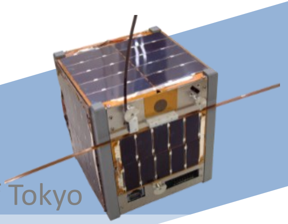
Prof. Ryu Funase
(Univ. of Tokyo & JAXA/ISAS)
(PI of PROCYON and EQUULEUS mission)

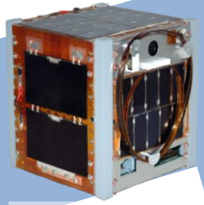
Small satellite missions I have been/am involved in

1) 2000~2007: Small sat missions @ U. of Tokyo

CanSat
(2002)



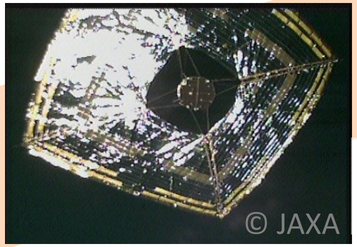
XI-IV (2003): 1kg
World's first CubeSat



XI-V (2005): 1kg
Tech Demo.

2) 2007~2012: (Not so small) deep space missions @ JAXA

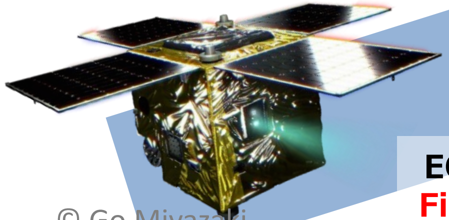
Hayabusa (2007-2010): 510kg
Asteroid sample return



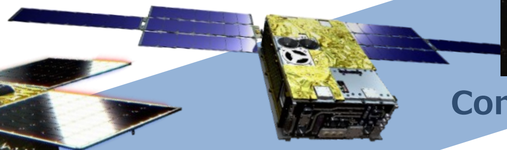
IKAROS (2007-2010): 315kg
World's first interplanetary solar sail

Hayabusa2 (2009-2012): 600kg
Asteroid sample return

3) 2012~2023+
Deep space × small sat @ U. Tokyo+JAXA

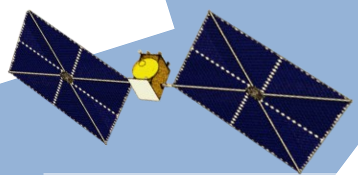


PROCYON(2014): 65kg
World's first deep space micro-sat



EQUULEUS(2022): 11kg
First CubeSat to explore lunar Lagrange point

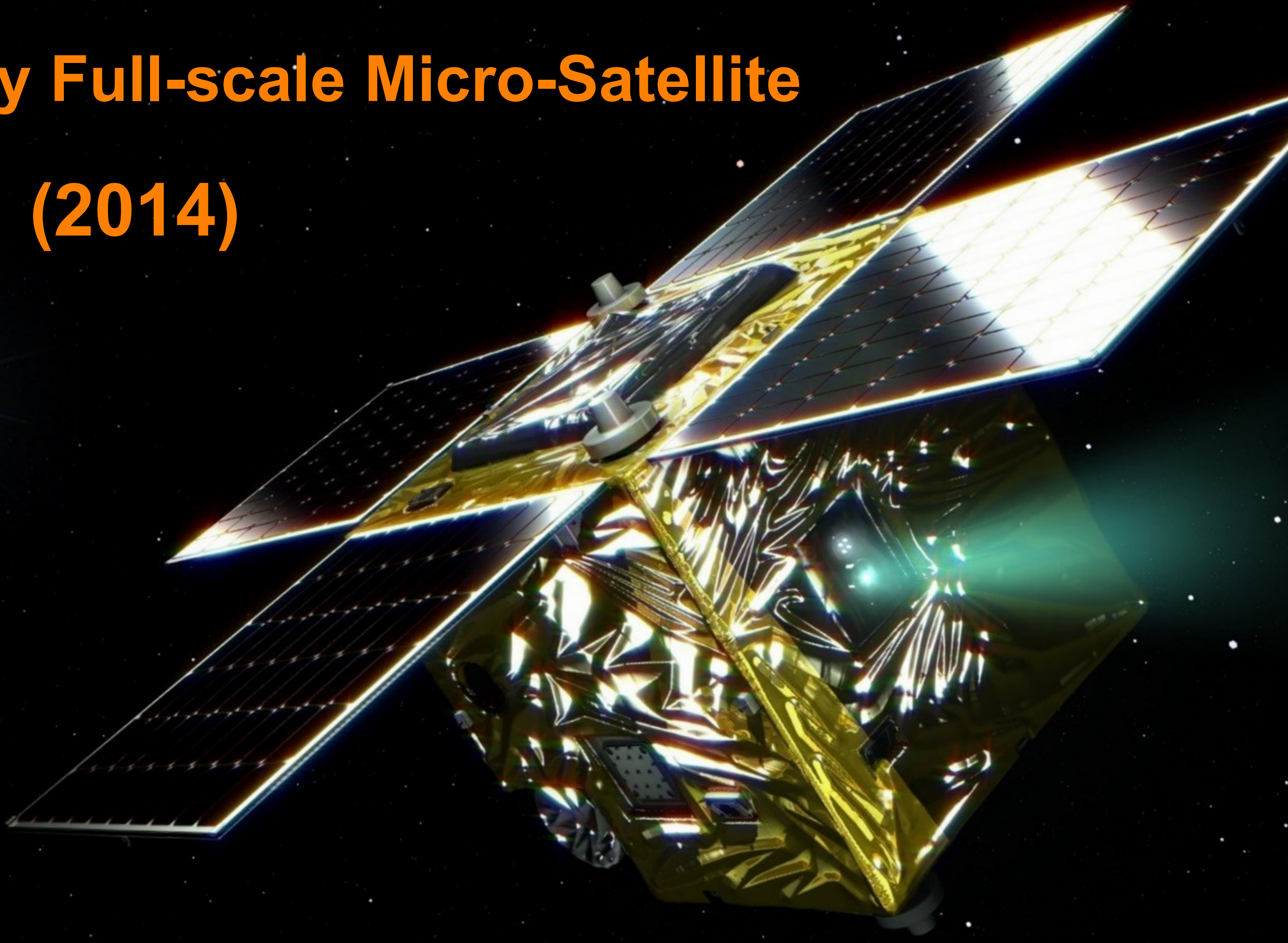
Comet Interceptor (2029): 35kg
First mission to explore long-period comet



