KiboCUBE Academy

Lecture 26

Introduction to CubeSat Operational Analysis and Planning

Tohoku University

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

JAXA

UNISEC JAPAN
University Space Engineering Consortium

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

Lecturer Introduction

Shinya FUJITA, Ph.D.

"ALE-1" in JAXA Tsukuba, 2018

"ALE-2", in Rocket Lab Facility, 2019

3U CubeSat "ASTERISC" in JAXA Uchinoura, 2021

Position:

2019 – 2021	Assistant Professor, Department of Aerospace Engineering, Tohoku University
2021 – 2024	Senior Assistant Professor, Department of Aerospace Engineering, Tohoku University
2023 –	Co-Founder / Board Director, Cislunar Technologies Inc.
2024 –	Researcher, Center for Space Business Frontier Research, Tohoku University

Cislunar Technologies

Research Topics:
Attitude Control, MicroSat/CubeSat System Design

Contents

1. Introduction to Satellite Operation

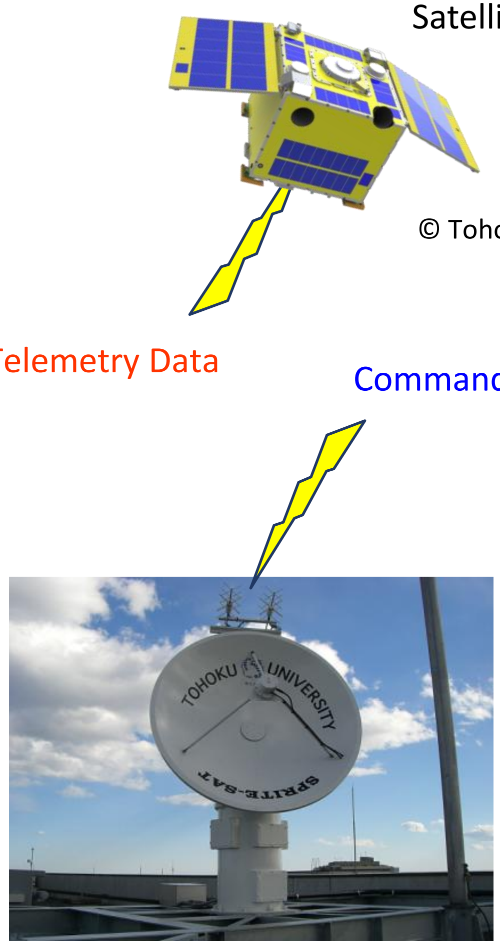
1. Introduction to Satellite Operation

Command and Telemetry

The most important element of a satellite mission is its operation. Communications between ground stations and satellites can be divided into two types: Command Data and Telemetry Data.

- **Command Data** – Data sent from ground stations to satellites in order to control the satellite system. The satellite must execute commands whenever they are received from the ground station.

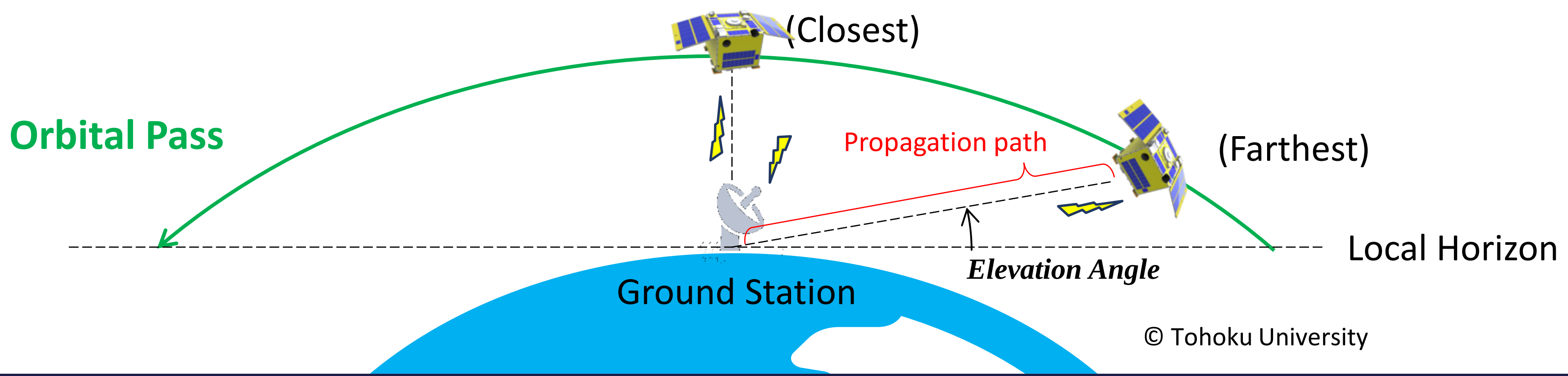
- **Telemetry Data** – Data sent from the satellite to ground stations.
  - **Housekeeping (HK) Data** : Basic status information of satellite components in order to monitor the health status of the satellite, such as voltages, temperature and so on. HK data is usually periodically and continuously sent to the ground stations during contact.
  - **Mission Data**: Data acquired from the mission instruments, such as Earth observation images, measured environmental sensor data, etc.
    The amount of mission data is usually very large and a long communication period and/or high-speed communications are required.



1. Introduction to Satellite Operation

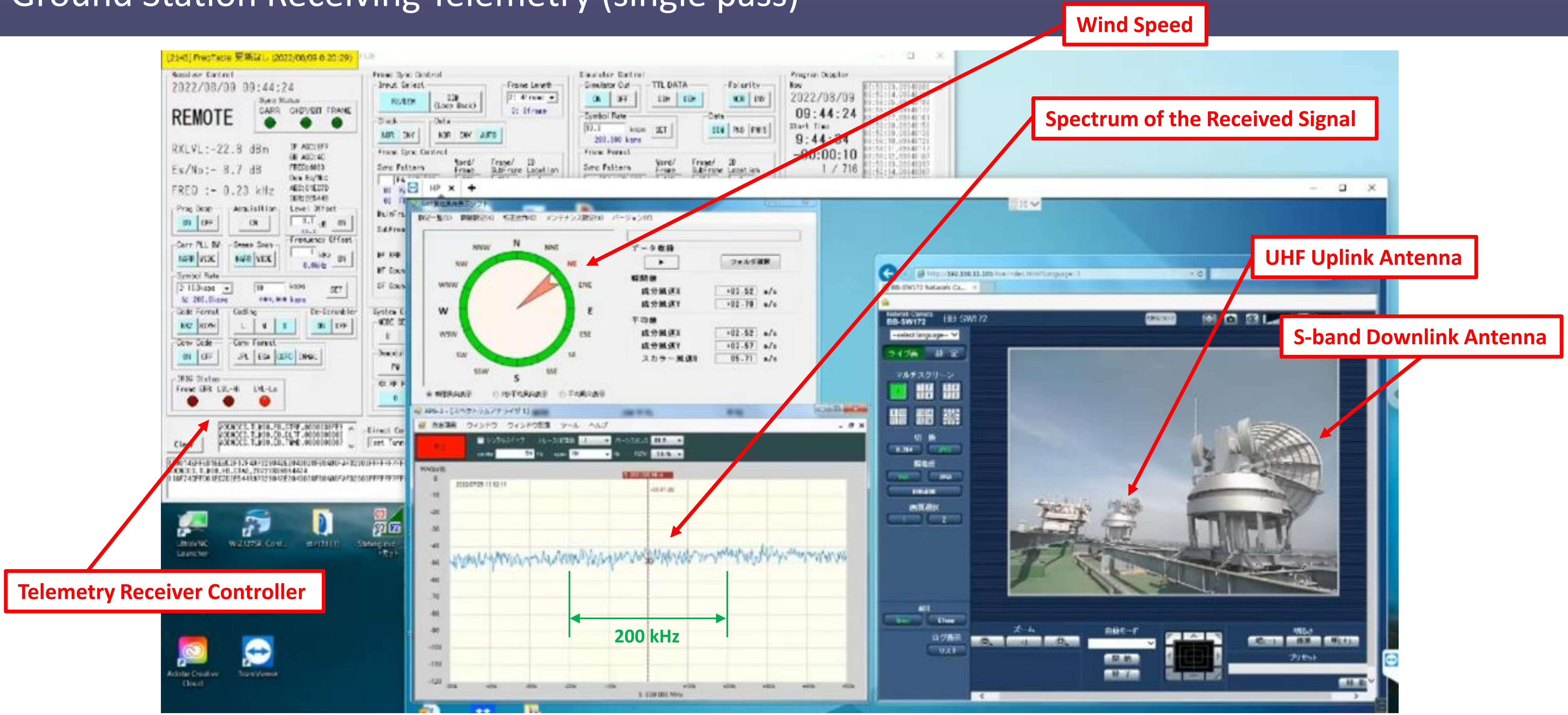
Orbital Pass

- An "orbital pass" is the period in which a spacecraft is above the local horizon.
  - The beginning of a pass is termed *acquisition of signal* (AOS)
  - The end of a pass is termed *loss of signal* (LOS).
- Line-of-sight communication between the satellite and the ground station is possible between this period.
- The duration of one pass depends on the type of satellite orbit, especially orbit altitude.
  - ISS orbit (altitude of 400km): about 10 minutes
  - Earth observation orbit around 500 – 600 km altitude: approximately less than 12 minutes
- The time available for communication is limited, which means that proper preparation must be made in advance for the operation.



1. Introduction to Satellite Operation

Ground Station Receiving Telemetry (single pass)



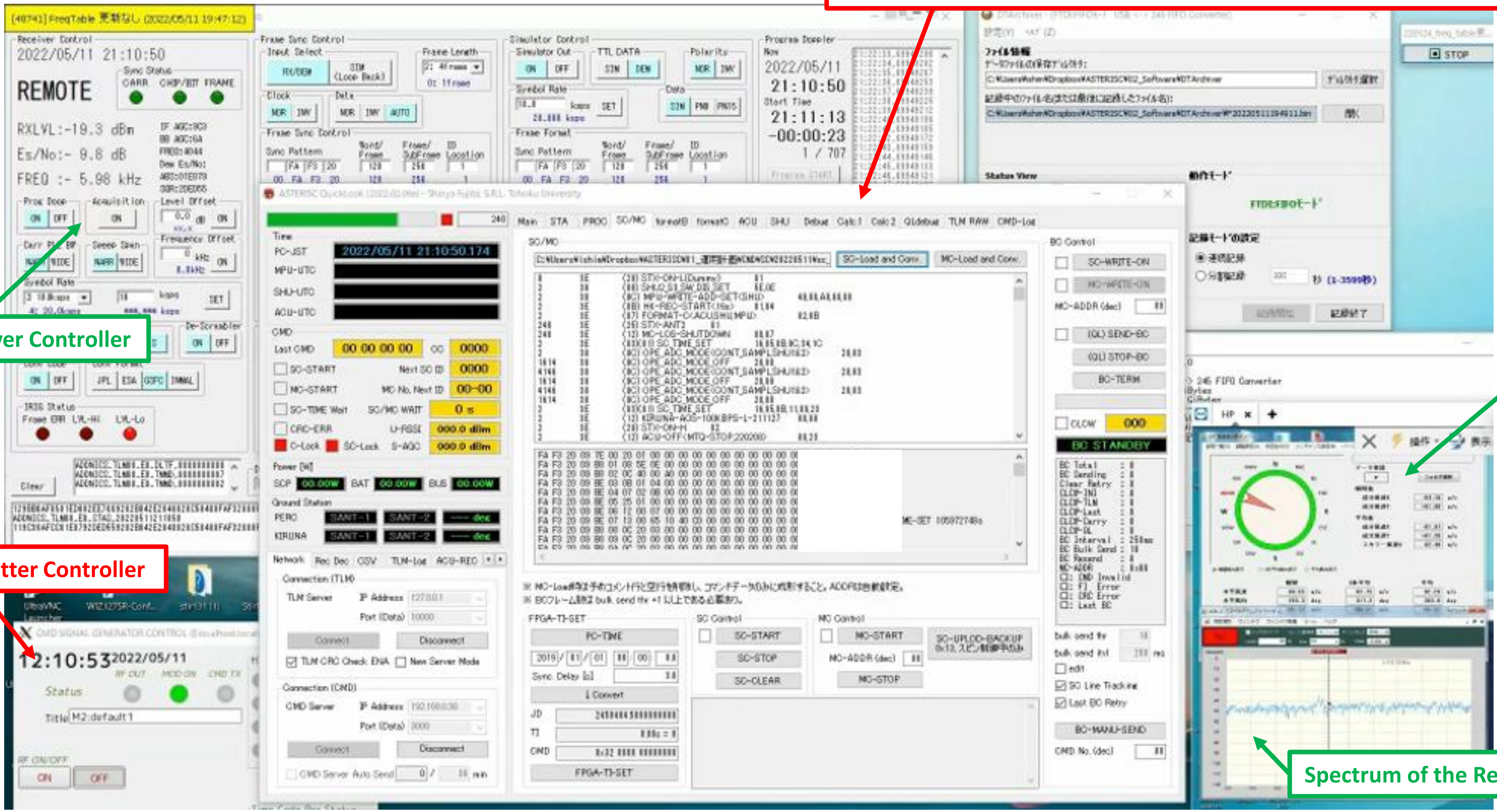
1. Introduction to Satellite Operation

Ground Station Receiving Telemetry (single pass)

AOS: **A**cquisition **O**f **S**ignal
MEL: **M**aximum **EL**evation
LOS: **L**oss **O**f **S**ignal

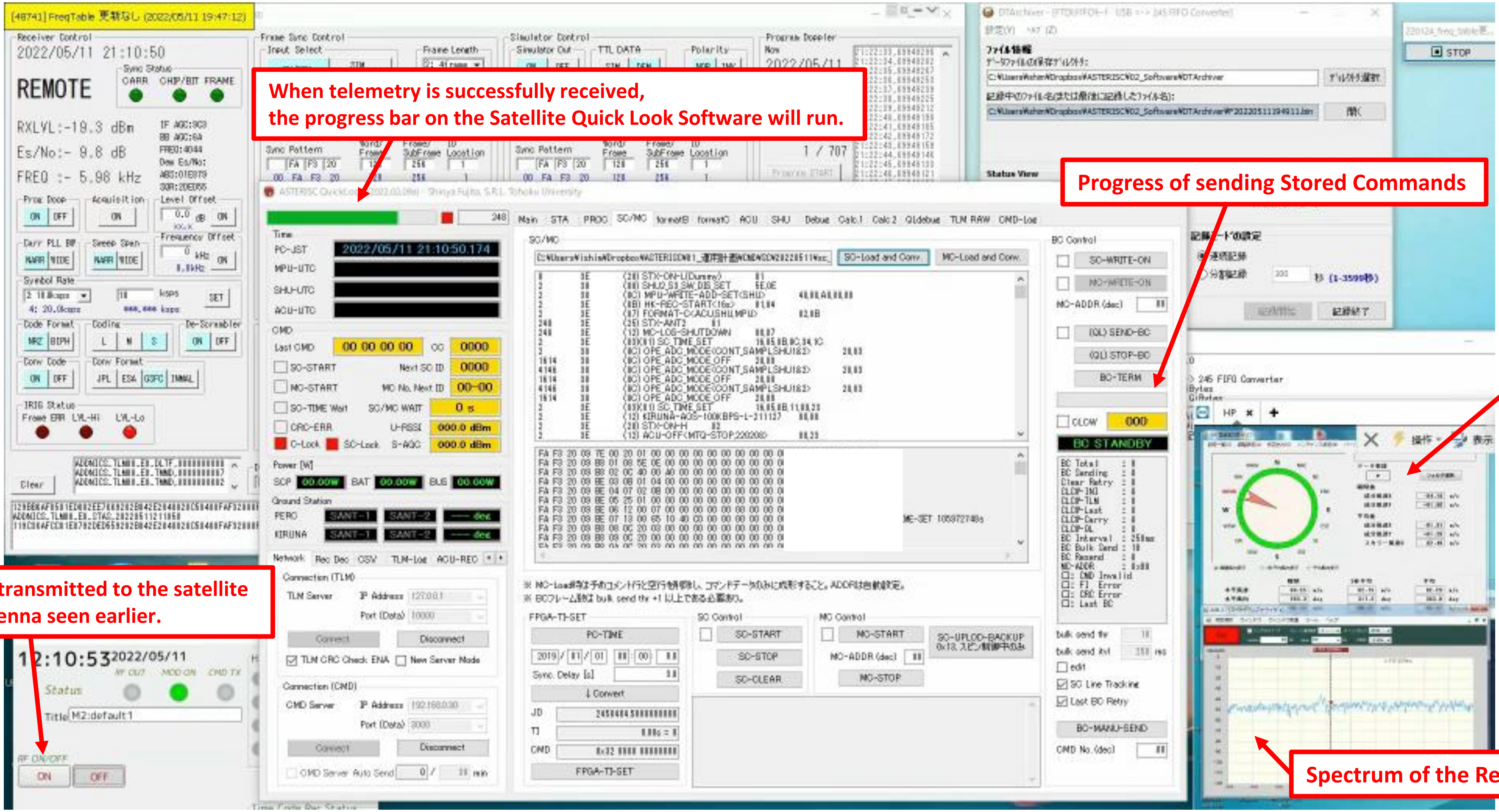
1. Introduction to Satellite Operation

Ground Station Sending Commands (single pass)



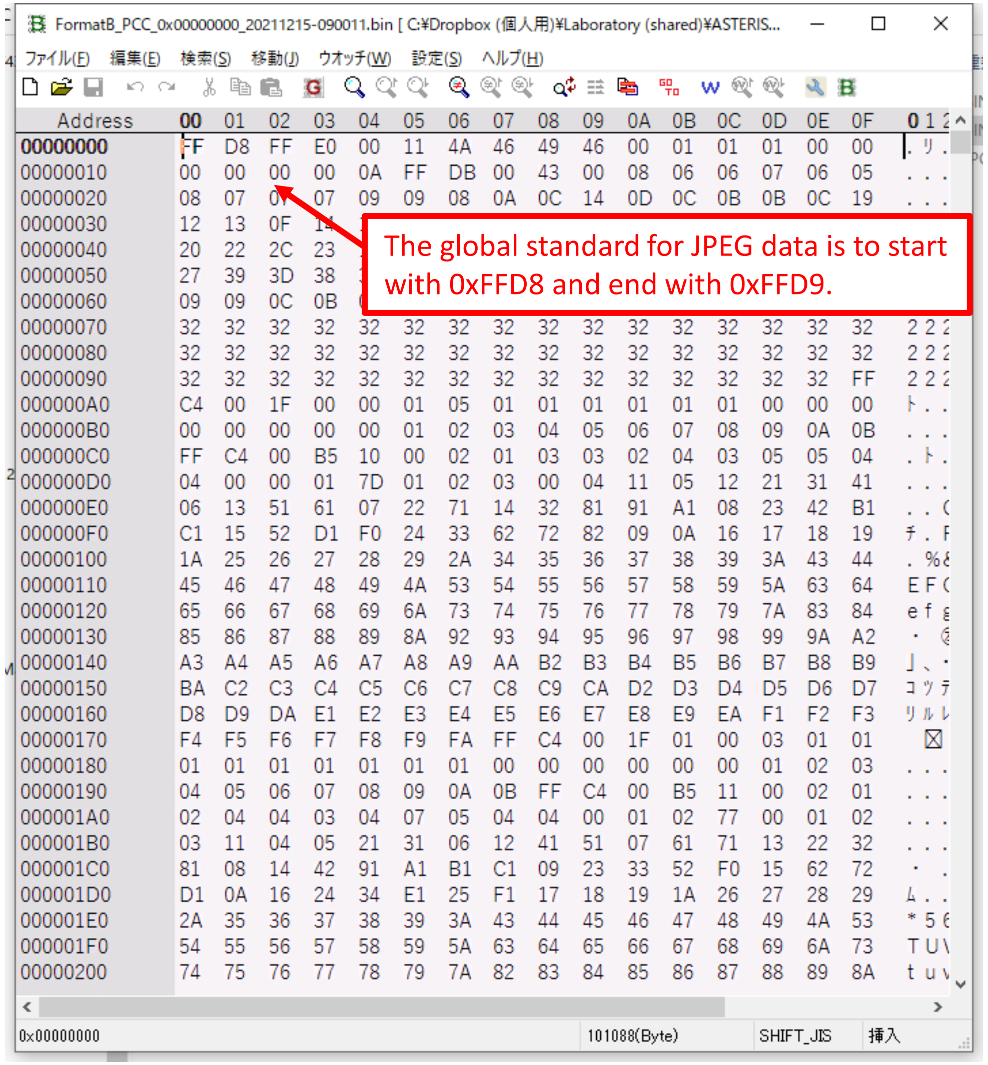
1. Introduction to Satellite Operation

Ground Station Sending Commands (single pass)



1. Introduction to Satellite Operation

Example of Real Telemetry Data



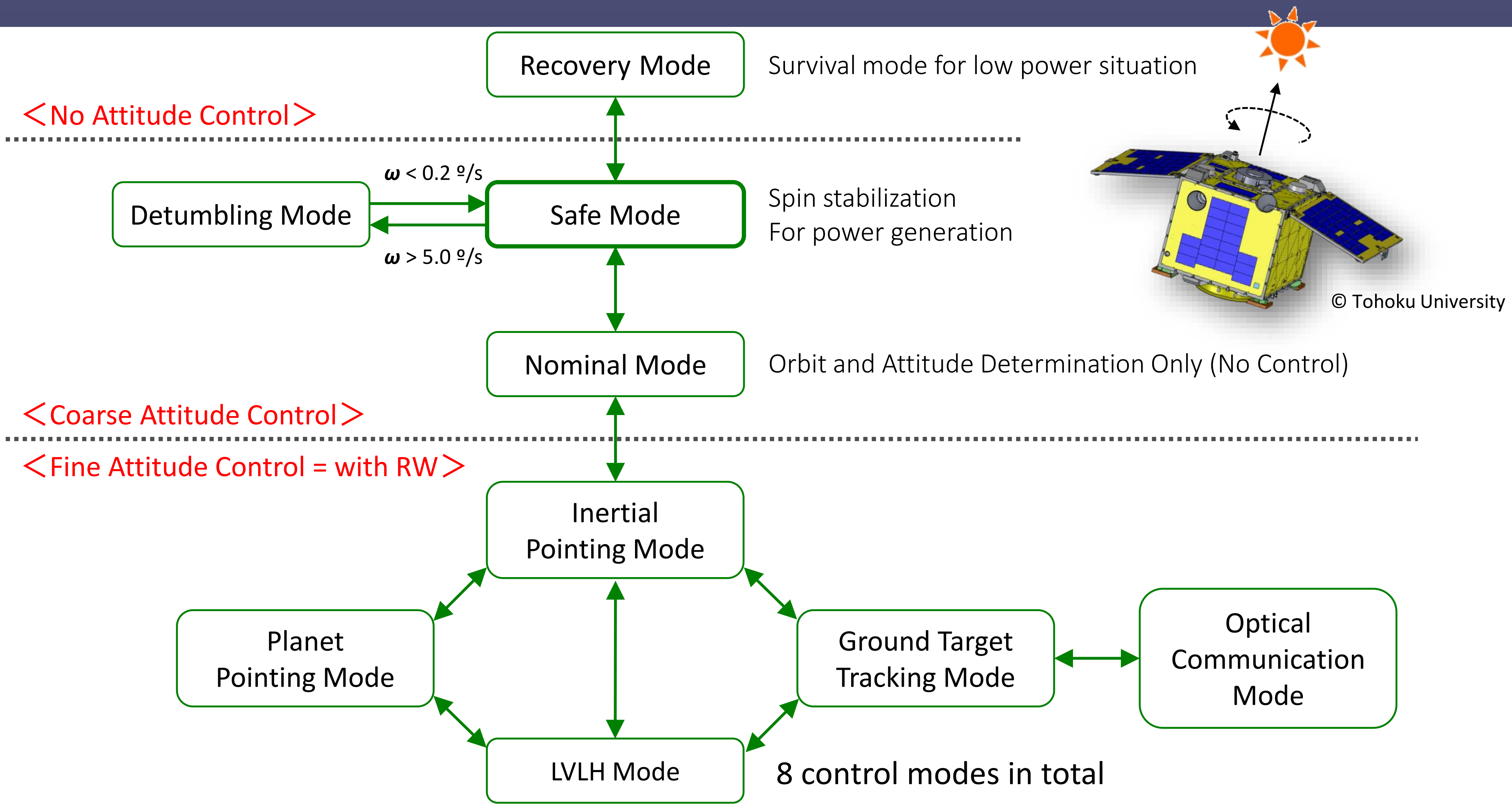
Cosmic Dust Detector Membrane

Taken by "ASTERISC"
2021/12/14 23:57:43 UTC
JPEG, 42 kB

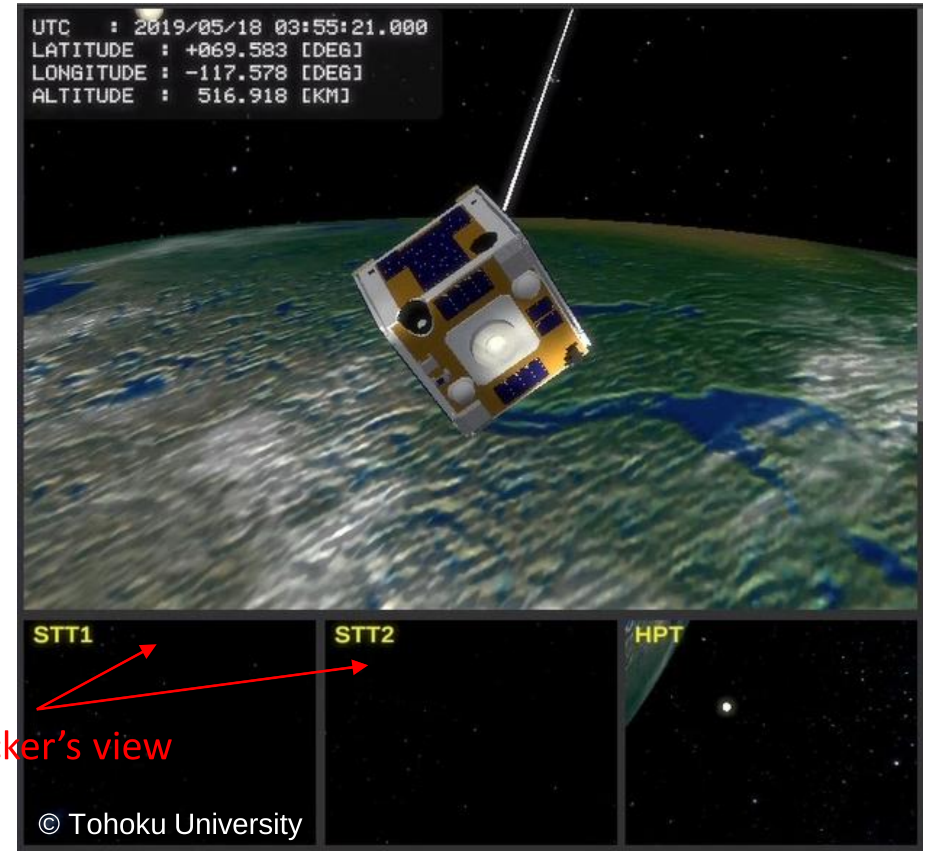
2. Essential Knowledge of Attitude and Orbit Required for the Operation

