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Weekday Technical Sessions, Year in Review

SSC21-III-09

In-orbit Demonstration of Reaction Control System for Orbital Altitude Change of Micro-Satellite ALE-2

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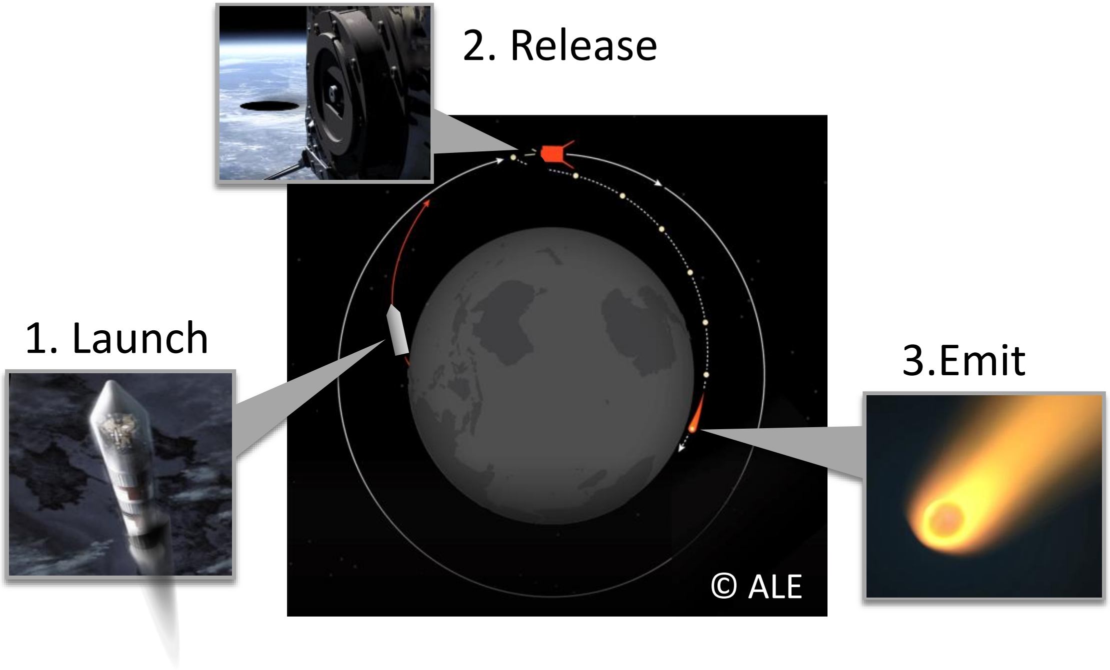
1. Introduction

- ALE Project – Generation of Man-made Meteors by Micro-satellites



① Launch satellite
② Release small pellet
③ Re-entry & Emit

Elucidation of Astrophysics
&
Space Entertainment
“Shooting Star Event”

Tohoku Univ. × ALE Co., Ltd.

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ALE Co., Ltd.

1st Satellite “ALE-1” : Launched on Jan. 18, 2019
2nd Satellite “ALE-2” : Launched on Dec. 6, 2019

Current status : Malfunction in the mission equipment

1. Introduction

- Micro-satellite ALE-2 (Launched on Dec. 6, 2019)

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1. Introduction

- Mission Goal – Painting the sky with the science of shooting stars.

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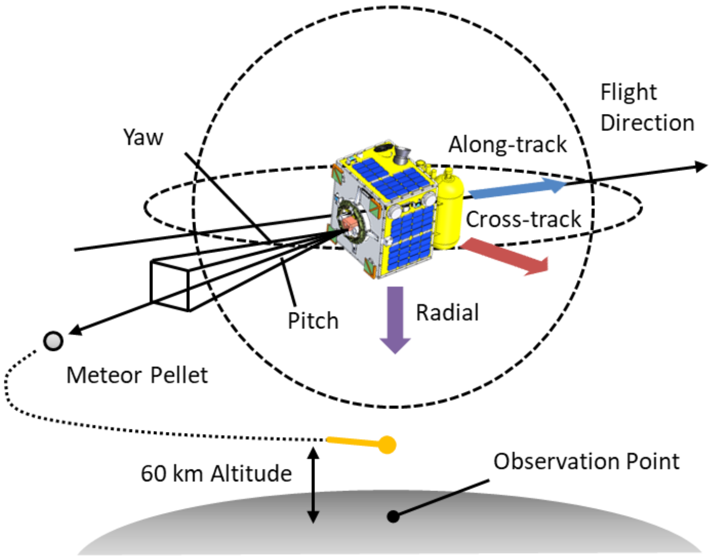
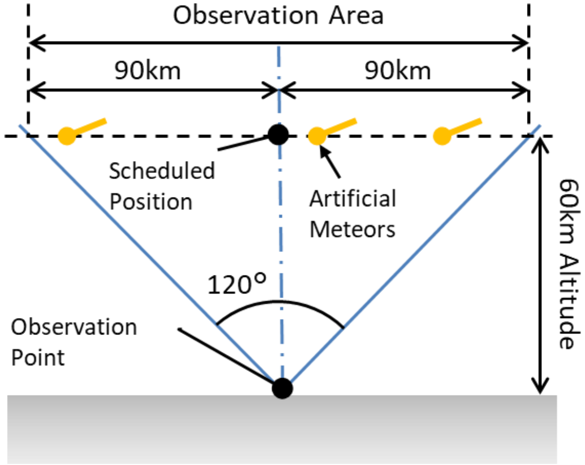
1. Introduction

- Requirement of Attitude and Orbit Control System (AOCS) for ALE-2 mission
  - **Fine Attitude Control** : The control accuracy of the meteor pellet release direction must be within 1.4° for safe and reliable mission.
  - **Active Orbit Control** : To extend the orbital lifetime against atmospheric drag, and to adjust the position and timing of the meteor release by changing the orbital altitude.





2. Research Objectives

Requirements for Reaction Control System (RCS)

① To extend **the orbital lifetime** for approx. **one year or more** by maintaining the orbital altitude (mission orbit of 375–400 km).

② To select **a specific location and timing to perform a shooting star event** in a cycle of **less than 30 days** by shifting the satellite passing area.

- The orbital altitude needs to be manipulated up or down to change to a specific orbital period.