OPENS (202x): ~150kg
First small satellite mission to Saturn

The First Interplanetary Full-scale Micro-Satellite

PROCYON (2014)



Size & Weight

55cm, 65kg

Developer

Univ. of Tokyo + JAXA

Development time

14 months

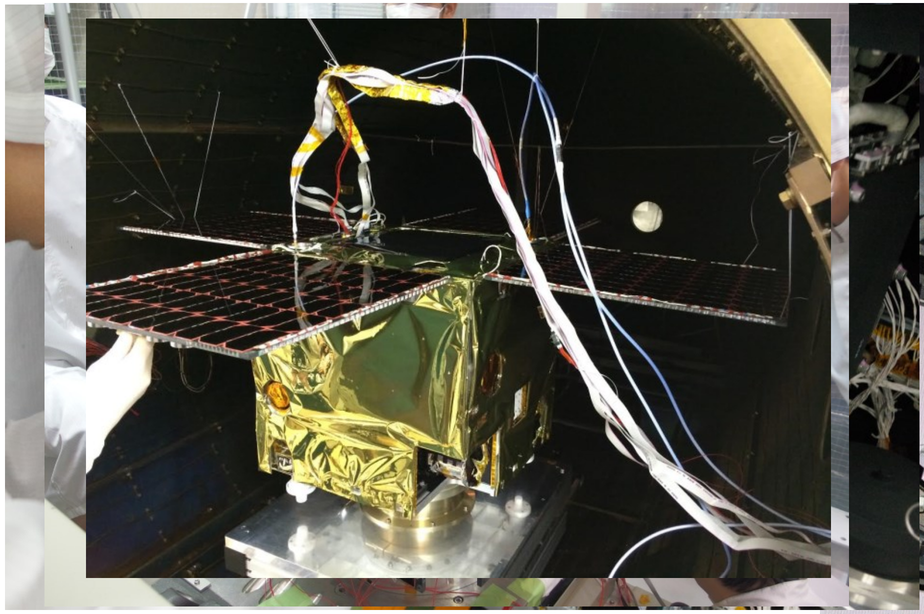
Development budget

< 5 M$

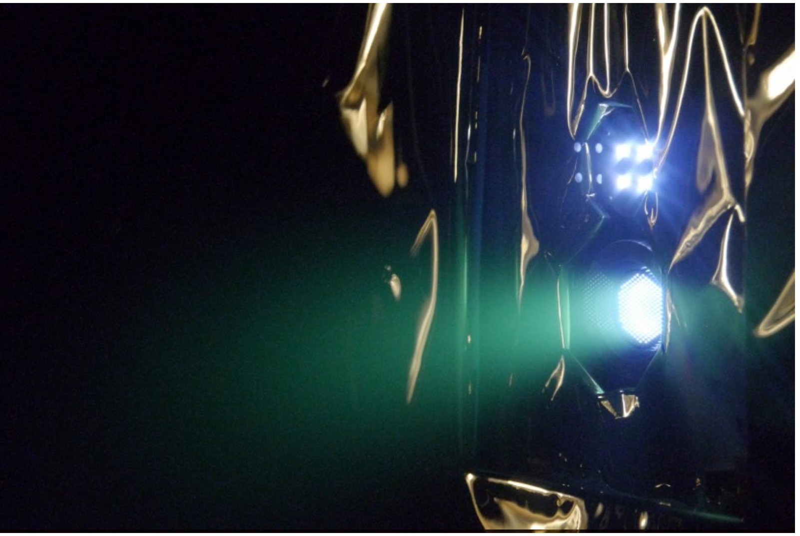
Launch date

Dec. 04, 2014 (with Hayabusa2)

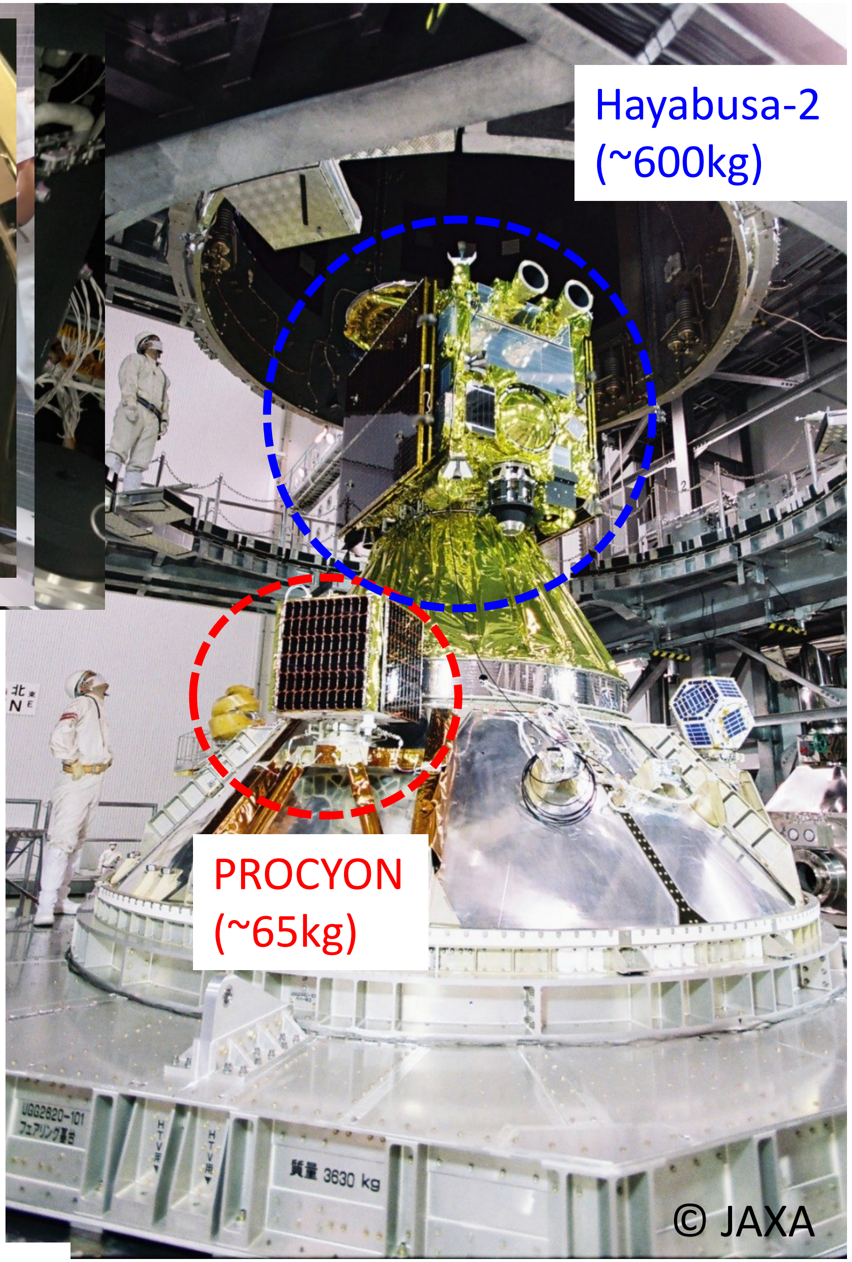
PROCYON proved the possibility of deep space exploration by small satellite

