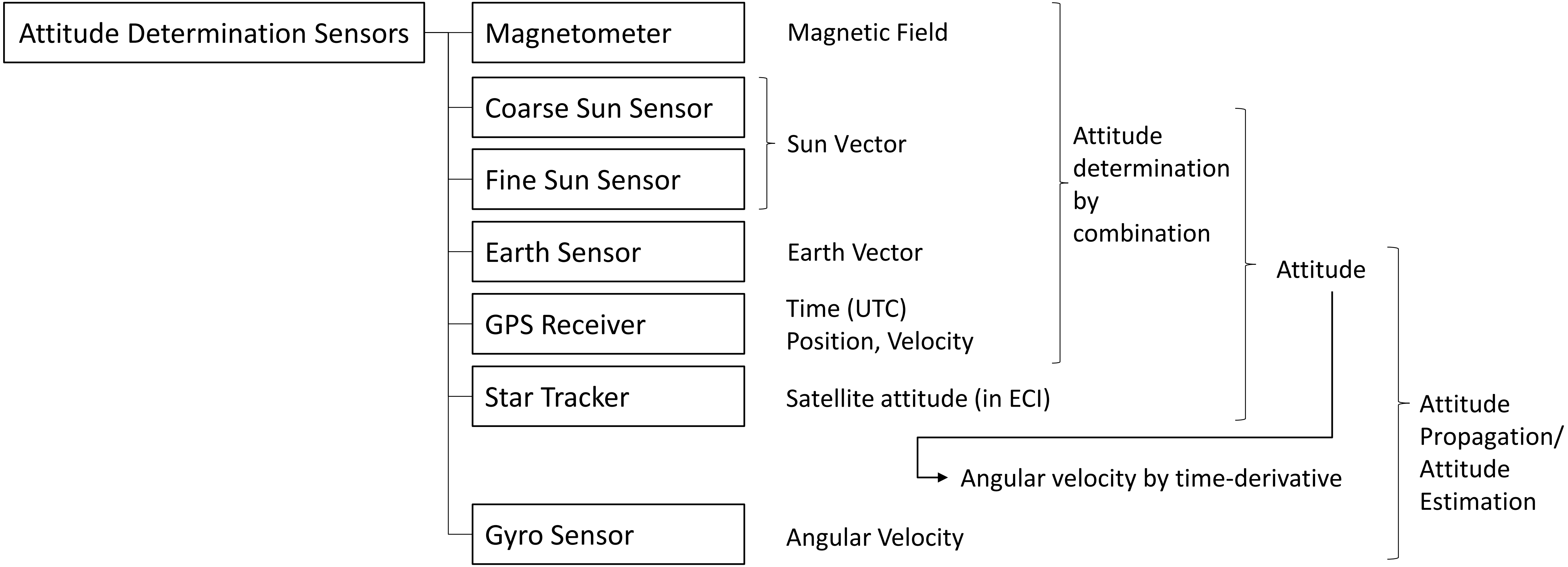
3. Hardware Components of Attitude Control System

3.2. Attitude Determination Sensors

- Sensor instruments and their corresponding variables, which are used for spacecraft attitude determination, are listed below.



Attitude Determination Sensors

Magnetometer	Magnetic Field
Coarse Sun Sensor	Sun Vector
Fine Sun Sensor	Sun Vector
Earth Sensor	Earth Vector
GPS Receiver	Time (UTC) Position, Velocity
Star Tracker	Satellite attitude (in ECI)
Gyro Sensor	Angular Velocity

Attitude determination by combination

Attitude

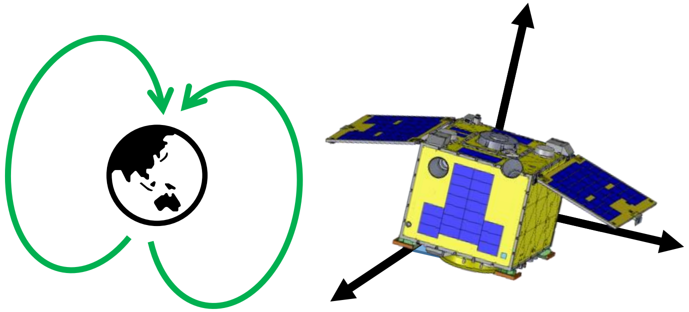
Angular velocity by time-derivative

Attitude Propagation/ Attitude Estimation

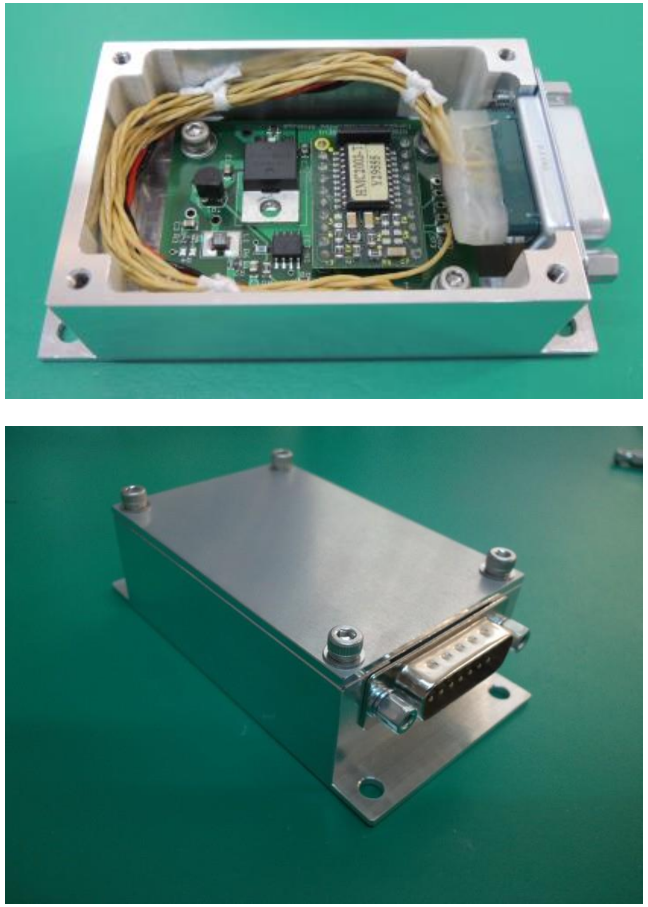
3. Hardware Components of Attitude Control System

3.3. Attitude Determination Sensors – Magnetometer

- Magnetometer / Geomagnetic Aspect Sensor
  - Measure the direction of the Earth's magnetic field.
  - Used to determine the attitude of the satellite by comparing the measured value and the calculated Earth magnetic field model at the position of the satellite.
  - Since it is affected by the magnetic field generated by the satellite itself, it is necessary to check whether there are any devices that consume a large current in the neighborhood of the sensor and whether the residual magnetic moment of the satellite is small enough.
  - It is beneficial that magnetic field information is available for Low Earth Orbit satellites all the time.
  - Especially, it is necessary to know the direction of the Earth's magnetic field for attitude control using magnetic torquers.
  - Some magnetometers have analog outputs and some have digital outputs.



Magnetometer



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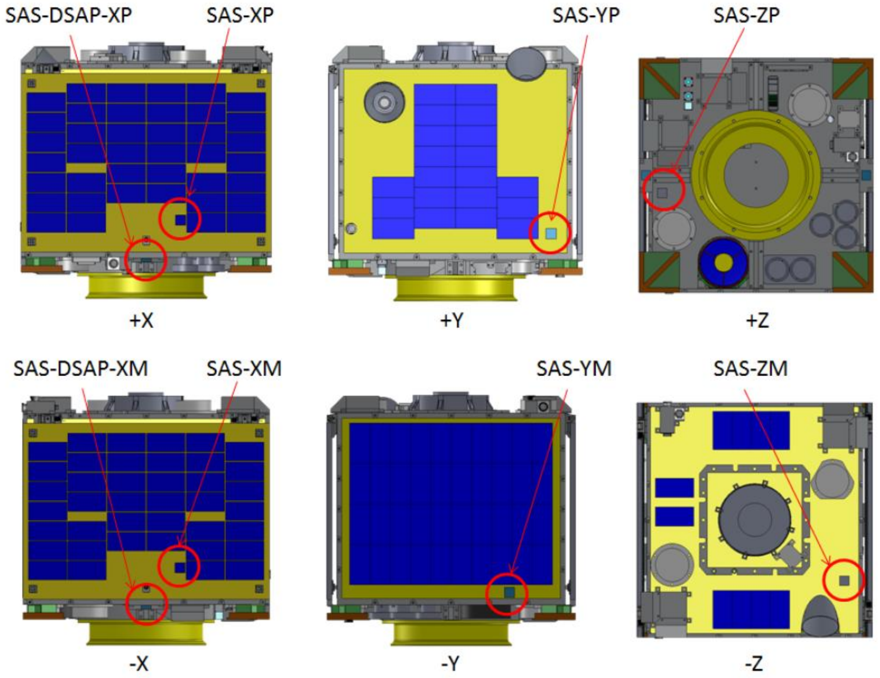
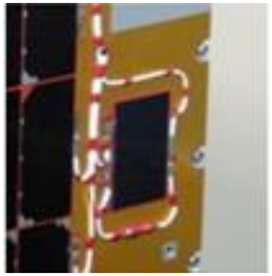
3. Hardware Components of Attitude Control System

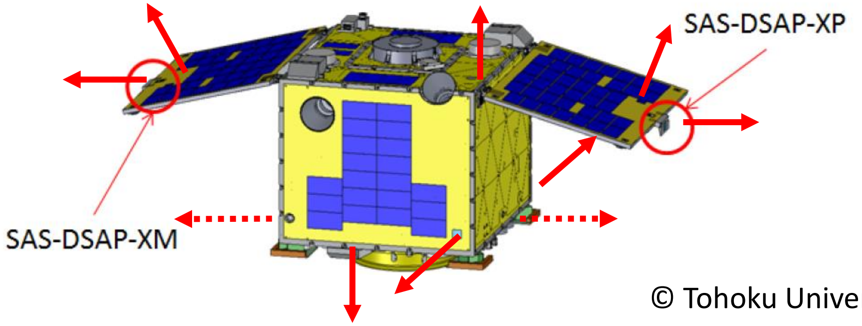
3.4. Attitude Determination Sensors – Coarse Sun Sensor

- Coarse Sun Sensor / Sun Aspect Sensor
  - Small solar cells or photodiodes can be used as the coarse sun sensor.
  - The amount of power generated by the sensors changes according to the angle of incidence of sunlight, which is converted into voltage for measurement.
  - By measuring the ratio of six sensors that are orthogonal to the three axes, the direction of the sun can be determined with coarse accuracy (several degrees).
  - It is very robust and stable.
  - It has a wide field of view and can cover the entire sky.

Coarse Sun Sensor Implementation based on Solar Cells.







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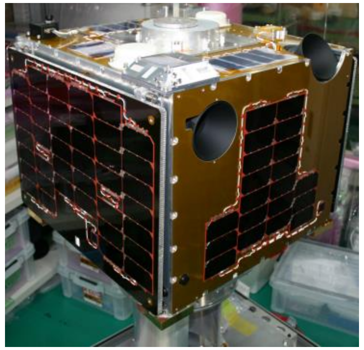
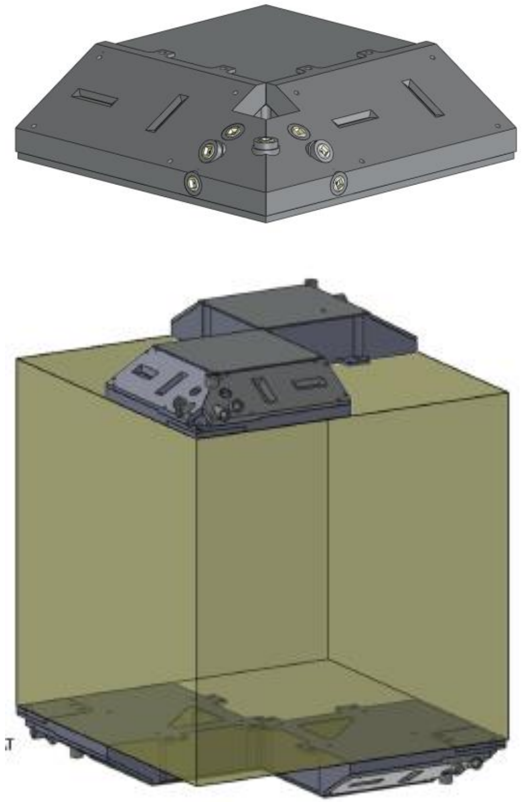
3. Hardware Components of Attitude Control System

3.5. Attitude Determination Sensors – Fine Sun Sensor

- Fine Sun Sensor
  - Can detect the sun direction very accurately.
  - There are various principles, such as slit type and pinhole type.
  - The field of view is narrow, and it is necessary to mount multiple sensors to cover the entire sky.
  - In the example illustrated in the figure on the right, two sets of solar sensors are mounted on the upper and lower surfaces of the satellite, each of them having a pair of two sun sensors in order to cover the entire sky.
  - If the attitude of the satellite to the sun is restricted in advance, it can be handled by a reduced number of sensors.
  - Can only be used in the sunshine area.



Fine Sun Sensor



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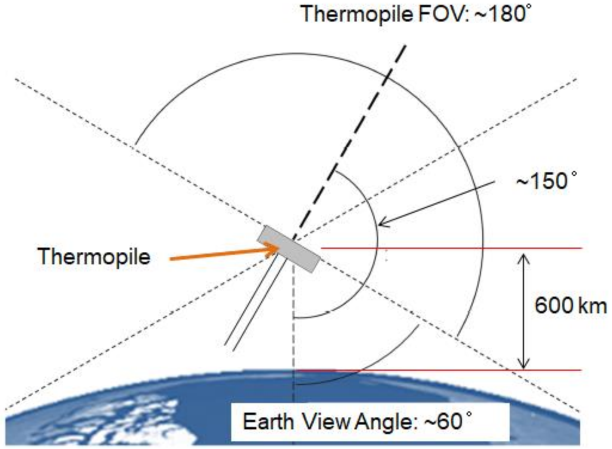
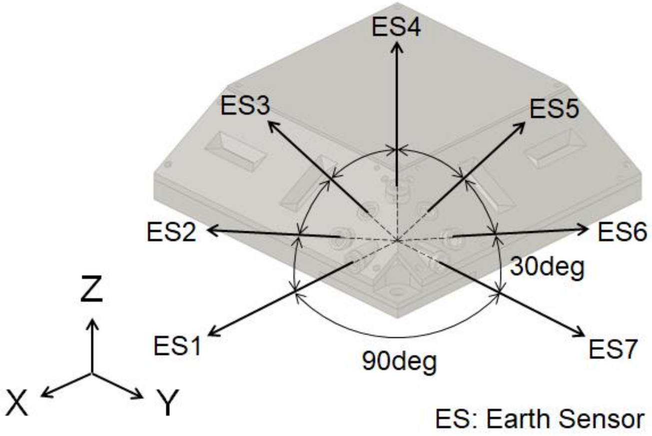
3. Hardware Components of Attitude Control System

3.6. Attitude Determination Sensors – Earth Sensor

- Earth Sensor
  - Some use optical sensors to determine the direction of the earth by detecting the rims of the Earth, while others use heat-sensitive sensors, such as thermopiles.
  - In Low Earth Orbit, Earth exists too close to the satellite to determine the direction accurately, and Earth sensors is not widely used.
  - The figure on the right is an example of an Earth sensor implementation example using thermopiles (still under investigation).
  - There is a demand for detecting the geocentric direction, even with coarse accuracy, in the eclipse.

Earth Sensor





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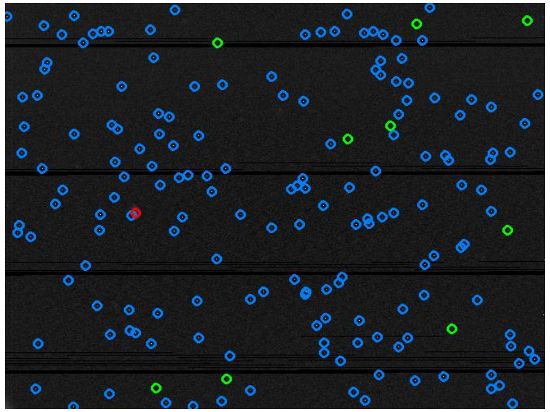
3. Hardware Components of Attitude Control System

3.7. Attitude Determination Sensors – Star Tracker

- Star Tracker / Star Sensor
  - Takes images of star constellation and compares with the star catalog information to determine the attitude of the sensor relative to the inertial coordinate.
  - The satellite attitude can be directly determined by single sensor very accurately.
  - After successfully detecting the attitude at the beginning (lost in space) when the power is turned on, it tracks and follows the identified stars to keep determining the satellite attitude.
  - Required exposure time is relatively long (typically several hundreds of milliseconds) to get clear star images, which limits the processing speed and sensor data output frequency.
  - The challenge is to perform a catalog matching process as fast as possible in order to reduce the data latency.
  - It is necessary to design the lifetime of the sensor in consideration of the deterioration of the sensor over time and the increase of white pixels.
  - By blocking the intrusion of ambient light using a baffle, the satellite's activity region can be expanded and flexible operation can be realized.
  - Attitude cannot be detected when the angular velocity of the satellite is too high.