③ The system should be able to be **additionally installed to the existing bus system** which has been used for ALE-1 satellite.

Research Objectives

- To **design a bus-system** with RCS for ALE-2 mission that meets the above mission requirements.
- To **demonstrate in orbit** that ALE-2 is capable of **changing its altitude by more than 1 km per orbit**. → Apply to practical mission operations.

2. Research Objectives

■ Development Policy

- An RCS of cold gas jet type with total impulse of 1400 Ns and wet mass of 9.3 kg is adopted.
  - The product was developed by Patchedconics, LLC, a Japanese venture company. For more detail, please check the poster session (Propulsion):

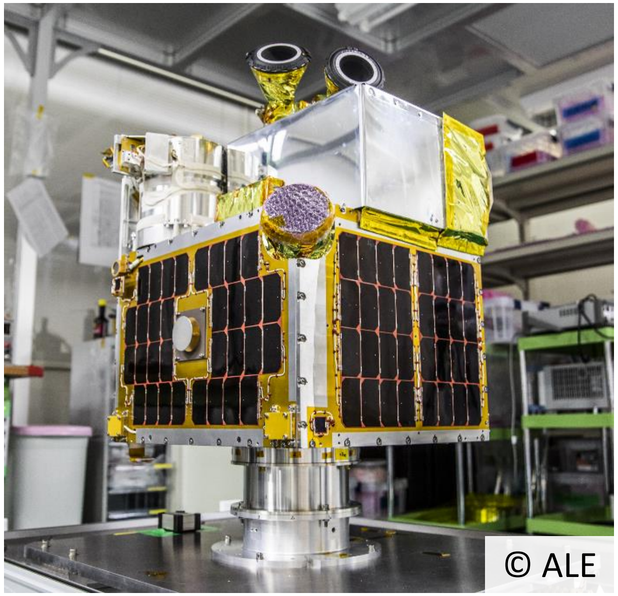
    > “Heater-Free, Lowest Power Consumption & Highest Volume Availability Gas-Generator Propulsion System - Most Suitable for Micro to Nano Satellites”
    >
    > Tiago Padovan, Junichiro Kawaguchi - Patchedconics, LLC

  - This is the first opportunity for space demonstration.
- The hardware, software, and control operation plan for the RCS onboard ALE-2 is newly designed.
  - Simple and reliable control logic: with off-pulse control of the four thrusters to generate thrust while balancing reaction torque.
  - Software-based FDIR (Fault Detection, Isolation and Recovery) function, thereby improving operational safety and system reliability.

Outline

3. System Design

ALE-1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ALE-1 Specification

Launch Date	January 18, 2019
Launch Vehicle	Epsilon, JAXA
Mass	68 kg
Size	W 570.0 x D 550.0 x H 720.0 mm
Orbit	Sun-synchronous orbit at 500 km

ALE-2


© ALE

ALE-2 Specification

Launch Date	December 6, 2019
Launch Vehicle	Electron, Rocket Lab
Mass	76 kg
Size	W 555.7 x D 656.2 x H 707.0 mm
Orbit	Sun-synchronous orbit at 400 km

3. System Design

■ ALE-2 Satellite Bus-system

© ALE

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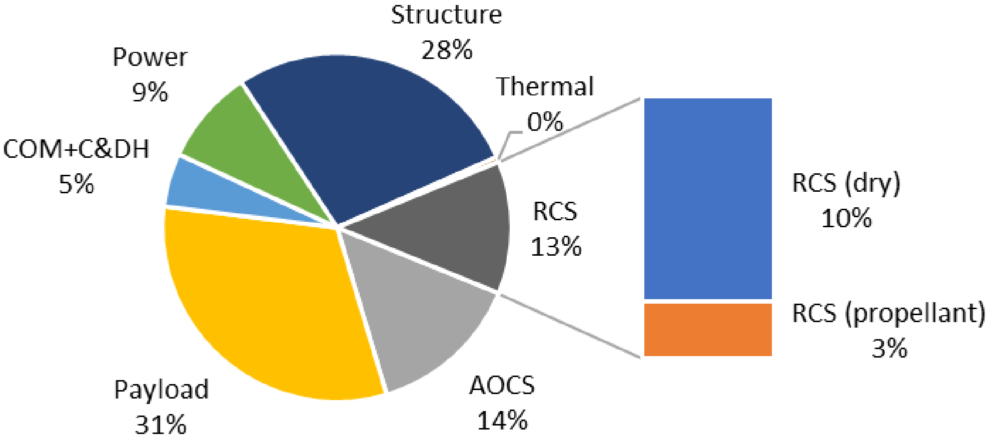
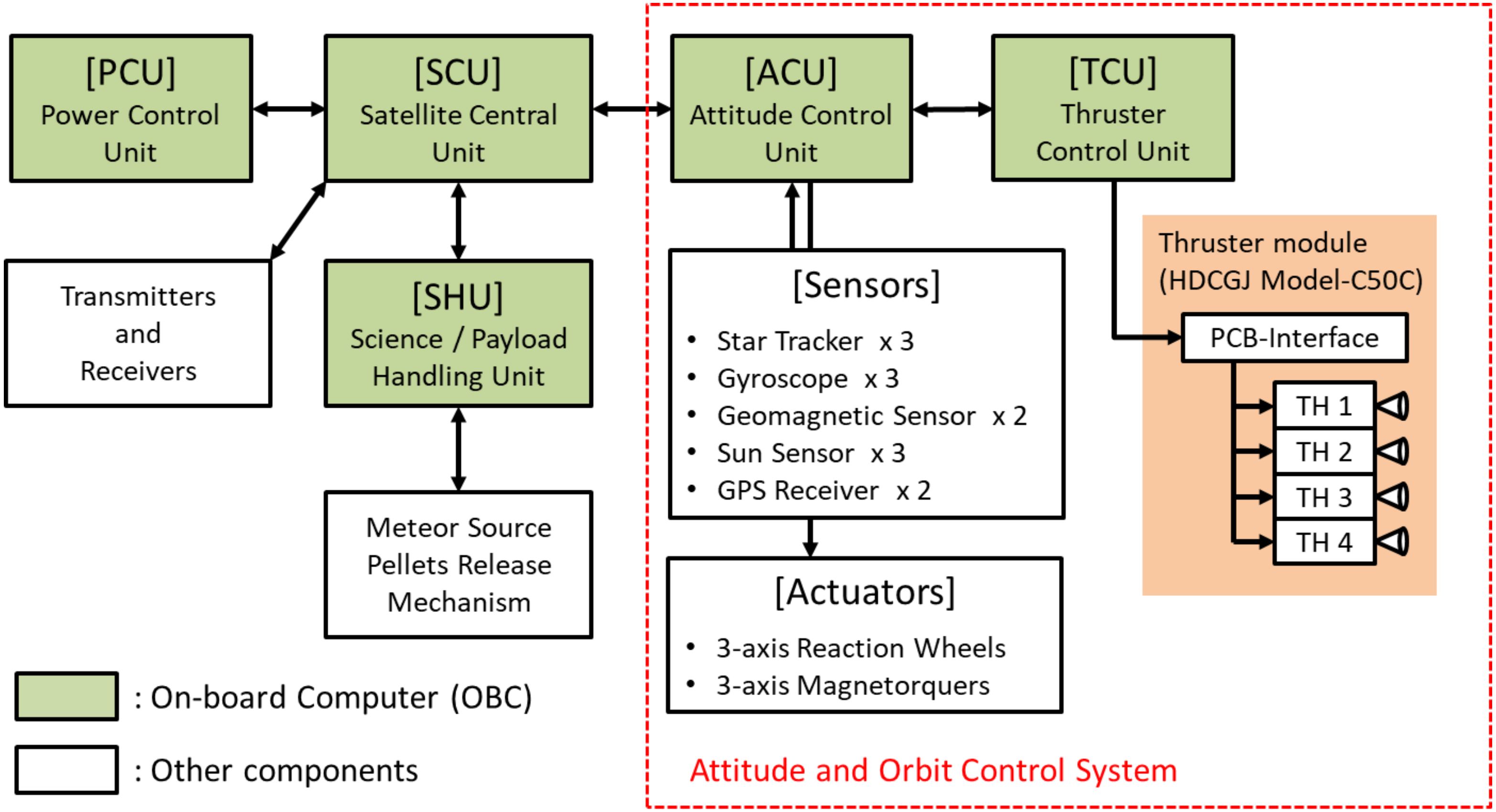