2. Essential Knowledge of Attitude Control Required for the Operation

Introduction to Satellite Attitude Control



Commonly used attitude control modes: Inertial Pointing Mode



star tracker's view

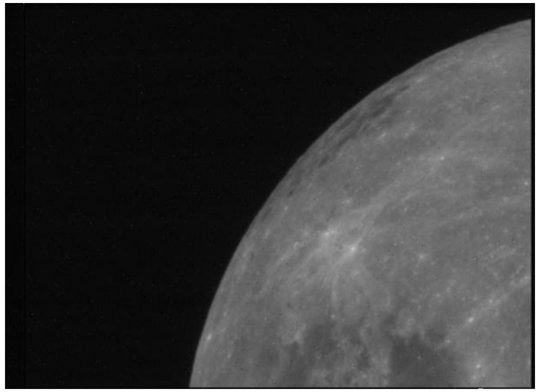
2019/05/18 03:55:21 ~ 04:00:07 UTC

- CG was generated from the real attitude log.
- 25 times faster

SN00361
OOC2, 490 nm
Exposure Time 1.9 ms

2019/5/18
04:00:31 UTC

© JSASS



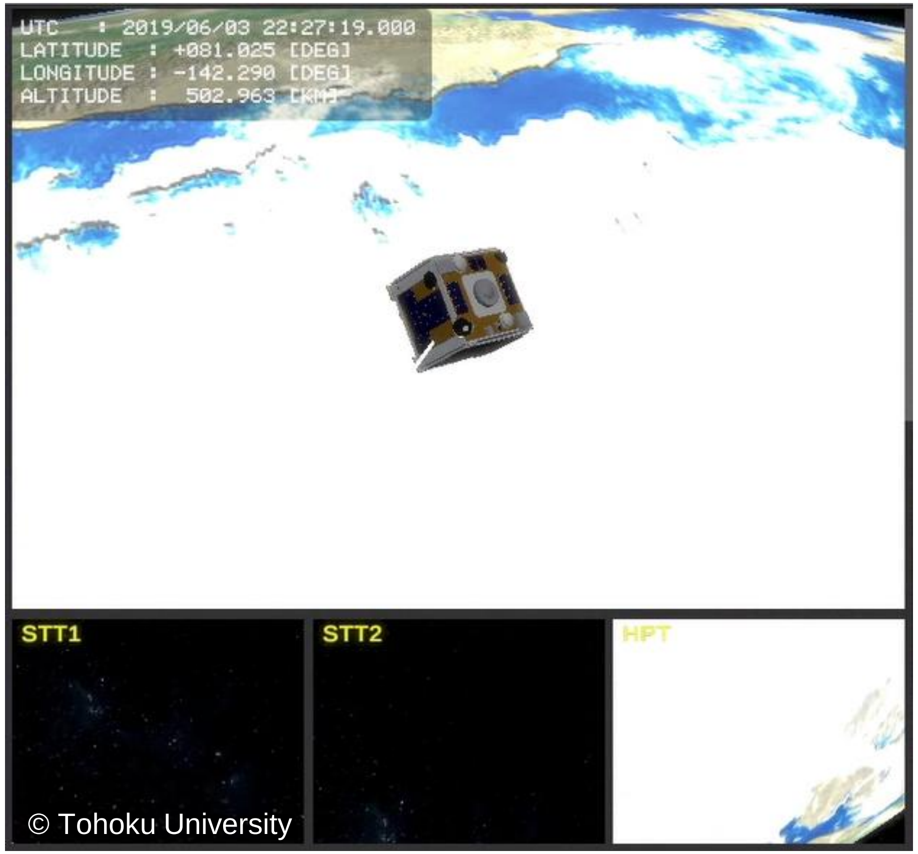
SN00362
HPT-VIS, 555 nm
Exposure Time 32.5 ms

2019/5/18
04:00:31 UTC

© JSASS

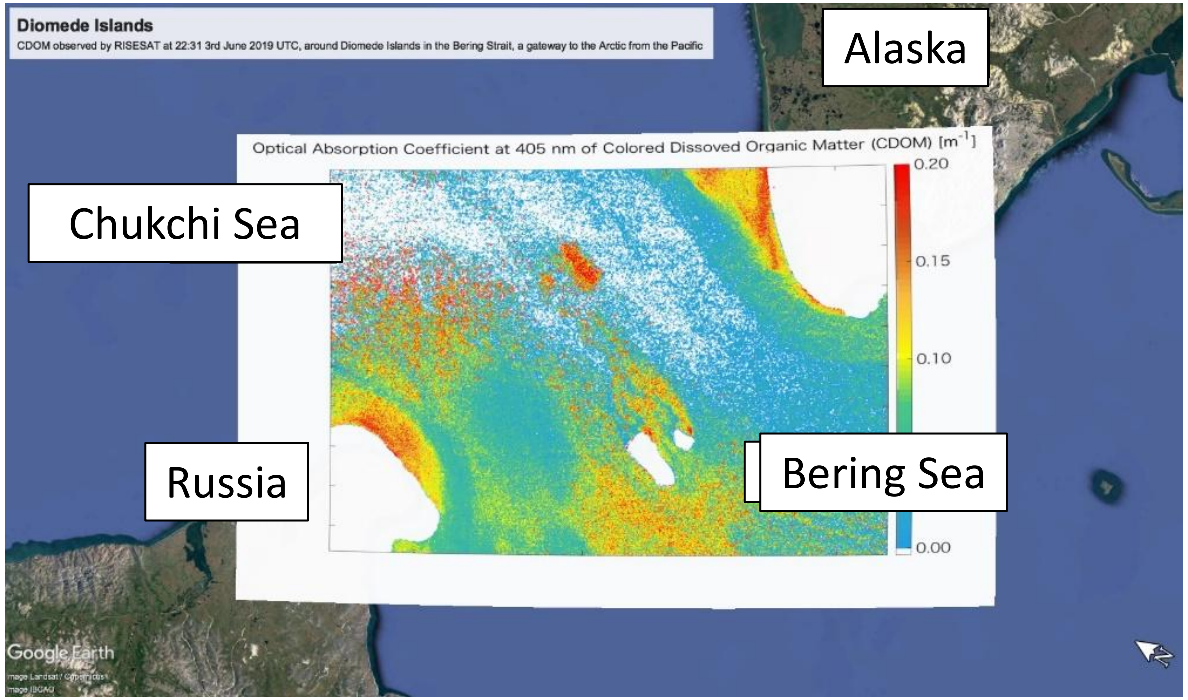
- Optical sensors like HPT and OOC degrade due to severe space environment.
- By observing the Moon on regular basis, we can quantitatively measure their degradation.
- Ground operators have to calculate appropriate target attitude and send as commands.
- Alignment error of attitude sensors can be measured.

Commonly used attitude control modes: LVLH Mode



2019/06/03 22:27:19 ~ 22:32:05 UTC

- CG was generated from the real attitude log.
- 50 times faster

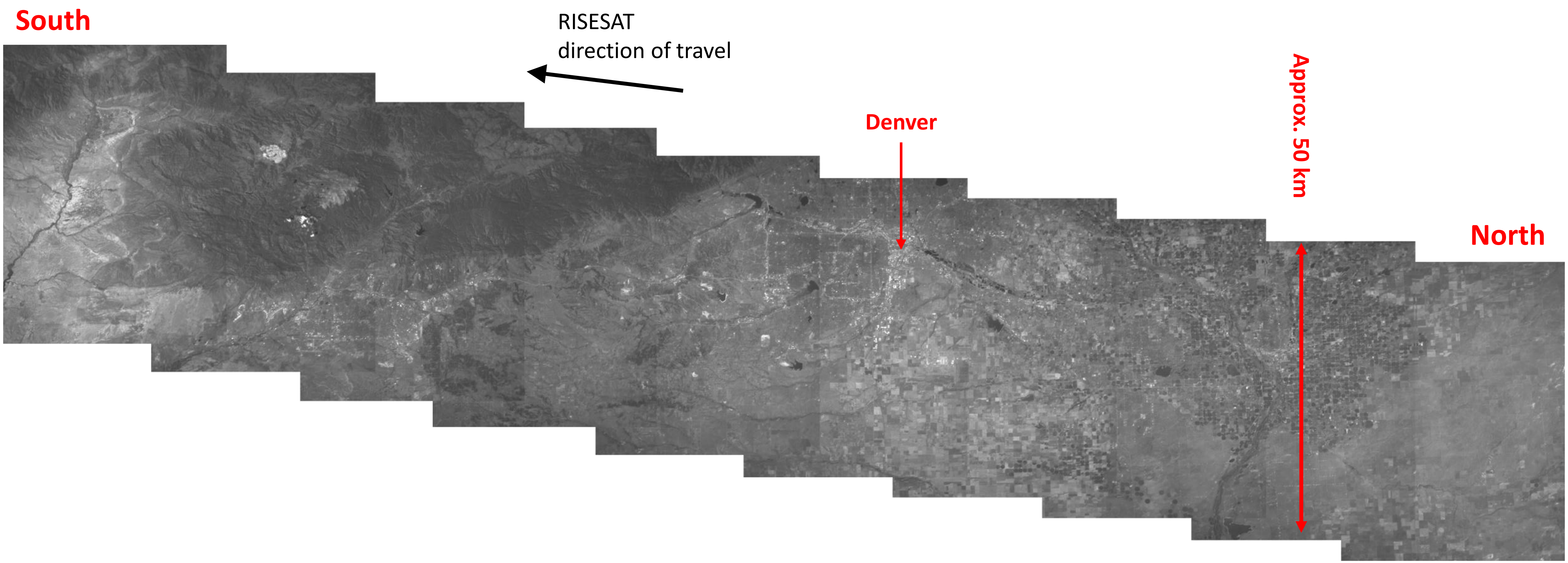


CDOM analysis around Diomede Island (2019/06/03 22:31 UTC)

- Visible and Near-Infrared 4-bands Observation
  - 405, 490, 555, 869 nm
- STTs are continuously available during LVLH mode.
- Ground operators have to calculate appropriate roll, pitch, yaw angle and send as commands.

2. Essential Knowledge of Attitude Control Required for the Operation

Commonly used attitude control modes: LVLH Mode



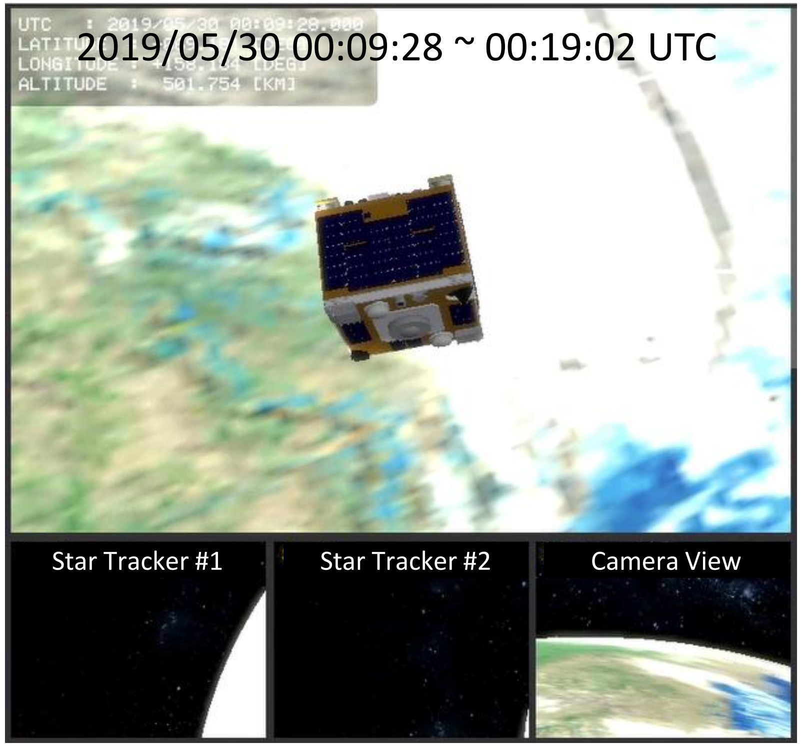
© JSASS

OOC3, 555 nm
2019/08/28 16:29:44 ~ 16:30:18 UTC, 4s interval, 10 continuous shots

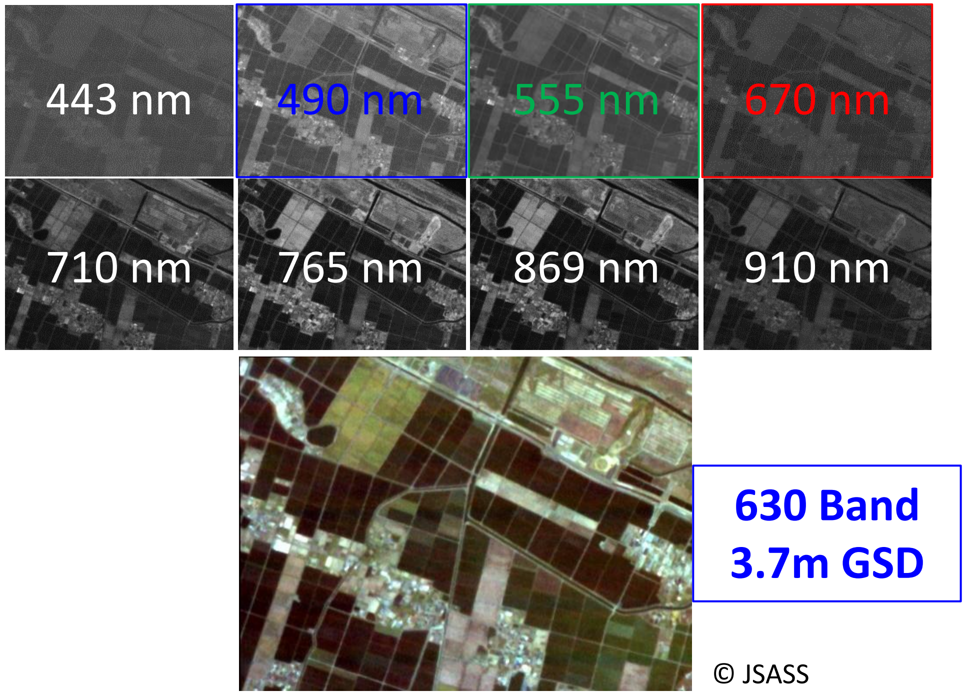
2. Essential Knowledge of Attitude Control Required for the Operation

Commonly used attitude control modes: Ground Target Pointing Mode

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



© Tohoku University



© JSASS

Sendai, True Color Composite

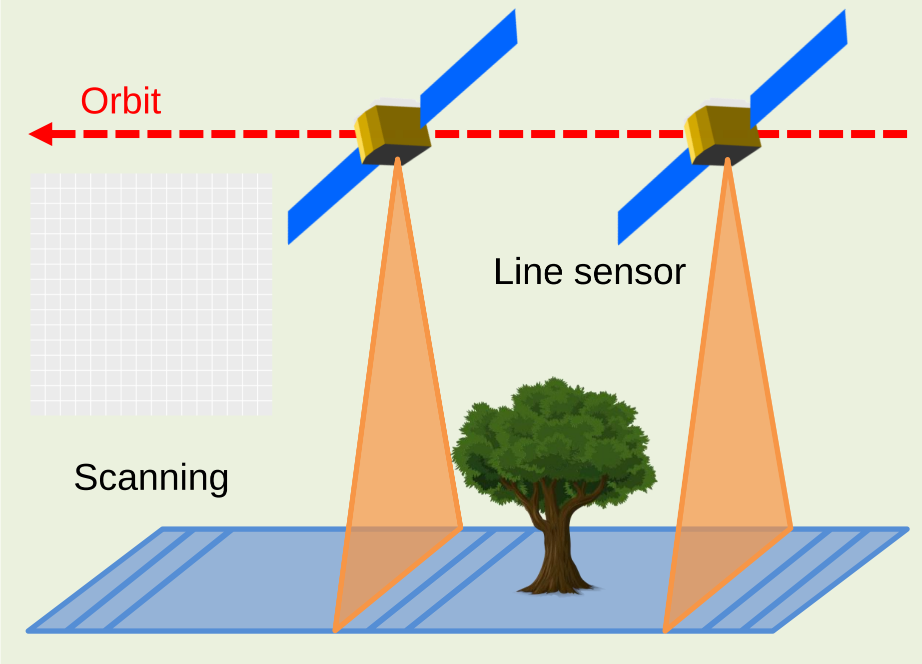
Multi-spectral observation with target pointing attitude control mod

* 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.

Commonly used attitude control modes: Ground Target Pointing Mode

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

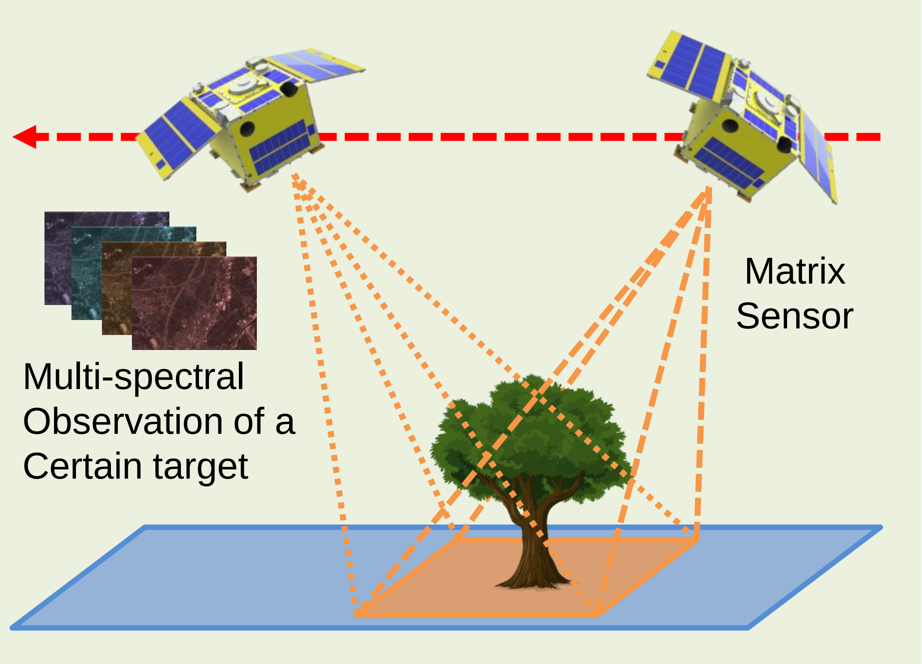
Push-Bloom Observation



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

Cons: Exposure time tends to become short.

Step-Stare Observation

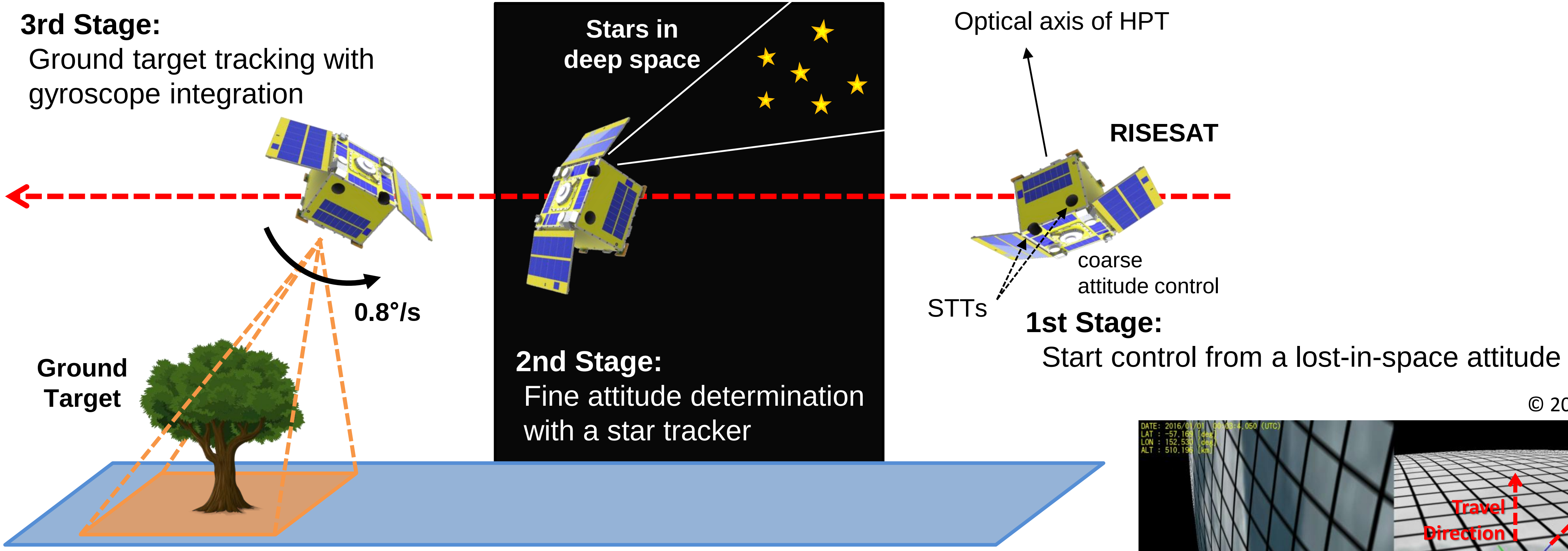


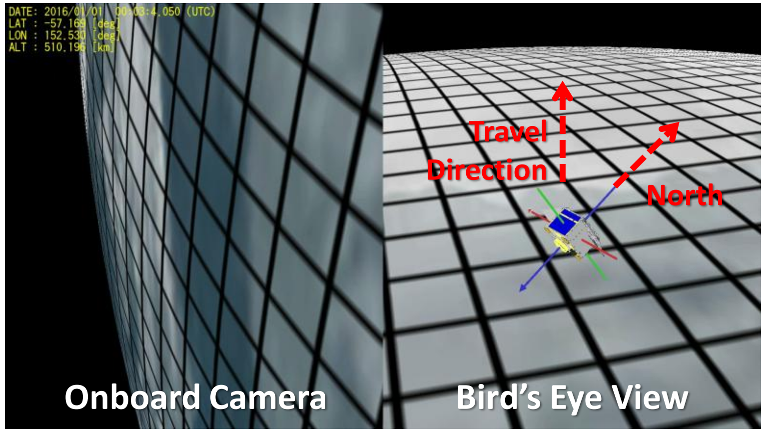
Pros: Exposure time can be long.