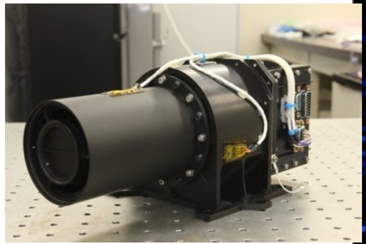


(during integration/testing)



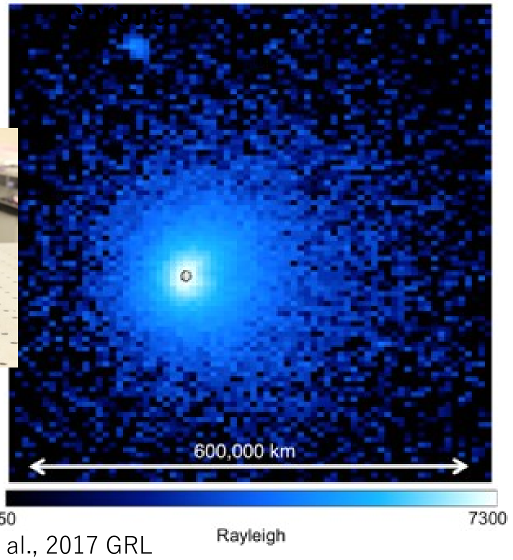
(ion thruster test in a vacuum chamber)



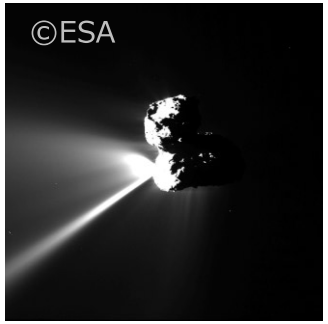


LAICA
(Hydrogen imager)