Star Tracker



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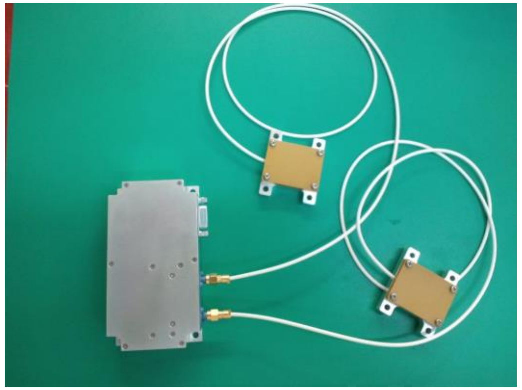
3. Hardware Components of Attitude Control System

3.8. Attitude Determination Sensors – GPS Receiver

- GPS Receiver, Antenna
  - GPS receivers can also be used in Low Earth Orbit.
  - GPS receivers provide information such as:
    - Time (UTC), and PPS (Pulse Per Second)
    - Satellite position
    - Satellite velocity
  - Since the relative velocity is faster in orbit than on the ground, it is necessary to use GPS receivers designed for space-use.
  - For satellites whose attitude may be oriented in any direction, it is better to mount a receiving antenna on the upper and lower surfaces of the satellite so that GPS signals can be received regardless of the attitude. Antennas on the upper and lower surfaces can be coupled as a single antenna (right figure).
  - It is better to select a GPS that has a short acquisition time after power on.
  - On-board processing of GPS data needs attention of leap years.

GPS Receiver and Antenna



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3. Hardware Components of Attitude Control System

3.9. Attitude Determination Sensors – Gyro Sensor

Angular rate/velocity sensor

- Fiber Optic Gyroscope (FOG)
  - A high-precision angular velocity sensor used for microsatellites.
  - Optical fiber is used inside and the device, the lifetime shall be evaluated paying attention to the optical deterioration due to radiation effects.
  - Several degrees of accuracy can be achieved even after just about 1 hour of numerical integration.
- MEMS Gyro Sensor
  - Middle-precision angular velocity sensor used for microsatellites.
  - Since it has excellent durability and a small form factor, it is suitable for building a redundant system or as a backup in the event of a failure.
  - When using FOG, it is recommended to install MEMS Gyro Sensor as well for redundancy.

Fiber Optic Gyroscope

© TAMAGA SEIKI

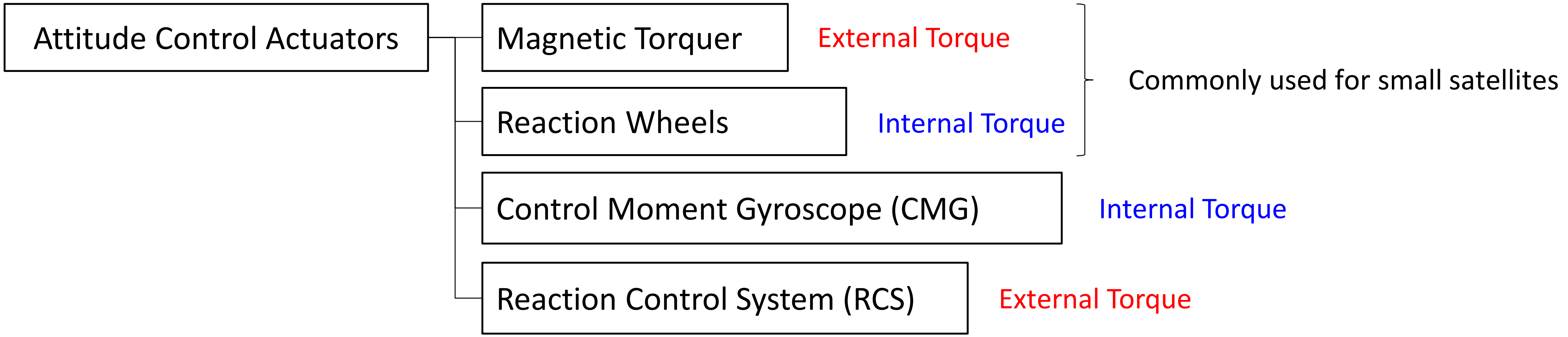
MEMS Gyro Sensor

© Sensonor

3. Hardware Components of Attitude Control System

3.10. Attitude Control Actuators

- Actuator instruments for the spacecraft attitude control are listed below.



Attitude Control Actuators

Magnetic Torquer — External Torque

Reaction Wheels — Internal Torque

(Magnetic Torquer and Reaction Wheels:) Commonly used for small satellites

Control Moment Gyroscope (CMG) — Internal Torque

Reaction Control System (RCS) — External Torque

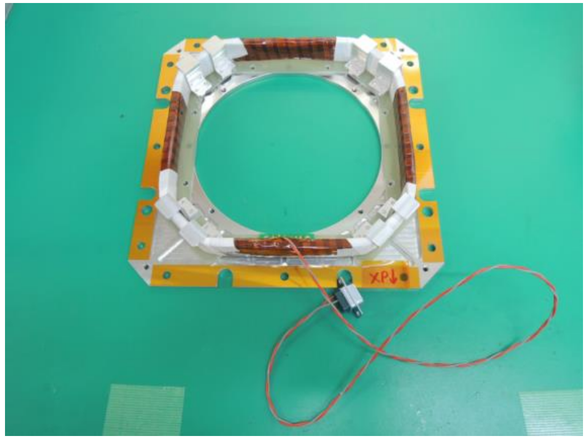
- Reaction wheels and CMGs can generate internal torques electronically by means of reaction torques generated from rotating elements inside of them.
- External disturbance torques acting on spacecraft are accumulated in forms of their angular momentum which needs to be desaturated using actuators with external torques.
- Satellite attitude can also be controlled using only actuators with external torques.

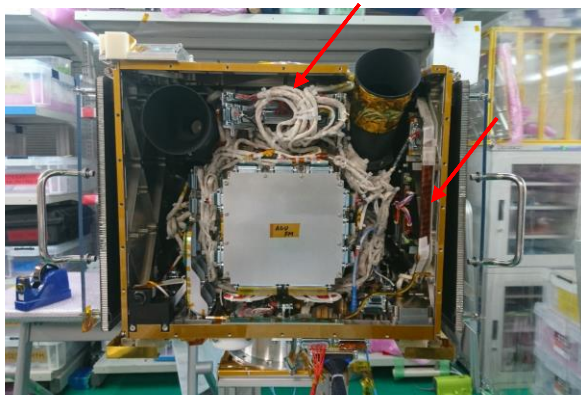
3. Hardware Components of Attitude Control System

3.11. Attitude Control Actuators – Magnetic Torquer

- Magnetic Torquer
  - A device that can generate a magnetic moment by electrical current.
  - The generated magnetic moment interacts with the Earth's magnetic field resulting in external torque acting on the satellite.
  - It can only be used in space where magnetic field exists. (Cannot be used in Lunar orbit)
  - It is common that a satellite is equipped with three magnetic torquers in each axis, so that the satellite can generate the desired magnetic moment for 3-axis attitude control.
  - It is also used for the detumbling control of the satellite rotational velocity, especially after the separation from the launch vehicle, or release from the International Space Station (ISS). Detumbling can be achieved by a fewer number of magnetic torquers.

Magnetic Torquer





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3. Hardware Components of Attitude Control System

3.12. Attitude Control Actuators – Reaction Wheel

- Reaction wheel
  - A reaction wheel contains a rotating wheel inside and makes it possible to control the attitude of the spacecraft by the reaction effects of the rotation.
  - Internal torque can be generated electronically and no propellant is needed, unlike thrusters.
  - In many cases, about 1 to 4 units will be installed in a spacecraft according to the mission requirements.
  - The performance of RWs is explained by the magnitude of output torque and the maximum angular momentum that can be accumulated.
  - The internal wheel can be rotated in either the positive or negative direction.
  - The wheel stops once when the direction of rotation changes. This situation is called “zero-cross”, and when this happens, the accuracy of attitude control and the lifetime of the internal mechanical elements, decreases.
  - When aiming for long-term use preventing deterioration of bearings, it is necessary to avoid zero-cross in operation.
  - There is a practical upper limit of the rotational speed of the internal wheel, such as up to around 3000 rpm.

Reaction Wheel

© TAMAGA SEIKI

3. Hardware Components of Attitude Control System

3.13. Attitude Control Actuators – Reaction Control System / Thruster

- Reaction Control System (RCS)
  - An attitude control system which utilizes several sets of thrusters.
  - RCS requires propellant, and hence the amount of propellant limits the device lifetime.
  - The same set of thrusters of RCS could be also used for the orbit control, depending on their alignment.
  - A pair of two thrusters are required in order to generate only torque without generating translational thrust.
  - There are different kinds of thrusters available for RCS.
    - Cold gas thruster
    - Hot gas thruster
    - Resistojet thruster
    - Ion thruster
    - etc.

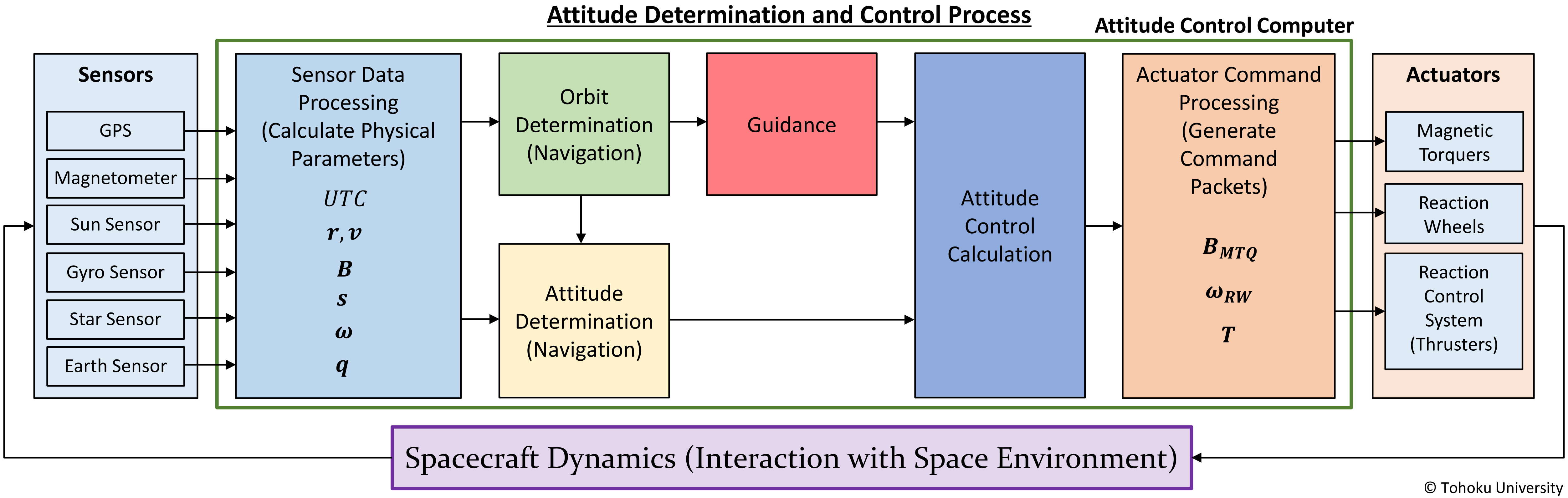
Micro-satellite ALE-2 © ALE / Tohoku University

4. Attitude Determination and Control Process

4. Attitude Determination and Control Process

4.1. Introduction to Attitude Determination and Control Process

- Attitude determination and control processes can be divided into several steps, executed one after another in a periodical manner continuously.
- The process consists of processing of sensor data, orbit determination, attitude determination, guidance, attitude control calculation, and the generation of command packets for actuators.



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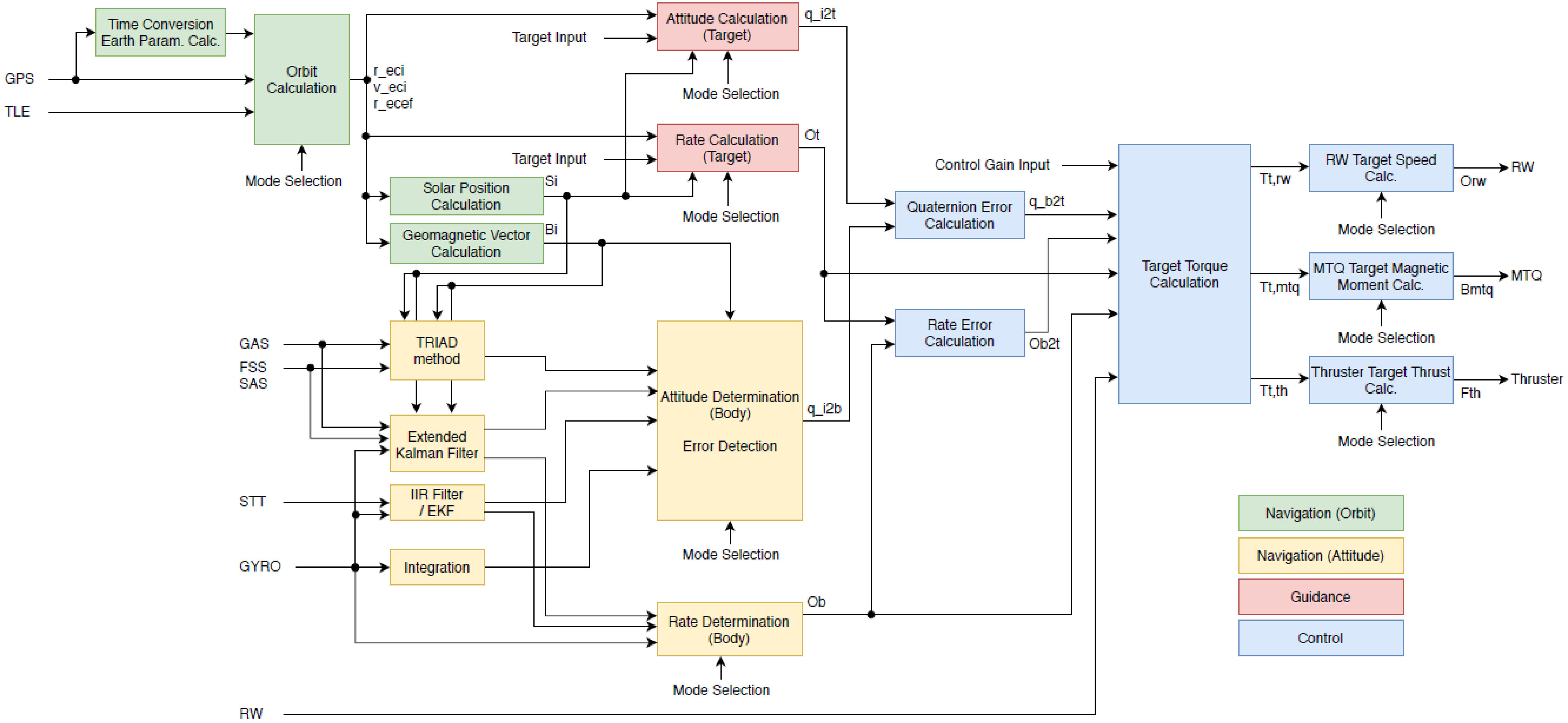
4. Attitude Determination and Control Process

4.2. Detailed Block Diagram of Attitude Determination and Control Process

- Guidance, Navigation and Control Classification of the Attitude Determination and Control Process.