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

2. Essential Knowledge of Attitude Control Required for the Operation

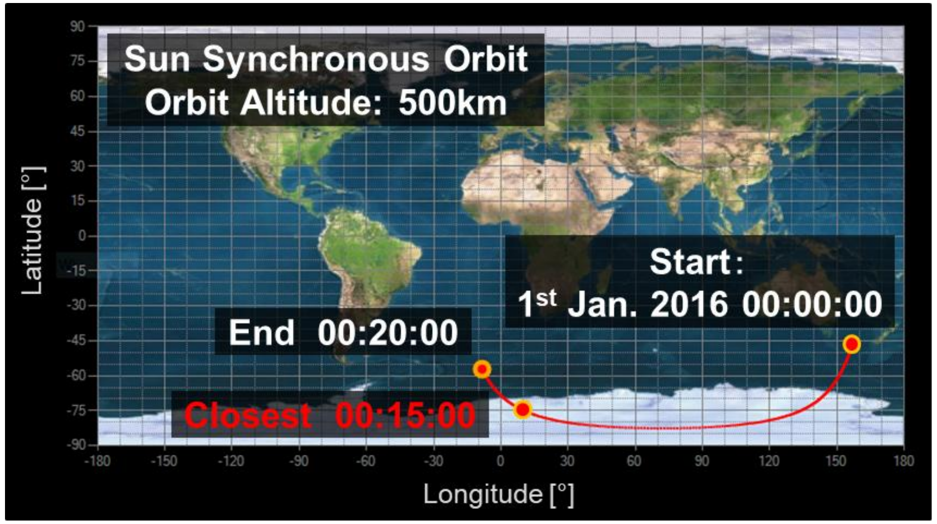
Combination of multiple attitude control modes for operation planning

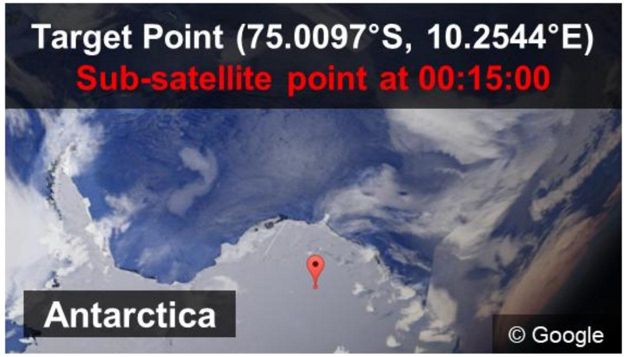




2. Essential Knowledge of Attitude Control Required for the Operation

Combination of multiple attitude control modes for operation planning

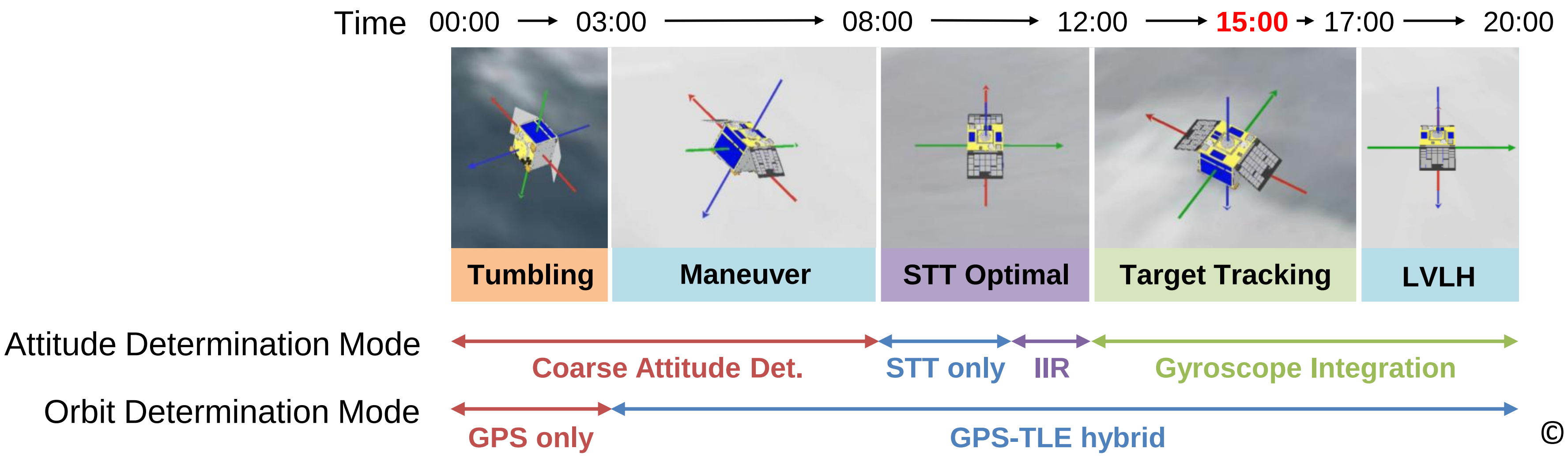




STT optimal attitude at 00:08:00 & 00:12:00

$$\boldsymbol{q}^{\alpha}_{stt2} = [-0.374920, 0.212529, 0.121786, 0.894111]$$

$$\boldsymbol{q}^{\beta}_{stt2} = [-0.373640, 0.205027, 0.143410, 0.893191]$$

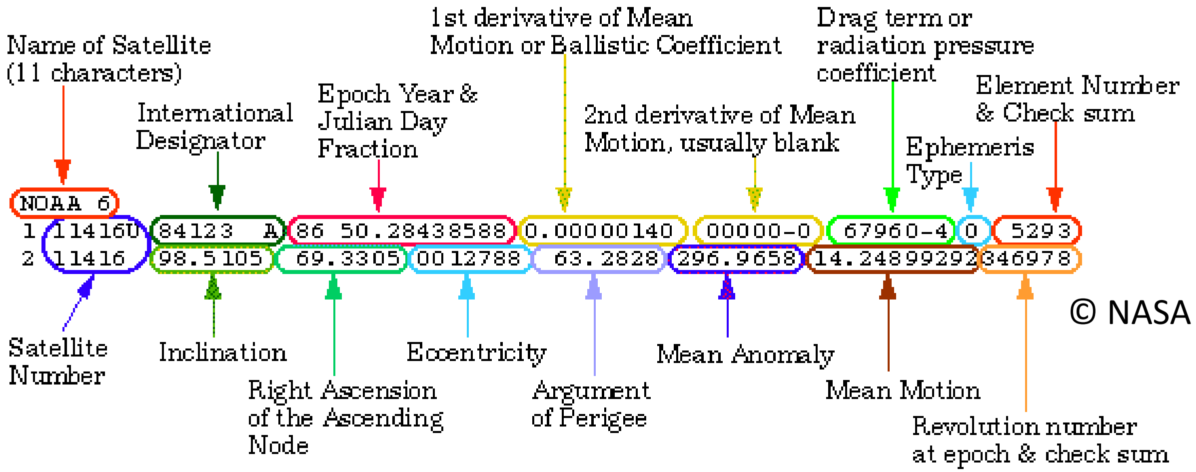


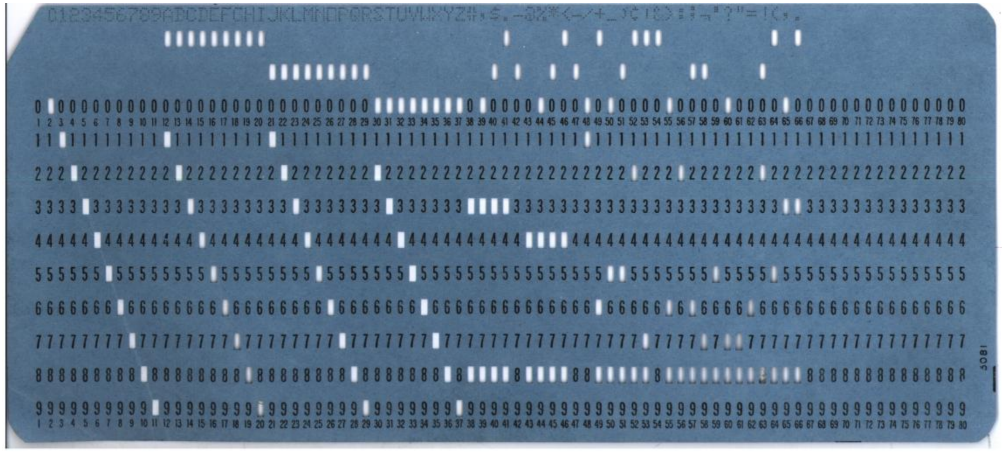
3. Essential Knowledge of Orbit Determination for Satellite Operation

3. Essential Knowledge of Orbit for Satellite Operation

What is "Two-line Element set (TLE)"

- A two-line element set (often called TLE) is one of the data formats used to represent orbital elements orbiting the Earth.
- The satellite orbit is represented by a 69-character, 2-line text. The format was originally intended for punched cards, encoding a set of elements on two standard 80-column cards.
- Satellites, debris, and other objects in orbit are monitored by the U.S. military, and TLEs are automatically created from this information. TLE information is available free of charge on the web and can be used by anyone.
- Using this TLE and the appropriate calculation algorithm, it is possible to determine the position of a satellite at any given time.





An 80-column punched card

By Blue-punch-card-front.png: Gwernderivative work: agr (talk) - Blue-punch-card-front.png, Public Domain, https://commons.wikimedia.org/w/index.php?curid=8511203

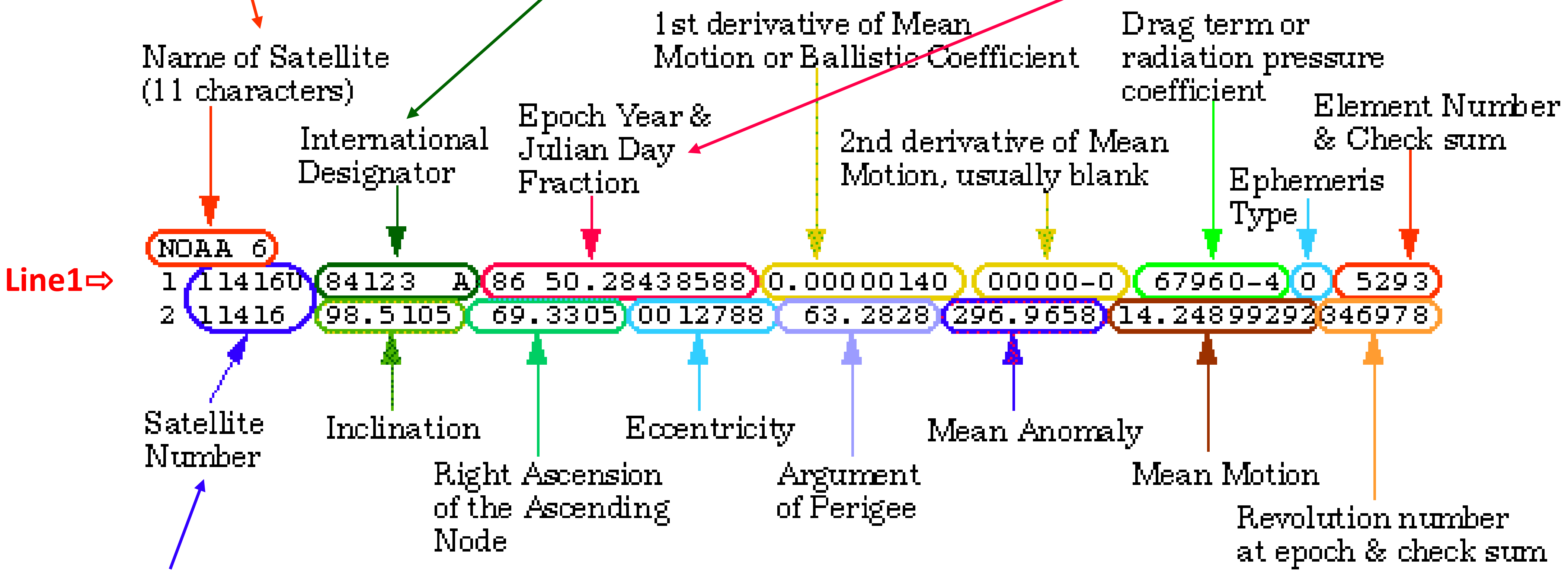
3. Essential Knowledge of Orbit for Satellite Operation

Understanding the "TLE", Reading Two-line Element set: Line1

This name is usually not necessary for TLE.
The name is for human understanding.

Numbered in the order of launch.
Not required for orbit calculation.

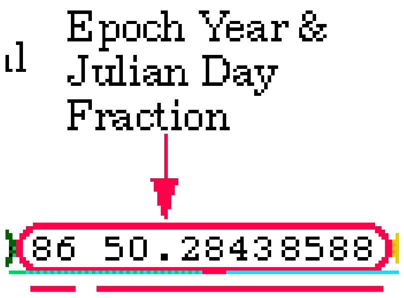
The reference date and time for this orbit element.



© NASA

"Satellite Number" is the serial number of the registered object.
Not required for orbit calculation.

Understanding the “TLE”, Epoch



The other: **Day of the year and fractional portion of the day**
In this case, 50.28438588 days after January 1st.
= February 19, 06:49:30.94

Start with 50.28438588 days (Days = 50)
50.28438588 days - 50 = 0.28438588 days
0.28438588 days x 24 hours/day = 6.8253 hours (Hours = 6)
6.8253 hours - 6 = 0.8253 hours
0.8253 hours x 60 minutes/hour = 49.5157 minutes (Minutes = 49)
49.5157 - 49 = 0.5157 minutes
0.5157 minutes x 60 seconds/minute = 30.94 seconds (Seconds = 30.94)

IMPORTANT: January 1st is Day 1, not Day 0.

First two-digit: **Last two digits of the year**
In this case, 1986. (This TLE example is very old)

3. Understanding the “TLE”, Julian Day

- **The Julian day** is commonly used to denote the date and time in the field of Astronomy.
  - Satellite orbit calculations and attitude control are strongly related to astronomy ⇨ we also recommend using the Julian day.

- The Julian day is the continuous count of days since the beginning of the Julian period.
  - That is, it is equivalent to the number of days elapsed since noon on January 1, 4713 BC.
  - Today, September 9, 2022 at 00:00 UTC = 2459831.5
  - For ease of use in astronomical observations at midnight, it is said that noon is defined as the beginning of the day.

Converting Gregorian calendar date to Julian Day Number [edit]

The algorithm is valid for all (possibly proleptic) Gregorian calendar dates after November 23, −4713. **Divisions are integer divisions towards zero**; fractional parts are ignored.[68]

JDN = (1461 × (Y + 4800 + (M − 14)/12))/4 +(367 × (M − 2 − 12 × ((M − 14)/12)))/12 − (3 × ((Y + 4900 + (M - 14)/12)/100))/4 + D − 32075

Converting Julian calendar date to Julian Day Number [edit]

The algorithm[69] is valid for all (possibly proleptic) Julian calendar years ≥ −4712, that is, for all JDN ≥ 0. Divisions are integer divisions, fractional parts are ignored.

JDN = 367 × Y − (7 × (Y + 5001 + (M − 9)/7))/4 + (275 × M)/9 + D + 1729777

Finding Julian date given Julian day number and time of day [edit]

For the full Julian Date of a moment after 12:00 UT one can use the following. Divisions are real numbers.

$$JD = JDN + \frac{\text{hour}-12}{24} + \frac{\text{minute}}{1440} + \frac{\text{second}}{86400}$$

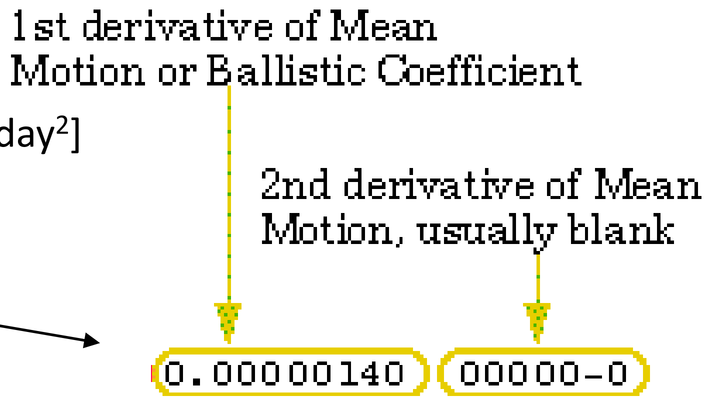
So, for example, January 1, 2000, at 18:00:00 UT corresponds to *JD* = 2451545.25

For a point in time in a given Julian day after midnight UT and before 12:00 UT, add 1 or use the JDN of the next afternoon.

https://en.wikipedia.org/wiki/Julian_day

Understanding the "TLE", Time Derivative of Mean Motion

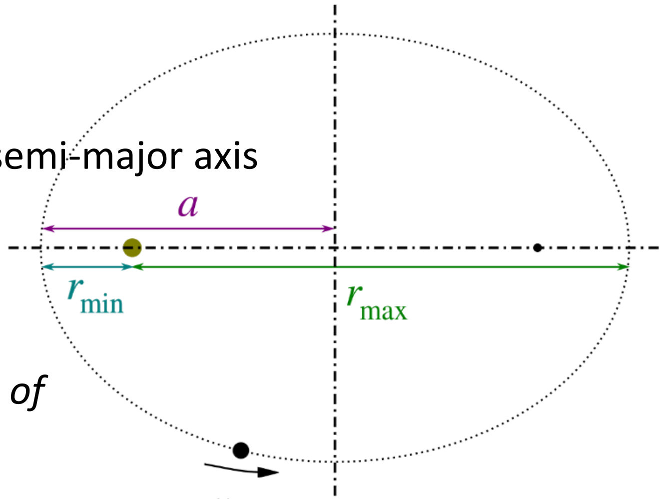
unit: [revs/day²]



unit: [revs/day³]

Used to compensate for the non-uniformity of the Earth's gravitational potential.

a: semi-major axis



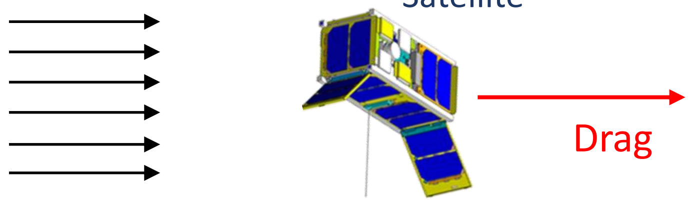
satellite

Mean Motion: unit [revs/day]

- The number of times a satellite orbits the earth in a day
- Related to the velocity of the satellite
- The size of the orbit can be determined from Kepler's third law.
  - *"The ratio of the square of an object's orbital period with the cube of the semi-major axis of its orbit is the same for all objects orbiting the same primary"*

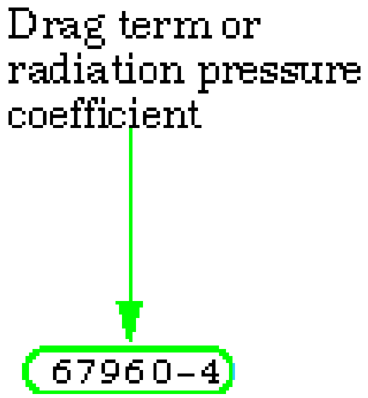
a: semi-major axis $$a^2 \propto p^3$$ p: orbital period

Understanding the “TLE”, Drag Term



Earth’s upper atmosphere

also called B* (B star)



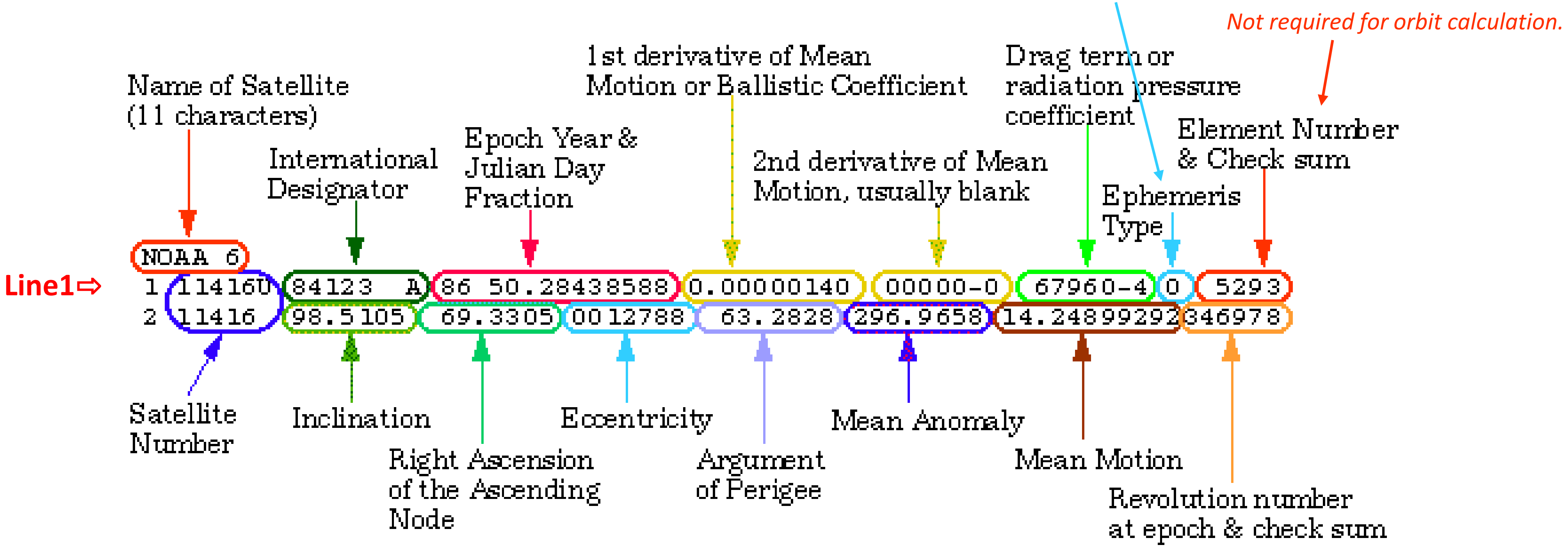
The last two characters define an applicable power of 10.
In this case, 0.67960×10^{-4} (no unit)

- For low orbits at altitudes of a few hundred kilometers, a rarefied atmosphere exists.
- Used to compensate for the slowing of the satellite's velocity due to aerodynamic drag.
- Even with this correction, TLE is only effective for about a week.

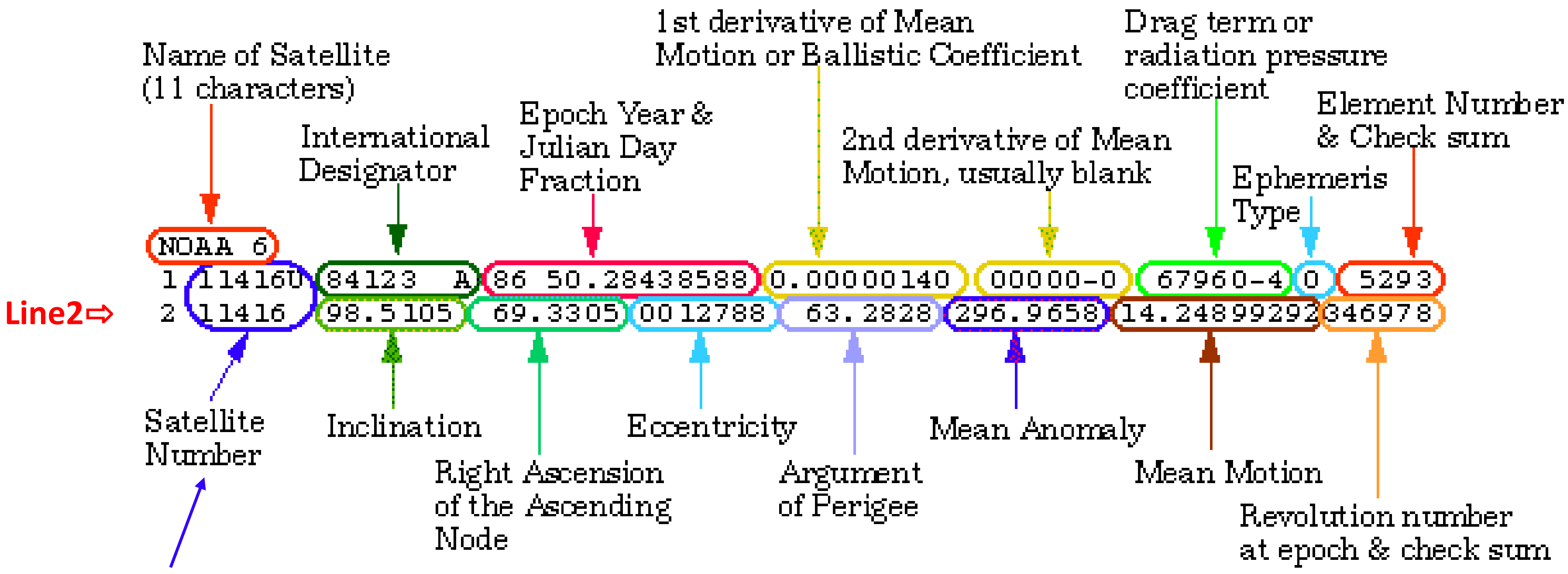
3. Essential Knowledge of Orbit for Satellite Operation

3. Understanding the “TLE”, Reading Two-line Element set: Line1

Specify the orbit calculation algorithm.
However, this value is always 0. The algorithm is unknown.
Generally, we use SGP4.