3. System Design

■ ALE-2 Satellite Bus-system



[PCU] Power Control Unit

[SCU] Satellite Central Unit

[ACU] Attitude Control Unit

[TCU] Thruster Control Unit

Transmitters and Receivers

[SHU] Science / Payload Handling Unit

Meteor Source Pellets Release Mechanism

[Sensors]
- Star Tracker x 3
- Gyroscope x 3
- Geomagnetic Sensor x 2
- Sun Sensor x 3
- GPS Receiver x 2

[Actuators]
- 3-axis Reaction Wheels
- 3-axis Magnetorquers

Thruster module (HDCGJ Model-C50C)

PCB-Interface

TH 1

TH 2

TH 3

TH 4

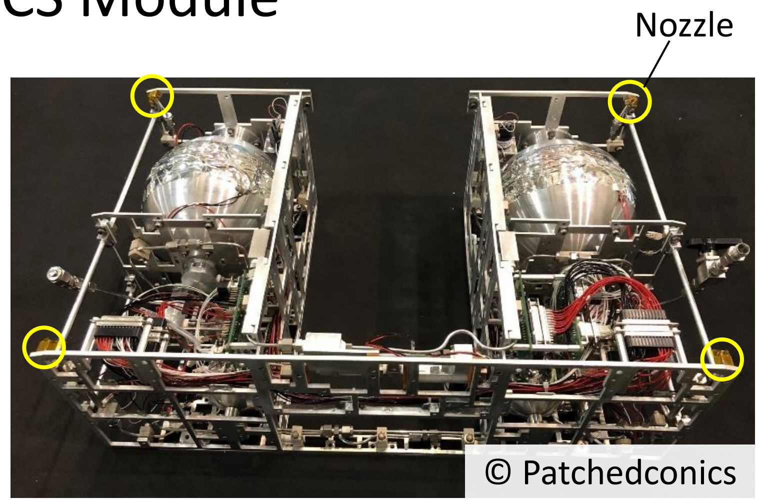
Attitude and Orbit Control System

🟩 : On-board Computer (OBC)

☐ : Other components

3. System Design

RCS Module



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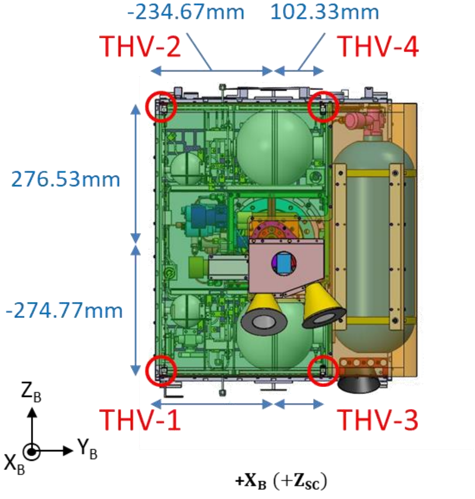
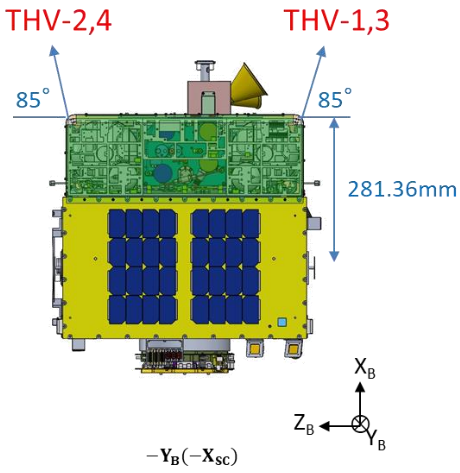
Top View



Side View



Thruster Module Specification	
Model Number	HDCGJ Model-C50C
Size	485 × 485 mm
Weight	7.3 kg (dry), 9.3 kg (wet)
Propellant	R600a (2 kg)
Number of nozzles	4
Thrust	3 mN (each nozzle, typ.)
Isp	70 s
Total Impulse	1400 Ns
Nozzle arrangement	See the left figure
Operation Temperature	0–60 ˚C
Power consumption	10–24 W
Communication Type	UART (RS-422)

$$\boldsymbol{\tau}_i = \boldsymbol{r}_i \times \boldsymbol{f}_i$$

$\boldsymbol{r}_i$: nozzle arm vector [mm]