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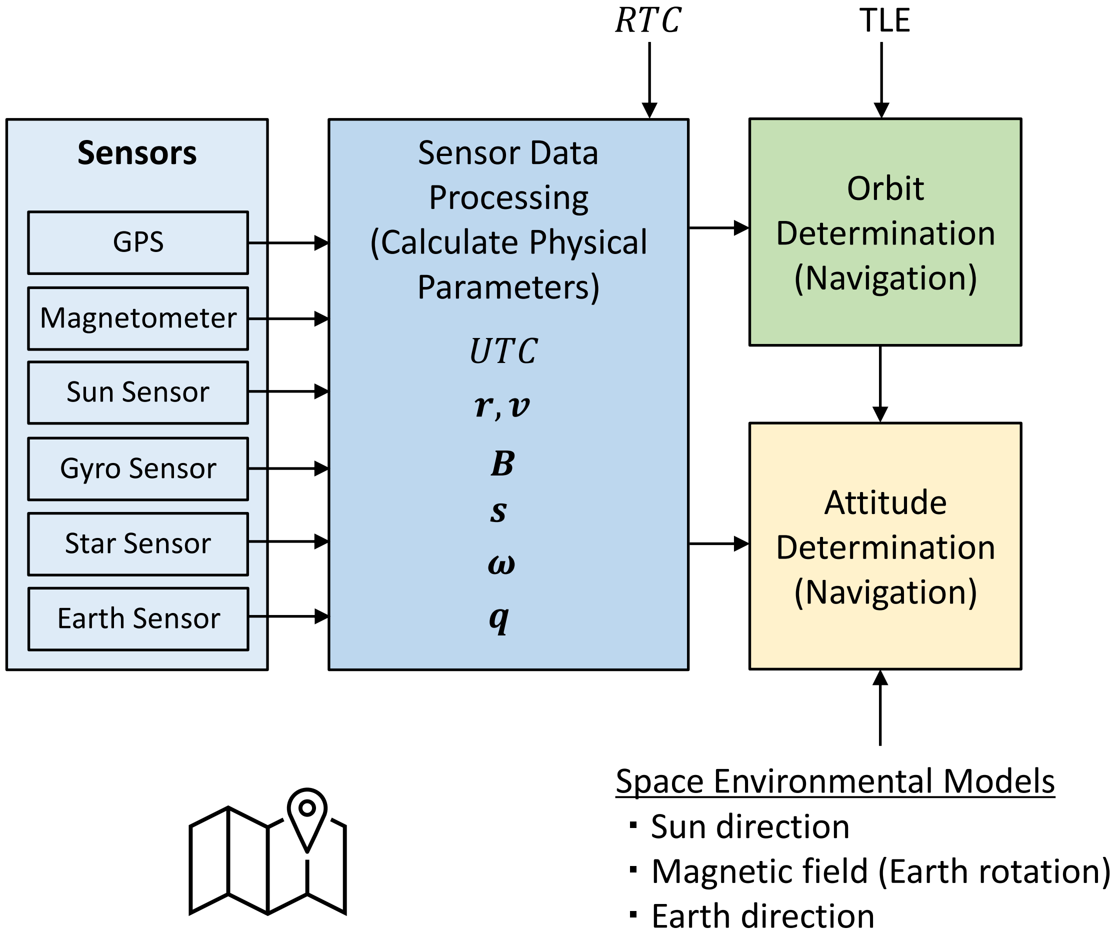
4. Attitude Determination and Control Process

4.3. Attitude Determination

- For the attitude determination, the following information shall be available.
  - Time Information – Time information can be obtained from the GPS receiver, or from the on-board RTC.
  - Orbital Position – Orbital Position can be obtained from the GPS receiver, or mathematical integration inside the on-board computer based on the orbital mechanics. TLE (Two Line Element) information can be used.
- Attitude determination calculations requires comparison between the measured physical parameters and estimation with space environmental models.
  - Sun direction
  - Magnetic field direction (Earth rotation)
  - Earth direction



RTC

TLE

Sensors

GPS

Magnetometer

Sun Sensor

Gyro Sensor

Star Sensor

Earth Sensor

Sensor Data Processing (Calculate Physical Parameters)

UTC

$\boldsymbol{r}, \boldsymbol{v}$

$\boldsymbol{B}$

$\boldsymbol{s}$

$\boldsymbol{\omega}$

$\boldsymbol{q}$

Orbit Determination (Navigation)

Attitude Determination (Navigation)

Space Environmental Models
- Sun direction
- Magnetic field (Earth rotation)
- Earth direction

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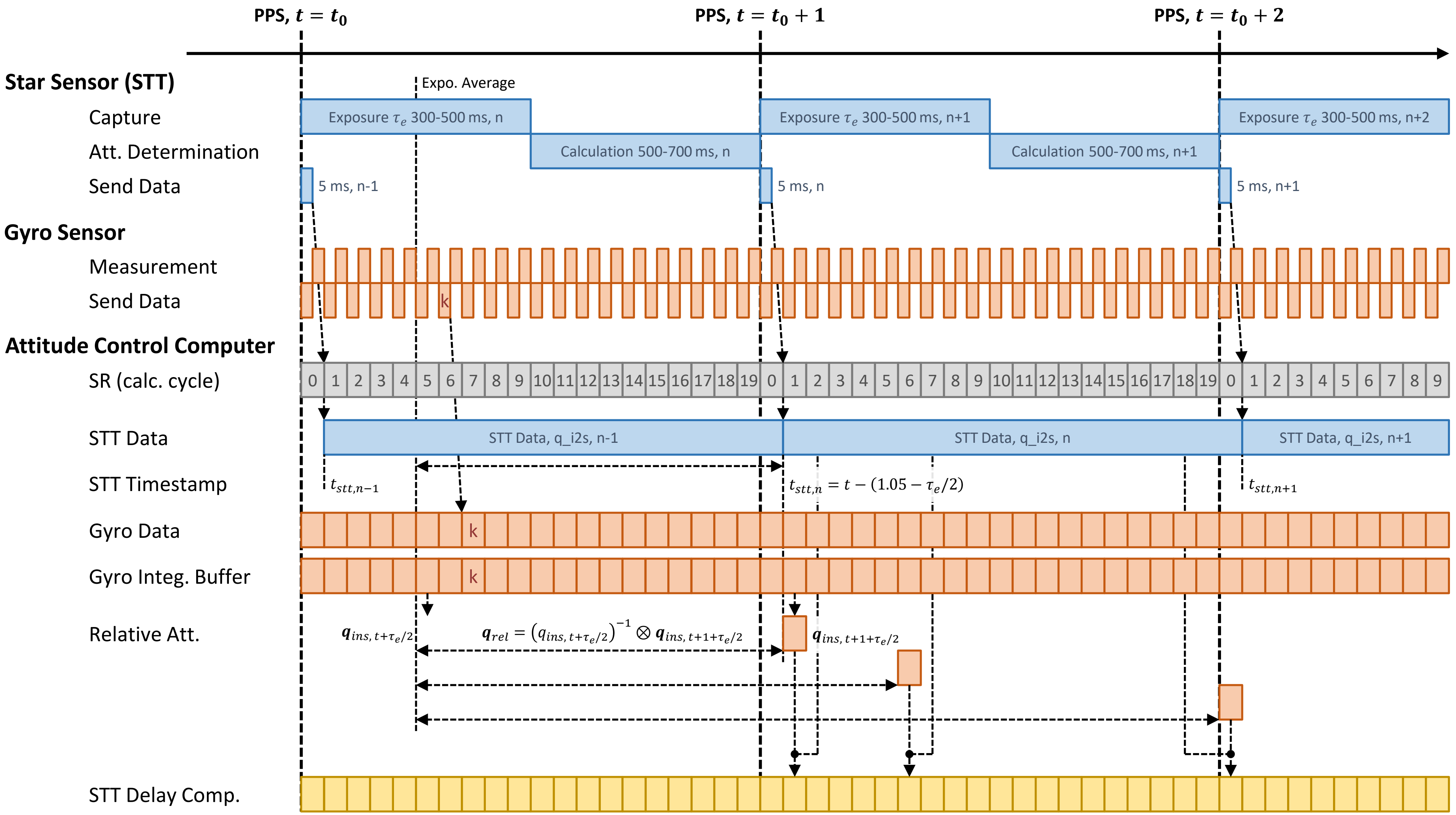
4. Attitude Determination and Control Process

4.4. Attitude Determination – Sensor Data Processing Timing



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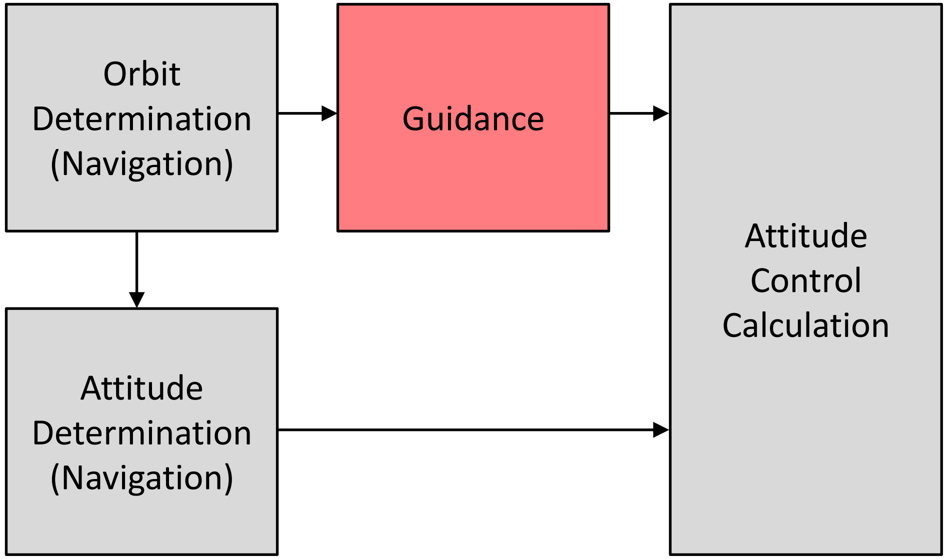
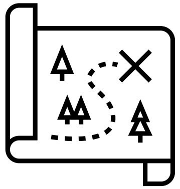
4. Attitude Determination and Control Process

4.5. Navigation

- Before the attitude control processing, the target attitude of the satellite needs to be calculated.
- The target attitude and rotational rate as well as their precision, depend on the mission objectives. There are a variety of target attitude definitions based on the mission objectives.
- Attitude determination and control is usually discussed relative to the inertial coordinate system.
- There are several different types of pointing controls as below:
  - Inertial Pointing Mode – Spacecraft attitude is controlled in the way that it is fixed to a certain direction of the inertial coordinate system. It is often used for star observation.
  - Nadir Pointing Mode – Spacecraft attitude is controlled in the way that a certain axis keeps pointing to the Earth (or a certain celestial body) center direction. It is often used for Earth surface observation in a scanning mode. The target attitude rotates with time based on the relative position of the Earth and the satellite.
  - Ground Target Pointing Mode – Spacecraft attitude is controlled in the way that a certain axis keeps pointing to a certain target object on the Earth's surface. It is often used for Earth observation in a pointing mode, or high-speed communication between the target ground station.





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4. Attitude Determination and Control Process

4.6. Navigation for Nadir Pointing Control

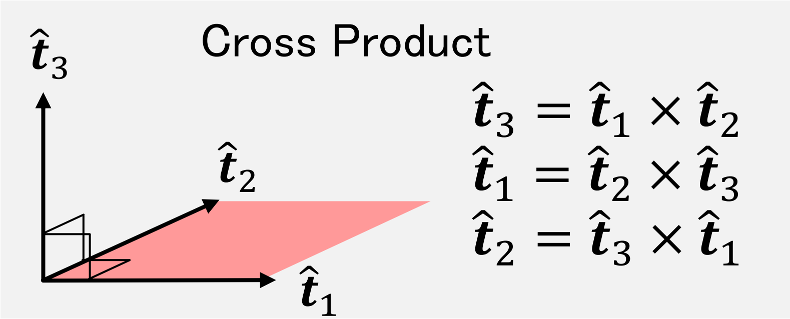
- Target coordinate system defined in the way that the corresponding body axis points toward the Earth center.
- Satellite attitude is controlled in the way that $\hat{\boldsymbol{b}}_i$ axis matches with the $\hat{\boldsymbol{t}}_i$ axis, respectively.

Target Coordinate System Definition

$$\hat{\boldsymbol{t}}_3 = -\hat{\boldsymbol{r}}_{sat,eci} = \vec{\boldsymbol{r}}_{sat,eci}/\left|\vec{\boldsymbol{r}}_{sat,eci}\right|$$

$$\hat{\boldsymbol{t}}_2 = \hat{\boldsymbol{t}}_3 \times \hat{\boldsymbol{v}}_{sat,eci}$$

$$\hat{\boldsymbol{t}}_1 = \hat{\boldsymbol{t}}_2 \times \hat{\boldsymbol{t}}_3$$

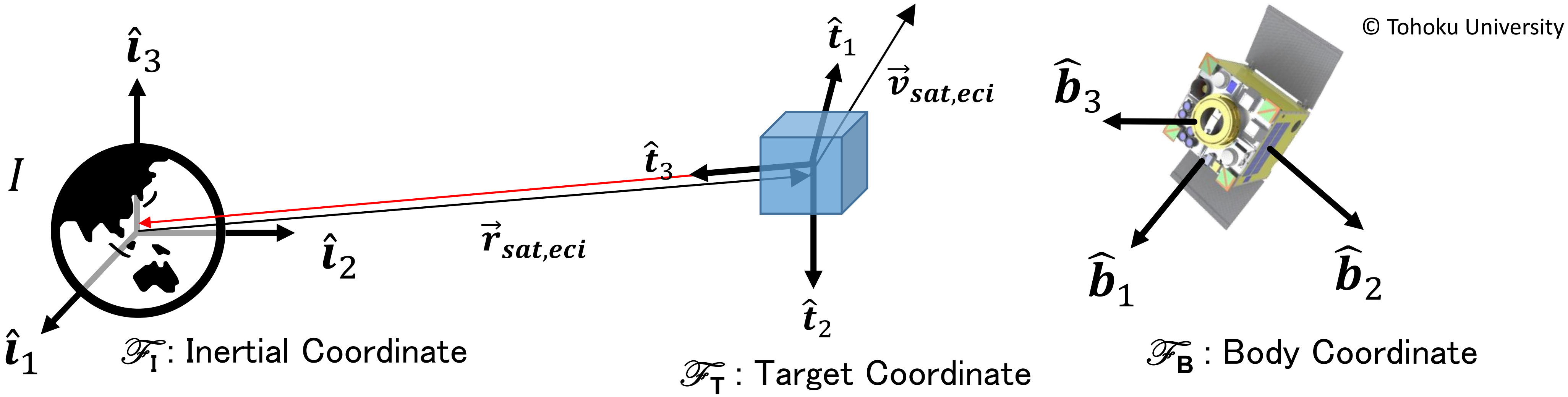


Cross Product

$$\hat{\boldsymbol{t}}_3 = \hat{\boldsymbol{t}}_1 \times \hat{\boldsymbol{t}}_2$$

$$\hat{\boldsymbol{t}}_1 = \hat{\boldsymbol{t}}_2 \times \hat{\boldsymbol{t}}_3$$

$$\hat{\boldsymbol{t}}_2 = \hat{\boldsymbol{t}}_3 \times \hat{\boldsymbol{t}}_1$$



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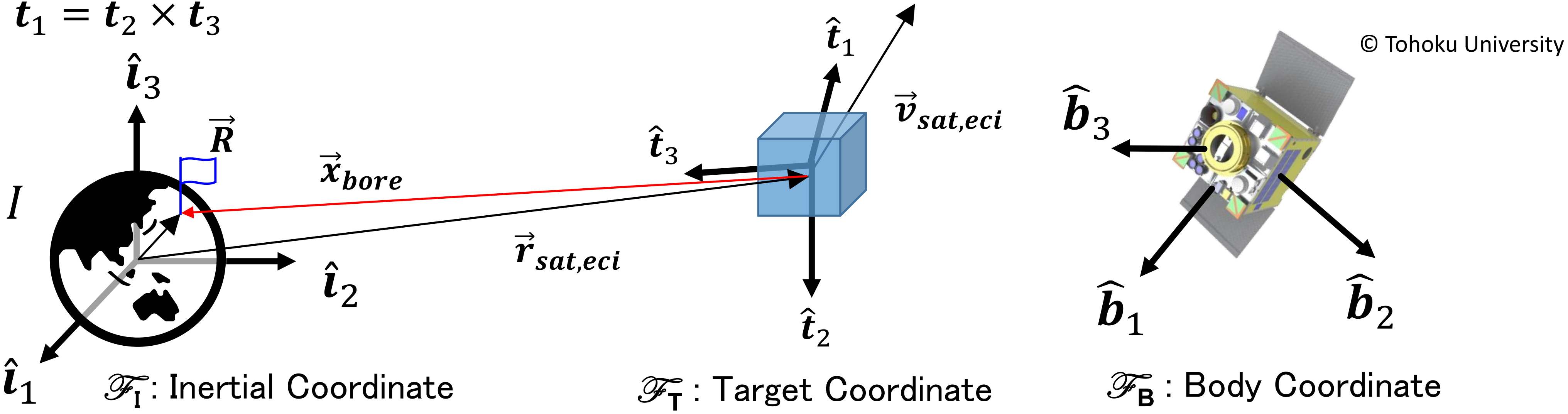
4. Attitude Determination and Control Process

4.7. Navigation for Target Pointing Control

- Target coordinate system defined in the way that the corresponding body axis points toward the specific target located on the Earth’s surface. Target position moves with time together with the Earth’s rotation.
- Target can be set at an arbitral position in space, in general.

Target Coordinate System Definition

$$\vec{x}_{bore} = \vec{R} - \vec{r}_{sat,eci}$$
$$\hat{t}_3 = \hat{x}_{bore}$$
$$\hat{t}_2 = \hat{t}_3 \times \hat{v}_{sat,eci}$$
$$\hat{t}_1 = \hat{t}_2 \times \hat{t}_3$$



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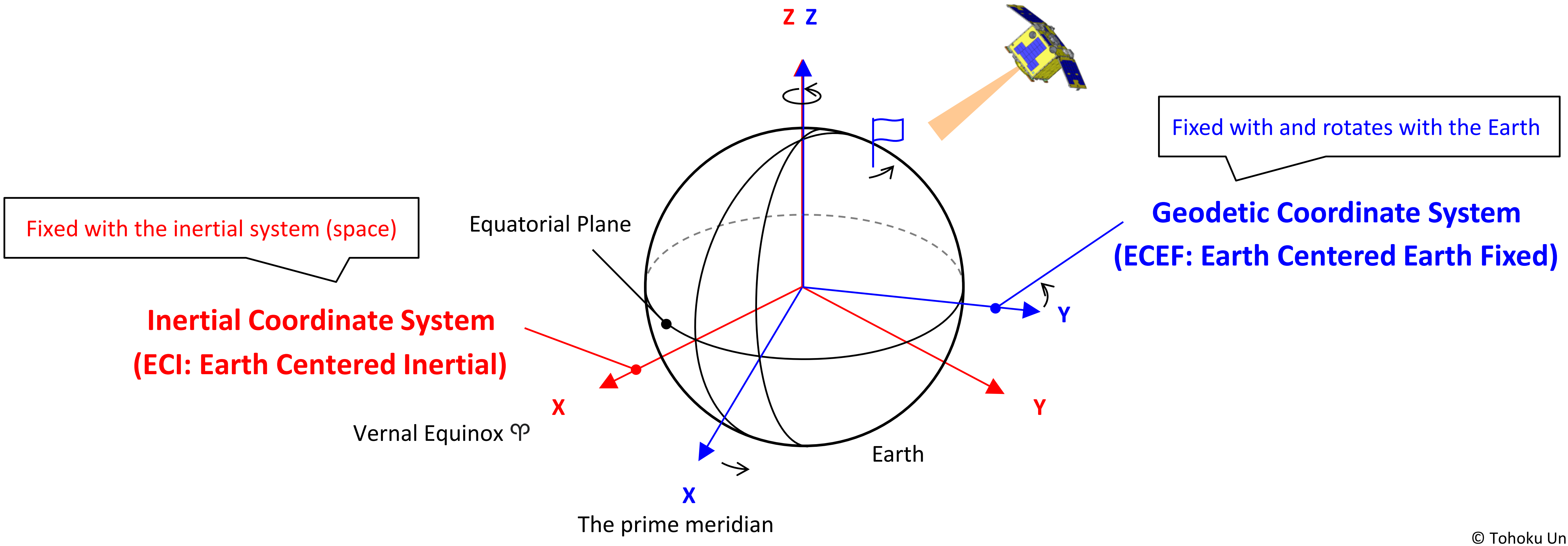
4. Attitude Determination and Control Process

4.8. Inertial Coordinate System and Geodetic Coordinate System

- Earth is rotating relative to the inertial coordinate. Understanding the relative motion of the geodetic coordinate system and inertial coordinate system, and hence the coordinate transformation matrix between them, is very important.
- A commonly used geodetic coordinate system is called ECEF (Earth Centered Earth Fixed), while the inertial coordinate system is called ECI: (Earth Centered Inertial). Earth's magnetic field is, for example, rotating with the Earth and needs to be described in ECEF.