Earth's hydrogen

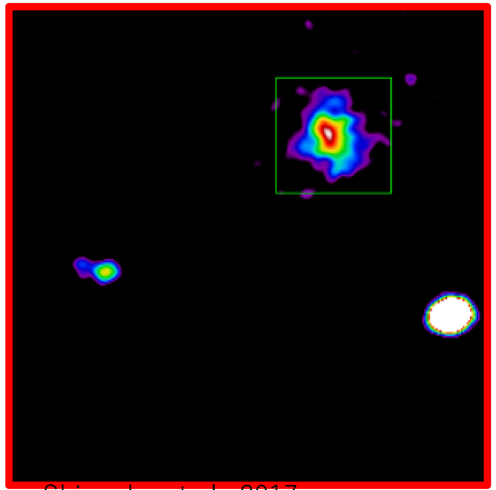


Kameda et al., 2017 GRL



Comet 67P/Churyumov−Gerasimenko

Hydrogen around 67P



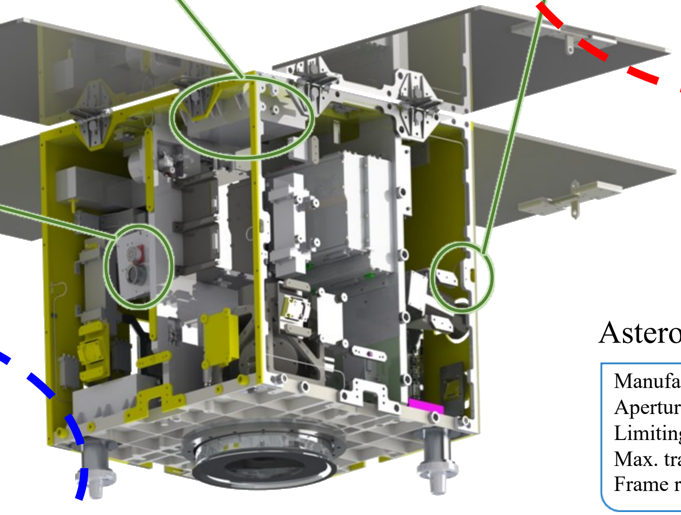
Shinnaka et al., 2017 AJ

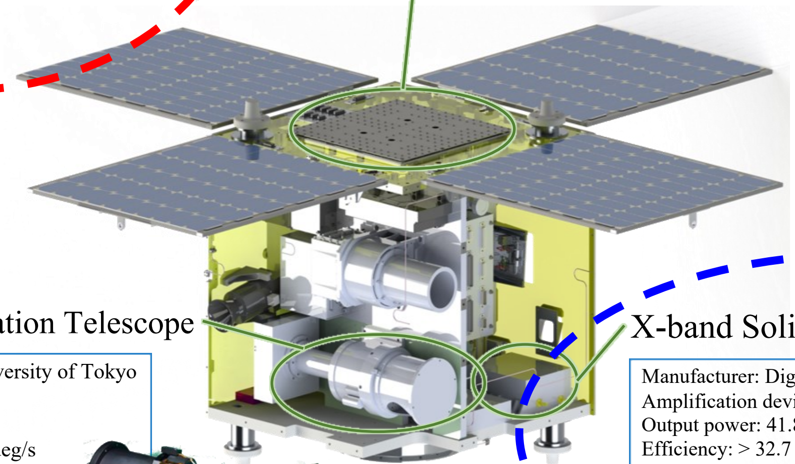
Challenges faced in PROCYON mission

- **Extremely short development time (only 14 months!)**
  - Opportunities come suddenly.
  - The rideshare interplanetary launch opportunity with Hayabusa-2 was solicited only 1.5 years before launch, and after being selected for launch, only 14 months remained for development.
  - Solution: Concentration of development resources on aspects specific to deep space missions
    - Maximum utilization of existing LEO microsatellite platform heritages ("Hodoyoshi-3, 4" bus)
    - Major new developments:
      communications system (deep space small X-band transponder, X-band SSPA (with world's highest efficiency))
      propulsion system (cold gas RCS integrated into Xe Ion engine system)

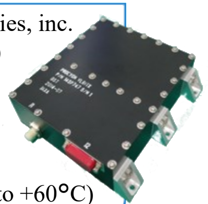
A lot of novel technology demonstrations by PROCYON

S/C size: 55cm
S/C mass: 65kg





DDOR Tone Generator

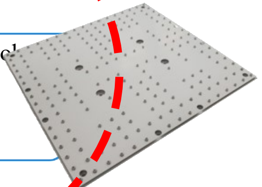


Manufacturer: Digital Signal Technologies, inc.
Max. output power: +9 dBm (each tone)
Max. tone width: 86 MHz
Max. sweep width: 7.9 MHz
Sweep time: 2 to 40 min
Alan variance: < 1×10^{-1} (1-100 s),
< 1×10^{-9} (1000 s) (-20 to +60°C)

Ion Thruster

Manufacturer: The University of Tokyo
Thrust: 300 µN
Specific impulse: 1000 s
Propellant: Xenon

Thrusters (RCS)



Manufacturer: The University of Tokyo
Thrust: 22 mN
Specific impulse: 24.5 s
Propellant: Xenon

High Gain Antenna

Manufacturer: Antenna Giken Co., Ltd.
Tx gain: 25.5 dBi
Rx gain: 24.7 dBi
3dB beam width: ±4 deg

X-band Transponder

Manufacturer: Addnics corp.
Max. output power: +17 dBm (tunable)
Receiving level: -150 to -50 dBm
Coherent ratio: 749/880
Modulation: PCM/PSK/PM,
two-way Range & two-way Doppler,
DDOR ($\pm0.5F_0$, $\pm2F_0$)

Asteroid Observation Telescope

Manufacturer: The University of Tokyo
Aperture: 40 mm
Limiting magnitude: 12
Max. tracking rate: 55 deg/s
Frame rate: 30 fps

X-band Solid State Power Amplifier

Manufacturer: Digital Signal Technologies, inc.
Amplification device: GaN HEMT
Output power: 41.85 ± 0.15 dBm
Efficiency: > 32.7 % (Max. 35.1 %) (-20 to +60°C)

RF Output > 15W
Efficiency > 32.7%

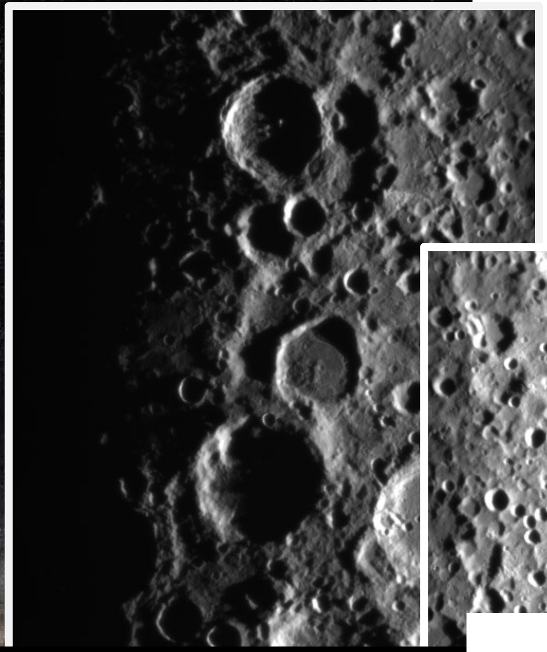
Deep space X-band SSPA
with world's highest efficiency