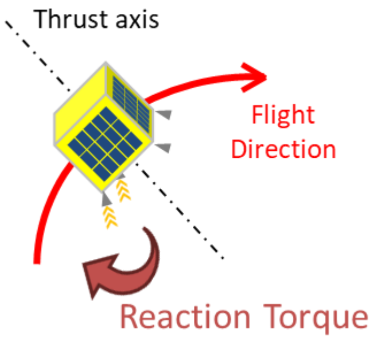
$\boldsymbol{f}_i$: thrust vector [mN]

$$\boldsymbol{r_1} = \begin{bmatrix} 281.36 \\ -234.67 \\ -274.77 \end{bmatrix}, \boldsymbol{r_2} = \begin{bmatrix} 281.36 \\ -234.67 \\ 276.53 \end{bmatrix}, \boldsymbol{r_3} = \begin{bmatrix} 281.36 \\ 102.33 \\ -274.77 \end{bmatrix}, \boldsymbol{r_4} = \begin{bmatrix} 281.36 \\ 102.33 \\ 276.53 \end{bmatrix}$$

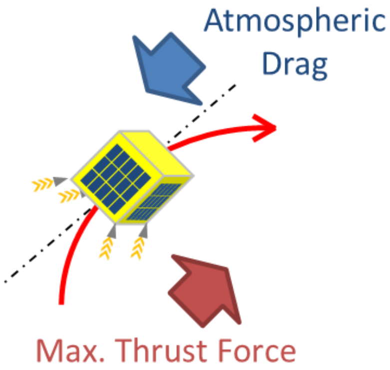
$$\boldsymbol{f_1} = \boldsymbol{f_2} = \begin{bmatrix} -3\cos 15° \\ 0 \\ -3\sin 15° \end{bmatrix}, \boldsymbol{f_3} = \boldsymbol{f_4} = \begin{bmatrix} -3\cos 15° \\ 0 \\ 3\sin 15° \end{bmatrix}$$

3. System Design

■ Strategy of Orbit Control for ALE-2 Mission (1/2)



Step 1
Attitude control to follow flight (along-track) direction



Step 2
Generate max. thrust to defeat atmospheric drag

Back to Step 1 to cancel imbalanced reaction torque

Return to appropriate orbit (higher altitude)

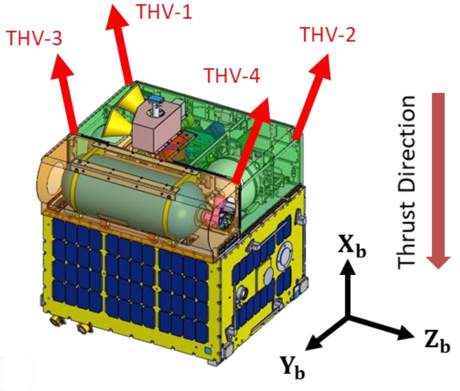
Estimated delta V (energy for altitude ascension in 1 orbital cycle around the Earth)

Change in momentum (Impulse) : $F\Delta t = m\Delta V$

With consideration of energy loss by imbalanced torque compensation,
Max. thrust force F = **8.32 mN**

Assuming that weight m = 75 kg, Δt = 5553.6 s,

Generated ΔV = 0.616 m/s



3. System Design

■ Strategy of Orbit Control for ALE-2 Mission (2/2)

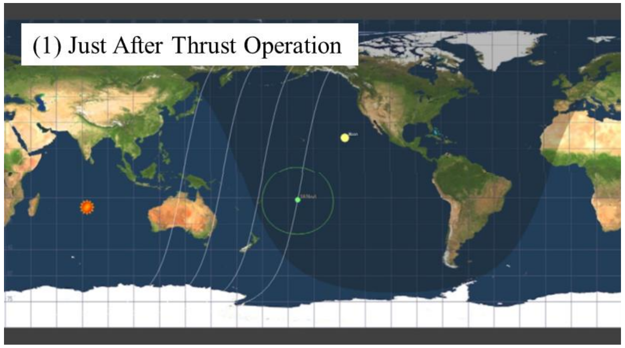
Application 1: Orbit altitude maintenance

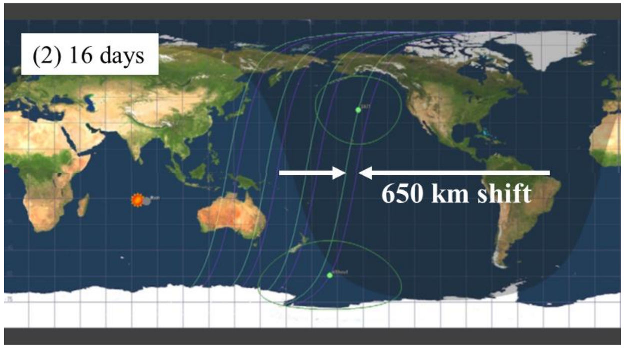
- Continuous thruster operation for **one orbital cycle**
- **Required ΔV = 0.566 m/s** for 1 km orbital ascension (assuming 400-km orbit, 100% thrust efficiency)
- The RCS operation should be conducted every 10 days, extending the orbital lifetime by **11 months**.

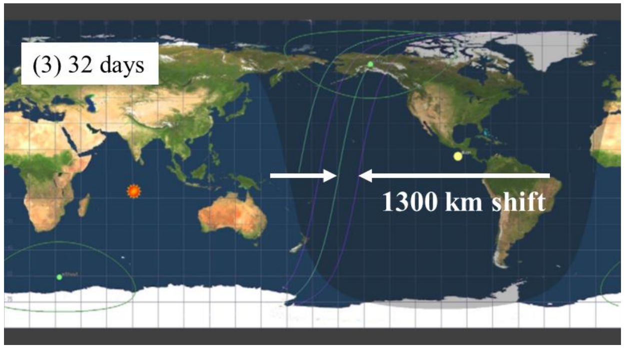
Application 2: Shift of satellite passing area

- Ground track moves about 2600 km per orbit. (Alt. = 400km)
- When **ΔV = 2.634 m/s** (equivalent to propulsion control for 4.3 orbital cycles) is given, it is possible to make **a change of 1300 km after 32 days**.
- We can select a specific point and hold a shooting star event within approx. 30 days.