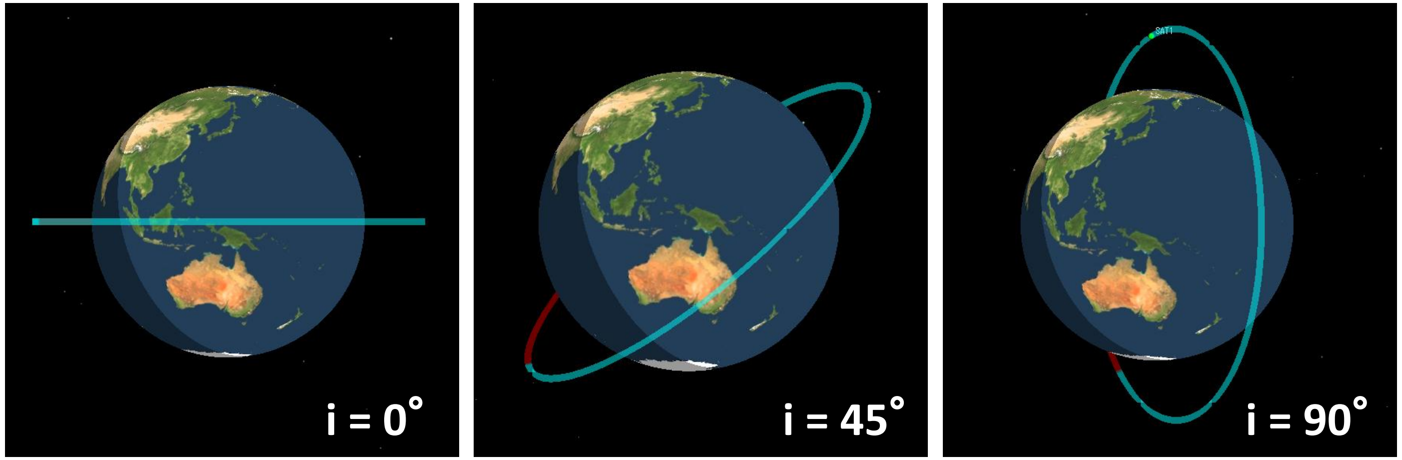
Understanding the "TLE", Reading Two-line Element set: Line2

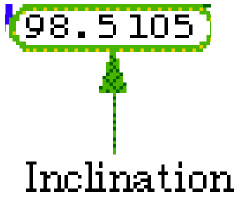


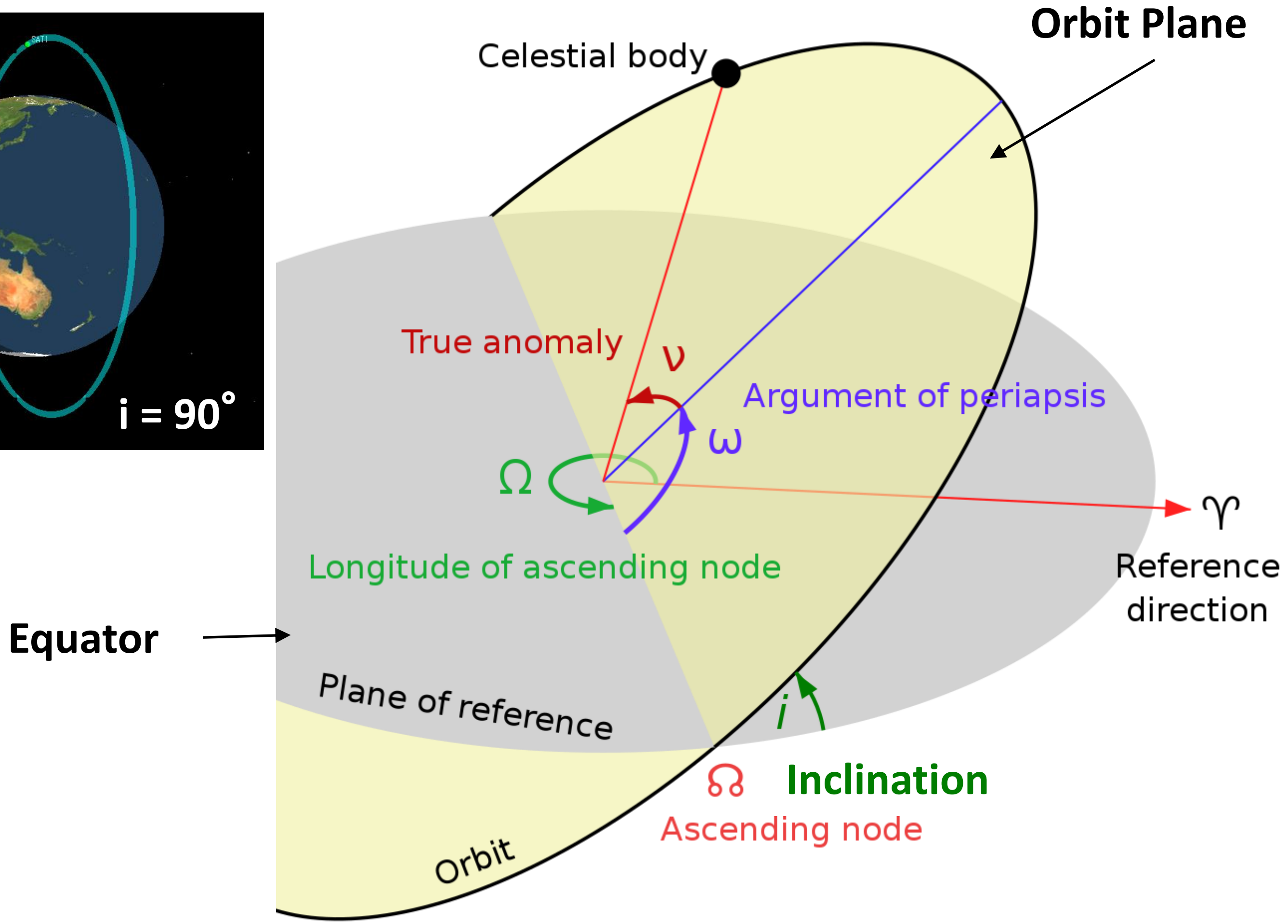
"Satellite Number" is the serial number of the registered object.
Not required for orbit calculations.

3. Essential Knowledge of Orbit for Satellite Operation

Understanding the "TLE", Inclination





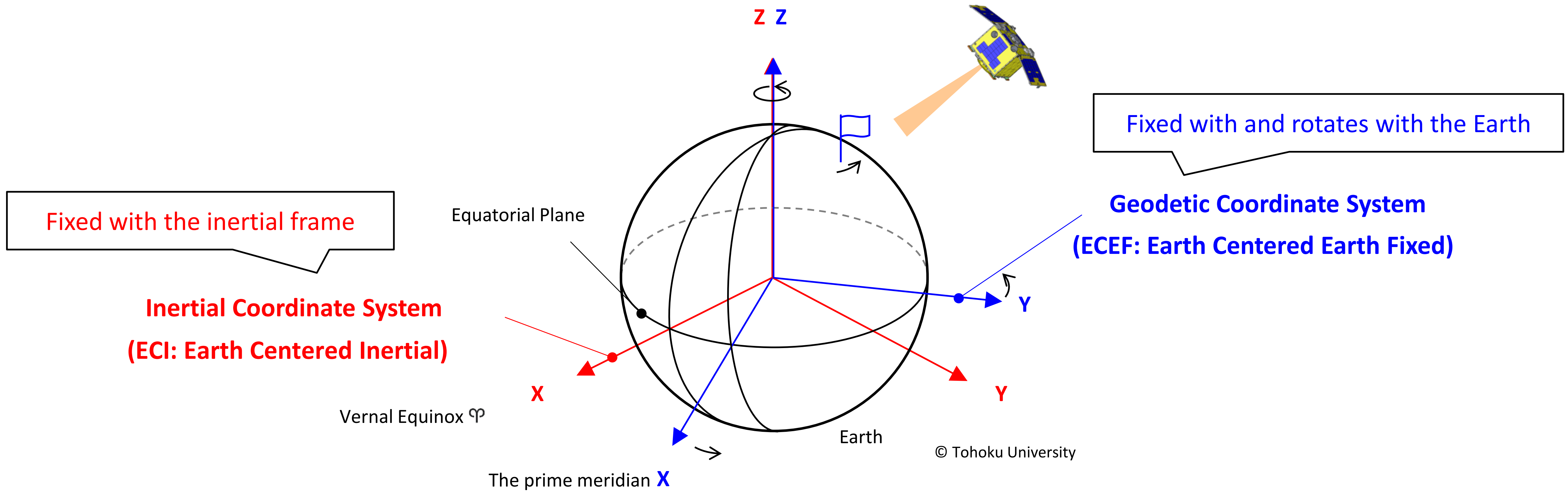


Inclination: [degrees]

- The angle between the equator and the orbit plane.
- The value is defined in the TEME coordinate system.

Understanding the "TLE", Inertial Coordinate System and Geodetic Coordinate System

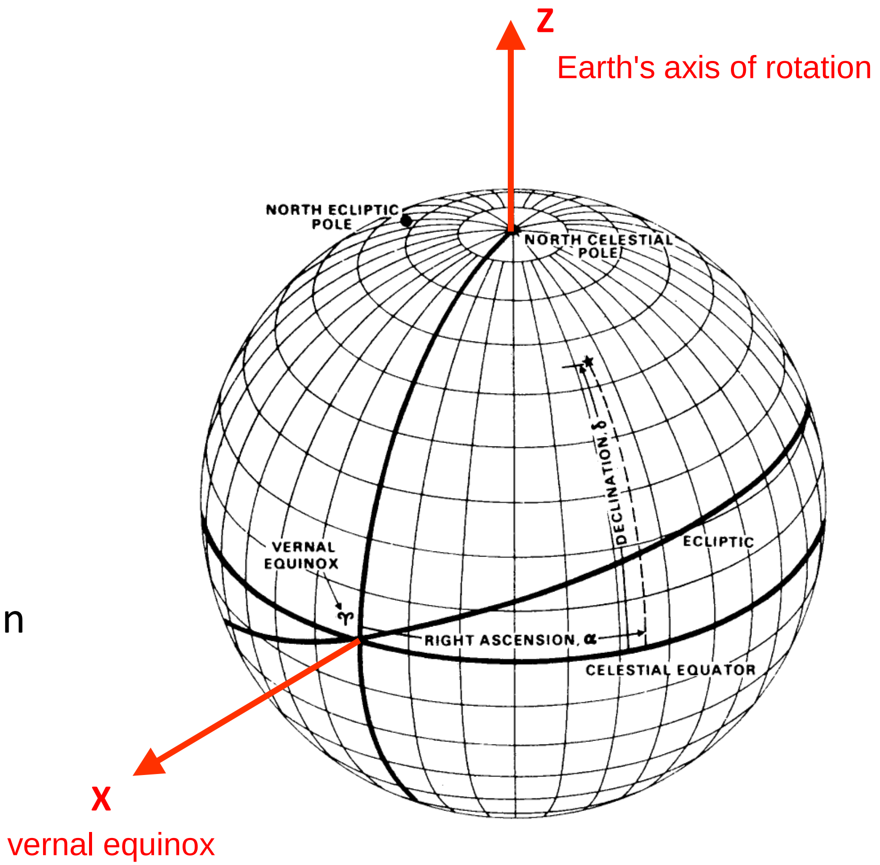
- It is important to be aware of the coordinate system when thinking about attitude and orbit calculation.
- Earth is rotating relative to the inertial coordinate system.
  - usually called **ECI**: **E**arth **C**entered **I**nertial coordinate system
- This ECI coordinate system is a generic term for a number of the inertial coordinate system.
  - various inertial coordinate systems exist due to differences in the detailed definition of the coordinate axes.



3. Essential Knowledge of Orbit for Satellite Operation

Understanding the "TLE", TEME Coordinate System

- The TEME coordinate system used by TLE is one of the Earth-centered inertial coordinate systems.
  - **TEME**: **T**rue **E**quator, **M**ean **E**quinox
- To define a right-handed Cartesian coordinate system, we must first determine the two axes. In ECI coordinate system,
  - X axis is in the direction of the vernal equinox
  - Z axis is in the direction of the Earth's axis of rotation
    ⇧ normal vector to the equatorial plane.
- These axes are not fixed with respect to the true inertial coordinate system because the Earth's rotation is oscillating.
- In TEME,
  - True Equator = Instantaneous equatorial plane, considering the oscillation of the Earth's rotation.
  - Mean Equinox = Mean direction of the vernal equinox at the concerned time.
- This coordinate system is basically used only for TLE calculations.



James R. Wertz, *Spacecraft Attitude Determination and Control*, Springer

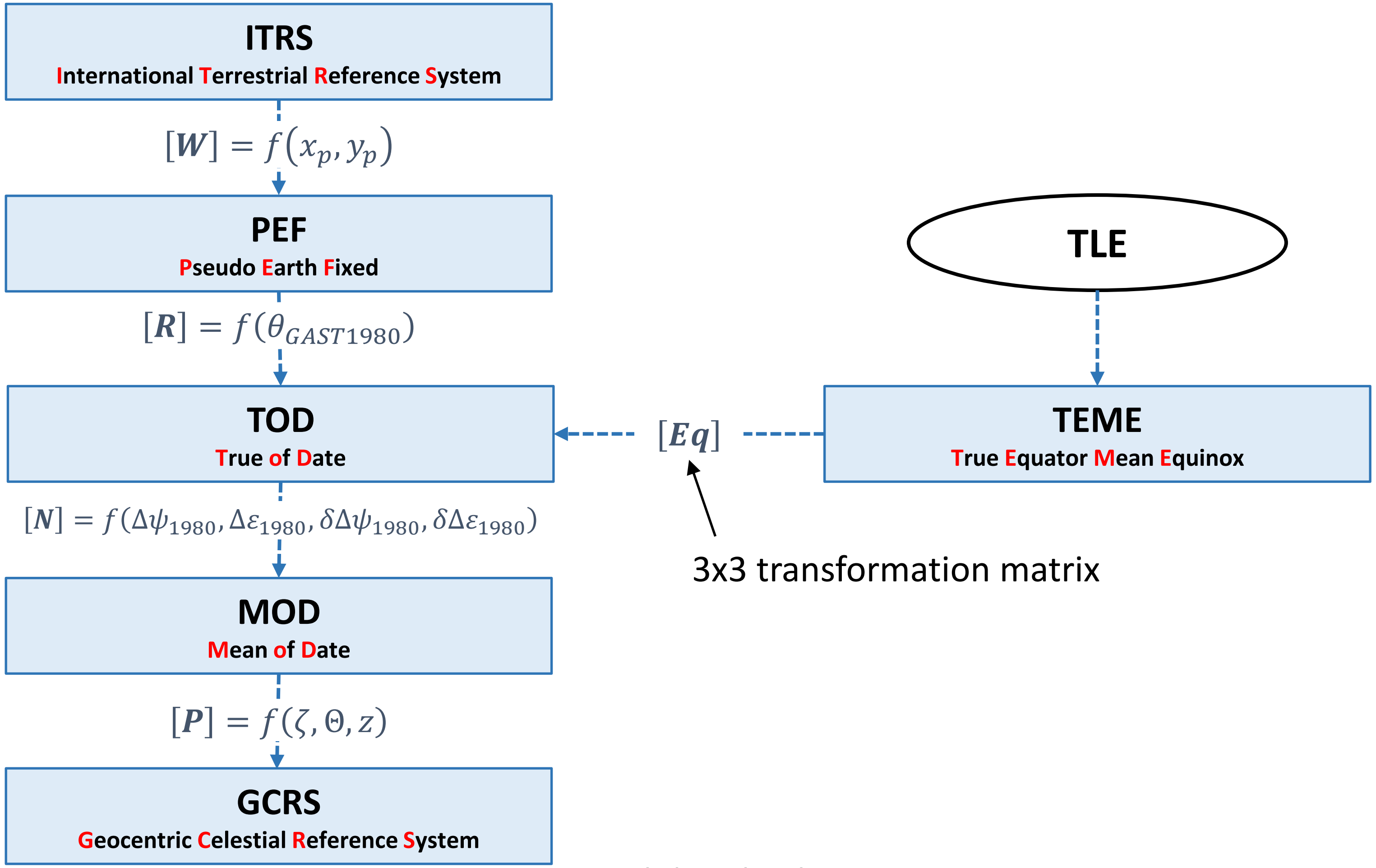
Understanding the “TLE”, Example of coordinate transformation method

Geodetic Coordinate:

This conversion transforms the nutation motion of the Earth’s rotation. ⇨

This conversion transforms the presession motion of the Earth’s rotation. ⇨

Inertial Coordinate:



3. Essential Knowledge of Orbit for Satellite Operation

Understanding the "TLE", How to obtain the coordinate transformation matrix parameters

- Parameters are needed to be used in the transformation calculation.
  - EOP: Earth Orientation Parameter
- Maintained by the International Earth Rotation Service (IERS) in Paris.
- On their web site, you can find latest and historical information of EOPs.

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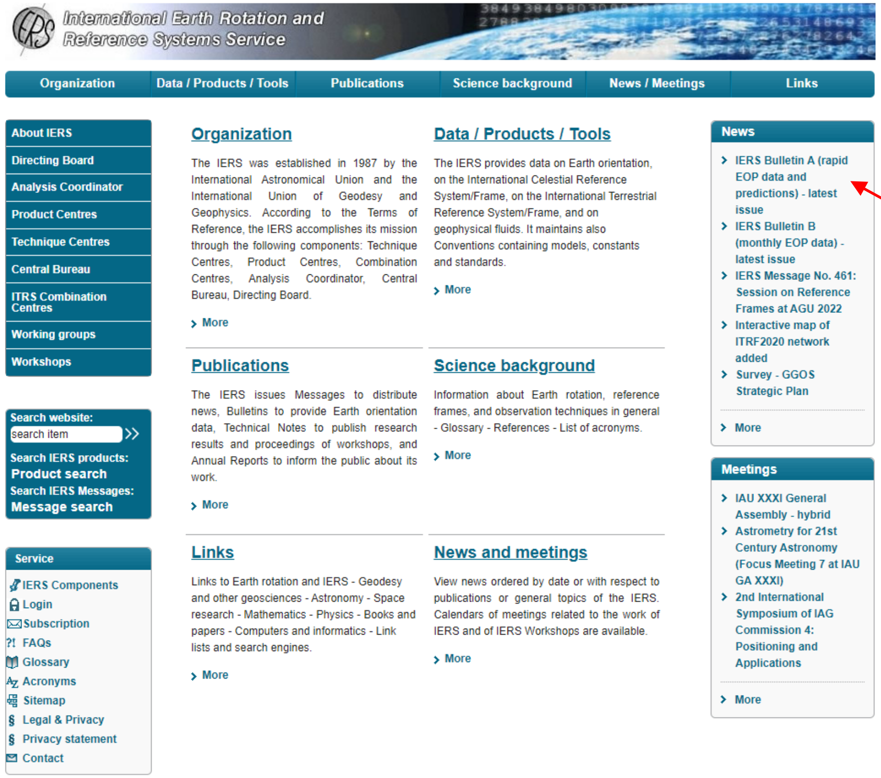
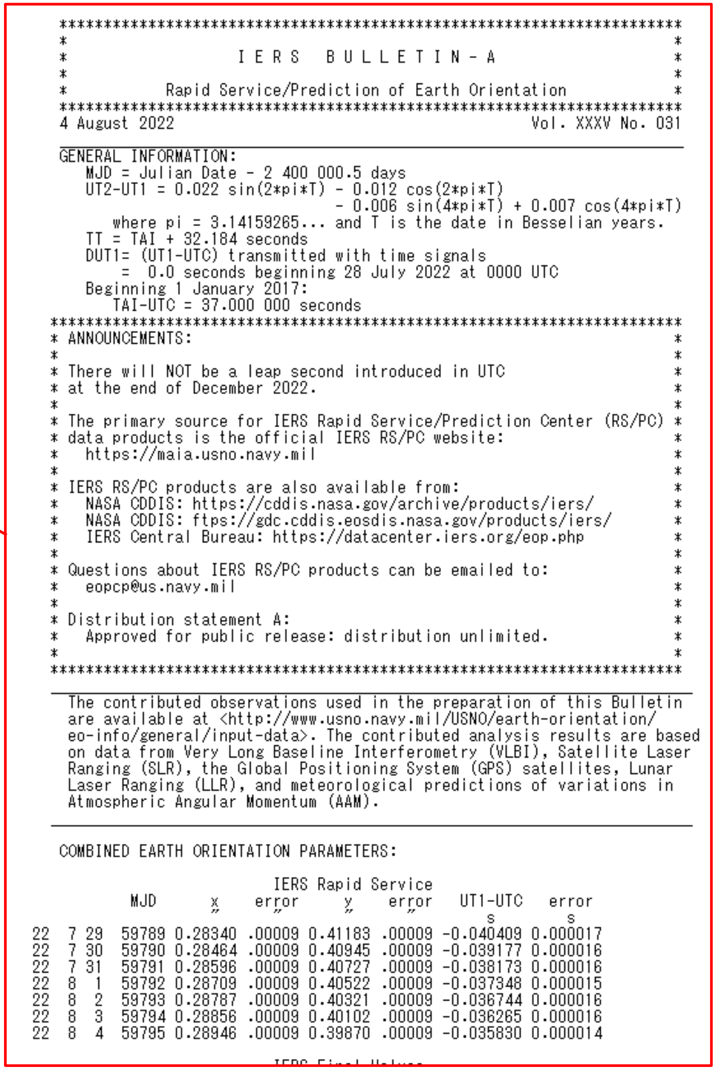


https://www.iers.org/IERS/EN/Home/home_node.html



I E R S   B U L L E T I N - A

Rapid Service/Prediction of Earth Orientation

4 August 2022 Vol. XXXV No. 031

GENERAL INFORMATION:
MJD = Julian Date - 2 400 000.5 days
UT2-UT1 = 0.022 sin(2*pi*T) - 0.012 cos(2*pi*T)
- 0.006 sin(4*pi*T) + 0.007 cos(4*pi*T)
where pi = 3.14159265... and T is the date in Besselian years.
TT = TAI + 32.184 seconds
DUT1= (UT1-UTC) transmitted with time signals
= 0.0 seconds beginning 28 July 2022 at 0000 UTC
Beginning 1 January 2017:
TAI-UTC = 37.000 000 seconds

ANNOUNCEMENTS:

There will NOT be a leap second introduced in UTC at the end of December 2022.

The primary source for IERS Rapid Service/Prediction Center (RS/PC) data products is the official IERS RS/PC website:
https://maia.usno.navy.mil

IERS RS/PC products are also available from:
NASA CDDIS: https://cddis.nasa.gov/archive/products/iers/
NASA CDDIS: ftps://gdc.cddis.eosdis.nasa.gov/products/iers/
IERS Central Bureau: https://datacenter.iers.org/eop.php

Questions about IERS RS/PC products can be emailed to:
eopcp@us.navy.mil

Distribution statement A:
Approved for public release: distribution unlimited.

The contributed observations used in the preparation of this Bulletin are available at <http://www.usno.navy.mil/USNO/earth-orientation/eo-info/general/input-data>. The contributed analysis results are based on data from Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), the Global Positioning System (GPS) satellites, Lunar Laser Ranging (LLR), and meteorological predictions of variations in Atmospheric Angular Momentum (AAM).