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4. Attitude Determination and Control Process

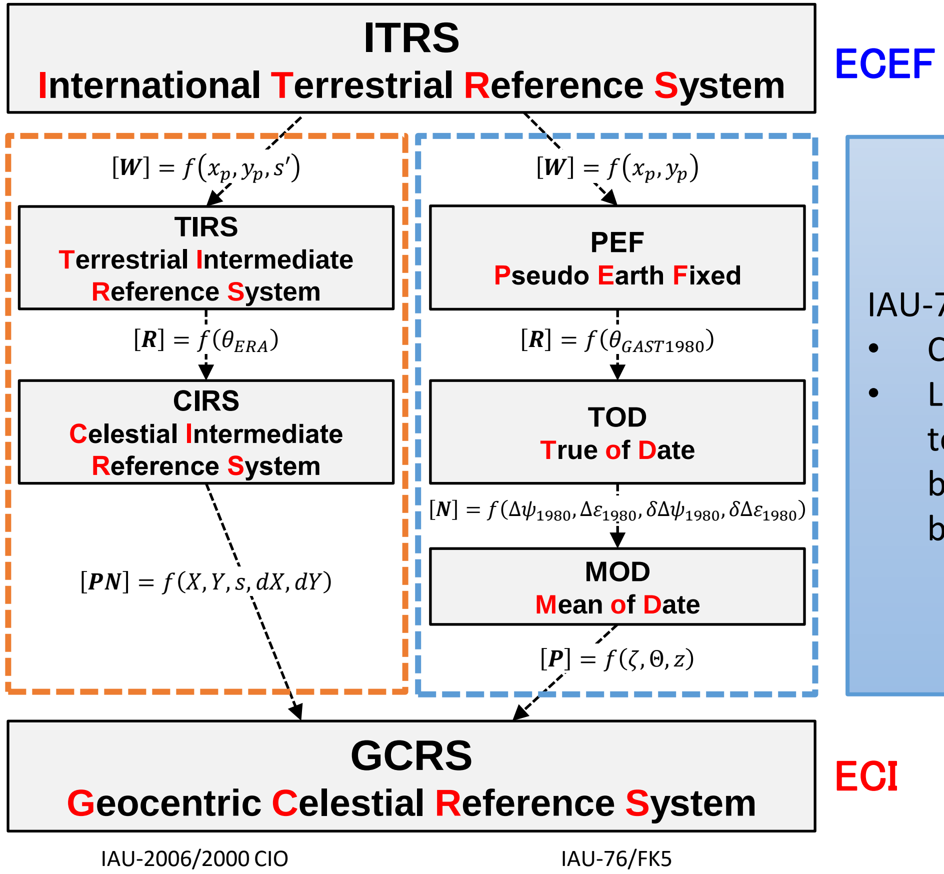
4.9. Coordinate Transformation between ECEF and ECI

Coordinate Transformation between ECEF(ITRF) and ECI(GCRF)

$$\boldsymbol{r}_{GCRF} = [\boldsymbol{P}(T)][\boldsymbol{N}(T)][\boldsymbol{R}(t)][\boldsymbol{W}(t)]\boldsymbol{r}_{ITRF}$$

$$\boldsymbol{r}_{ITRF} = [\boldsymbol{W}(t)]^T[\boldsymbol{R}(t)]^T[\boldsymbol{N}(t)]^T[\boldsymbol{P}(t)]^T\boldsymbol{r}_{GCRF}$$

IAU-2006/2000 CIO
- International Astronomical Union (IAU) recommendation.
- https://www.iausofa.org/
- High accuracy, but large computational load.

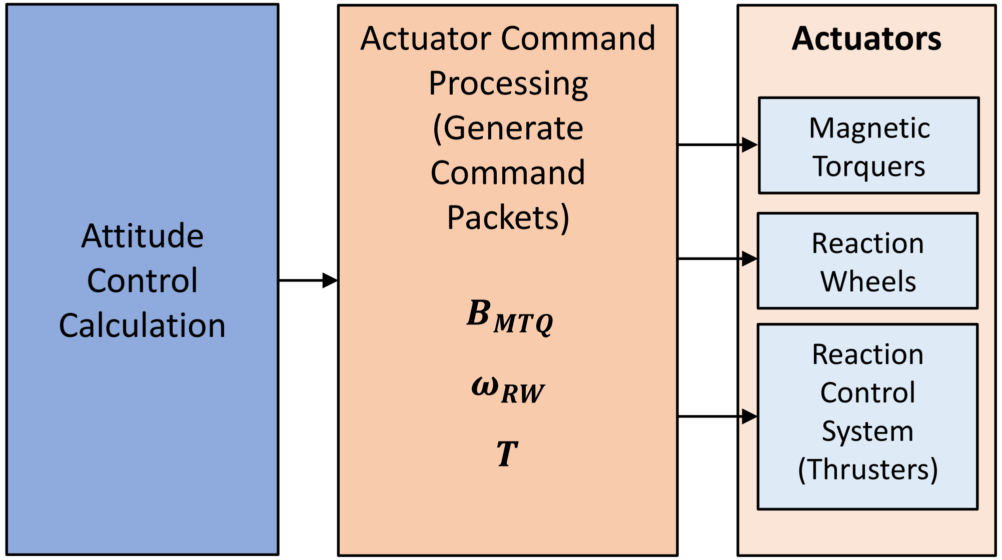


IAU-76/FK5
- Classical method
- Lower accuracy compared to the IAU-2006/2000 CIO, but easy to compute in on-board computers.

4. Attitude Determination and Control Process

4.10. Attitude Control

- Current attitude error is measured by comparing the target coordinate system and current body coordinate system, and attitude control torque is generated in the way that the attitude error decreases in order to achieve the desired attitude.
- Accuracy of the attitude control depends on the accuracy of attitude determination. Usually, the attitude determination accuracy shall be more than 10 times better than the desired attitude control accuracy.
- The limitation of the performance of the actuators and their mechanical alignment shall be taken into account when generating the actual commands sent to the hardware components.
- Spacecraft attitude can be controlled both by internal forces, such as the torque generated by reaction wheels, and external forces, such as the torque generated by magnetic torquers and thrusters.



Attitude Control Calculation

Actuator Command Processing (Generate Command Packets)

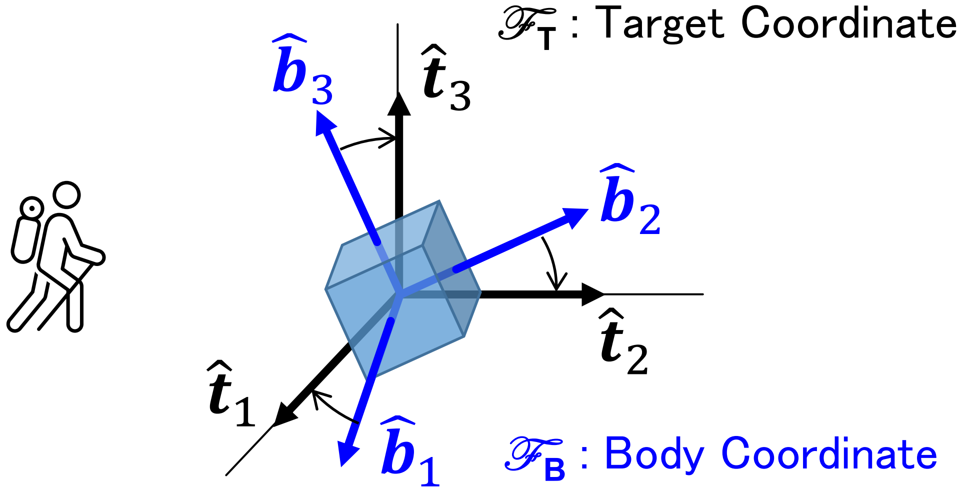
$\boldsymbol{B_{MTQ}}$

$\boldsymbol{\omega_{RW}}$

$\boldsymbol{T}$

Actuators

- Magnetic Torquers
- Reaction Wheels
- Reaction Control System (Thrusters)

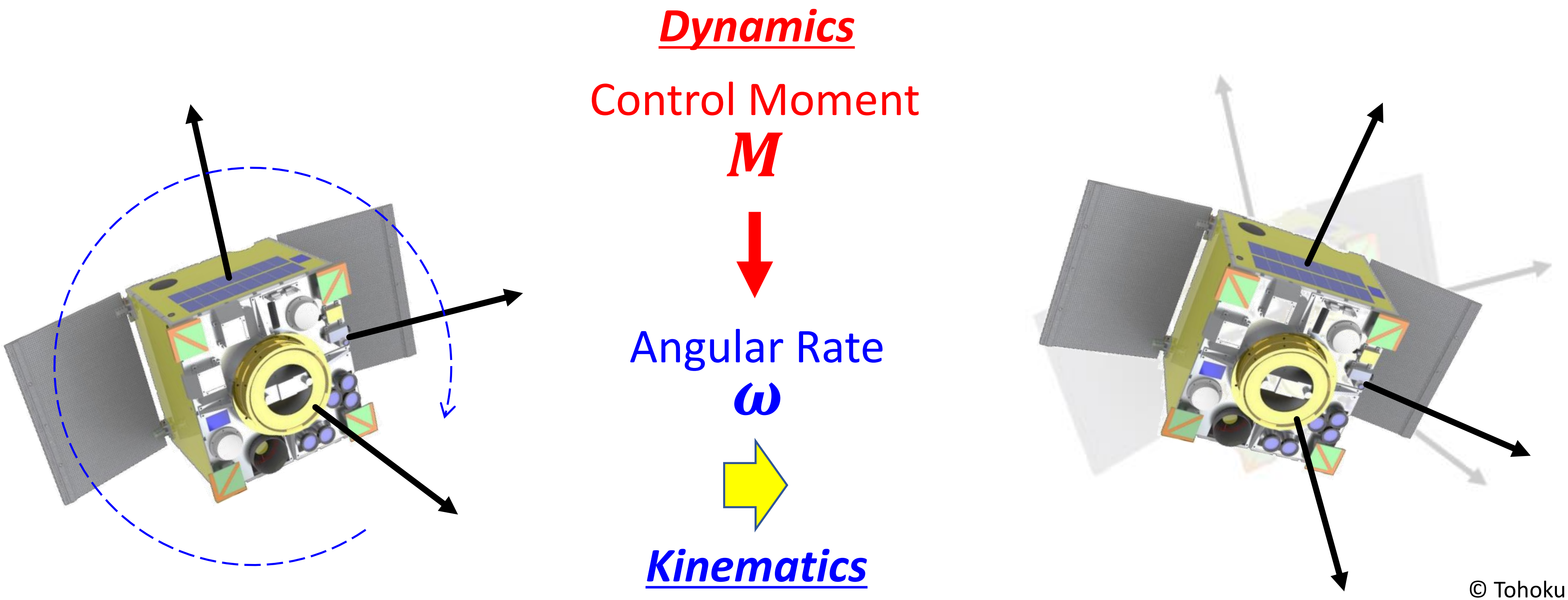


5. Attitude Determination and Control Algorithms

5. Attitude Determination and Control Algorithms

5.1. Satellite Attitude Kinematics, Dynamics, and Control

- Satellite motion can be described as the combination of **kinematics** and **dynamics**.
- Attitude kinematics describes the relationship between the rotational rate and the resulting satellite attitude.
- Attitude control moment (torque) can affect the angular rate through the satellite dynamics.



Dynamics

Control Moment

$\boldsymbol{M}$

Angular Rate

$\boldsymbol{\omega}$

Kinematics

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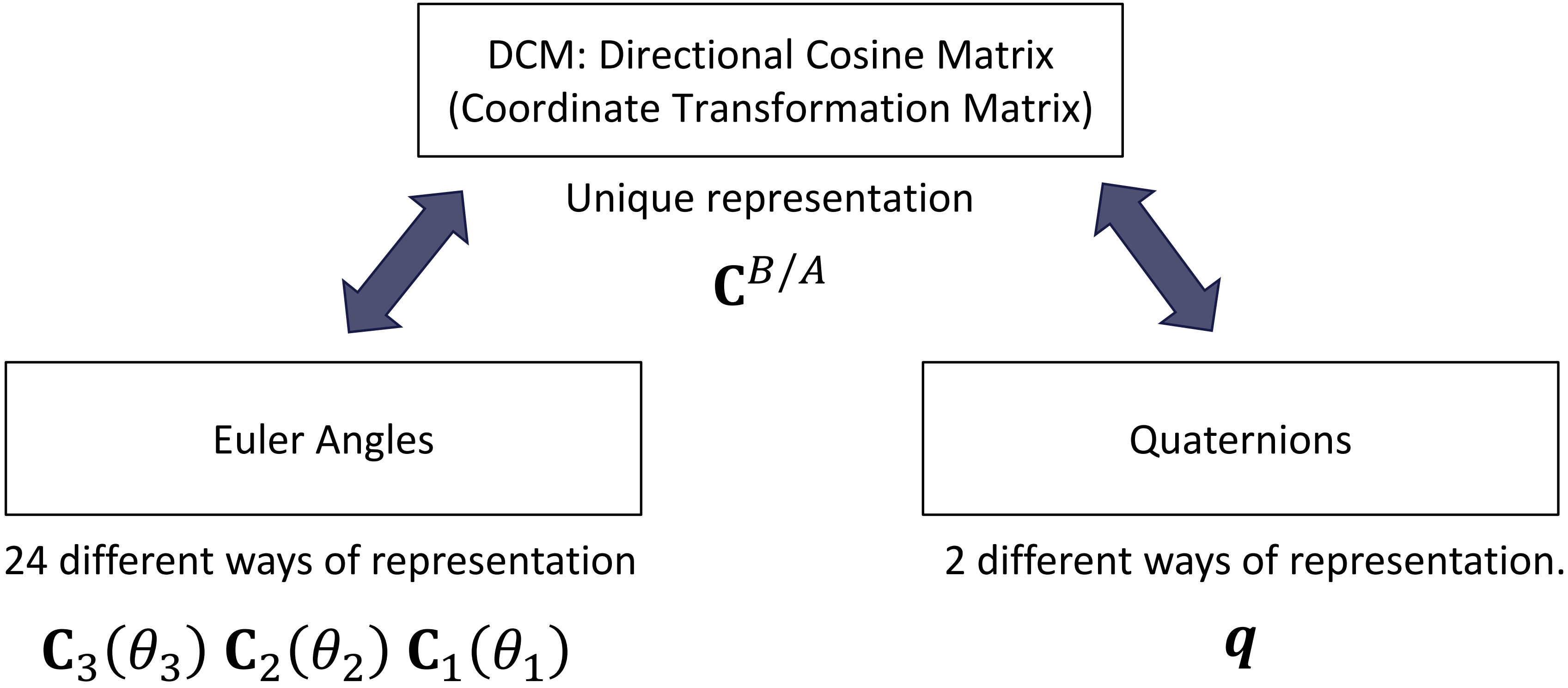
5. Attitude Determination and Control Algorithms

5.2. Description Method of Satellite Attitude

- The attitude of a spacecraft can be described in several different ways. The most commonly used three examples are described below; DCM (Directional Cosine Matrix, Euler Angles, Quaternions.
- These three representations are interchangeable through the DCM.