→ RCS design and its performance are compatible with both bus system design and mission requirement.


(1) Just After Thrust Operation

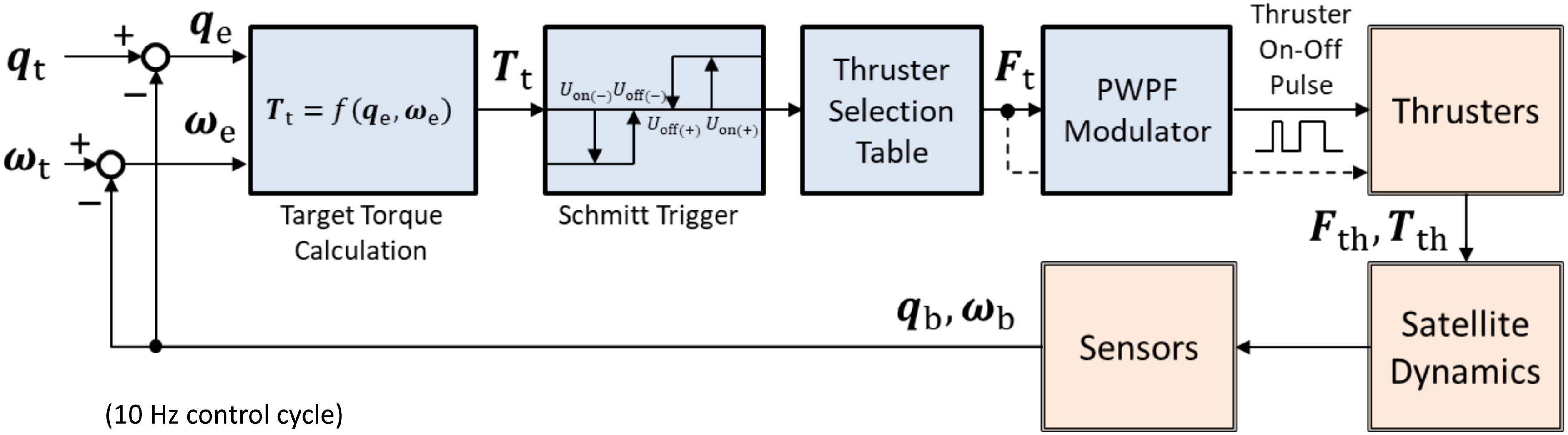

(2) 16 days


(3) 32 days

3. System Design

- Control Software
  - Algorithm of thruster control
    1. Calculate target thrust torque $\boldsymbol{T}_t$ by PID control law
    2. Apply a Schmitt trigger with the hysteresis and the dead-band threshold to determine the sign of target thrust torque $\boldsymbol{T}_t$
    3. Determine the nozzle on-off combination based on thruster nozzle selection table
    4. Generate valve on-off switching pulse using a PWPF modulator

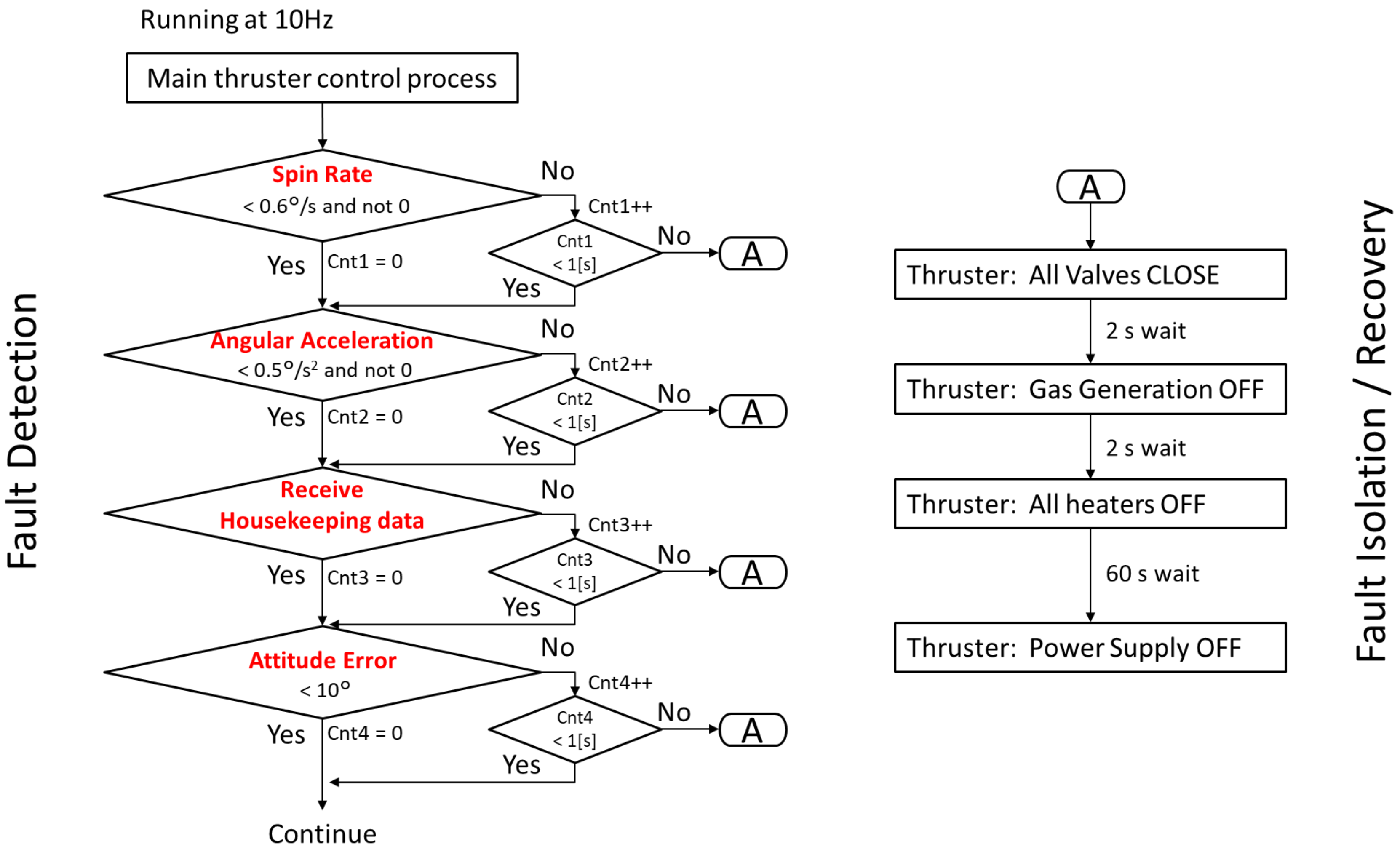
* PWPF = Pulse-width pulse-frequency



(10 Hz control cycle)