COMBINED EARTH ORIENTATION PARAMETERS:

IERS Rapid Service

			MJD	x "	error "	y "	error "	UT1-UTC s	error s
22	7	29	59789	0.28340	.00009	0.41183	.00009	-0.040409	0.000017
22	7	30	59790	0.28464	.00009	0.40945	.00009	-0.039177	0.000016
22	7	31	59791	0.28596	.00009	0.40727	.00009	-0.038173	0.000016
22	8	1	59792	0.28709	.00009	0.40522	.00009	-0.037348	0.000015
22	8	2	59793	0.28787	.00009	0.40321	.00009	-0.036744	0.000016
22	8	3	59794	0.28856	.00009	0.40102	.00009	-0.036265	0.000016
22	8	4	59795	0.28946	.00009	0.39870	.00009	-0.035830	0.000014

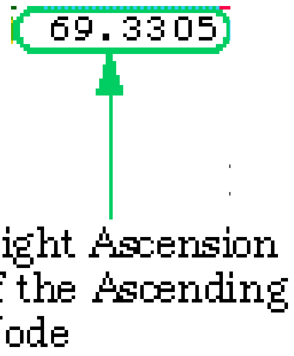
3. Essential Knowledge of Orbit for Satellite Operation

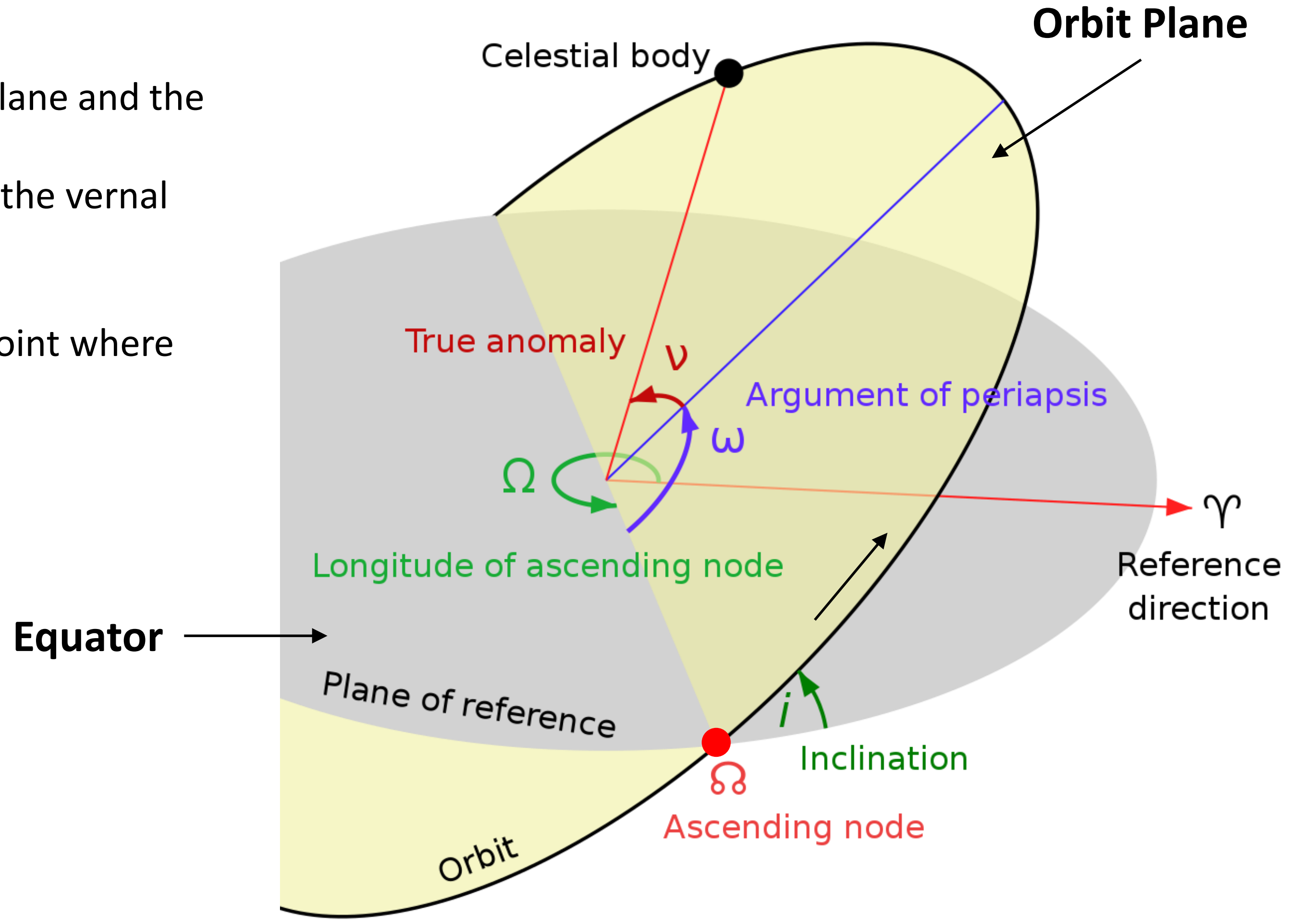
Understanding the “TLE”, RAAN

Right Ascension of the Ascending Node (RAAN) Ω: [degrees]

- Ascending Node = the crossing point between the orbital plane and the Earth's equatorial plane. Ascending means “going north”.
- Right Ascension = the longitude relative to the direction of the vernal equinox.

- The angle between (TEME mean) vernal equinox and the point where the orbit crosses the equatorial plane.





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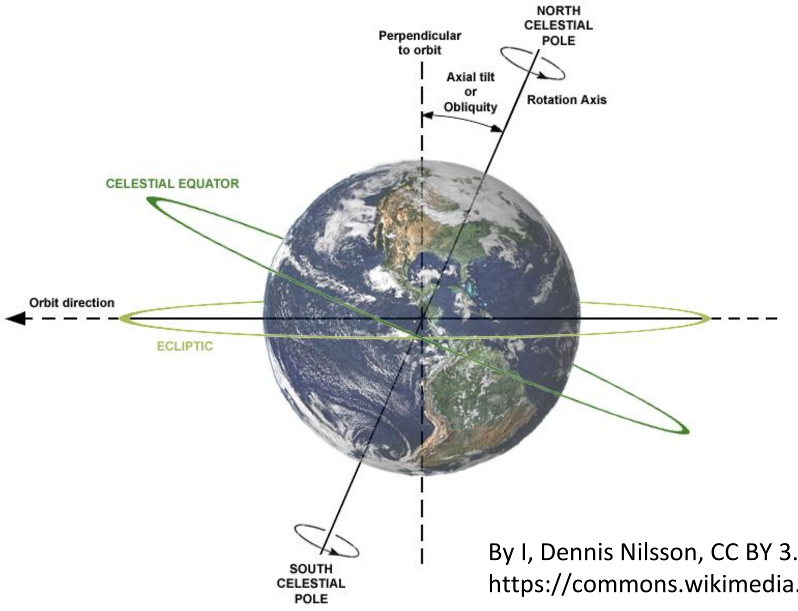
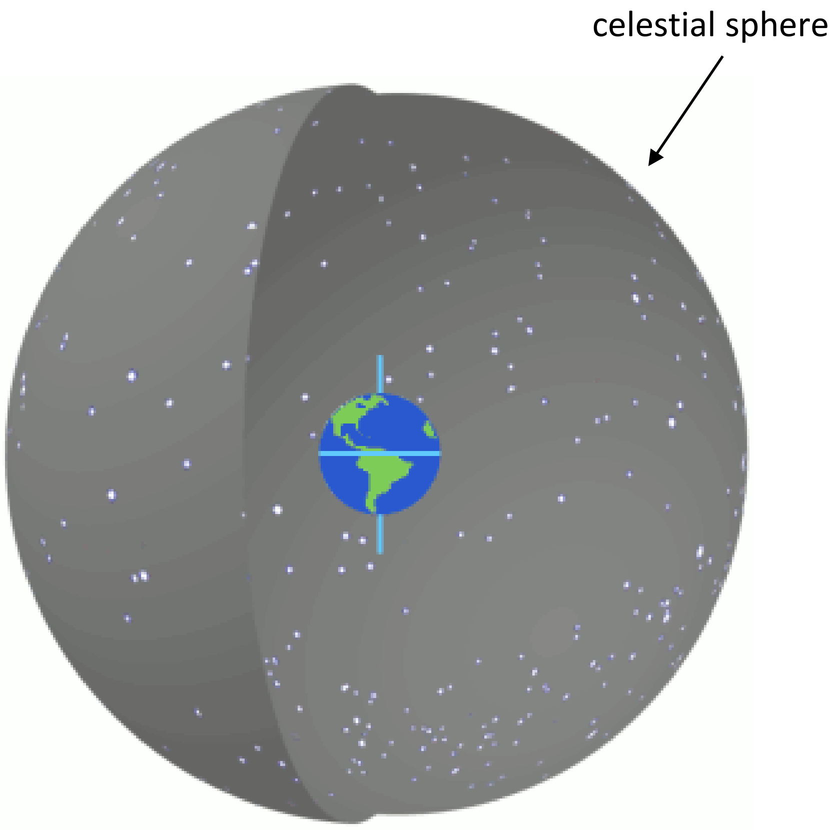
3. Essential Knowledge of Orbit for Satellite Operation

Understanding the “TLE”, Equatorial Coordinate System

- The equatorial coordinate system is a celestial coordinate system used to specify the positions of celestial objects.
  - Fundamental plane (0° latitude) = celestial equator ≈ Earth’s equator
  - Poles = Celestial poles ≈ Earth’s rotation axis
  - Primary direction (0° longitude) = vernal equinox
- When describing the location of an object in this coordinate system, Latitude ⇨ Declination δ, Longitude ⇨ Right ascension α



By I, Dennis Nilsson, CC BY 3.0, https://commons.wikimedia.org/w/index.php?curid=3262268



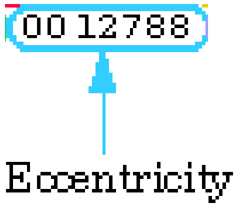
https://commons.wikimedia.org/wiki/File:Ra_and_dec_demo_animation_small.gif#/media/File:Ra_and_dec_demo_animation_small.gif

Understanding the "TLE", Eccentricity

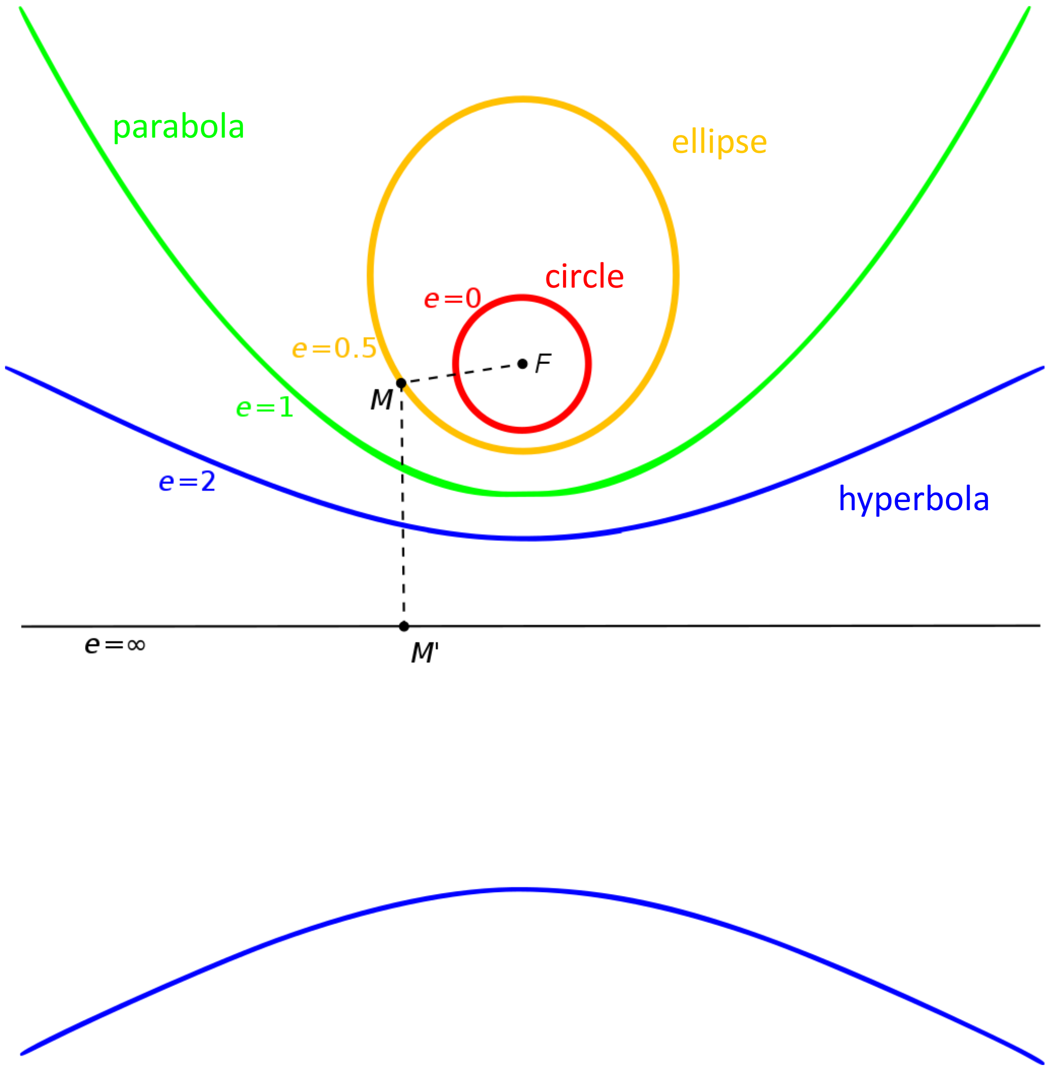
Eccentricity *e*: [-]

- A constant defining the shape of the orbit
  - $e = 0 \cdots$ circle
  - $0 < e < 1 \cdots$ ellipse
  - $e = 1 \cdots$ parabola
  - $e > 1 \cdots$ hyperbola

- When used in a TLE, e is always less than 1.



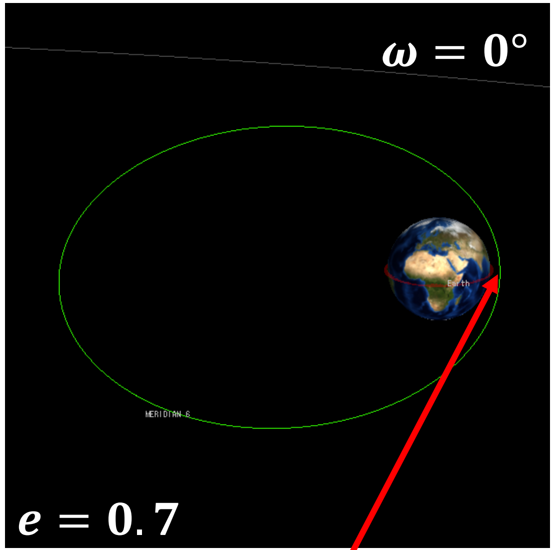
Add a leading decimal point
In this case, 0.001278

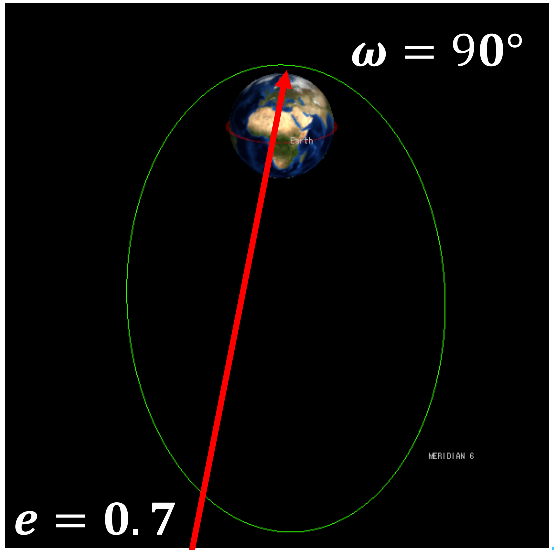


https://commons.wikimedia.org/wiki/File:Eccentricity.svg#/media/File:Eccentricity.svg

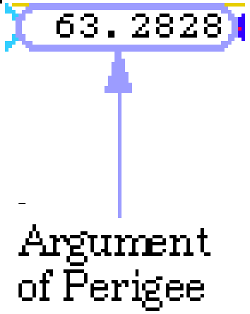
3. Essential Knowledge of Orbit for Satellite Operation

Understanding the “TLE”, Argument of Perigee





https://www.lizard-tail.com/isana/tle/misc/what_is_tle

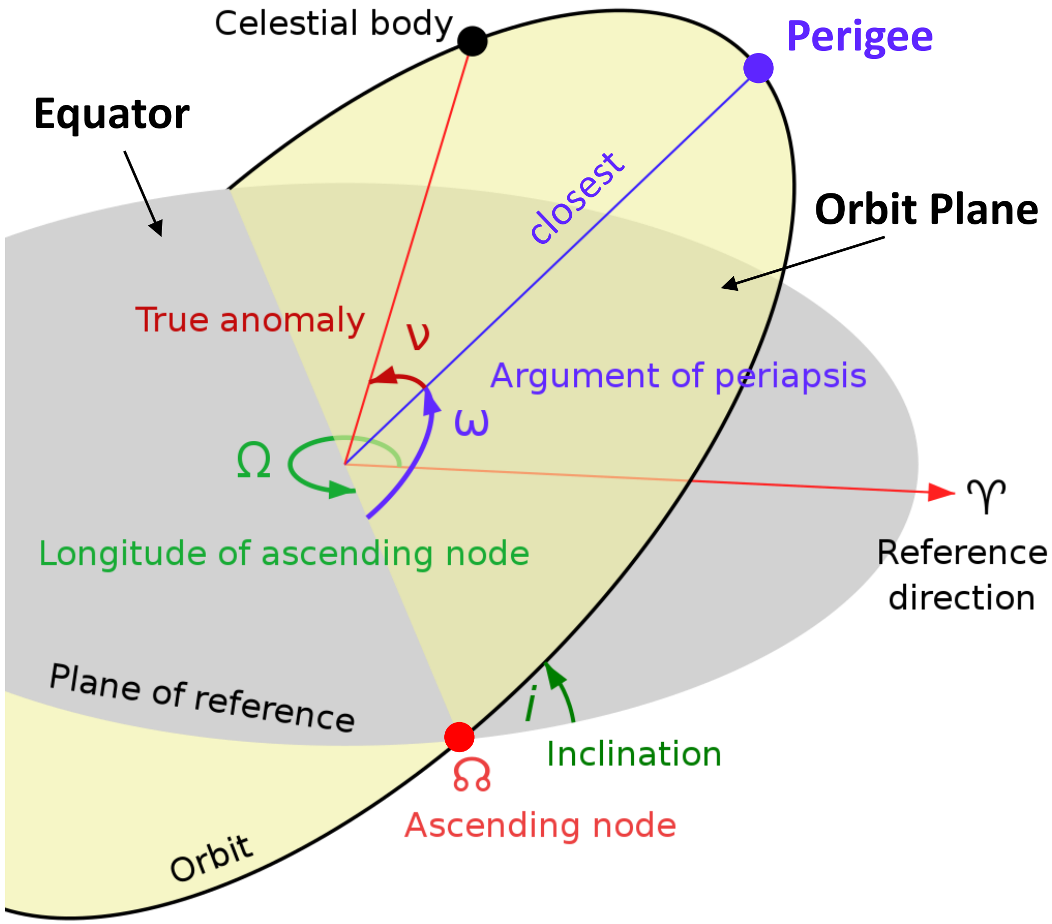


When Argument of perigee is 0, the perigee is at the equator.

When the Argument of perigee is 90 degrees, the phase of the ellipse rotates 90 degrees and shifts to the north pole side.

Argument of Perigee ω: [degrees]

- Perigee is the orbit's point of closest approach to the Earth.
- The angle between the ascending node and the perigee.



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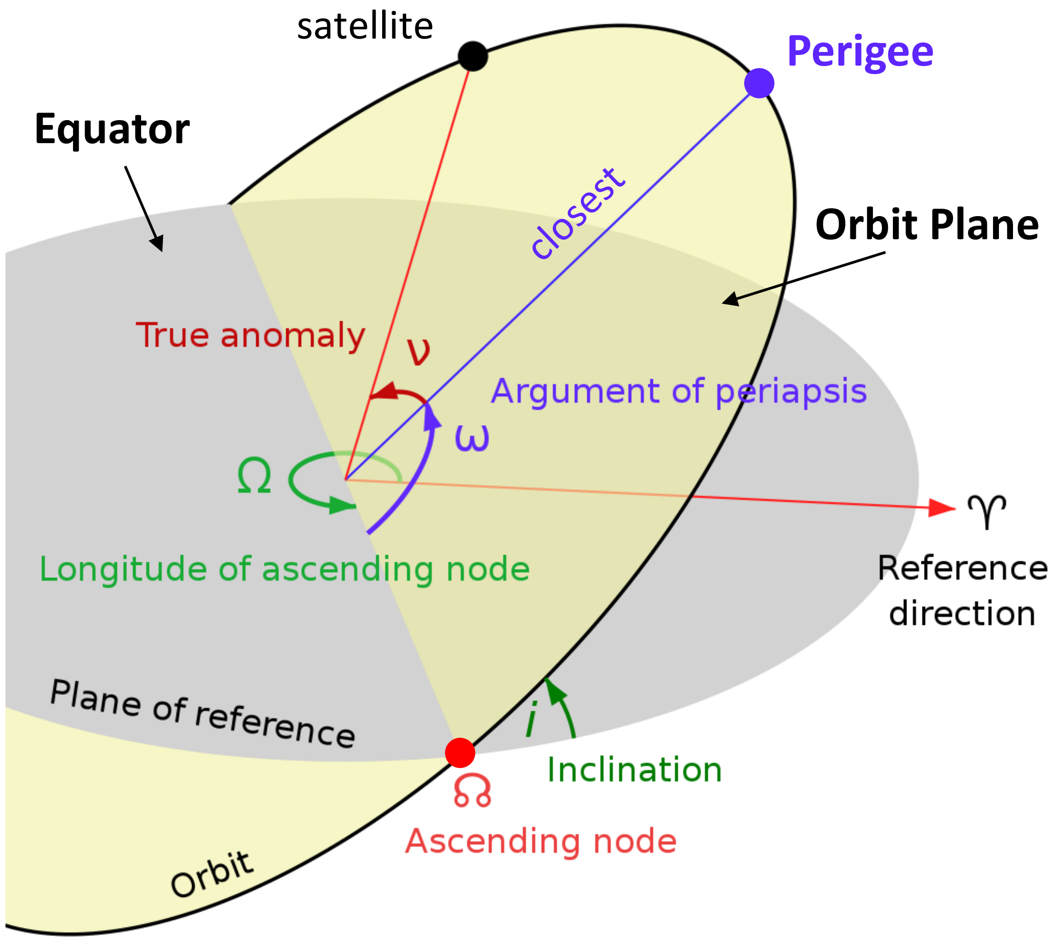
3. Essential Knowledge of Orbit for Satellite Operation

Understanding the “TLE”, Mean Anomaly



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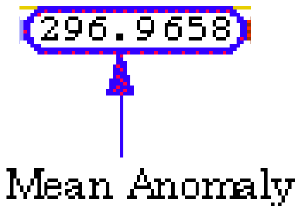
https://commons.wikimedia.org/w/index.php?curid=8971052

- The parameters that have appeared so far were parameters that define the shape of the orbit.
  - These alone do not determine the satellite's position in orbit.
  - ⇨ True Anomaly ν & Mean Anomaly M

- True Anomaly
  - The angle between the direction of perigee and the current position of the satellite, as seen from the main focus of the ellipse.

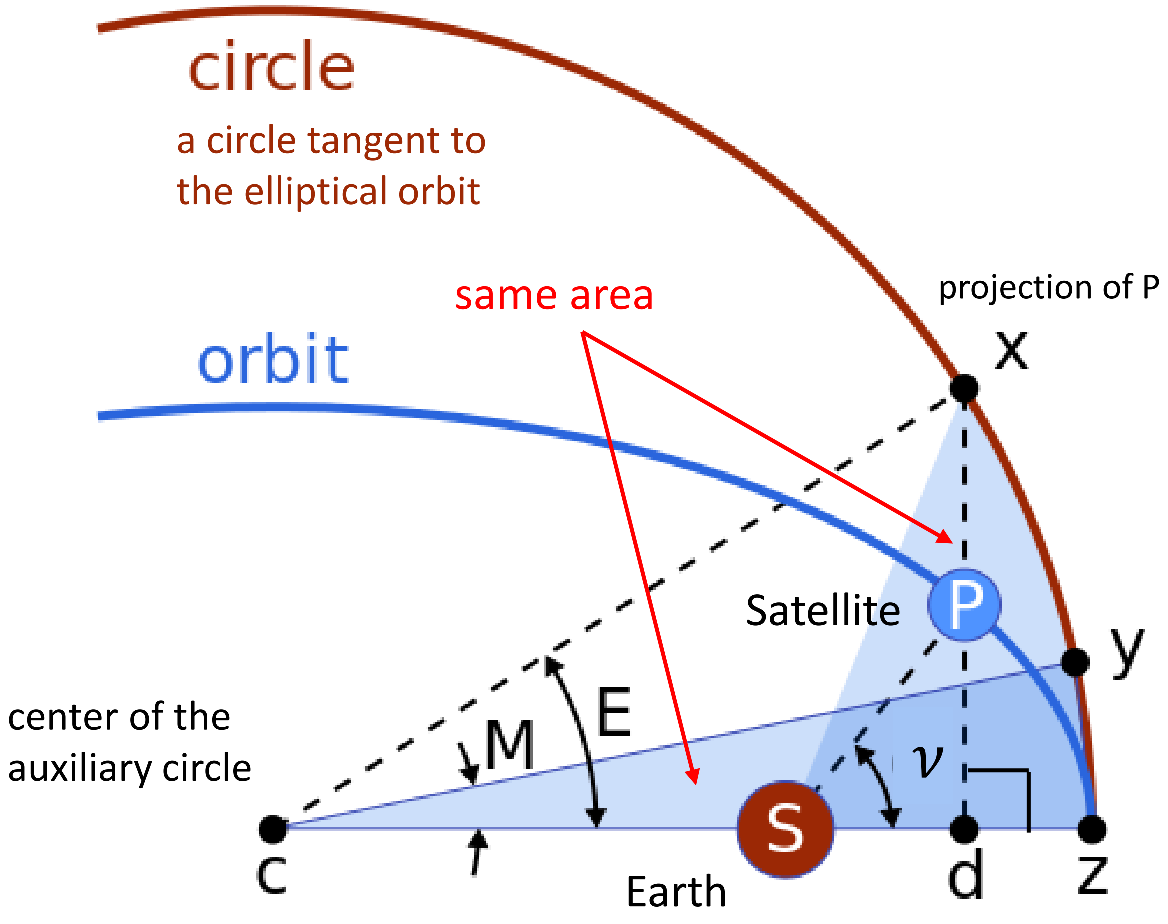


Mean Anomaly M: [degrees]

- The angle, measured from perigee, of the satellite location in the orbit referenced to a circular orbit with radius equal to the semi-major axis.

3. Essential Knowledge of Orbit for Satellite Operation

Understanding the “TLE”, True Anomaly and Mean Anomaly



https://commons.wikimedia.org/wiki/File:Mean_Anomaly.svg#/media/File:Mean_Anomaly.svg

- True Anomaly has a physical entity, but is mathematically harder to handle.
  - use Mean Anomaly M instead.