DCM: Directional Cosine Matrix
(Coordinate Transformation Matrix)

Unique representation

$$\mathbf{C}^{B/A}$$

Euler Angles

24 different ways of representation

$$\mathbf{C}_3(\theta_3)\ \mathbf{C}_2(\theta_2)\ \mathbf{C}_1(\theta_1)$$

Quaternions

2 different ways of representation.

$$\boldsymbol{q}$$

5. Attitude Determination and Control Algorithms

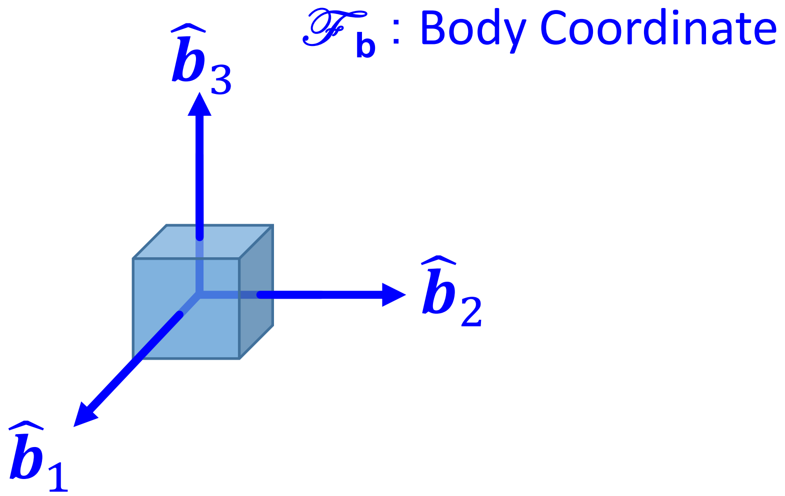
5.3. Direction Cosine Matrix (Coordinate Transformation Matrix)

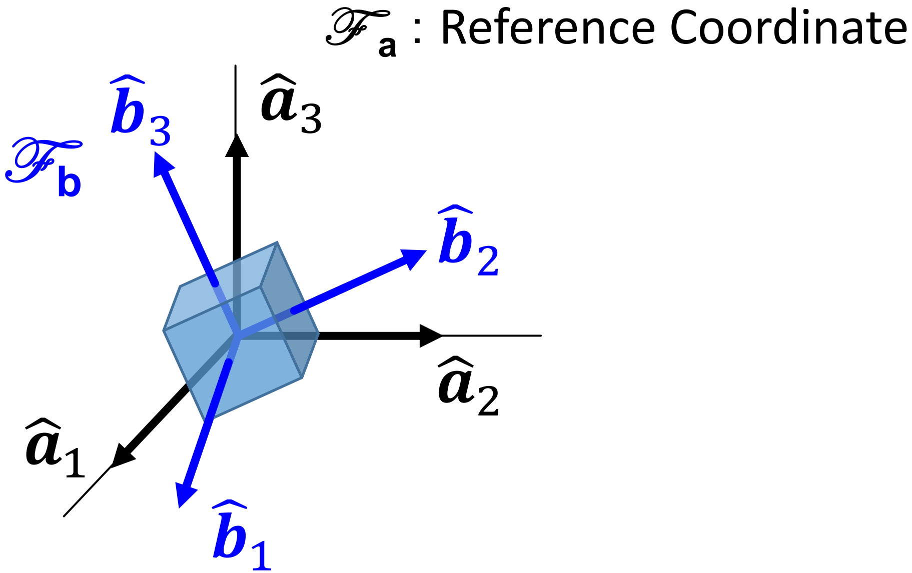
- Body Coordinate System: $\mathscr{F}_{\mathbf{b}} = \{\hat{\boldsymbol{b}}_1, \hat{\boldsymbol{b}}_2, \hat{\boldsymbol{b}}_3\}$
  - Coordinate system which is fixed with the satellite body.
- Reference Coordinate System: $\mathscr{F}_{\mathbf{a}} = \{\hat{\boldsymbol{a}}_1, \hat{\boldsymbol{a}}_2, \hat{\boldsymbol{a}}_3\}$
  - Coordinate system which is used as the reference to describe the satellite attitude.
- Direction Cosine Matrix (Coordinate Transformation Matrix)

$$\mathscr{F}_{\mathbf{a}} \xrightarrow{\mathbf{C}^{B/A}} \mathscr{F}_{\mathbf{b}}$$

$$\begin{bmatrix} \hat{\boldsymbol{b}}_1 \\ \hat{\boldsymbol{b}}_2 \\ \hat{\boldsymbol{b}}_3 \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix} \begin{bmatrix} \hat{\boldsymbol{a}}_1 \\ \hat{\boldsymbol{a}}_2 \\ \hat{\boldsymbol{a}}_3 \end{bmatrix} = \mathbf{C}^{B/A} \begin{bmatrix} \hat{\boldsymbol{a}}_1 \\ \hat{\boldsymbol{a}}_2 \\ \hat{\boldsymbol{a}}_3 \end{bmatrix}.$$

$c_{ij} \equiv \vec{b}_i \cdot \vec{a}_j$ - Direction Cosine





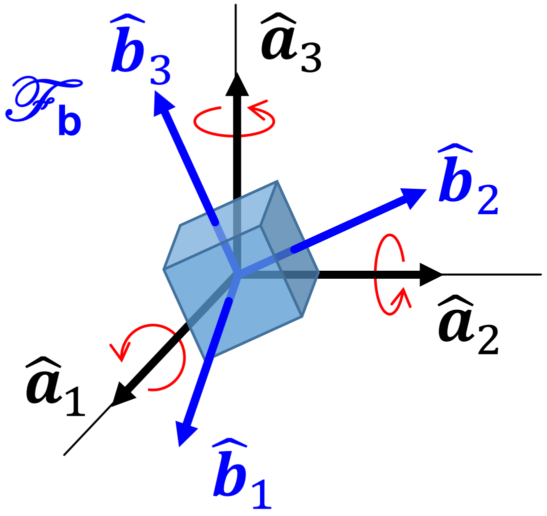
5. Attitude Determination and Control Algorithms

5.4. Euler Angles

Definition of Euler Angles.

- Single rotation motion of a spacecraft can be decomposed into three consequent rotations around three rotational axes. These three rotation angles around three axes are called Euler Angles.
  - The rotation angles are intuitively understandable in the 3-dimensional space.
  - There are 24 different ways of selection of the rotational axes (only several of them are commonly used).
  - Use trigonometric functions in the description.

$\mathscr{F}_a$: Reference Coordinate



$\mathscr{F}_b$: Body Coordinate

- Type of Euler Angles
  - 3-2-1 system: Rotation around Z, Y, X axis in this order.
  - 1-2-3 system: Rotation around X, Y, Z axis in this order. Also known as “Roll-Pitch-Yaw” rotation.

5. Attitude Determination and Control Algorithms

5.4. Euler Angles

Example: 1-2-3 system

① First rotation: θ_1 around X-axis (Roll)

② Second rotation: θ_2 around Y-axis (Pitch)

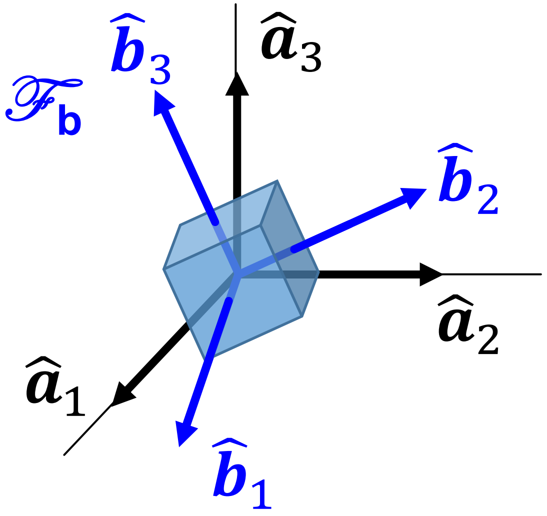
③ Third rotation: θ_3 around Z-axis (Yaw)

$$\begin{tikzcd}
\mathscr{F}_{\mathrm{b}} = & \mathbf{C}_3(\theta_3) & \mathbf{C}_2(\theta_2) \arrow[l, bend right, "③"'] & \mathbf{C}_1(\theta_1) \arrow[l, bend right, "②"'] & \mathscr{F}_{\mathrm{a}} \arrow[l, bend right, "①"']
\end{tikzcd}$$

$$\mathscr{F}_{\mathrm{b}} = \mathbf{C}^{B/A}\, \mathscr{F}_{\mathrm{a}}$$

$$\therefore\ \underbrace{\mathbf{C}^{B/A}}_{\text{Direction Cosine Matrix}} = \underbrace{\mathbf{C}_3(\theta_3)\, \mathbf{C}_2(\theta_2)\, \mathbf{C}_1(\theta_1)}_{\text{Euler Angles Representation}}$$

$\mathscr{F}_{\mathbf{a}}$: Reference Coordinate



$\mathscr{F}_{\mathbf{b}}$: Body Coordinate

5. Attitude Determination and Control Algorithms

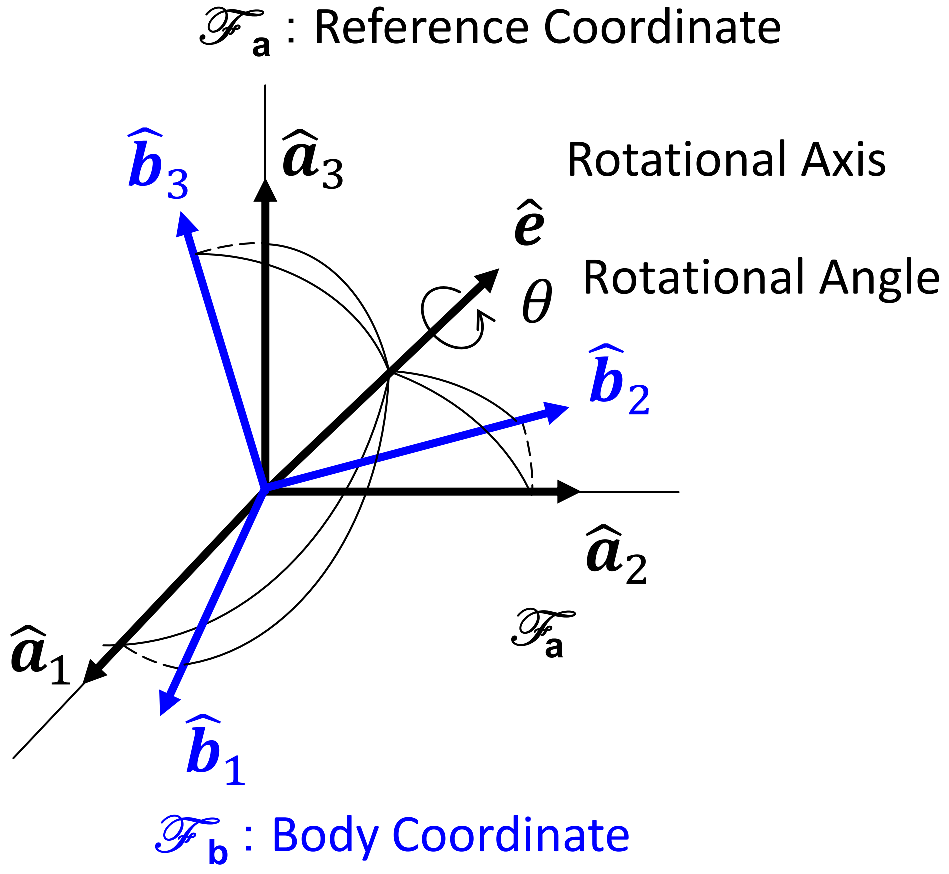
5.5. Quaternions

- Quaternion representation $\boldsymbol{q}$ is based on four Euler parameters and describing the rotation around the rotational axis (Euler Axis).

$$q_1 = e_1 \sin(\theta/2)$$
$$q_2 = e_2 \sin(\theta/2)$$
$$q_3 = e_3 \sin(\theta/2)$$
$$q_4 = cos(\theta/2)$$
$$q_1^2 + q_2^2 + q_3^2 + q_4^2 = 1$$

$$\tilde{\boldsymbol{q}} = \begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix} = \hat{\boldsymbol{e}} \sin(\theta/2)$$

$$\boldsymbol{q} = \begin{bmatrix} \tilde{\boldsymbol{q}} \\ q_4 \end{bmatrix} = \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{bmatrix} = [q_1 \quad q_2 \quad q_3 \quad q_4]^{\boldsymbol{T}}$$



5. Attitude Determination and Control Algorithms

5.6. Characteristics of Attitude Description Methods

Attitude Description Method	Characteristics
DCM: Directional Cosine Matrix (Coordinate Transformation Matrix)	☺ Simple matrix representation ☺ Simple numerical calculation (Suitable for on-board computer) ☺ No singularity point ☹ Need 3 x 3 = 9 parameters ☹ Difficult to imagine the satellite attitude intuitively
Euler Angles	☺ Easy to imagine the satellite attitude intuitively ☺ Need only 3 parameters 😭 Require trigonometric function calculation (Not suitable for on-board computers) 😢 Singularity points exist ☹ 24 different ways of representations
Quaternions	☺ Need only four parameters ☺ No singularity point ☺ Suitable for on-board computers ☹ Difficult to imagine the satellite attitude intuitively

5. Attitude Determination and Control Algorithms

5.7. Attitude Kinematics

Attitude Description Method

$$\boldsymbol{\omega} = \omega_1 \hat{\boldsymbol{b}}_1 + \omega_2 \hat{\boldsymbol{b}}_2 + \omega_3 \hat{\boldsymbol{b}}_3$$

DCM: Directional Cosine Matrix
(Coordinate Transformation Matrix)

$\dot{\boldsymbol{C}}^{B/A}$

$$\dot{\boldsymbol{C}} = -\boldsymbol{\Omega}\boldsymbol{C}, \quad \boldsymbol{\Omega} \equiv \begin{bmatrix} 0 & -\omega_3 & \omega_2 \\ \omega_3 & 0 & -\omega_1 \\ -\omega_2 & \omega_1 & 0 \end{bmatrix}$$

Euler Angles

$(\dot{\theta}_1, \dot{\theta}_2, \dot{\theta}_3)$

In case: $\mathbf{C}_1(\theta_1)\,\mathbf{C}_2(\theta_2)\,\mathbf{C}_3(\theta_3)$

$$\begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \end{bmatrix} = \frac{1}{c\theta_2} \begin{bmatrix} c\theta_2 & s\theta_1 s\theta_2 & c\theta_1 s\theta_2 \\ 0 & c\theta_1 c\theta_2 & -s\theta_1 c\theta_2 \\ 0 & s\theta_1 & c\theta_1 \end{bmatrix} \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{bmatrix}$$

$\theta_2 \neq \pm\pi/2$: Singular point, or Gimbal Lock.

Quaternions

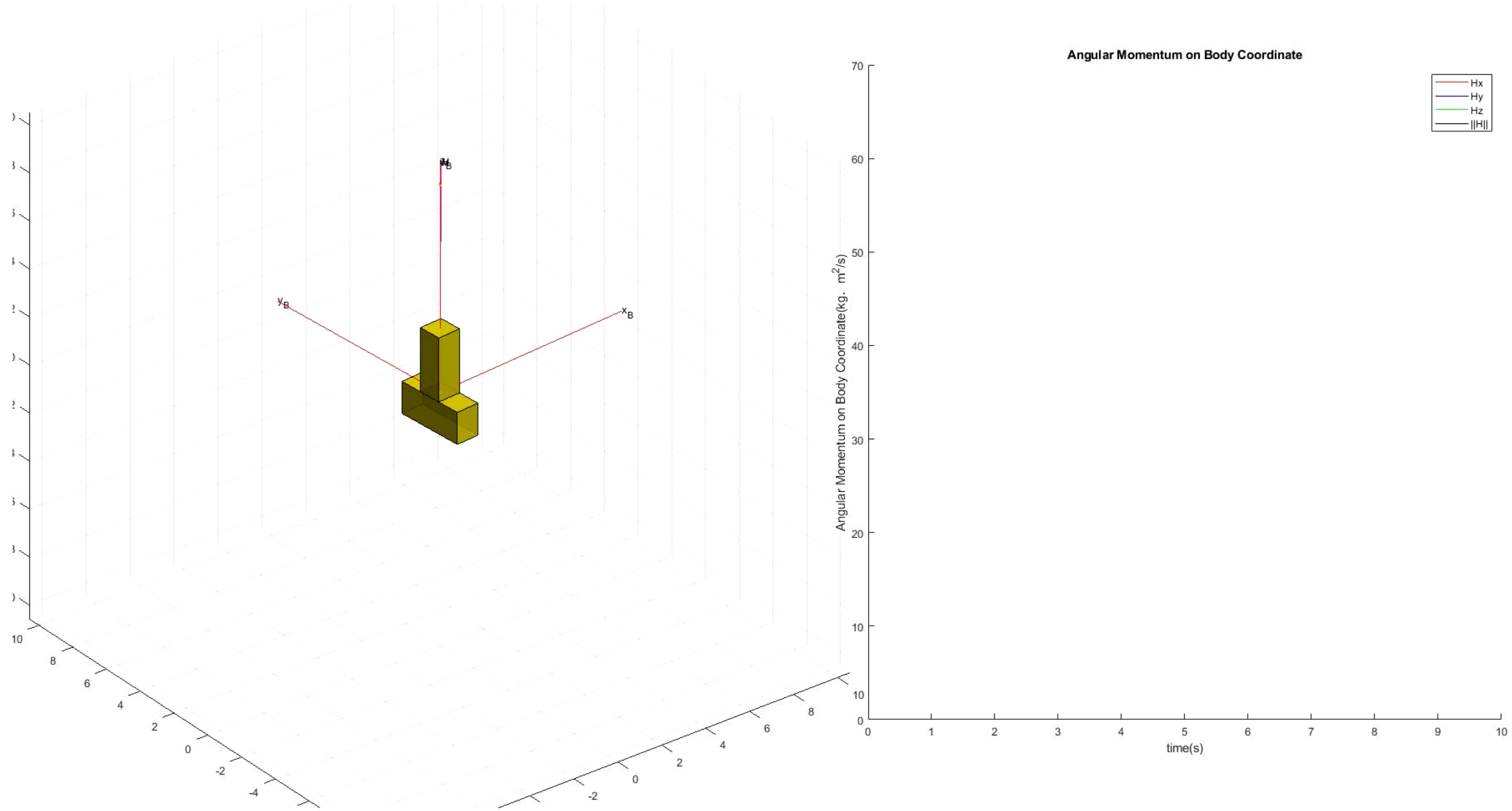
$\dot{\boldsymbol{q}}$

$$\dot{\boldsymbol{q}} = \frac{1}{2}\boldsymbol{\Omega}_b \boldsymbol{q}, \quad \boldsymbol{\Omega}_b = \begin{bmatrix} 0 & \omega_3 & -\omega_2 & \omega_1 \\ -\omega_3 & 0 & \omega_1 & \omega_2 \\ \omega_2 & -\omega_1 & 0 & \omega_3 \\ -\omega_1 & -\omega_2 & -\omega_3 & 0 \end{bmatrix}$$