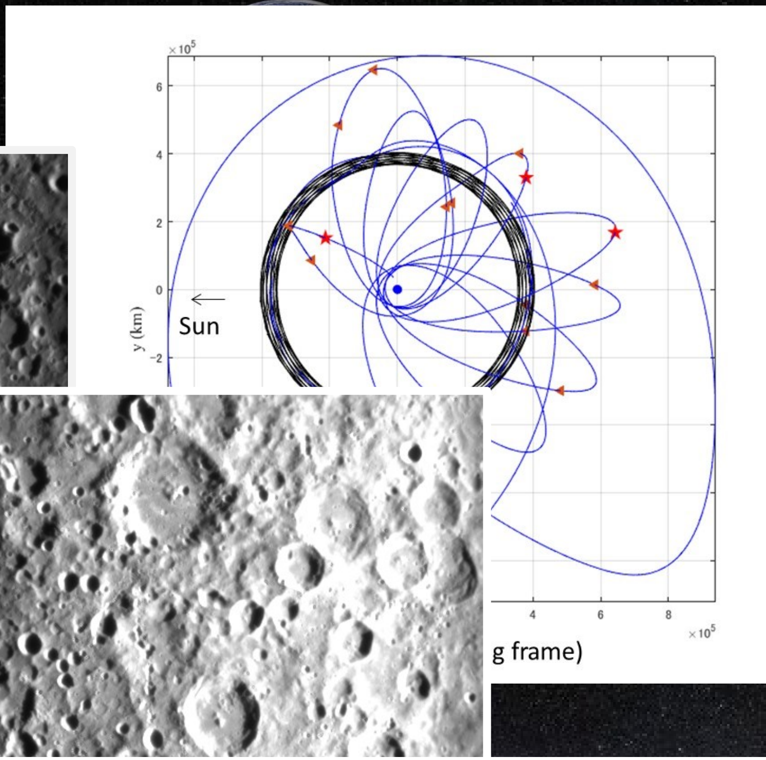
EQUULEUS on SLS Artemis-1

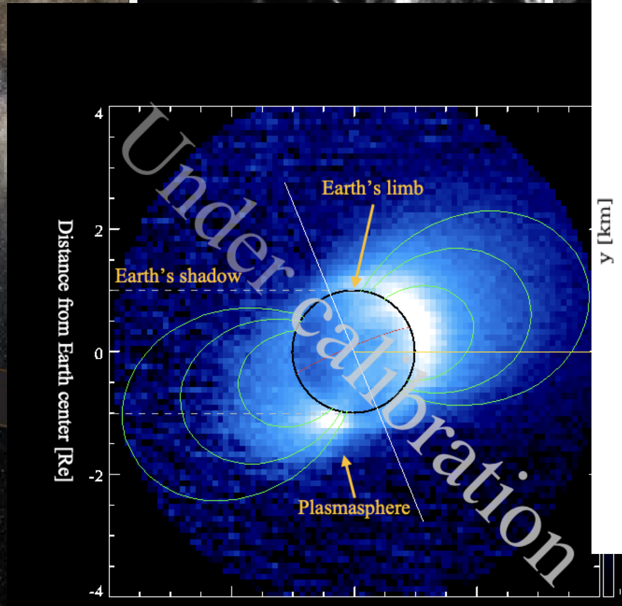
(EQUULEUS = EQUilibriUm Lunar-Earth point 6U Spacecraft)

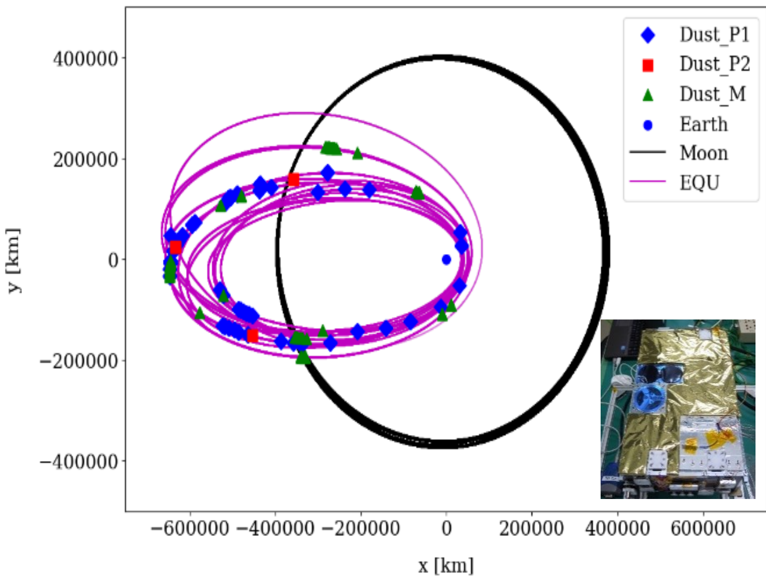
Achieved its full success!!

- ✓ Demonstration of the efficient and precise trajectory control techniques within the Earth-Moon region by a nano-spacecraft
  → Enables deep space exploration by small satellites using lunar gateway in the future
- ✓ Orbital maneuver using a water-based propulsion system beyond LEO (world's first!)
- ✓ Capture of the entire image of the Earth's plasmasphere
- ✓ Dust detection in the cis-lunar space