- The mean anomaly M can be calculated from the eccentric anomaly *E* and the eccentricity *e* with Kepler's Equation:

$$M = E - e \sin E \, .$$

  - e: eccentricity, E: eccentric anomaly

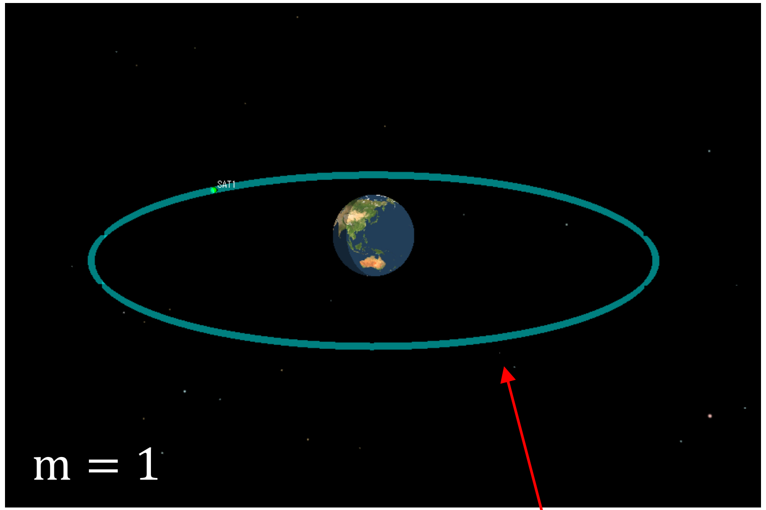
What is the Eccentric anomaly?

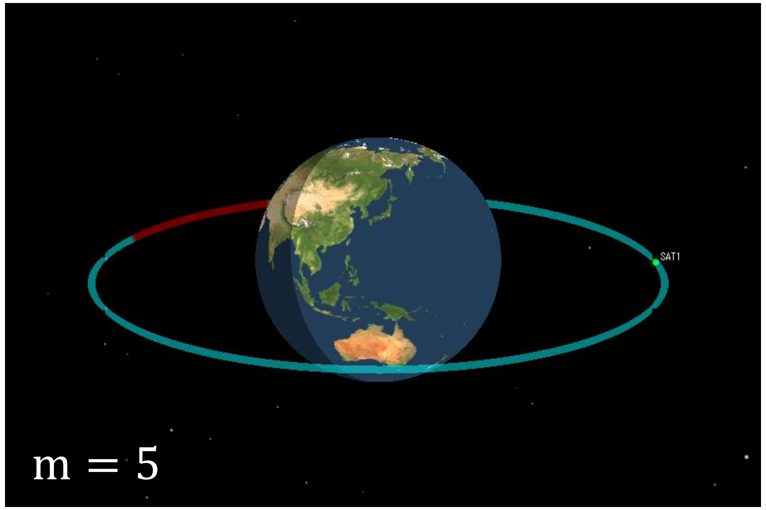
①Create a circle tangent to the elliptical orbit as an auxiliary circle.

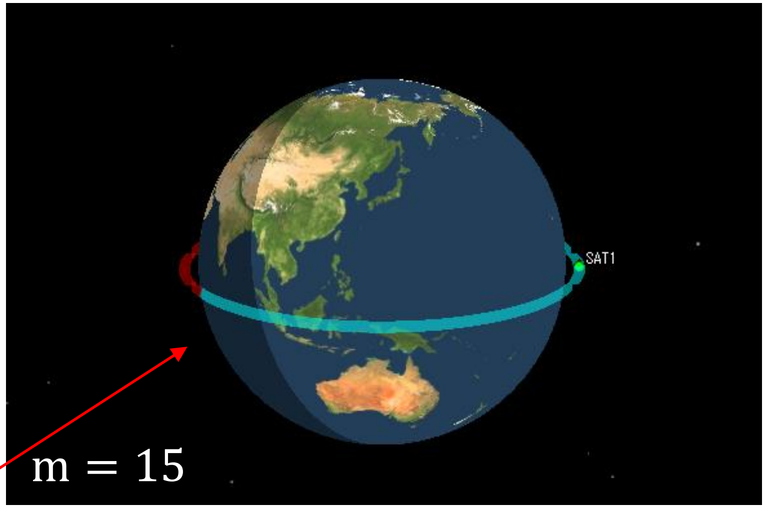
②Let X be the point of projection of satellite P onto its auxiliary circle.

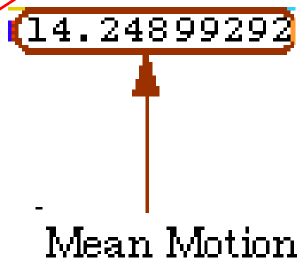
③The angle XCZ at this time is the eccentric anomaly.

Understanding the “TLE”, Mean Motion









When mean motion is 1, the satellite orbits the earth once a day.
This is the same as a geostationary satellite.

The larger the mean motion, the smaller the orbit size.

Mean Motion m: [revs/day]

- The value is the mean number of orbits per day the object completes.

3. Essential Knowledge of Orbit for Satellite Operation

Understanding the “TLE”, SGP4 model

- TLE contains all the information that describes the orbit geometry and satellite position at epoch time
  ⇧ It is not simple to determine it from the position and velocity of the satellite at a particular time, because satellites are affected by a force called perturbation.

- Simplified perturbations models were invented in the 1950s.
  - a set of five mathematical models
  - calculate orbital state vectors of space objects in the Earth-centered inertial (ECI) coordinate system.

- Simplified General Perturbations (SGP) models are for near Earth objects with an orbital period of less than 225 minutes.
- Simplified Deep Space Perturbations (SDP) models are for deep space objects with an orbital period of more than 225 minutes.

- The SGP4 is generally used to calculate satellite orbits with TLE.
  - has an error ~1 km at epoch and grows at ~1-3 km per day.

  ⇧ sufficient accuracy for ground stations to track satellites.

Simplified Perturbations Models

Simplified General Perturbations models

SGP | **SGP4** | SGP8

for near Earth objects with an orbital period of less than 225 minutes (≈ 5,877.5 km circular orbit).

Simplified Deep Space Perturbations models

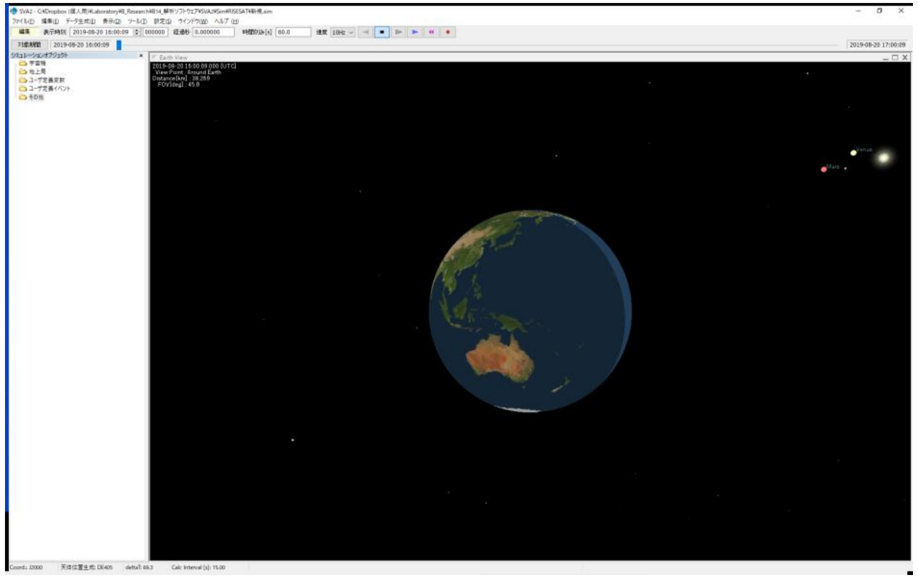
SDP4 | SDP8

for deep space objects with an orbital period of more than 225 minutes (≈ 5,877.5 km circular orbit).
e.g., Geostationary orbit, 12-hour Molniya orbit

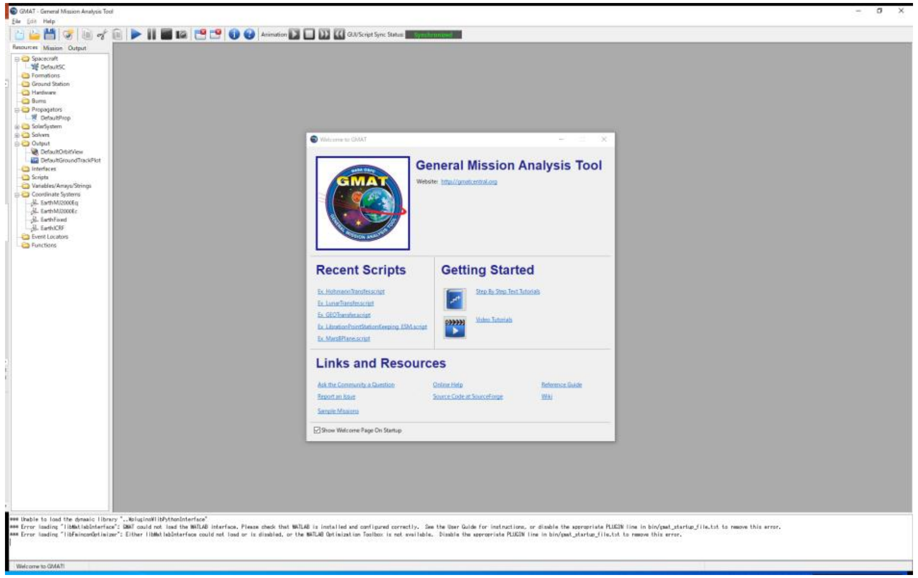
4. Spacecraft Simulations for Operational Analysis and Planning

4. Spacecraft Simulations for Operational Analysis and Planning

Satellite attitude & orbit simulation



SVA2 (Spacecraft Visualization and Analysis tool)
by Spheresoft

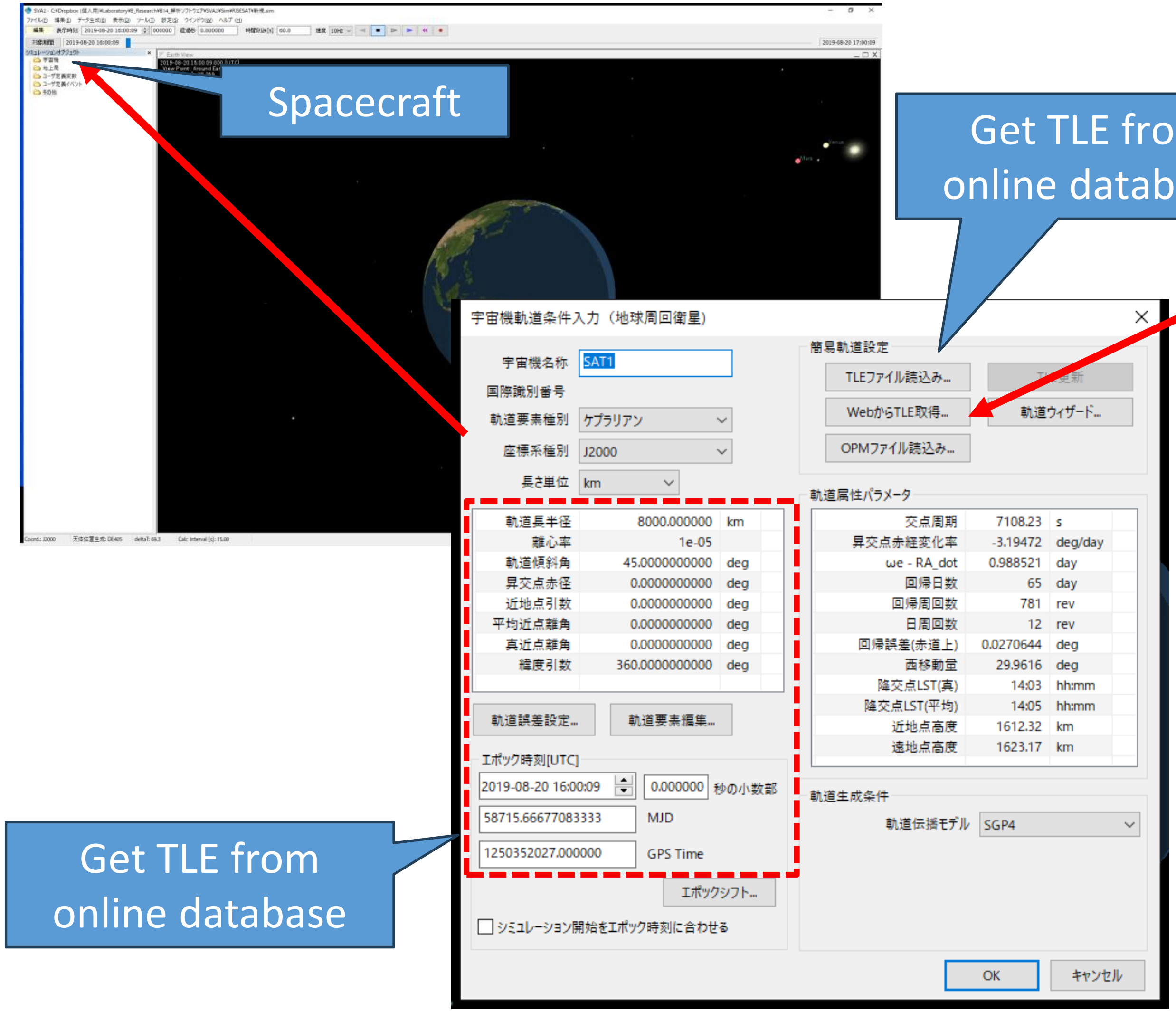


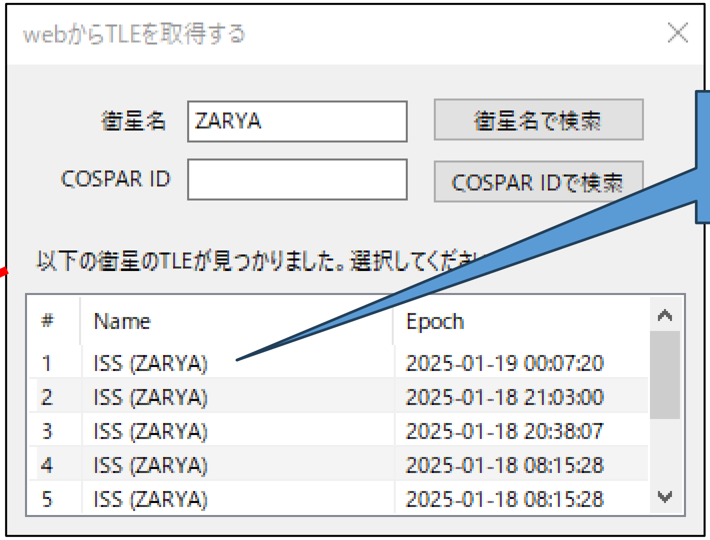
GMAT (General Mission Analysis Tool)
by NASA

- There are several simulation tools in the world. Some are free, and some are commercial, but the basic concept is similar.
- The purpose of this presentation is not to provide a tutorial on the tools, so we will not discuss detailed operating procedures for specific software.

4. Spacecraft Simulations for Operational Analysis and Planning

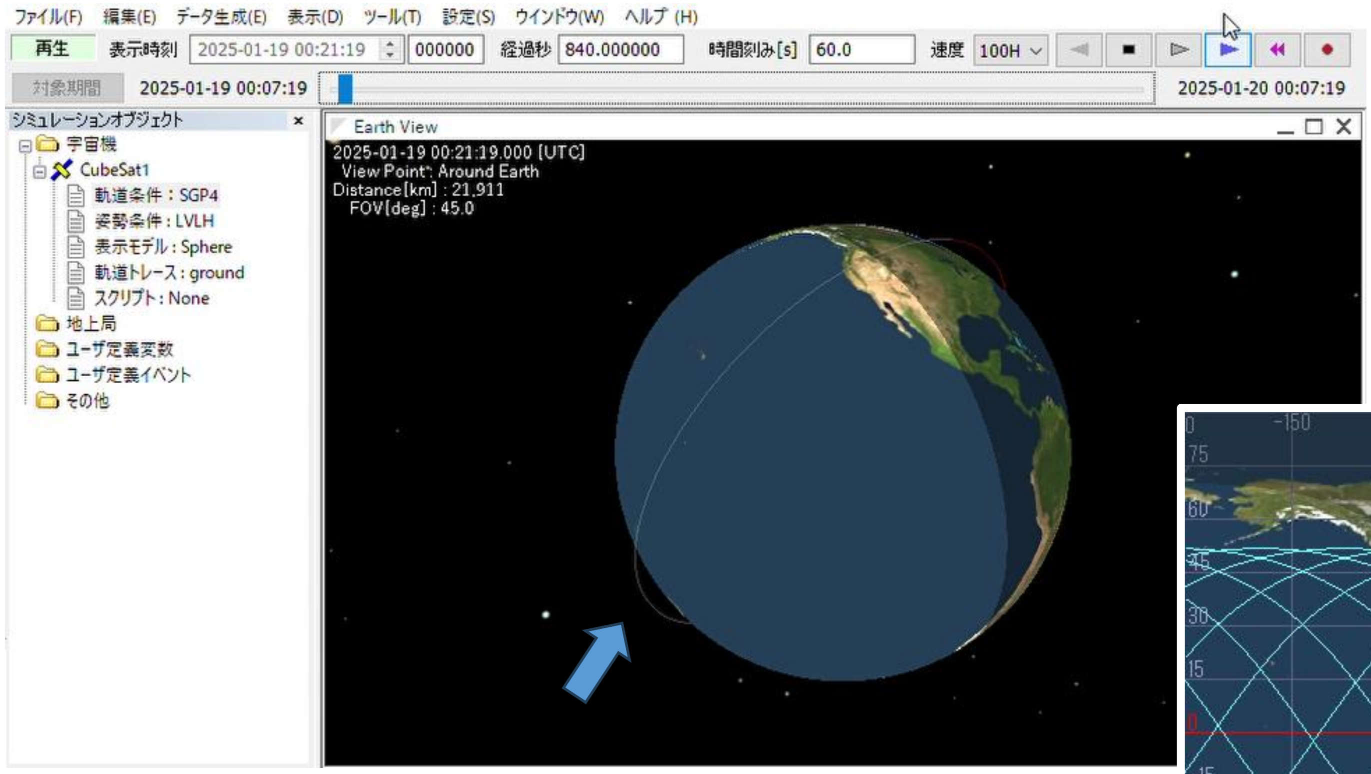
Initial Orbit Setup



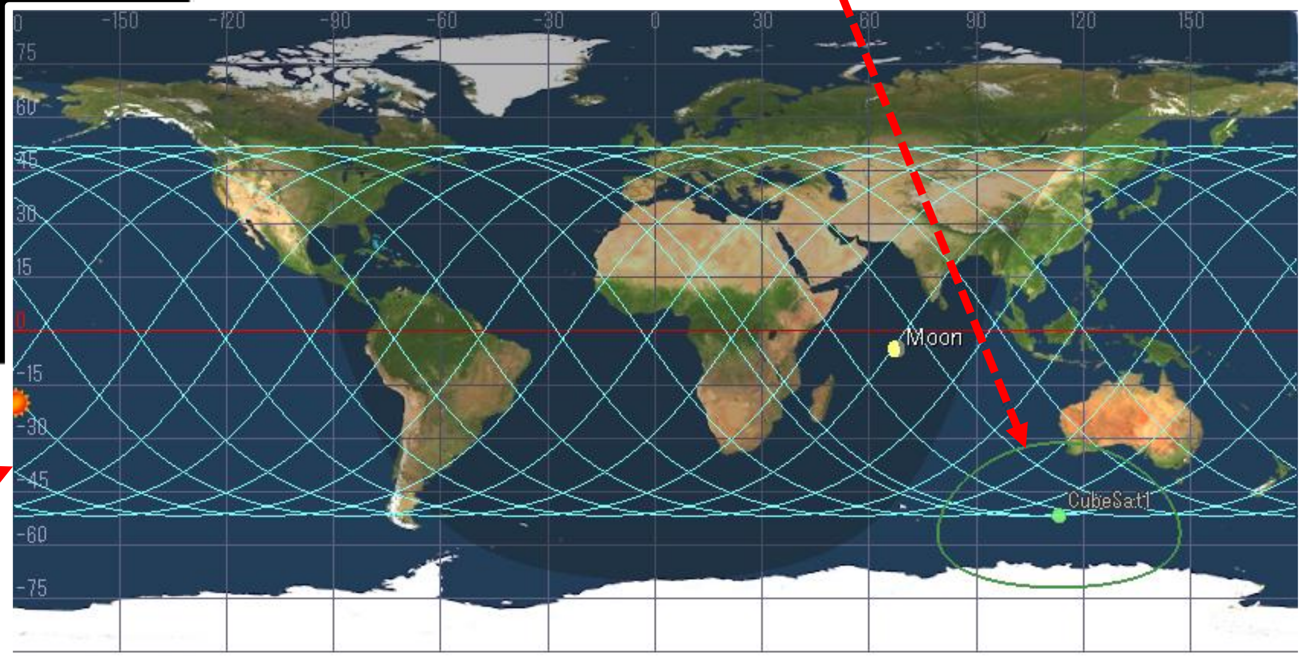


- Analysis cannot begin without information about where and when the satellite will be present.
- If the satellite you want to analyze has already been launched, then the TLE should be registered in the online database described in the previous chapter.
- In the case of a CubeSat released from the ISS, there is also the option of using the ISS's own TLE information as it is to perform a quick analysis.

Initial Orbit Setup



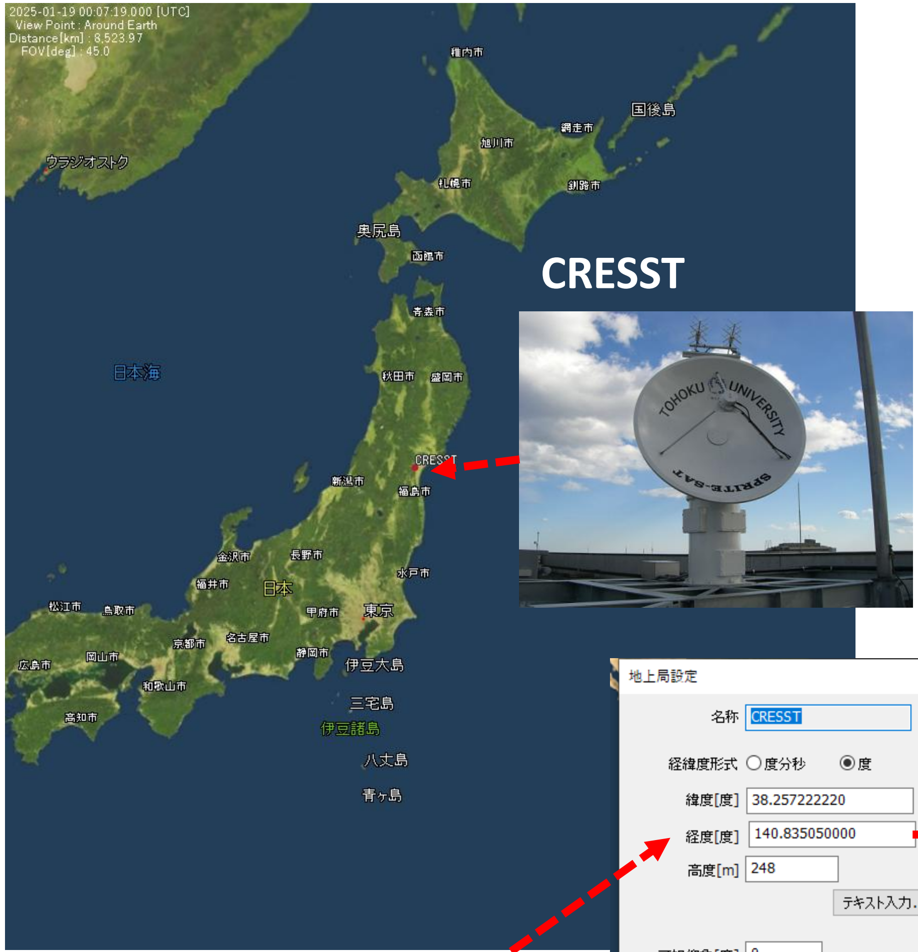
The area on the ground that is visible from the satellite. ⇔ Communication is possible if there is a ground station within this range.