5. Attitude Determination and Control Algorithms

5.8. Torque-Free Satellite Attitude Motion

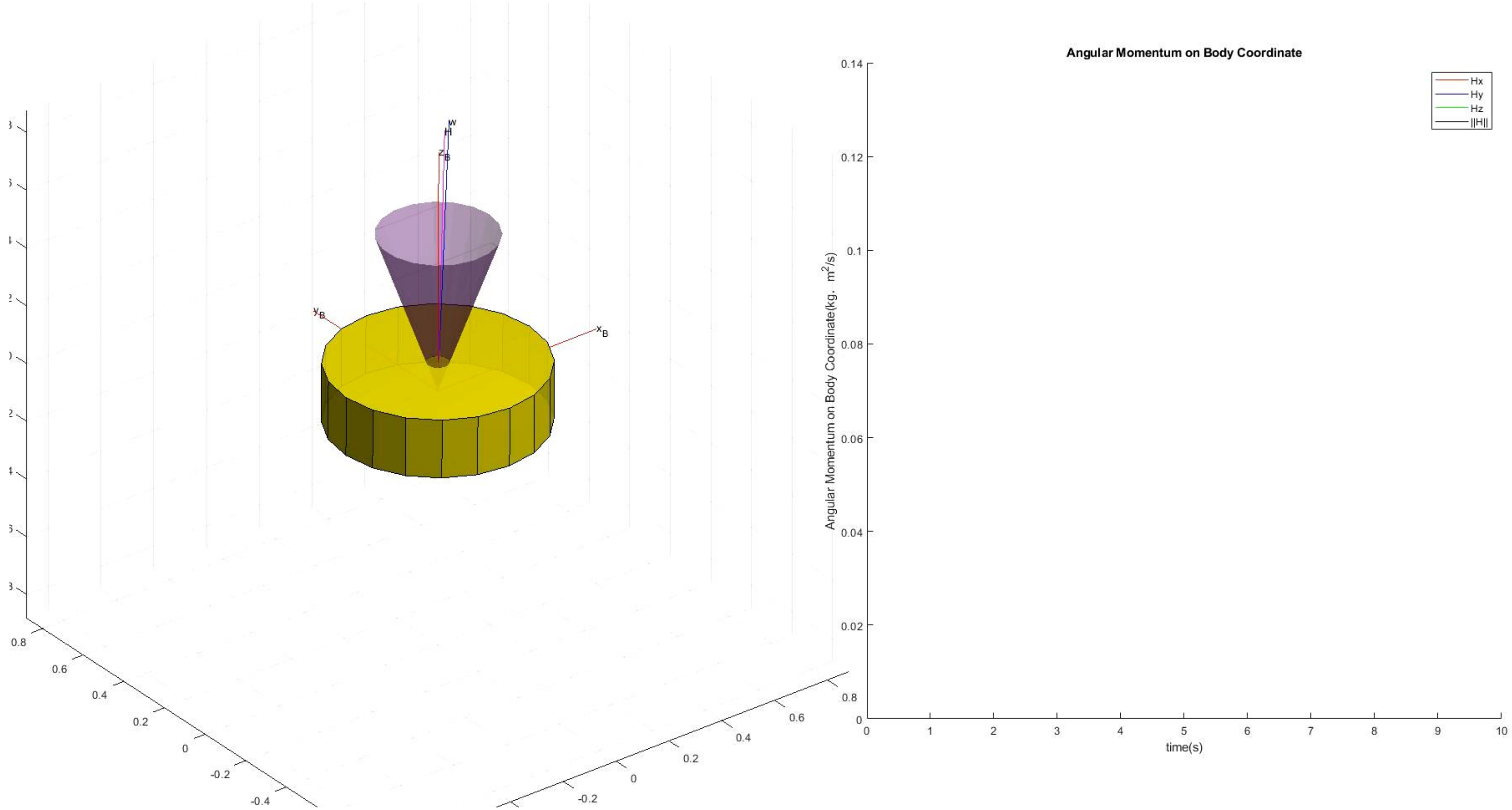
- Rotational motion of the satellite is affected by the mass property of the satellite.



- Angular momentum vector is fixed with the inertial coordinate.
- Angular velocity vector and satellite body coordinate system is randomly rotating.

5. Attitude Determination and Control Algorithms

5.9. Torque-Free Motion of Oblate Body



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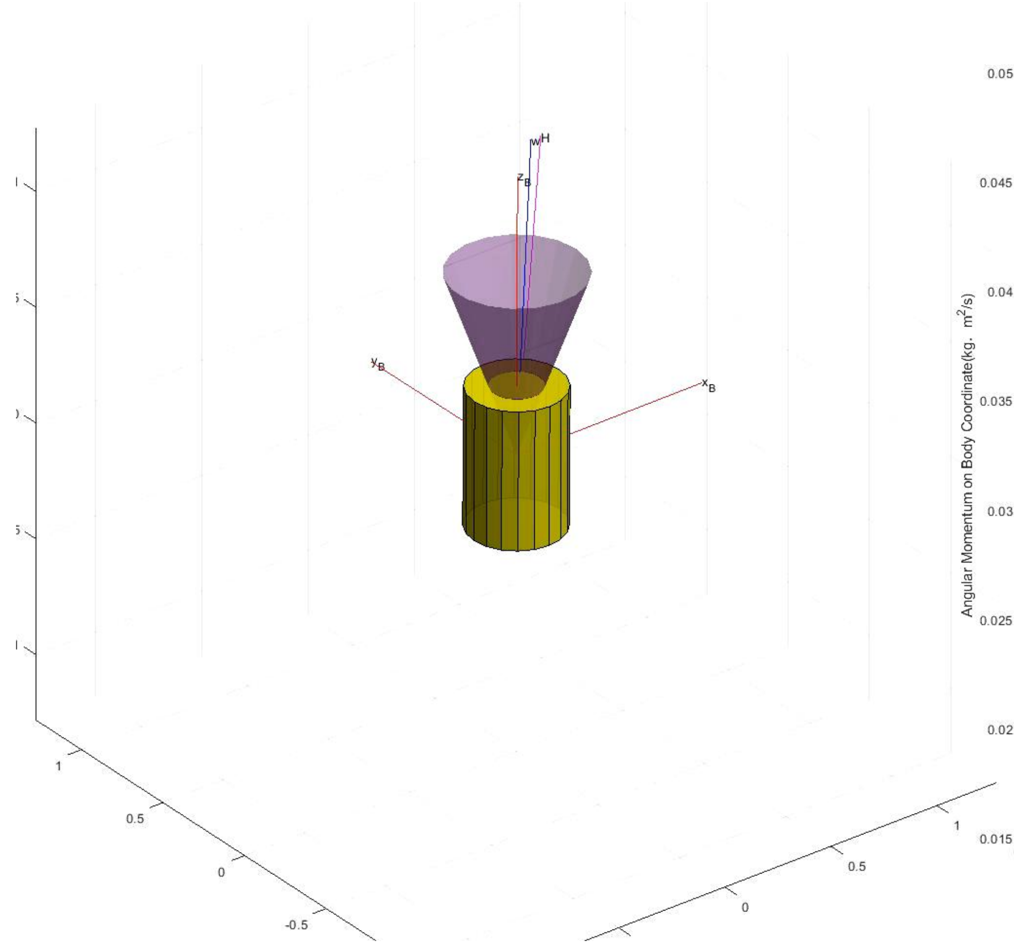
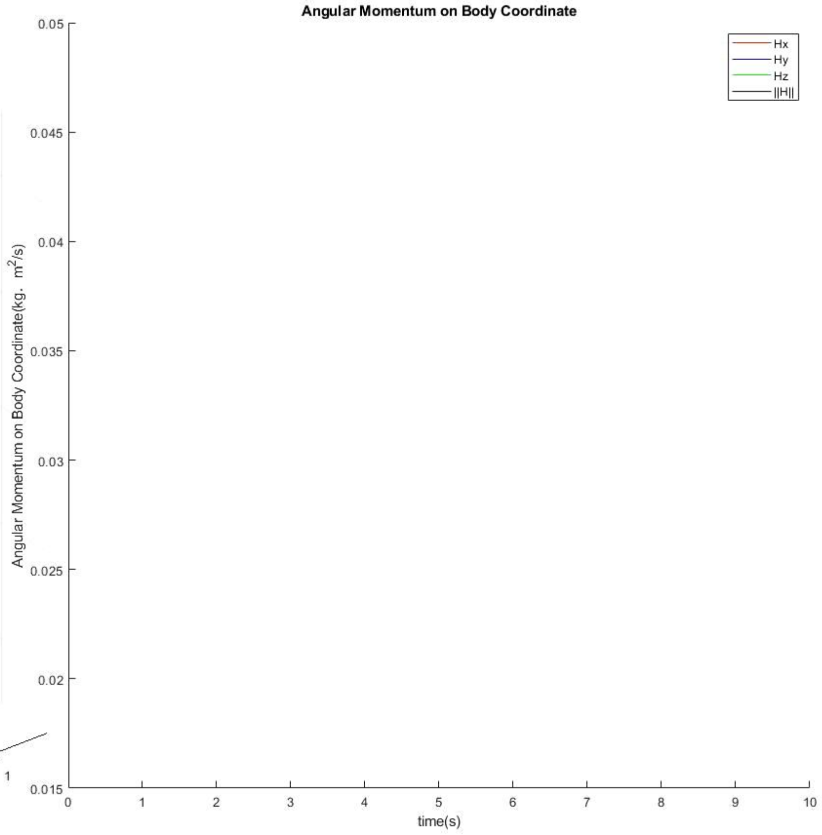
5. Attitude Determination and Control Algorithms

5.10. Torque-Free Motion of Prolate Body





5. Attitude Determination and Control Algorithms

5.11. Satellite Attitude Dynamics

Euler's Equation of Rotational Motion

- Time derivative of the angular momentum of a rigid body around its center of mass is equivalent to the applied torque.

$$\boldsymbol{M} = \boldsymbol{J}\dot{\boldsymbol{\omega}} + \boldsymbol{\Omega}\boldsymbol{J}\boldsymbol{\omega}$$

$$\underbrace{\boldsymbol{M} = \begin{bmatrix} M_1 \\ M_2 \\ M_3 \end{bmatrix}}_{\text{Torque}}, \quad \underbrace{\boldsymbol{J} = \begin{bmatrix} J_{11} & J_{12} & J_{13} \\ J_{21} & J_{22} & J_{23} \\ J_{31} & J_{32} & J_{33} \end{bmatrix}}_{\text{Moment of Inertia}}, \quad \underbrace{\boldsymbol{\omega} = \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{bmatrix}}_{\text{Angular Velocity}}, \quad \boldsymbol{\Omega} = \begin{bmatrix} 0 & -\omega_3 & \omega_2 \\ \omega_3 & 0 & -\omega_1 \\ -\omega_2 & \omega_1 & 0 \end{bmatrix}$$

Also known as

$\boldsymbol{M} = \boldsymbol{J}\dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \times (\boldsymbol{J}\boldsymbol{\omega})$ or $\boldsymbol{M} = \dot{\boldsymbol{H}} + \boldsymbol{\Omega}\boldsymbol{H}$, $\boldsymbol{H} = \boldsymbol{J}\boldsymbol{\omega}$: Angular Momentum

- Attitude control system generates $\boldsymbol{M}$ so that the ($\boldsymbol{\omega}$, $\dot{\boldsymbol{\omega}}$) become desired values.

5. Attitude Determination and Control Algorithms

5.12. Attitude Determination – TRIAD Method

TRIAD method

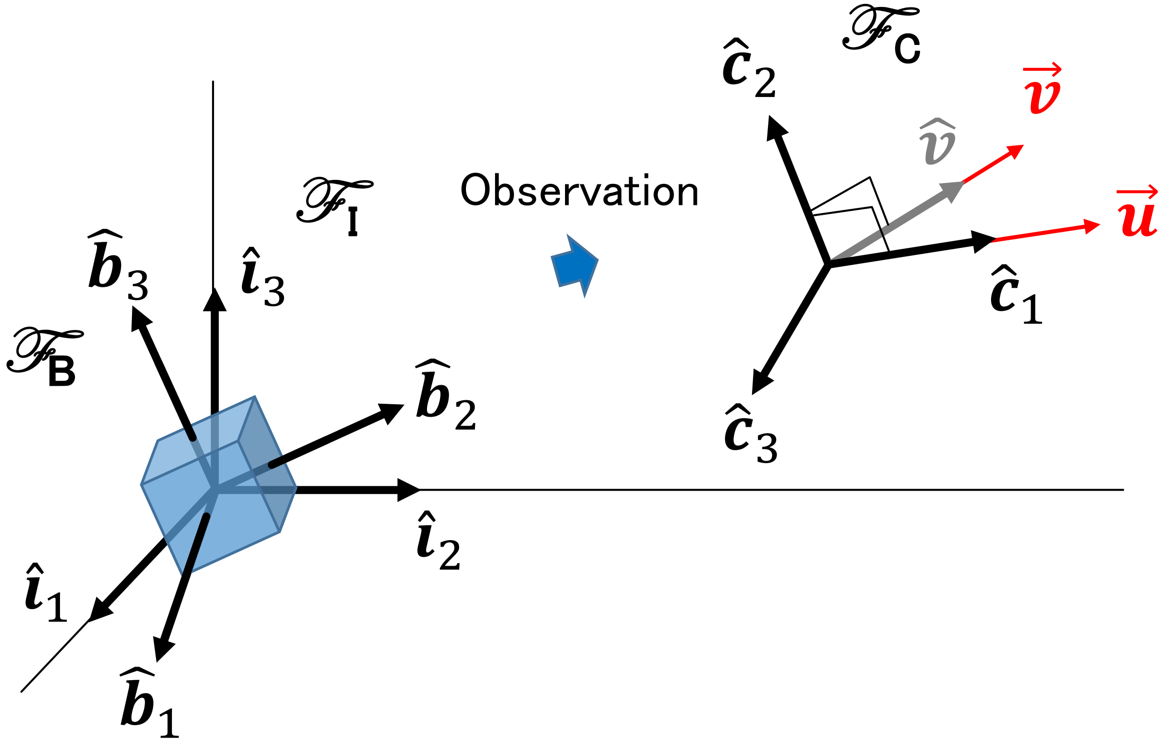
- Basic method of spacecraft attitude determination based on the measurements of two reference vectors.
- Compare two vectors observed from inertial coordinate $\mathscr{F}_\mathrm{I}$ and body coordinate $\mathscr{F}_\mathrm{B}$ to calculate relative attitude $\boldsymbol{C}^{B/I}$ between the two coordinates.
- Third coordinate system $\mathscr{F}_\mathrm{C}$ is defined using the two non-parallel vectors.

$$\hat{\boldsymbol{c}}_1 = \vec{\boldsymbol{u}}/|\vec{\boldsymbol{u}}|$$

$$\widehat{\boldsymbol{v}} = \vec{\boldsymbol{v}}/|\vec{\boldsymbol{v}}|$$

$$\hat{\boldsymbol{c}}_2 = \hat{\boldsymbol{c}}_1 \times \widehat{\boldsymbol{v}}$$

$$\hat{\boldsymbol{c}}_3 = \hat{\boldsymbol{c}}_1 \times \hat{\boldsymbol{c}}_2$$



5. Attitude Determination and Control Algorithms

5.13. Attitude Determination – TRIAD Method

- When the basis vectors of coordinate systems $\mathscr{F}_\mathrm{C}$ observed from $\mathscr{F}_\mathrm{I}$ and $\mathscr{F}_\mathrm{B}$ can be described as $\{\hat{\boldsymbol{c}}_{1i}, \hat{\boldsymbol{c}}_{2i}, \hat{\boldsymbol{c}}_{3i}\}$ and $\{\hat{\boldsymbol{c}}_{1b}, \hat{\boldsymbol{c}}_{2b}, \hat{\boldsymbol{c}}_{3b}\}$, respectively, the following equations hold:

$$\begin{aligned} \hat{\boldsymbol{c}}_{1b} &= \mathbf{C}^{B/I}\hat{\boldsymbol{c}}_{1i} \\ \hat{\boldsymbol{c}}_{2b} &= \mathbf{C}^{B/I}\hat{\boldsymbol{c}}_{2i} \\ \hat{\boldsymbol{c}}_{3b} &= \mathbf{C}^{B/I}\hat{\boldsymbol{c}}_{3i} \end{aligned} \qquad \therefore \quad \begin{aligned} &[\hat{\boldsymbol{c}}_{1b} \quad \hat{\boldsymbol{c}}_{2b} \quad \hat{\boldsymbol{c}}_{3b}] = \mathbf{C}^{B/I}[\hat{\boldsymbol{c}}_{1i} \quad \hat{\boldsymbol{c}}_{2i} \quad \hat{\boldsymbol{c}}_{2i}] \\ &\hat{\boldsymbol{c}}_{k} = [c_{k1} \quad c_{k2} \quad c_{k3}]^T \end{aligned}$$

which can be re-written as:

$$\begin{bmatrix} c_{1b1} & c_{2b1} & c_{3b1} \\ c_{1b2} & c_{2b2} & c_{3b2} \\ c_{1b3} & c_{2b3} & c_{3b3} \end{bmatrix} = \mathbf{C}^{B/I} \begin{bmatrix} c_{1i1} & c_{2i1} & c_{3i1} \\ c_{1i2} & c_{2i2} & c_{3i2} \\ c_{1i3} & c_{2i3} & c_{3i3} \end{bmatrix}$$