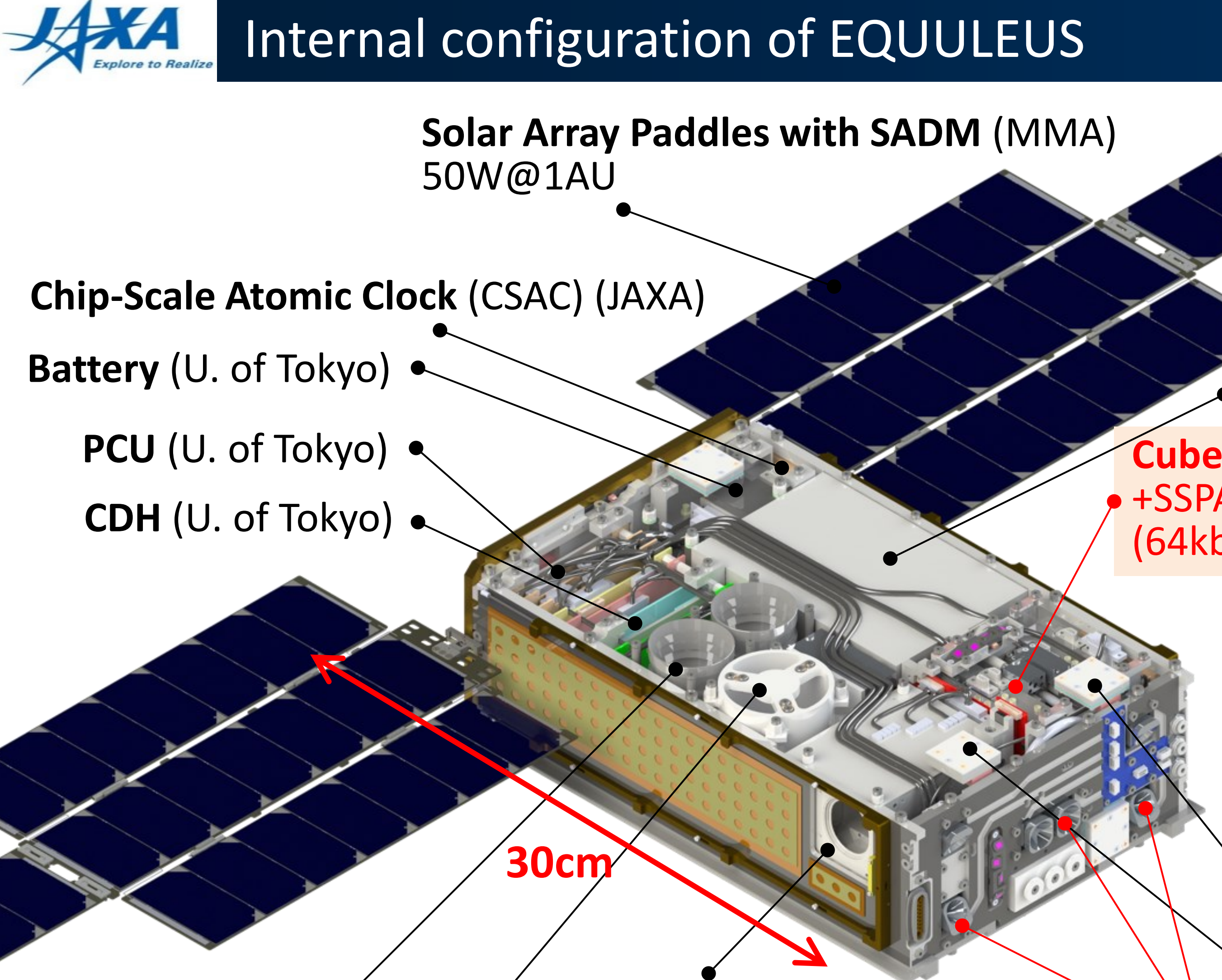




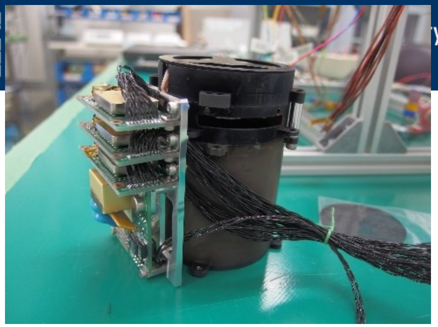


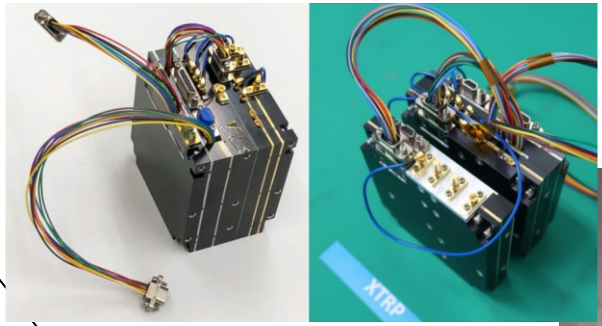


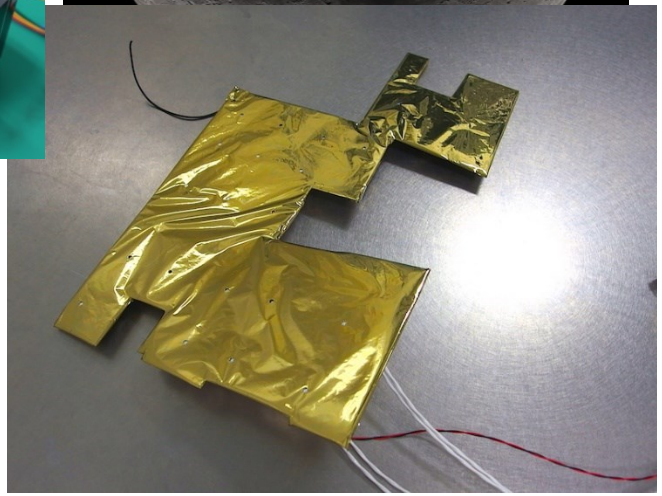
Internal configuration of EQUULEUS



S/C size: 6U
S/C mass: 10.5kg


Earth's plasmasphere observation telescope

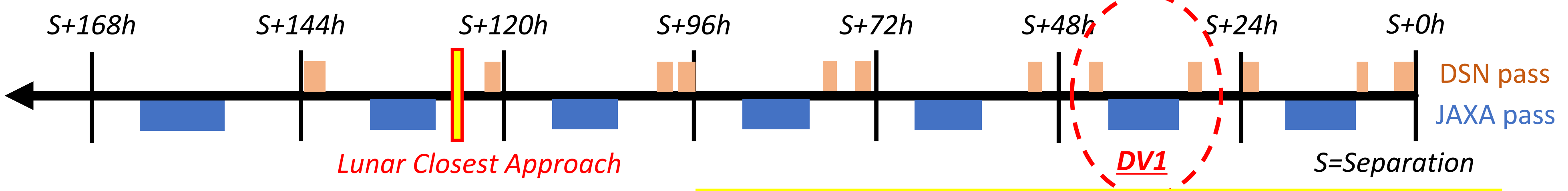



Dust detector in a thermal insulator (MLI)