3. System Design

■ Fault Detection, Isolation and Recovery (FDIR) function



Running at 10Hz

Main thruster control process

Spin Rate
< 0.6°/s and not 0
Yes: Cnt1 = 0
No: Cnt1++ → Cnt1 < 1[s]; Yes / No → A

Angular Acceleration
< 0.5°/s² and not 0
Yes: Cnt2 = 0
No: Cnt2++ → Cnt2 < 1[s]; Yes / No → A

Receive Housekeeping data
Yes: Cnt3 = 0
No: Cnt3++ → Cnt3 < 1[s]; Yes / No → A

Attitude Error
< 10°
Yes: Cnt4 = 0
No: Cnt4++ → Cnt4 < 1[s]; Yes / No → A

Continue

Fault Detection

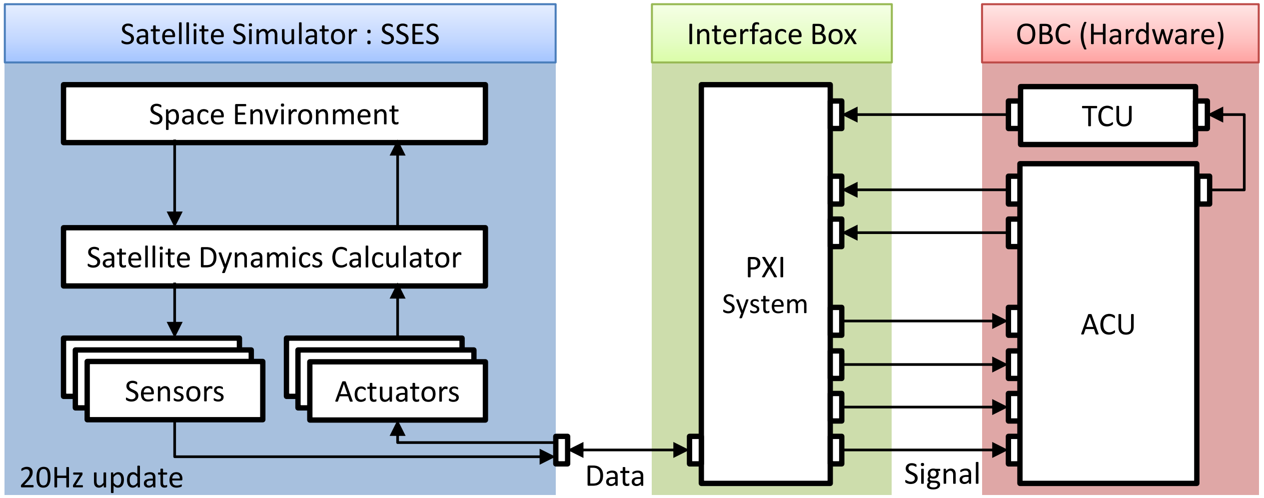
A

Thruster: All Valves CLOSE
2 s wait
Thruster: Gas Generation OFF
2 s wait
Thruster: All heaters OFF
60 s wait
Thruster: Power Supply OFF

Fault Isolation / Recovery

3. System Design

- Closed-loop Control Simulation
  - Hardware-In-the-Loop Simulation (HILS) system
  - To evaluate both on-board software logic and OBC physical interface