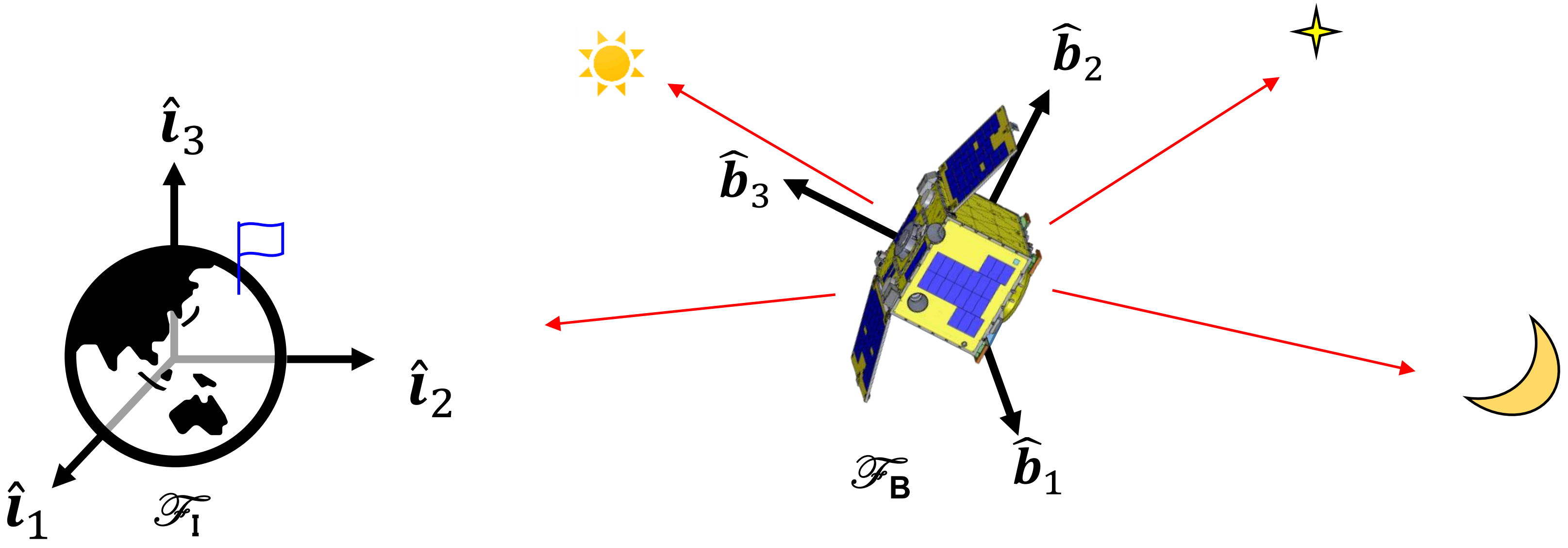
And hence, the direction cosine matrix $\mathbf{C}^{B/I}$ can be obtained as:

$$\begin{aligned} \mathbf{C}^{B/I} &= [\hat{\boldsymbol{c}}_{1b} \quad \hat{\boldsymbol{c}}_{2b} \quad \hat{\boldsymbol{c}}_{3b}][\hat{\boldsymbol{c}}_{1i} \quad \hat{\boldsymbol{c}}_{2i} \quad \hat{\boldsymbol{c}}_{2i}]^T \\ &= \begin{bmatrix} c_{1b1} & c_{2b1} & c_{3b1} \\ c_{1b2} & c_{2b2} & c_{3b2} \\ c_{1b3} & c_{2b3} & c_{3b3} \end{bmatrix} \begin{bmatrix} c_{1i1} & c_{1i2} & c_{1i3} \\ c_{2i1} & c_{2i2} & c_{2i3} \\ c_{3i1} & c_{3i2} & c_{3i3} \end{bmatrix} \end{aligned}$$

※No trigonometric functions
Suitable to on-board computers

5.14. Attitude Control

- There are a wide variety of observation targets for small satellites, such as the Earth, moon, sun, planets, deep space, etc., depending on the mission requirements, unlike larger satellites.
- Attitude control system of small satellites are often required to be flexible in terms of the pointing direction.
- Small satellites are often required to conduct attitude control maneuvers in an agile manner through the shortest and quickest path.



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5.14. Attitude Control

Quaternion Feedback Control (large Angle Slew Maneuver)

- Quaternion feedback control is one of the satellite attitude control methods where satellites need to rotate for a large angle from one attitude to another.
- Realize stable attitude control maneuver without having singularity points.
- Rotation around the Euler axis.
- "Error Quaternion" is defined with the equation below, which is indicating the difference between the current attitude and desired attitude.

$$\boldsymbol{q}_e = \begin{bmatrix} q_{t4} & q_{t3} & -q_{t2} & -q_{t1} \\ -q_{t3} & q_{t4} & q_{t1} & -q_{t2} \\ q_{t2} & -q_{t1} & q_{t4} & -q_{t3} \\ q_{t1} & q_{t2} & q_{t3} & q_{t4} \end{bmatrix} \begin{bmatrix} q_{b1} \\ q_{b2} \\ q_{b3} \\ q_{b4} \end{bmatrix} = \boldsymbol{q}_t^{-1} \boldsymbol{q}_b$$

$\boldsymbol{q}_b$: Current Attitude

$\boldsymbol{q}_t$: Target Attitude

$$\boldsymbol{M} = \boldsymbol{J}\dot{\boldsymbol{\omega}} + \boldsymbol{\Omega J \omega}$$

$$\boldsymbol{M} = -\boldsymbol{D\omega} - \boldsymbol{K}\tilde{\boldsymbol{q}}_e + \boldsymbol{\Omega J \omega},$$

$\boldsymbol{M}$: Control torque, $\boldsymbol{D}, \boldsymbol{K}$: Control Gain

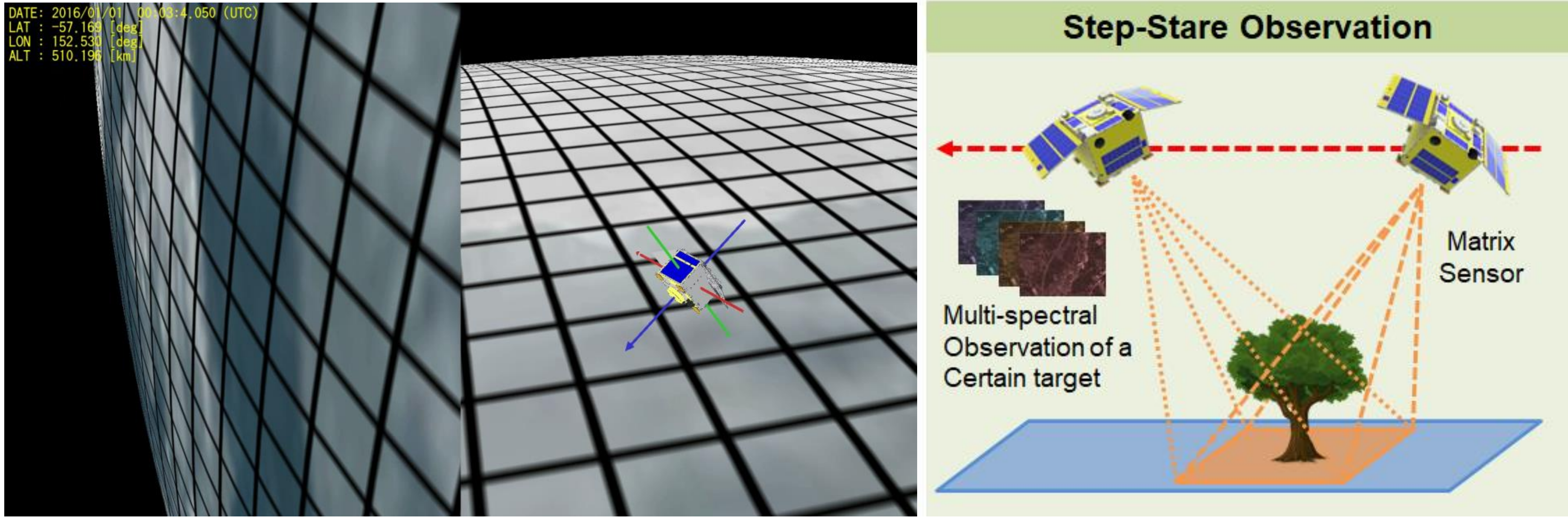
Wie, B., Space Vehicle Dynamics and Control (Second Edition) , AIAA Education Series, Reston, 2008.

5. Attitude Determination and Control Algorithms

5.14. Attitude Control

- Two examples of quaternion feedback control applications are illustrated below.
  - Attitude control for target pointing Earth observation
  - Attitude control for laser communication

Target Pointing Earth Observation



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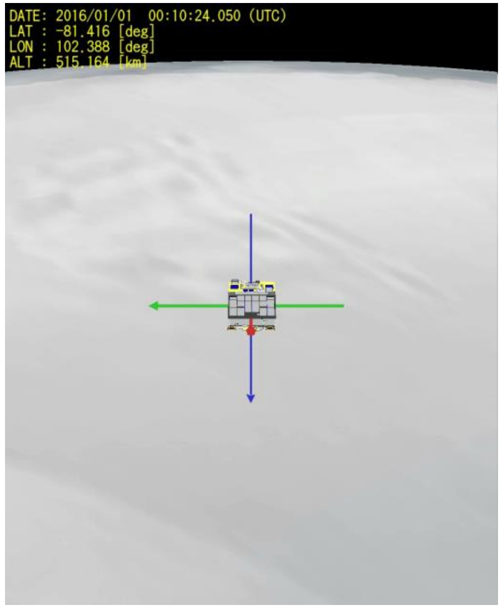
Laser Communication



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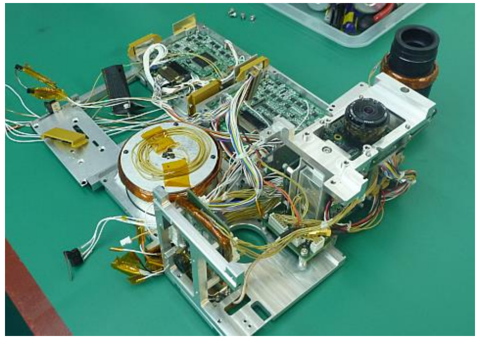
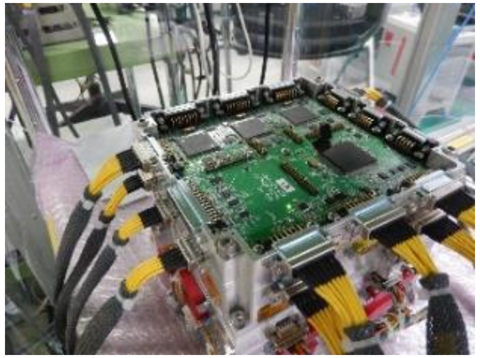
6. Functional Verification of Attitude Control System

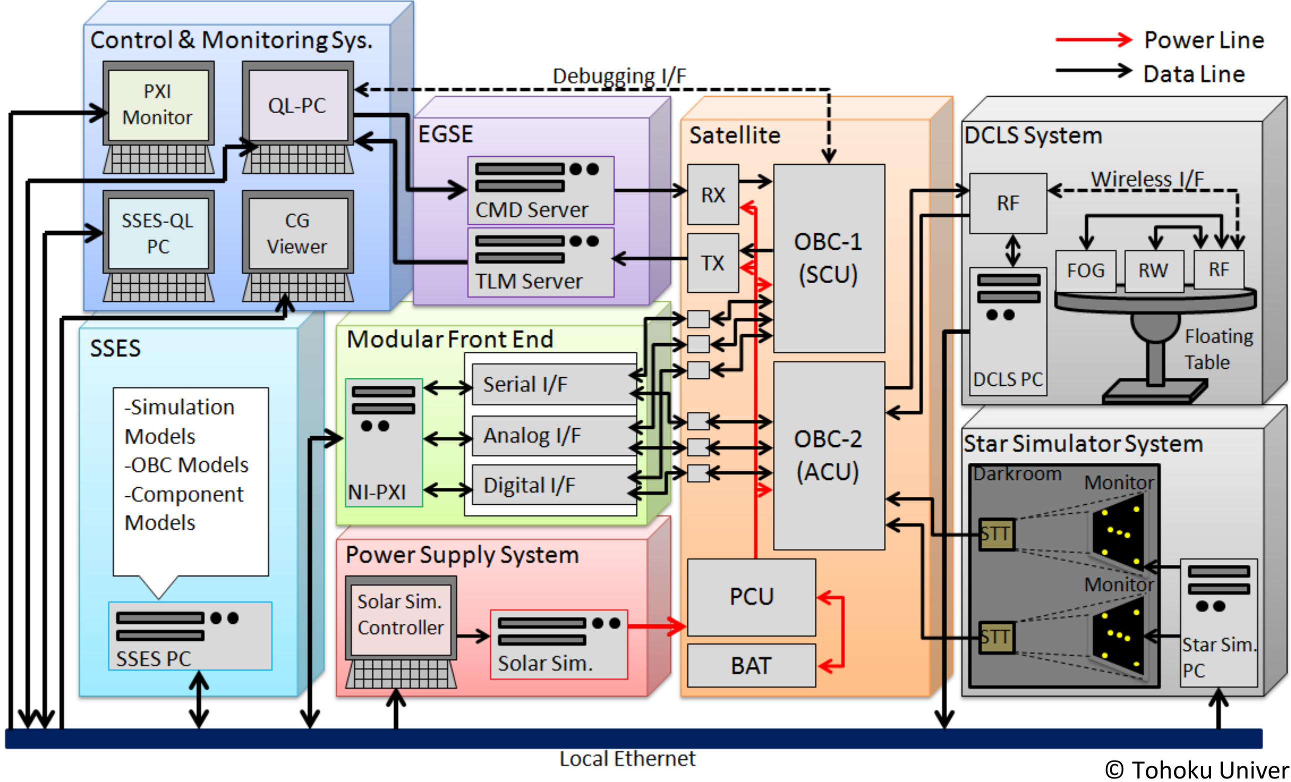
6. Functional Verification of Attitude Control System

6.1. Electrical Testing

- Ground testing facilities are required to conduct tests of electrical functionalities of the satellite components and satellite system, and are especially indispensable for the evaluation of attitude control algorithms and performance verification.
- Software-based simulators are utilized for hardware-in-the-loop tests in real-time in order to verify the correct functionalities of on-board software running on the actual flight hardware.