One-day orbits projected onto a world map

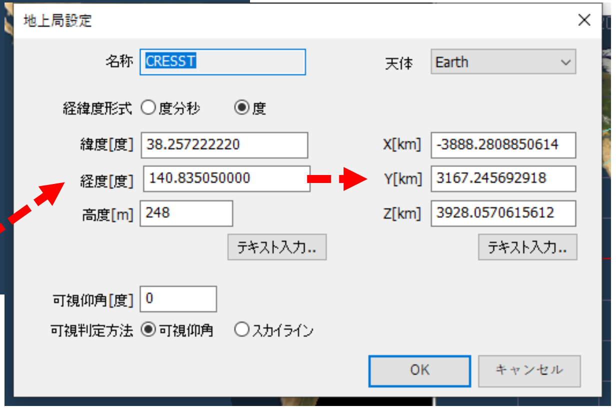
4. Spacecraft Simulations for Operational Analysis and Planning

Orbit propagation and forecast of satellite passes



CRESST

© Tohoku University

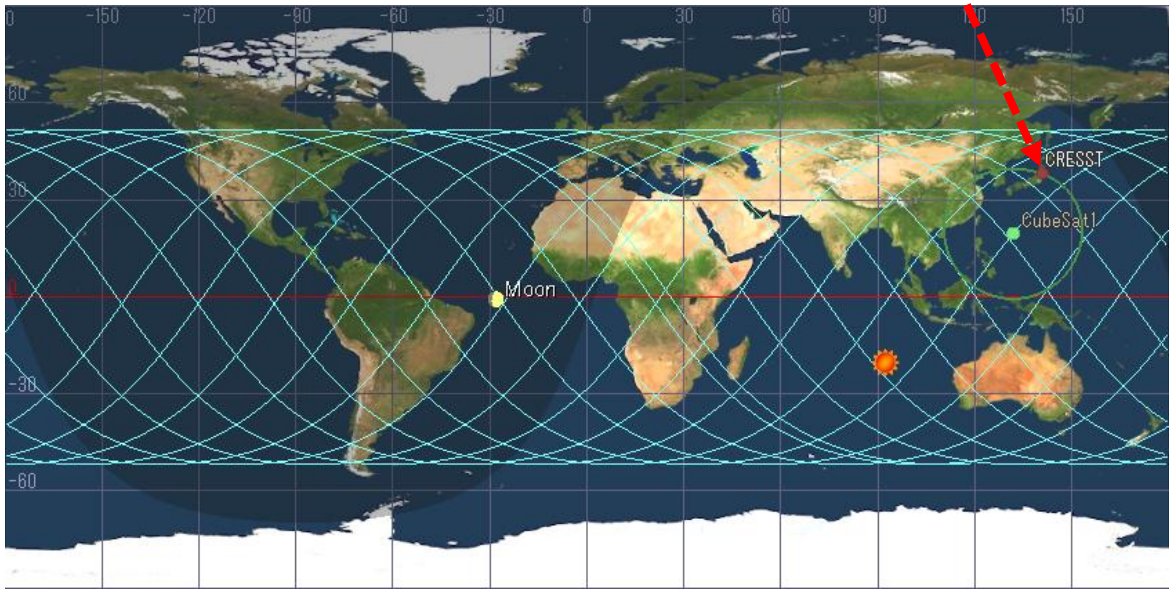


Use geodetic coordinate system

The visible passes for one day

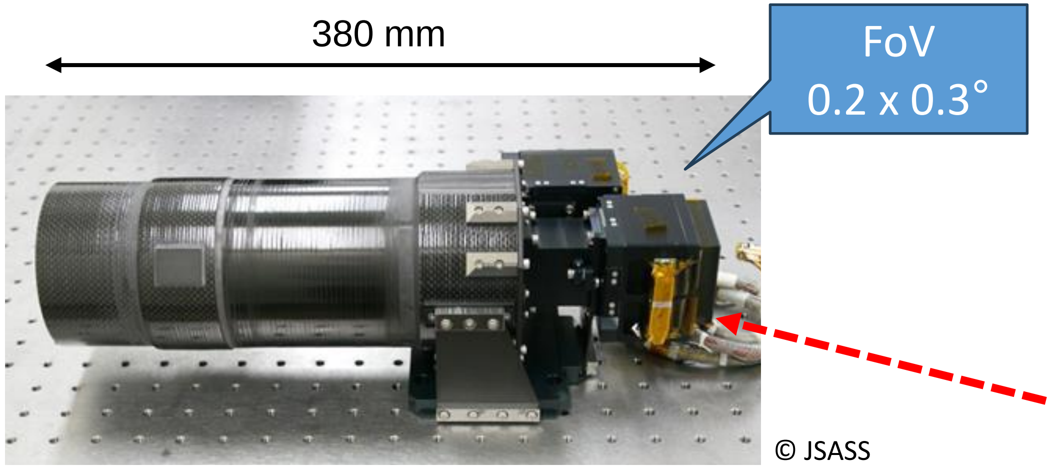
Stn	Sat	pass	Type	Start	End	Period[s]	AZ1[deg]	EL1[deg]	Range1[km]
CRESST	CubeSat1	4	EL>0.0	2025-01-19 06:01:36	2025-01-19 06:11:55	619	-154.6	0.0	2334.7
CRESST	CubeSat1	5	EL>0.0	2025-01-19 07:38:11	2025-01-19 07:48:41	630	-106.4	-0.1	2349.6
CRESST	CubeSat1	6	EL>0.0	2025-01-19 09:16:39	2025-01-19 09:25:23	524	-65.9	-0.0	2352.7
CRESST	CubeSat1	7	EL>0.0	2025-01-19 10:54:46	2025-01-19 11:03:20	515	-43.5	-0.0	2358.5
CRESST	CubeSat1	8	EL>0.0	2025-01-19 12:31:34	2025-01-19 12:41:53	619	-43.4	-0.0	2355.8
CRESST	CubeSat1	9	EL>0.0	2025-01-19 14:08:15	2025-01-19 14:18:47	632	-57.8	-0.0	2352.0
CRESST	CubeSat1	10	EL>0.0	2025-01-19 15:47:39	2025-01-19 15:51:12	213	-101.9	0.0	2342.4

This path is not suitable for operation because the satellite passes just above the horizon.



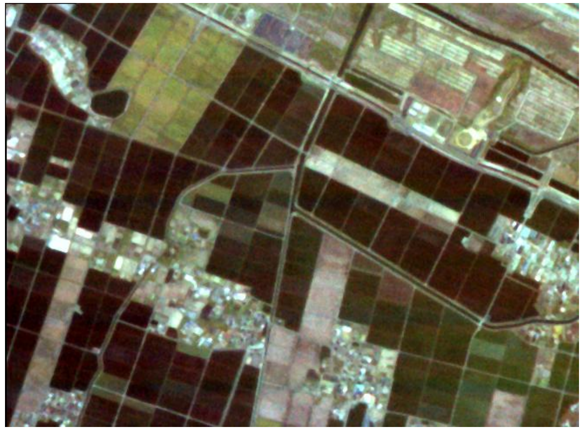
4. Spacecraft Simulations for Operational Analysis and Planning

Simulation of observation instruments



© JSASS

HPT : High Precision Telescope (RISESAT)



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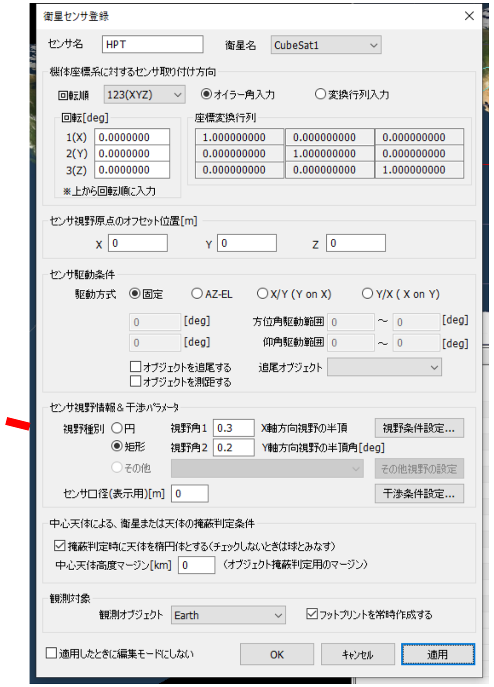
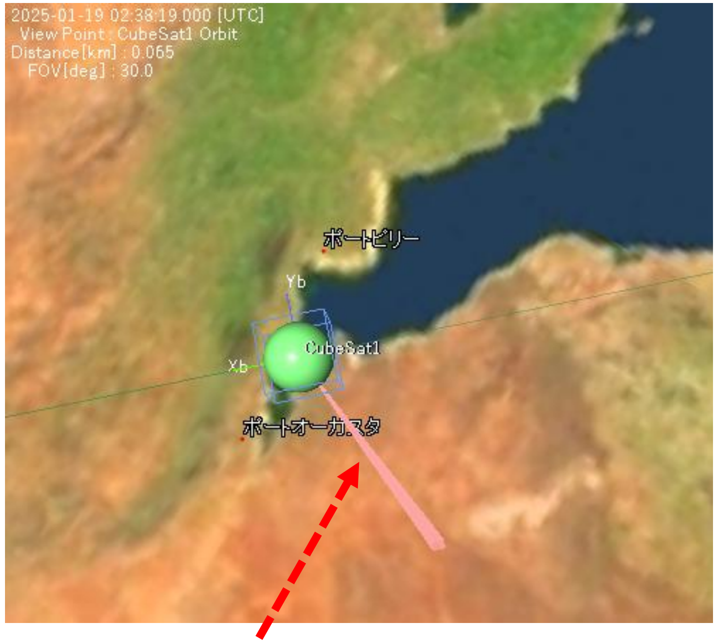
RISESAT HPT's First Light Image
Suburb of Sendai (2019/5/30), True Color Composite



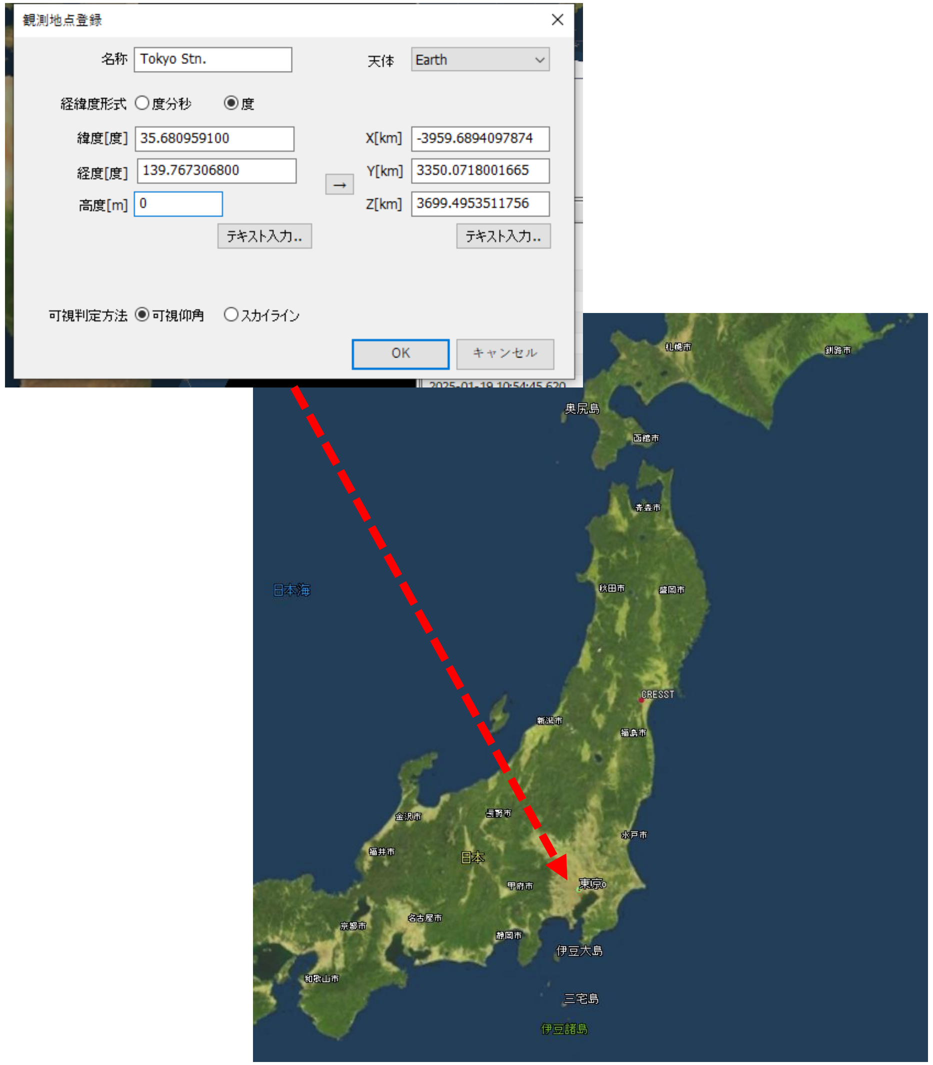


FoV of the HPT

- Some analysis software can register the field of view of the observation instrument and alignment information to the satellite, and have the software calculate the area visible from the sensor.
- With such a tool, it is possible to confirm in advance that the target attitude setting is correct, allowing for more efficient operation.

4. Spacecraft Simulations for Operational Analysis and Planning

Simulation of observation instruments

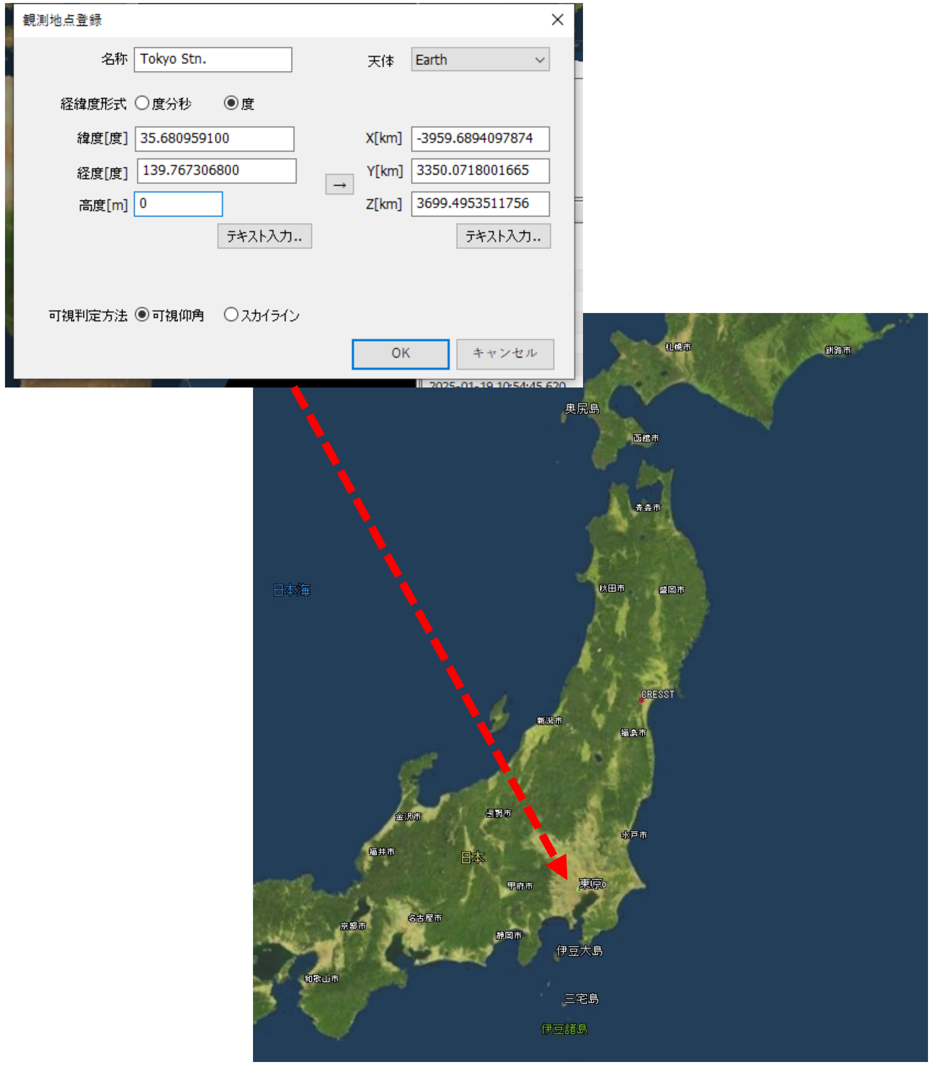


Stn	Sat	pass	Type	Start	End	Period[s]	AZ1[deg]	EL1[deg]	Range1[km]	A
Tokyo	CubeSat1	4	EL>0.0	2025-01-19 06:00:51	2025-01-19 06:11:21	630	-151.9	-0.1	2344.2	
Tokyo	CubeSat1	4	MaxEL	2025-01-19 06:06:05	-	-	132.8	33.6	707.6	
Tokyo	CubeSat1	5	EL>0.0	2025-01-19 07:37:46	2025-01-19 07:47:59	612	-102.4	-0.0	2348.9	
Tokyo	CubeSat1	5	MaxEL	2025-01-19 07:42:51	-	-	-32.1	22.6	943.7	
Tokyo	CubeSat1	6	EL>0.0	2025-01-19 09:16:49	2025-01-19 09:24:26	457	-57.9	0.0	2346.6	
Tokyo	CubeSat1	6	MaxEL	2025-01-19 09:20:37	-	-	-12.9	6.4	1744.3	
Tokyo	CubeSat1	7	EL>0.0	2025-01-19 10:55:20	2025-01-19 11:02:31	431	-33.4	0.0	2351.3	
Tokyo	CubeSat1	7	MaxEL	2025-01-19 10:58:55	-	-	8.3	5.4	1828.0	
Tokyo	CubeSat1	8	EL>0.0	2025-01-19 12:32:00	2025-01-19 12:41:43	583	-35.9	-0.0	2355.4	
Tokyo	CubeSat1	8	MaxEL	2025-01-19 12:36:52	-	-	28.3	16.4	1159.4	
Tokyo	CubeSat1	9	EL>0.0	2025-01-19 14:08:27	2025-01-19 14:19:13	646	-51.8	0.0	2349.8	
Tokyo	CubeSat1	9	MaxEL	2025-01-19 14:13:51	-	-	-134.7	59.6	478.3	
Tokyo	CubeSat1	10	EL>0.0	2025-01-19 15:46:58	2025-01-19 15:52:50	352	-89.2	0.0	2343.0	
Tokyo	CubeSat1	10	MaxEL	2025-01-19 15:49:54	-	-	-122.3	3.5	1985.1	

The distance between the satellite and Tokyo Station is minimum (487.3 km).

- In order to obtain higher resolution pictures, it is necessary to take pictures when the satellite and the target point are closest to each other.

Simulation of observation instruments



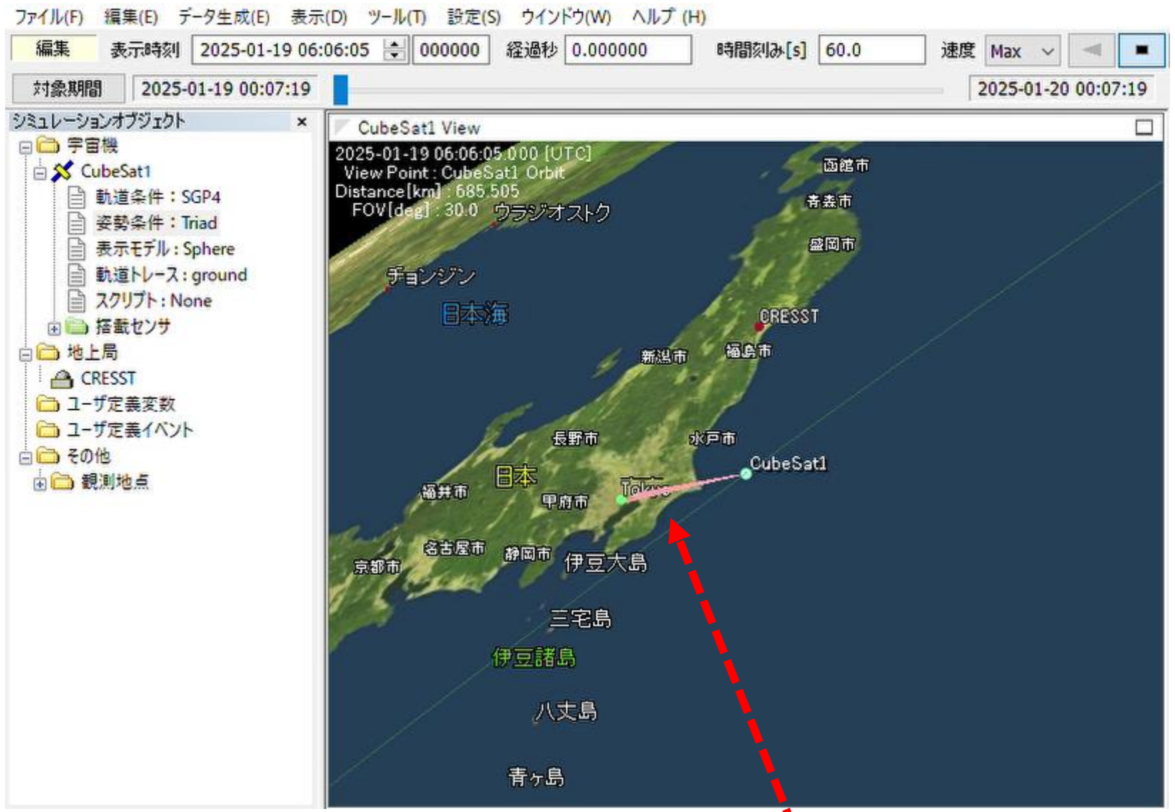
Stn	Sat	pass	Type	Start	End	Period[s]	AZ1[deg]	EL1[deg]	Range1[km]	A
Tokyo	CubeSat1	4	EL>0.0	2025-01-19 06:00:51	2025-01-19 06:11:21	630	-151.9	-0.1	2344.2	
Tokyo	CubeSat1	4	MaxEL	2025-01-19 06:06:05	-	-	132.8	33.6	707.6	
Tokyo	CubeSat1	5	EL>0.0	2025-01-19 07:37:46	2025-01-19 07:47:59	612	-102.4	-0.0	2348.9	
Tokyo	CubeSat1	5	MaxEL	2025-01-19 07:42:51	-	-	-32.1	22.6	943.7	
Tokyo	CubeSat1	6	EL>0.0	2025-01-19 09:16:49	2025-01-19 09:24:26	457	-57.9	0.0	2346.6	
Tokyo	CubeSat1	6	MaxEL	2025-01-19 09:20:37	-	-	-12.9	6.4	1744.3	
Tokyo	CubeSat1	7	EL>0.0	2025-01-19 10:55:20	2025-01-19 11:02:31	431	-33.4	0.0	2351.3	
Tokyo	CubeSat1	7	MaxEL	2025-01-19 10:58:55	-	-	8.3	5.4	1828.0	
Tokyo	CubeSat1	8	EL>0.0	2025-01-19 12:32:00	2025-01-19 12:41:43	583	-35.9	-0.0	2355.4	
Tokyo	CubeSat1	8	MaxEL	2025-01-19 12:36:52	-	-	28.3	16.4	1159.4	
Tokyo	CubeSat1	9	EL>0.0	2025-01-19 14:08:27	2025-01-19 14:19:13	646	-51.8	0.0	2349.8	
Tokyo	CubeSat1	9	MaxEL	2025-01-19 14:13:51	-	-	-134.7	59.6	478.3	
Tokyo	CubeSat1	10	EL>0.0	2025-01-19 15:46:58	2025-01-19 15:52:50	352	-89.2	0.0	2343.0	
Tokyo	CubeSat1	10	MaxEL	2025-01-19 15:49:54	-	-	-122.3	3.5	1985.1	

The satellite-target distance is smallest during the daytime. (707.6 km).

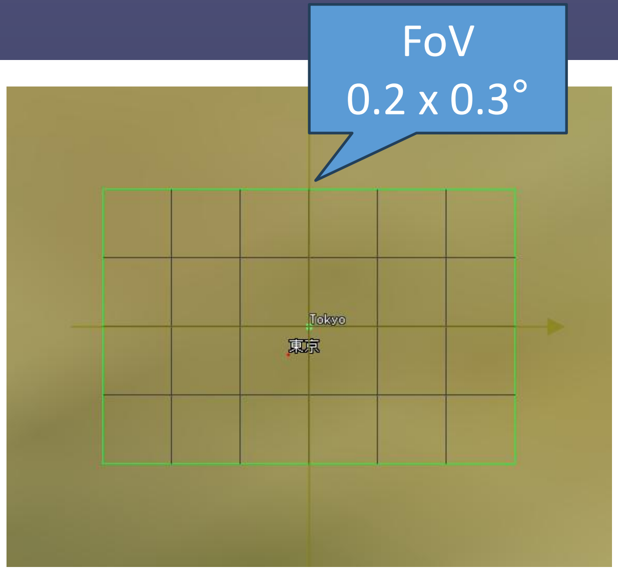
- Weather conditions must also be checked when observing the earth with optical instruments.
- While orbital calculations can be accurate enough, weather forecasts are not, so planning observations a week or two ahead can be difficult.

4. Spacecraft Simulations for Operational Analysis and Planning

Utilization of different types of visualizations



This represents the telescope's field of view.



Target location from the viewpoint of the observation instrument.