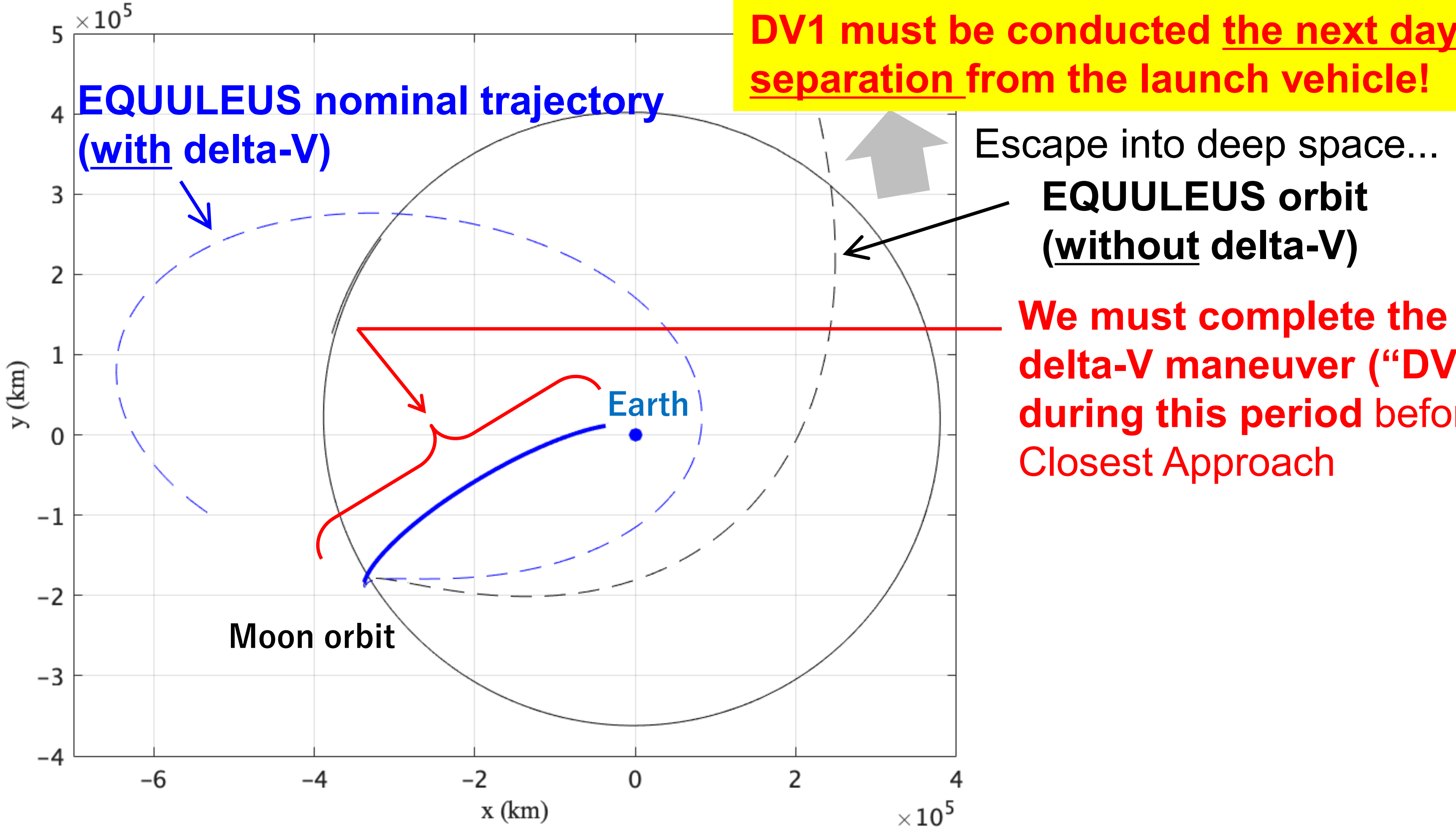
Challenges faced in EQUULEUS mission

- **Extremely critical operation** just after deployment (see next slides)

DV1: most critical operation



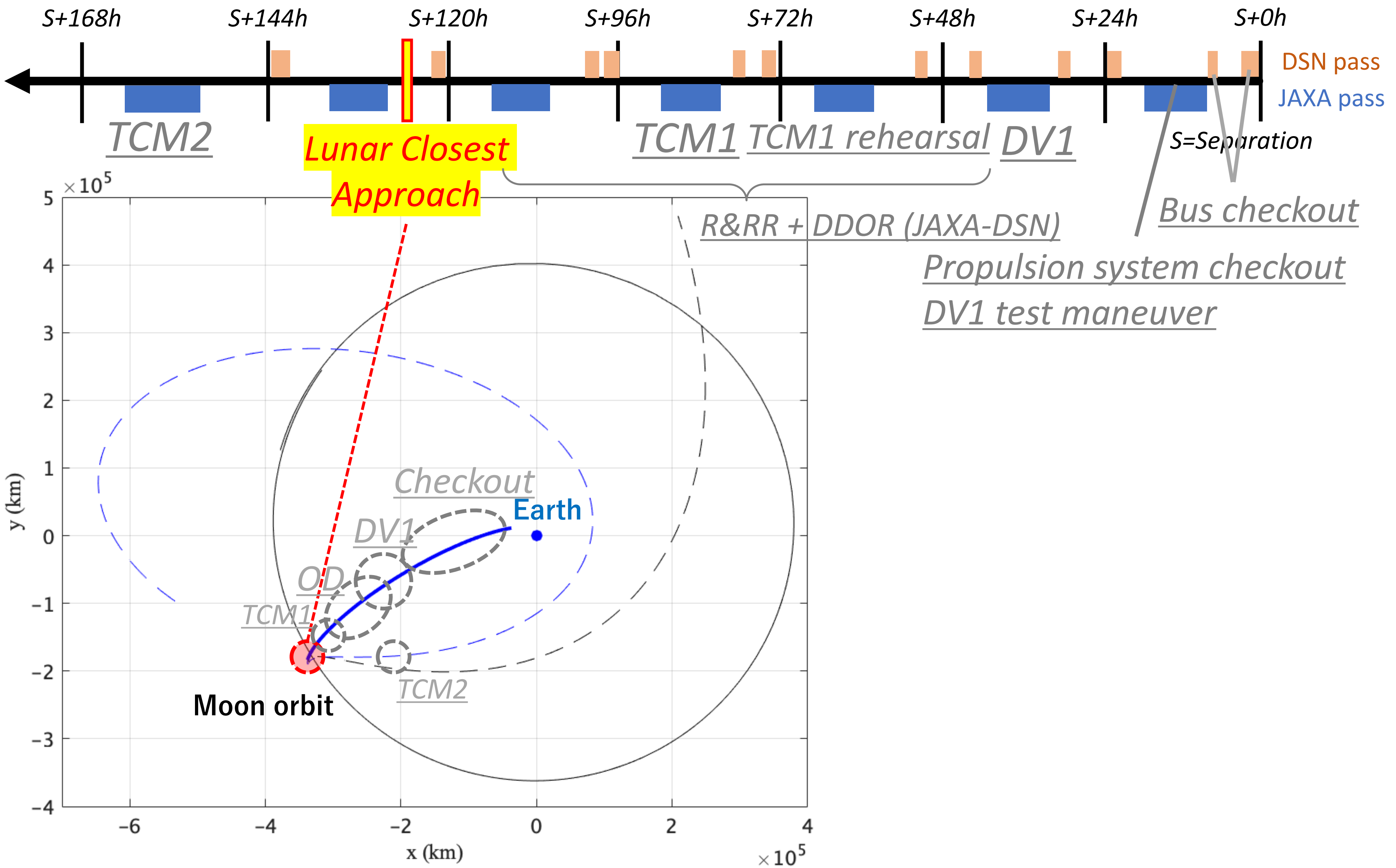
DV1 must be conducted <u>the next day after separation</u> from the launch vehicle!