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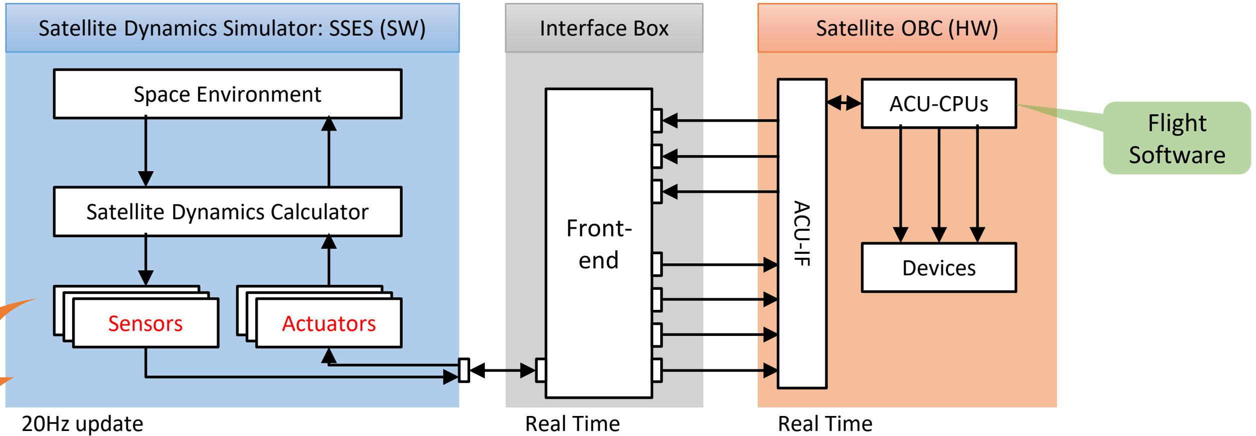
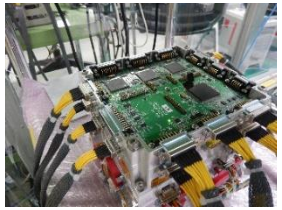
6. Functional Verification of Attitude Control System

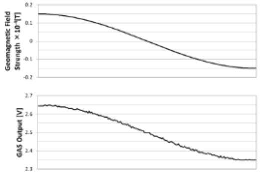
6.2. Precise Implementation of Software Models of Sensors and Actuators

Hardware-in-the-Loop Test Environment



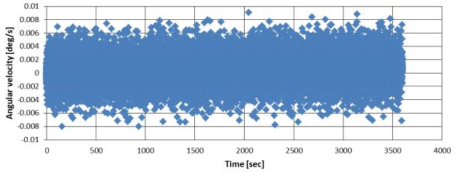


Magnetometer



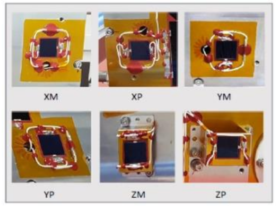
Analog output

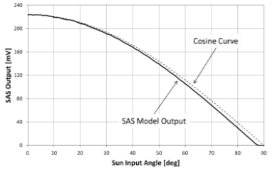
Gyro Sensor



Random noise

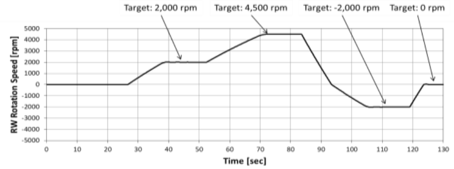
Sun Sensors





Analog output

Reaction Wheel



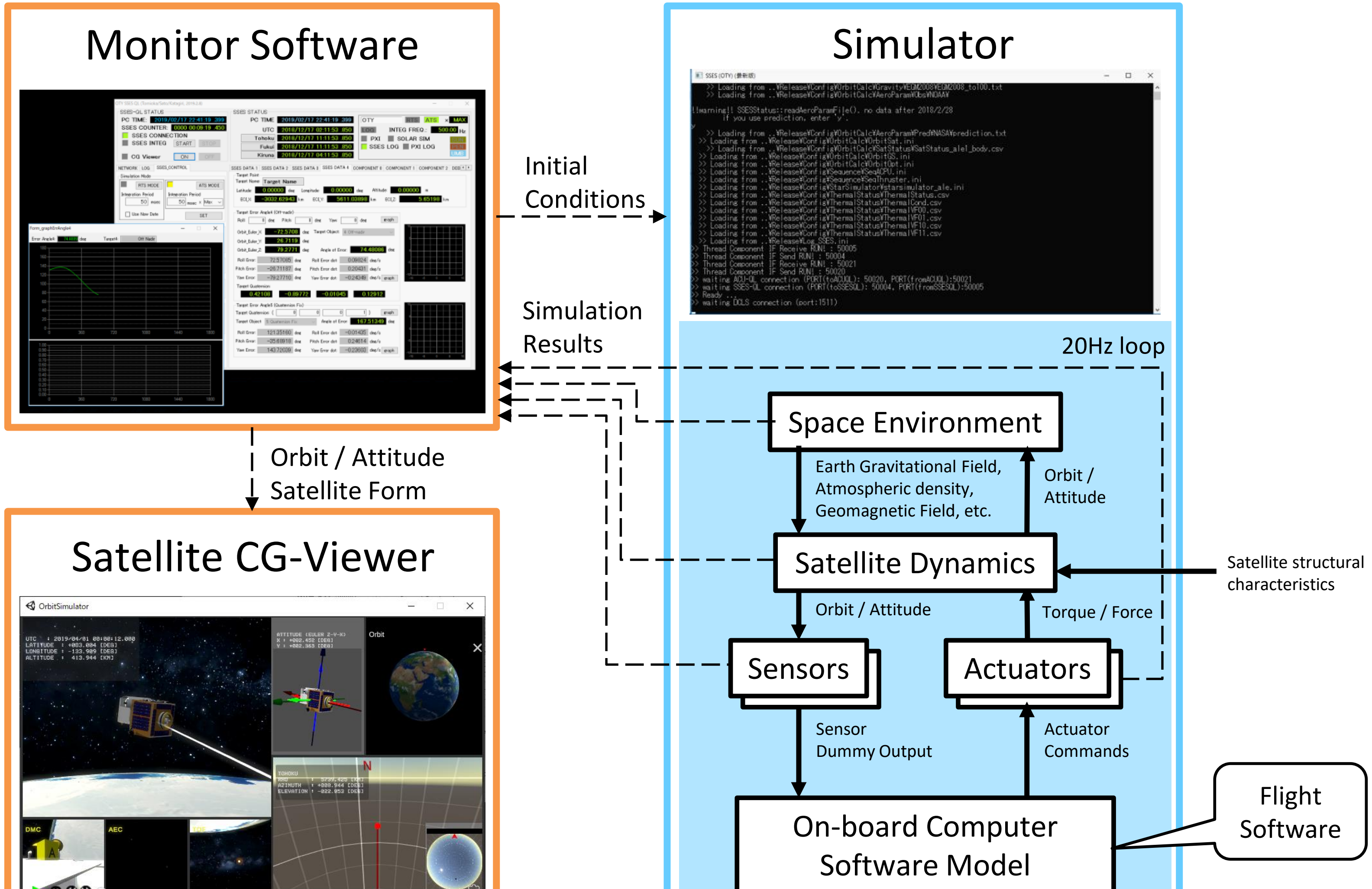
Rotational characteristics

The precision of the sensor and actuator models shall be improved through the ground tests and orbit operation heritage.

6. Functional Verification of Attitude Control System

6.3. Software Simulation

- Full software simulators are very useful for the simulation of the satellite’s orbital and attitude behavior.
- The simulation process can be accelerated to conduct a large number of simulation trials.
- On-board software can be developed using this kind of simulation, software development, and verification environment.



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   >> Loading from ..¥Release¥Config¥OrbitCalc¥AeroParam¥Obs¥NOAA¥

!!warning!! SSESStatus::readAeroParamFile(). no data after 2018/2/28
        if you use prediction, enter 'y'.
y
   >> Loading from ..¥Release¥Config¥OrbitCalc¥AeroParam¥Pred¥NASA¥prediction.txt
  >> Loading from ..¥Release¥Config¥OrbitCalc¥OrbitSat.ini
   >> Loading from ..¥Release¥Config¥OrbitCalc¥SatStatus¥SatStatus_ale1_body.csv
  >> Loading from ..¥Release¥Config¥OrbitCalc¥OrbitGS.ini
  >> Loading from ..¥Release¥Config¥OrbitCalc¥OrbitOpt.ini
  >> Loading from ..¥Release¥Config¥Sequence¥SeqACPU.ini
  >> Loading from ..¥Release¥Config¥Sequence¥SeqThruster.ini
  >> Loading from ..¥Release¥Config¥StarSimulator¥starsimulator_ale.ini
  >> Loading from ..¥Release¥Config¥ThermalStatus¥ThermalStatus.csv
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  >> Loading from ..¥Release¥Config¥ThermalStatus¥ThermalVF00.csv
  >> Loading from ..¥Release¥Config¥ThermalStatus¥ThermalVF01.csv
  >> Loading from ..¥Release¥Config¥ThermalStatus¥ThermalVF10.csv
  >> Loading from ..¥Release¥Config¥ThermalStatus¥ThermalVF11.csv
  >> Loading from ..¥Release¥Log_SSES.ini
>> Thread Component IF Receive RUN! : 50005
>> Thread Component IF Send RUN! : 50004
>> Thread Component IF Receive RUN! : 50021
>> Thread Component IF Send RUN! : 50020
>> waiting ACU-QL connection (PORT(toACUQL): 50020, PORT(fromACUQL):50021
>> waiting SSES-QL connection (PORT(toSSESQL): 50004, PORT(fromSSESQL):50005
>> Ready ...
>> waiting DCLS connection (port:1511)
```

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6. Functional Verification of Attitude Control System

6.4. Dynamic Closed-Loop Simulator

- Satellite attitude dynamics can be tested on-ground, for example, on a dynamic closed-loop simulator with a 3 degrees of freedom motion table with air bearing.

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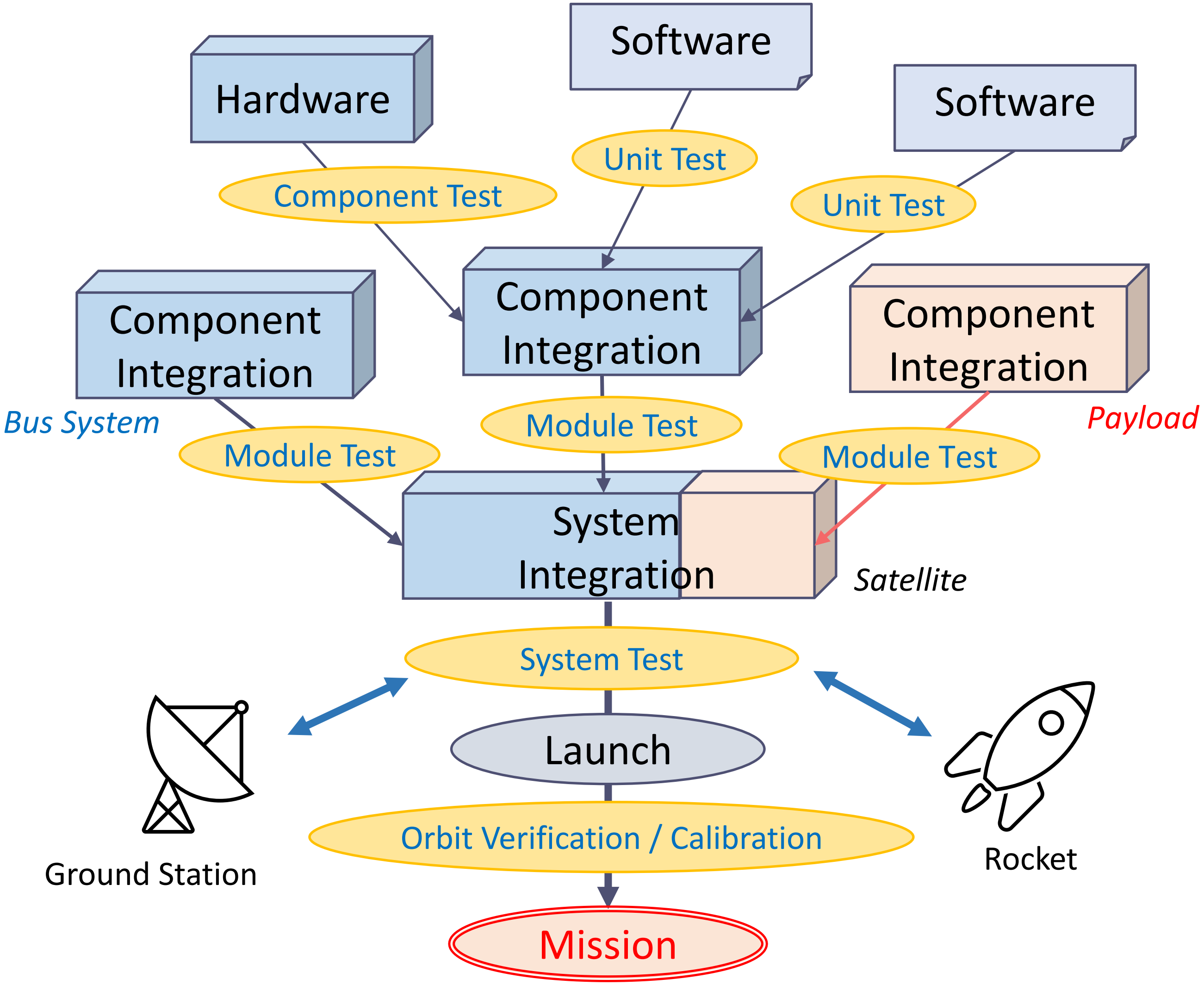
6. Functional Verification of Attitude Control System

6.5. Satellite System Orbit Verification and Calibration

- Satellite system integration takes place in a bottom-up manner, starting from the hardware and software integration of each component, integration between components, and integration between the bus system and payload.
- Assembly and testing shall be conducted in each integration test. This activity is sometimes referred as Assembly, Integration, and Test (AIT).
- The scope of the system level testing shall include testing together with the ground stations and launch vehicles, or its interfaces.
- Satellite hardware and software functionalities, including attitude determination and control, shall be tested and calibrated even after the launch, in order to ensure that the satellite can fulfil the mission requirements.

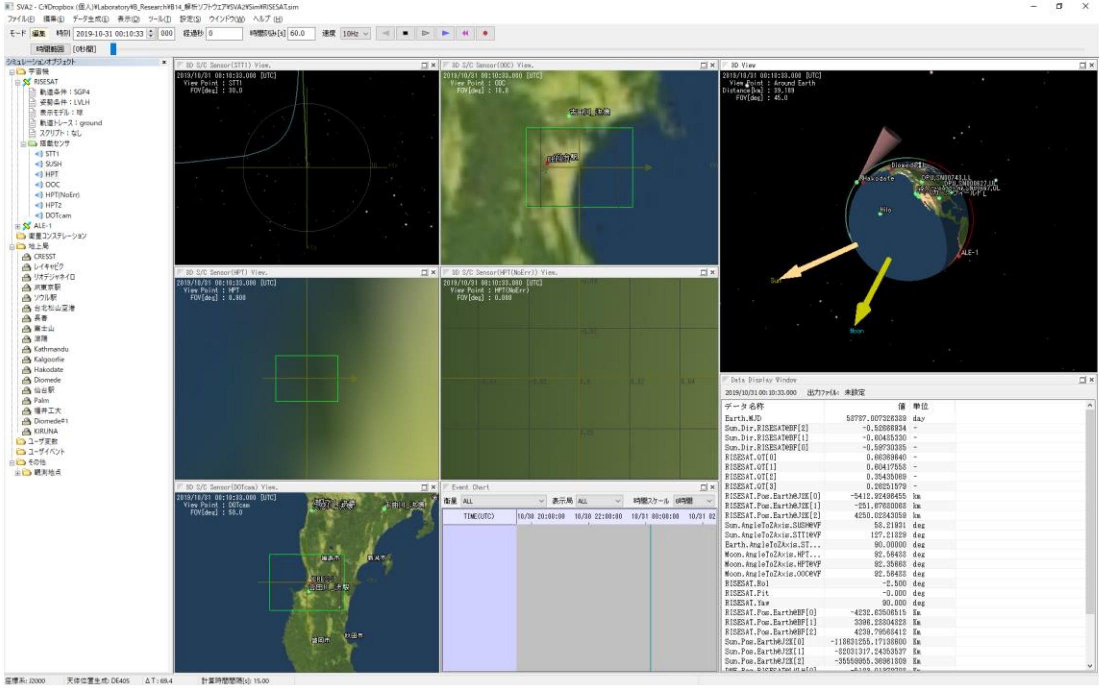


6. Functional Verification of Attitude Control System

6.6. Operational Planning of Attitude Control System

- Stable satellite operation is possible only with thorough operational planning of the attitude control system.
- Operational planning of the attitude control system requires careful analysis of the operational scenario including the positions/directions of celestial bodies (such as the sun, Earth, moon, etc.), direction of the pointing target, and direction of the attitude determination sensors with respect with to their field of view and obstacle avoidance angles.
- Attitude determination and control accuracy, power consumption, mission duration are influenced by this planning.

Attitude Control Planning based on Simulation Analysis



Data Display Window

2019/10/31 00:10:33.000 出力ファイル: 未設定

データ名称	値	単位
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Sun.Dir.RISESAT@BF[2]	-0.52866934	-
Sun.Dir.RISESAT@BF[1]	-0.60485330	-
Sun.Dir.RISESAT@BF[0]	-0.59730385	-
RISESAT.QT[0]	0.66369640	-
RISESAT.QT[1]	0.60417553	-
RISESAT.QT[2]	0.35435069	-
RISESAT.QT[3]	0.26251579	-
RISESAT.Pos.Earth@J2K[0]	-5412.92498455	km
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RISESAT.Pos.Earth@J2K[2]	4250.02843059	km
Sun.AngleToZAxis.SUSH@VF	58.21931	deg
Sun.AngleToZAxis.STT1@VF	127.21829	deg
Earth.AngleToZAxis.ST...	90.00000	deg
Moon.AngleToZAxis.HPT...	92.56433	deg
Moon.AngleToZAxis.HPT@VF	92.35663	deg
Moon.AngleToZAxis.OOC@VF	92.56433	deg
RISESAT.Rol	-2.500	deg
RISESAT.Pit	-0.000	deg
RISESAT.Yaw	90.000	deg
RISESAT.Pos.Earth@BF[0]	-4232.63506515	Km
RISESAT.Pos.Earth@BF[1]	3396.23804823	Km
RISESAT.Pos.Earth@BF[2]	4239.79568412	Km
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Spheresoft

7. Conclusion

7. Conclusion

- Introduction to CubeSat attitude control system is provided. It was explained that the attitude determination and control process consists of several steps, such as navigation, guidance, and control, and that attitude control and orbit control influence each other.
- Various kinds of attitude control modes and an example of attitude control system state machine diagram with mode transitions are introduced.
- Hardware components of the attitude control system were introduced, such as attitude determination sensors, attitude control actuators, and attitude control system computers.
- Processing tasks of navigation, guidance, and control are described in detail, together with some examples of reference coordinate system definitions, and coordinate transformation between inertial coordinate system and geodetic coordinate system.
- Mathematical background of attitude determination and control algorithms were explained including three different kinds of attitude description methods, as well as satellite attitude kinematics, dynamics, and control.
- Functional verification aspects of the satellite attitude control system were described. Several verification and simulation infrastructures were introduced, and the importance of operational planning of attitude control systems based on the satellite and the space environment simulator, was emphasized.

Thank you very much.