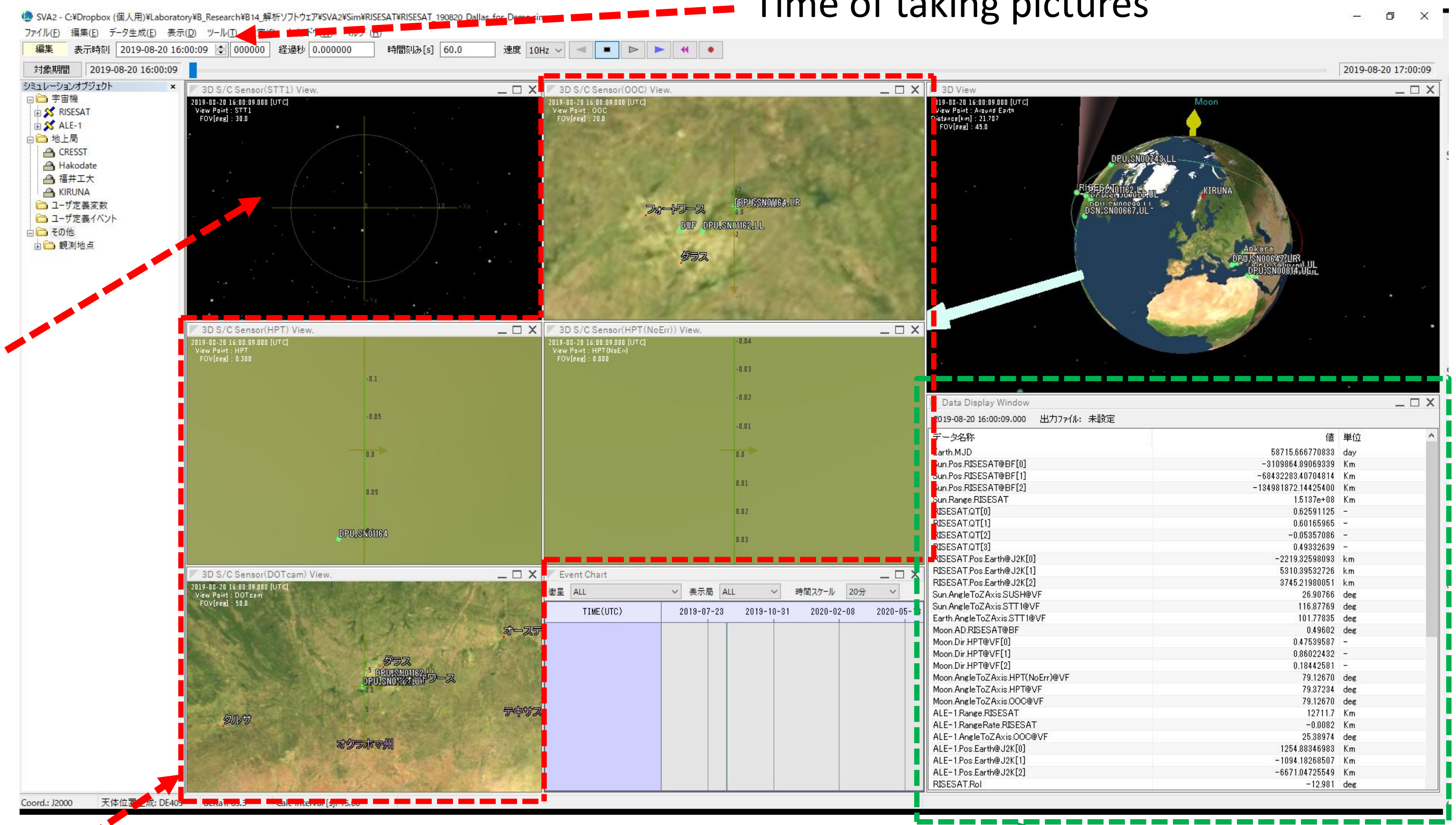
- Although the distance seems close at 707 km, the elevation angle from the target point is only 33° ⇨ capturing the image from a very steep angle.
- Such distorted observations may not satisfy the science requirement.
- It is important for the operator to understand well in advance not only the orbit and attitude, but also what kind of observations will be required and for what purpose.

4. Spacecraft Simulations for Operational Analysis and Planning

Observation planning: On-ground target

Time of taking pictures

FoV of a star tracker

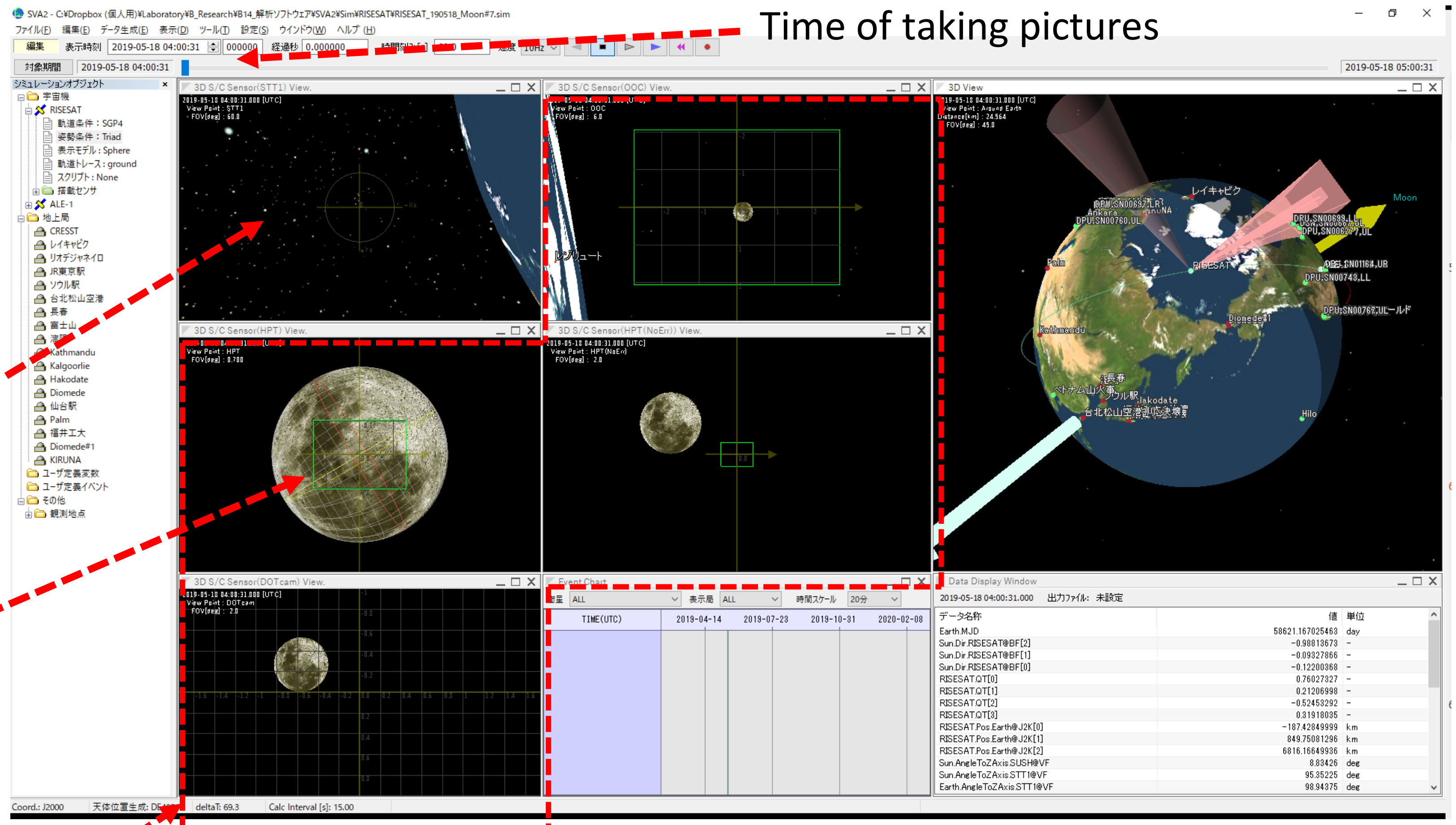


FoV of multiple observation instruments

Calculation results for various parameters

4. Spacecraft Simulations for Operational Analysis and Planning

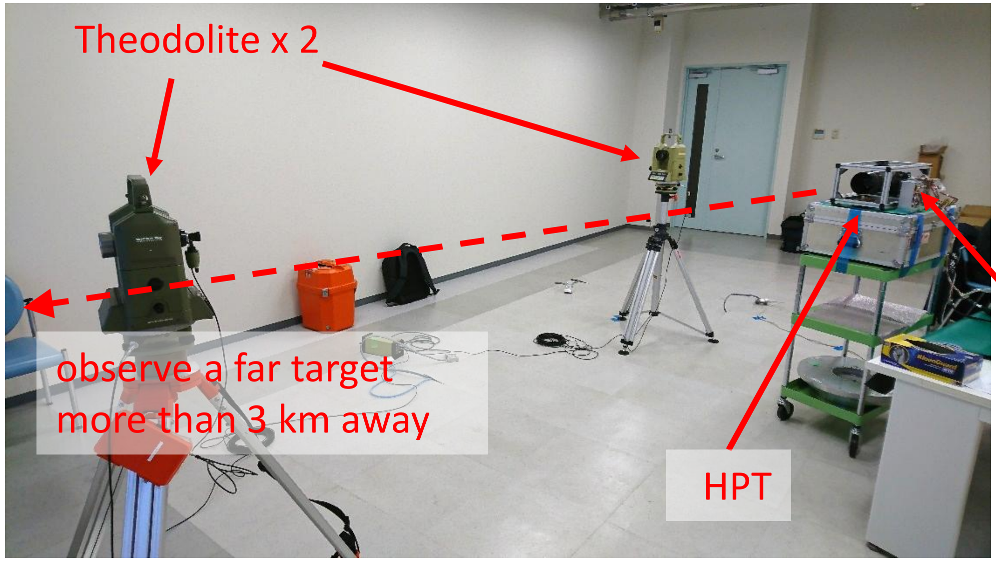
Observation planning: Celestial body



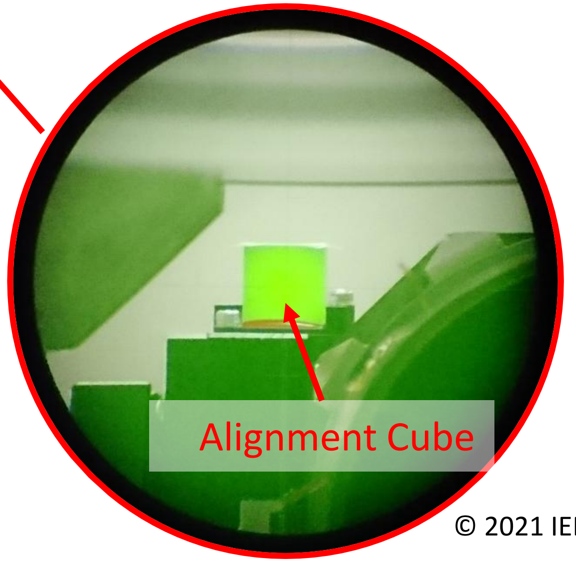
5. On-orbit Calibration of a Camera Alignment

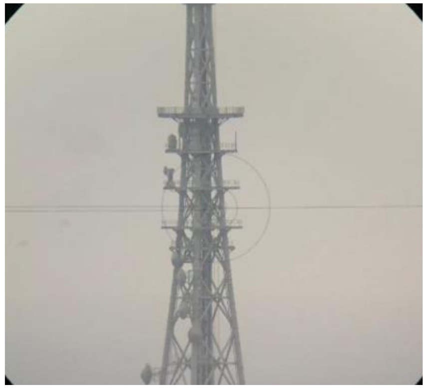
5. On-orbit Calibration of a Camera Alignment

Conventional Alignment Measurement: On Ground Inspection



- Field of View (FoV) of the HPT is narrow (0.5°)
  ⇨ The alignment error when mounting the instrument on the satellite structure has a significant influence on the pointing accuracy.
- Conventional method: Using theodolites and alignment cubes.
- We cannot measure alignment change during the rocket launch, ⇨ measurement accuracy is limited to about 0.01°.





FoV of the Theodolite

FoV of the HPT

Put an Alignment Cube on the HPT

5. On-orbit Calibration of a Camera Alignment

On-orbit Calibration Method

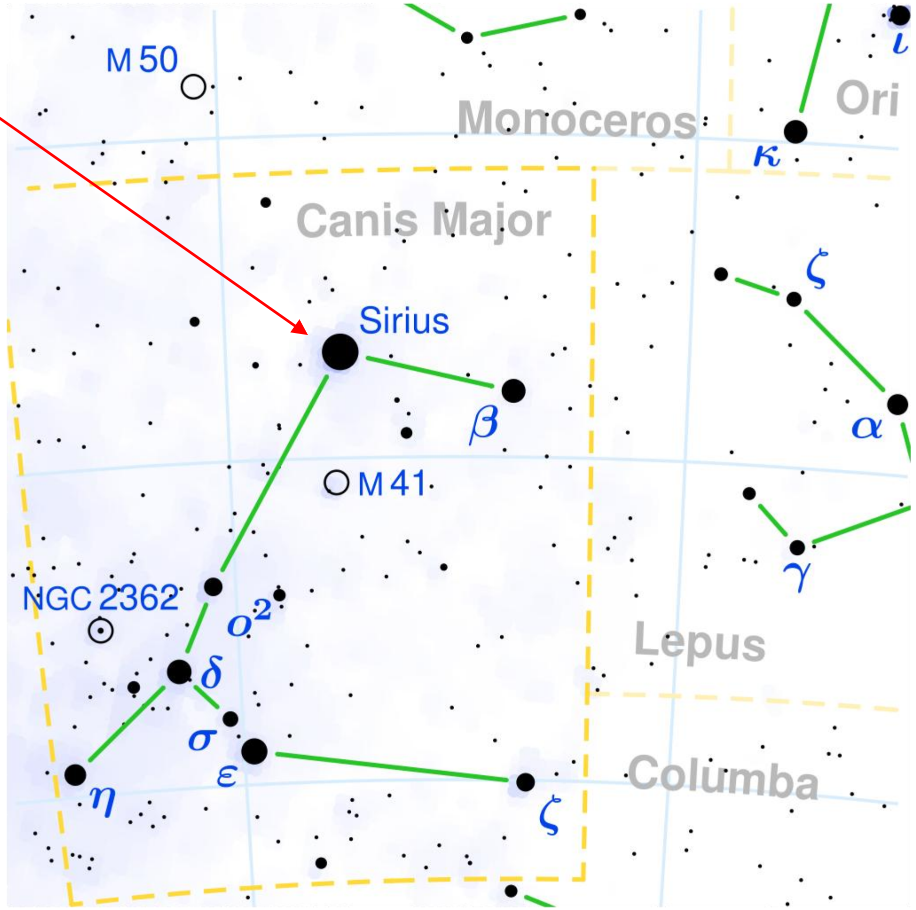
- Use stars for a reference target (e.g. Sirius A in Canis Major)

Advantages

- The small angular diameter makes it possible to capture the whole figure even with a high-resolution telescope.
  ⇨ Easy & accurate image processing

- Since there is no waxing and waning, the timing of observations can be set without being affected by the moon phase.
- Since there are 21 first-magnitude stars in the entire sky, a star in a suitable direction can be selected.
  ⇨ Wider opportunity for observation

- Combine with the **"QUEST"** method, we can estimate a three-axis alignment error angle.
  ⇨ Provide geometrically correct estimation



By Canis_major_constellation_map.png: Torsten Bronger.derivative work: Kxx (talk) - Canis_major_constellation_map.png, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=10827753

5. On-orbit Calibration of a Camera Alignment

Estimating Alignment using QUEST method

$\boldsymbol{C}_{\mathrm{b}}^{\mathrm{cam}} \in \mathrm{SO}(3)$
a camera alignment matrix

$\boldsymbol{C}_{\mathrm{i}}^{\mathrm{b}} \in \mathrm{SO}(3)$
a satellite attitude matrix

$$\boldsymbol{s}_{\mathrm{cam}} = \boldsymbol{C}_{\mathrm{b}}^{\mathrm{cam}} \boldsymbol{s}_{\mathrm{b}} = \boldsymbol{C}_{\mathrm{b}}^{\mathrm{cam}} \boldsymbol{C}_{\mathrm{i}}^{\mathrm{b}} \ \boldsymbol{s}_{\mathrm{i}}$$

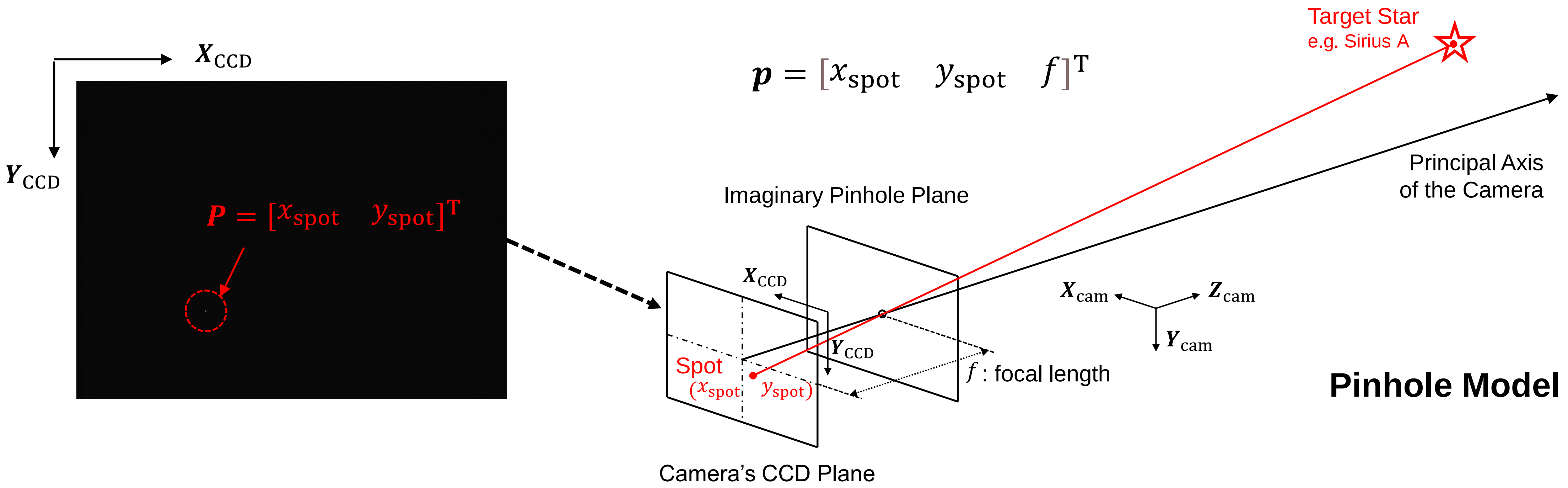
$\boldsymbol{s}_{\mathrm{cam}} \in \boldsymbol{S}^2$
a reference star vector in the camera coordinate

$\boldsymbol{s}_{\mathrm{b}} \in \boldsymbol{S}^2$
a reference star vector in the body coordinate

$\boldsymbol{s}_{\mathrm{i}} \in \boldsymbol{S}^2$
a reference star vector in the inertial coordinate

- **Step1: Observe a star (or stars) and take multiple images.**
  - Theoretically, more than two images are required.
  - Calculate observed star vectors in the camera coordinate from each of the images.
- **Step2: Run QUEST method to analyze the alignment matrix.**
  - Prepare corresponding reference star vectors in the body coordinate.
  - QUEST calculates the optimal alignment matrix in a maximum likelihood manner.

Step1: Get Observed Star Vectors

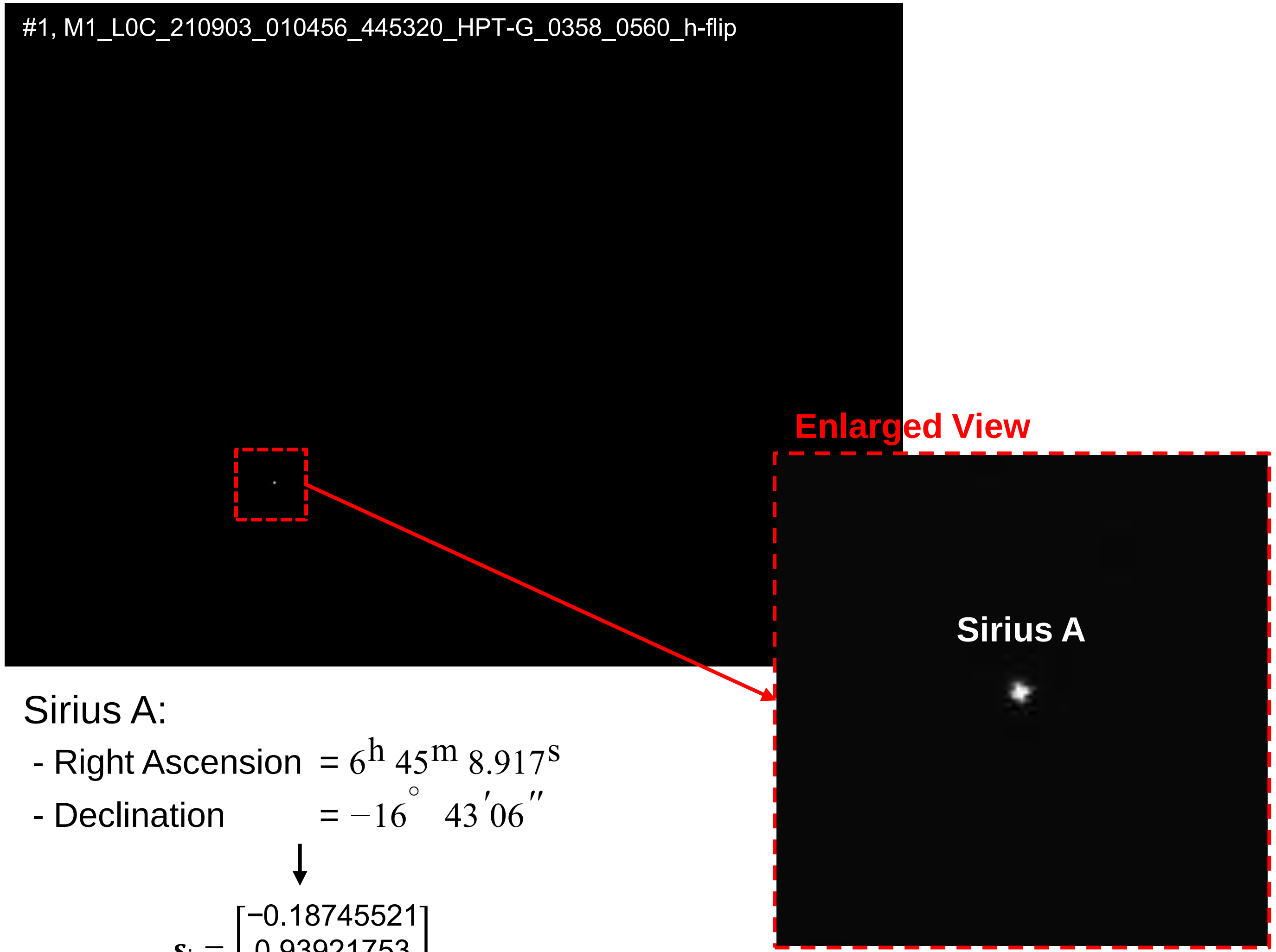


- Use an ideal pinhole camera model ⇦ Simple camera model without distortions.
- When we have $\boldsymbol{P} \in \mathbb{R}^2$ as a two-dimensional position vector on image sensor plane, $\boldsymbol{p} = [x_{spot} \quad y_{spot} \quad f]^T$.
- After normalization, we can get a star direction vector.

$$\boldsymbol{s}_{cam} = \frac{\boldsymbol{p}}{\|\boldsymbol{p}\|}$$

5. On-orbit Calibration of a Camera Alignment

Calibration Result



Sirius A:

- Right Ascension $= 6^{h}\ 45^{m}\ 8.917^{s}$
- Declination $= -16^{\circ}\ 43'06''$

↓

$$s_i = \begin{bmatrix} -0.18745521 \\ 0.93921753 \\ -0.28762993 \end{bmatrix}$$

⇩ 7 images of Sirius A are captured

#	Capture UTC	Results
1	2021/9/3 01:04:57	Success
2	2021/9/3 01:05:12	Success
3	2021/9/3 01:05:42	Fail
4	2021/9/3 01:06:12	Fail
5	2021/9/3 01:06:42	Fail
6	2021/9/3 01:07:12	Success
7	2021/9/4 15:46:34	Success
8	2021/9/4 15:46:39	Success
9	2021/9/4 15:47:34	Success
10	2021/9/4 15:47:39	Success
11	2021/9/4 15:48:34	Fail
12	2021/9/4 15:48:39	Fail

$$\hat{C}_{b}^{cam} = \begin{bmatrix} 0.999976857 & 0.000210596 & 0.006800025 \\ -0.000232280 & 0.999994890 & 0.003188313 \\ -0.006799319 & -0.003189819 & 0.999971797 \end{bmatrix}$$

6. Conclusions

6. Conclusions

- Chapter 1
  - Explained what we do in satellite operations based on videos of actual operations.
  - Especially in the case of the ISS orbit, each orbital pass is only about 10 minutes long, so it is important to prepare for the operation in advance.
- Chapter 2
  - A brief description of the attitude control mode used during the observation was given.
  - Practical observation operations cannot be performed in only one attitude control mode, but need to be carried out while switching between multiple modes depending on the application.
- Chapter 3
  - Knowledge about orbits, which is indispensable for operations, was explained using TLE, a typical orbit information format, as an example.
- Chapter 4
  - Operation planning methods were explained with examples of analysis software.
- Chapter 5
  - As a more advanced operation, a method for estimating the alignment of instruments in orbit was introduced.
  - By improving operation methods, it is possible to improve results while reducing the effort required during development.

Thank you very much.

[Disclaimer]
The views and opinions expressed in this presentation are those of the authors and do not necessarily reflect those of the United Nations.