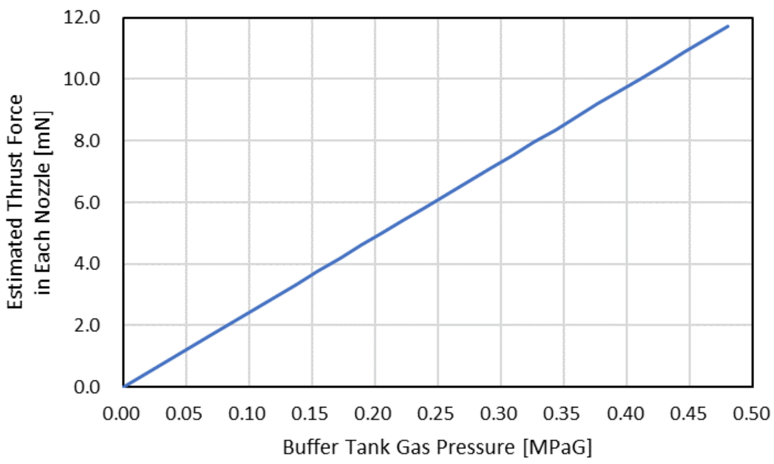
Outline

1. Introduction
2. Research Objectives
3. System Design
4. In-orbit Demonstration
5. Lessons Learned
6. Conclusion

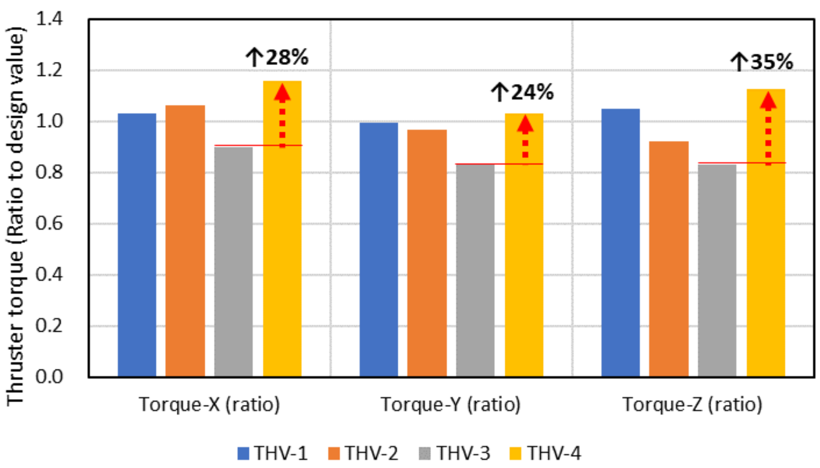
4. In-orbit Demonstration

■ Measurement of Thruster Operational Performance

Thrust vs. Tank Pressure



Torque imbalance



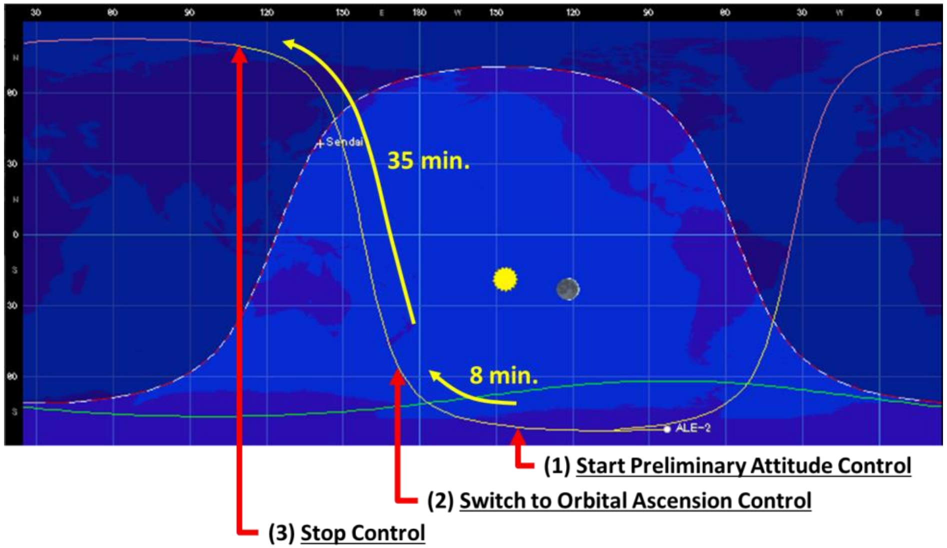
- Indirect measurement from changes in spinning behavior during thrust
- Clarify the relationship between **buffer tank pressure** and **output thrust**

- Indirect measurement from changes in momentum stored in reaction wheels
- Recognize a large gap between THV-3/4 (**24–35% stronger for THV-4**)

4. In-orbit Demonstration

■ Altitude Ascending Operation (1/4)

- Attitude stabilization (**8 min.**) , followed by orbital ascending control (**35 min.**)
- High thrust level: **larger than 5.85N**
- **Half-orbit**, **Sunshine area** (operational limits, explained later)



(1) Start Preliminary Attitude Control

(2) Switch to Orbital Ascension Control

(3) Stop Control

Operation Condition	
Operation time	21:32:00 UTC, Nov. 16, 2020
Operation sequence	21:32:00 UTC: (−0:08:00) Start preliminary attitude control 21:40:00 UTC: (+0:00:00) Switch to orbital ascending control 22:15:00 UTC: (+0:35:00) Stop thruster control All sequence is conducted at sunshine.
Thruster gas control	Enabled, within 0.223–0240 MPaG
Thrust level	Approximately 5.85 mN in each nozzle
Thruster control cycle	10 Hz interval
Thruster control gain (X,Y,Z)	K_p = { 5000, 5000, 5000 } K_d = { 300000, 300000, 300000 } K_i = { 0, 0, 0 } K_f = { 2160, 2110, 2120 }
Thruster control dead band threshold (X,Y,Z)	U_{on} (+) = { +200, +200, +200 } U_{off} (+) = { +50, +50, +50 } U_{on} (−) = { −200, −200, −200 } U_{off} (−) = { −50, −50, −50 }

4. In-orbit Demonstration

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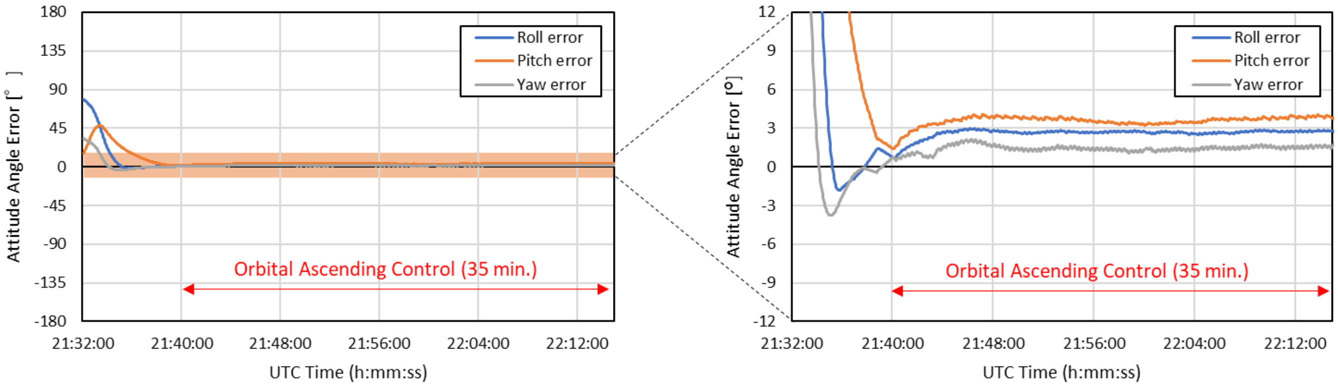
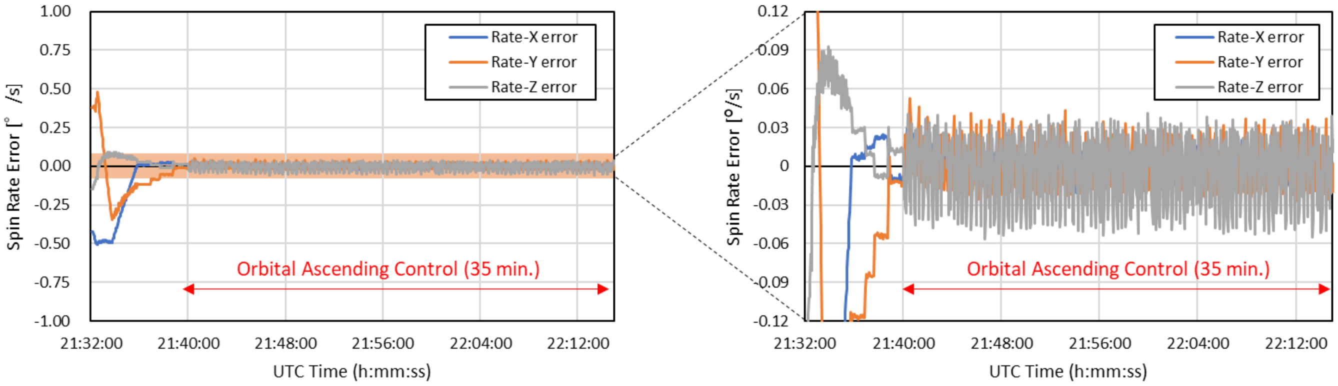
■ Altitude Ascending Operation (2/4)