We must complete the first delta-V maneuver ("DV1") during this period before Lunar Closest Approach

(Earth-centered inertial coordinate)

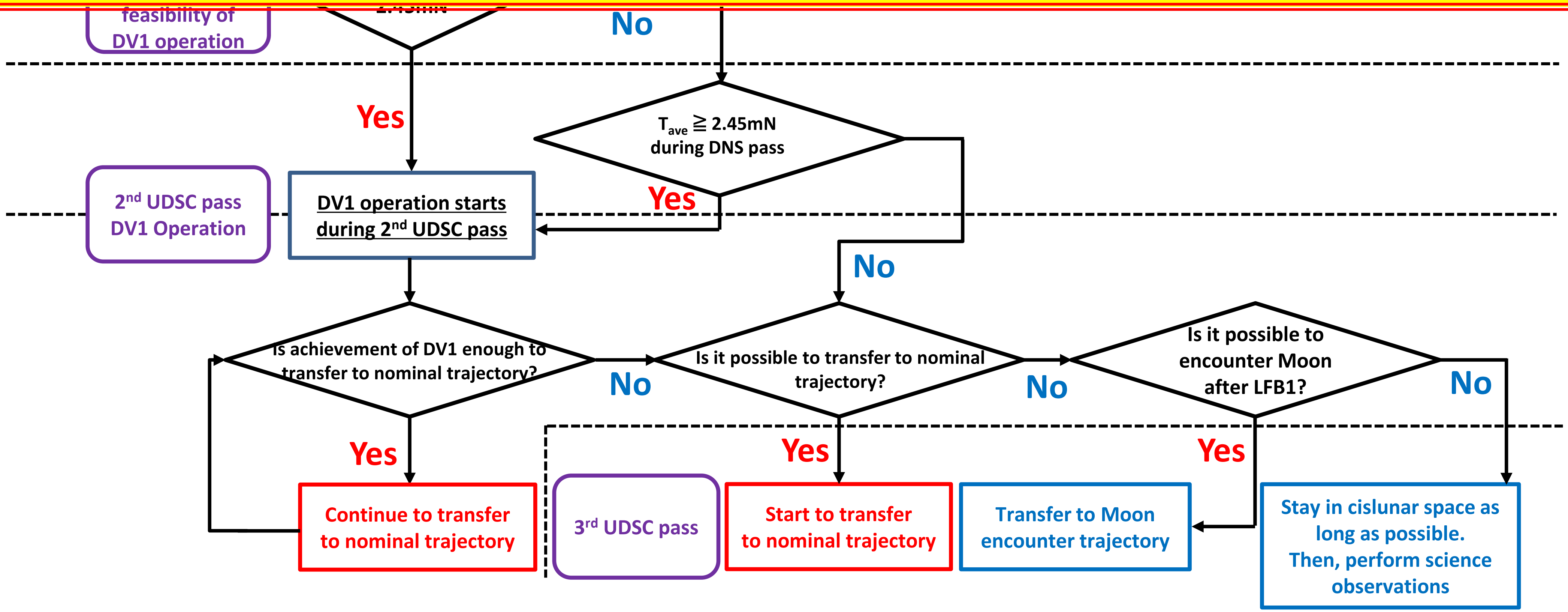
Critical phase operation (actual results)



(Earth-centered inertial coordinate)

Prepared DV1 backup trajectory plan **for every launch candidate**

In order to ensure DV1 execution, we prepared these multiple backup operation plans for all potential launch dates whenever a launch was slipped.



Challenges faced in EQUULEUS mission

- **Extremely critical operation** just after deployment
  → **Common challenges for future rideshare launches to lunar transfer orbit**
  - How efficiently this operation and its preparation can be carried out is a key issue for CubeSat missions that take advantage of the increasing launch opportunity to the Moon.

- Challenges in **mission assurance**
  - Propulsion system and related safety activities
    - Increases the complexity of the system design and the cost of verification
  - Design, and verification of FDIR logic and operational training for successful time-critical orbit control event
    - We cannot rely on "reset" in case of anomaly in such a time-critical operation

Round 2: Lessons Learned

- What are the keys to success in small deep-space missions?
- What lessons should future developers keep in mind?
- What are the common pitfalls or things to avoid?

Keys to success from Univ. of Tokyo's perspective

- Ground station support
- FDIR design to realize a "Die Hard" system
- Preparation for the harsh environment in deep space
- Connection with experts on deep space missions