Attitude Angle



within ±4°

Spin Rate



within ±**0.06**° /s

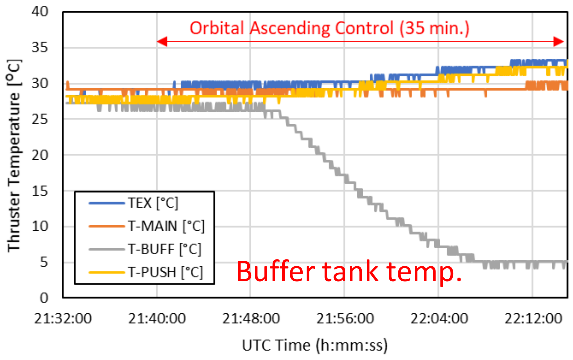
Attitude was properly controlled, resulting in large delta V and high stability.

4. In-orbit Demonstration

■ Altitude Ascending Operation (3/4)

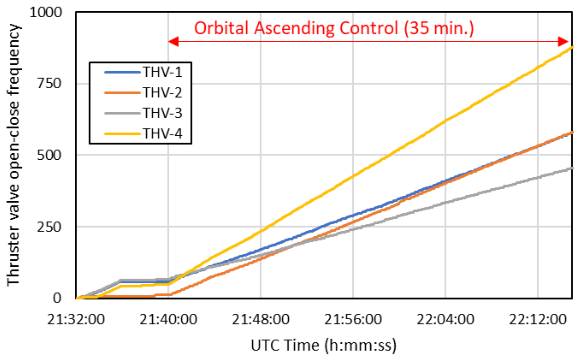
RCS Housekeeping data

Tank Temperature



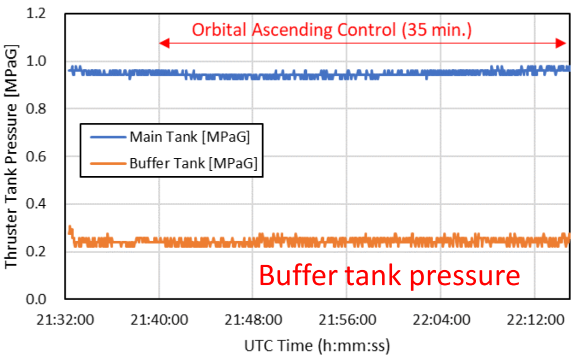
Controlled
> 5℃

Valve Open/Close Frequency



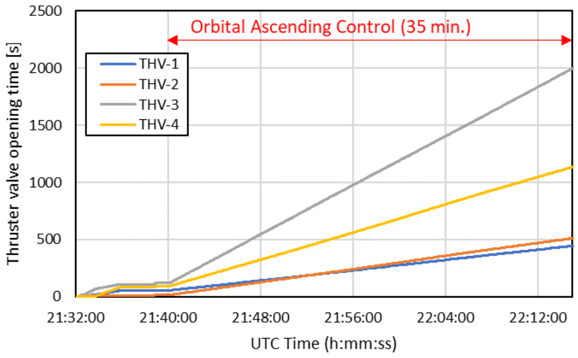
Auto-adjusted

Tank Pressure



Controlled
> 0.223MPaG

Valve Total Opening Time

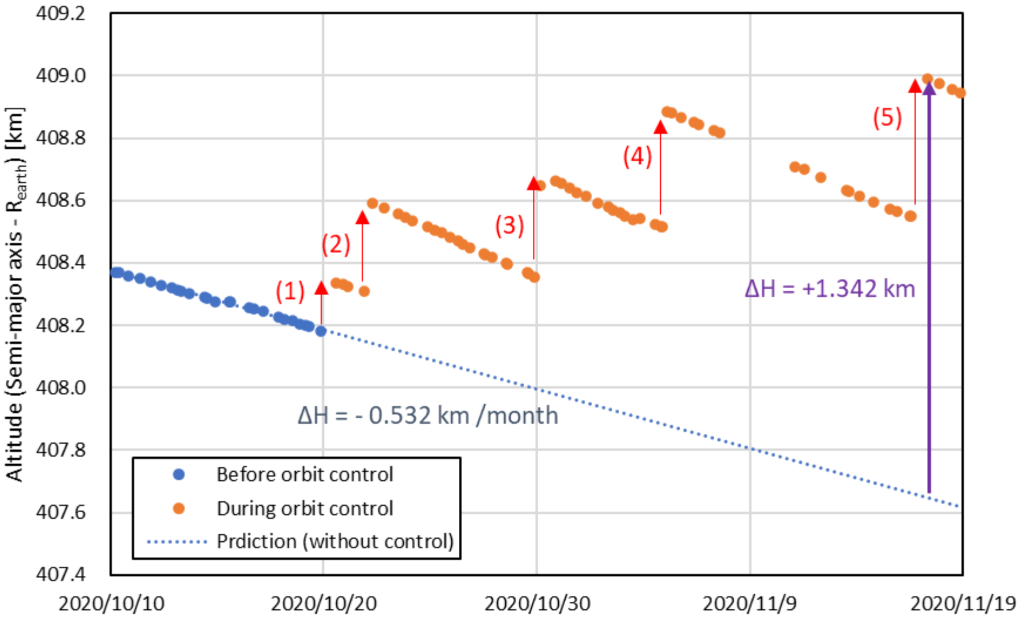


Auto-adjusted

4. In-orbit Demonstration

■ Altitude Ascending Operation (4/4)

Altitude Change



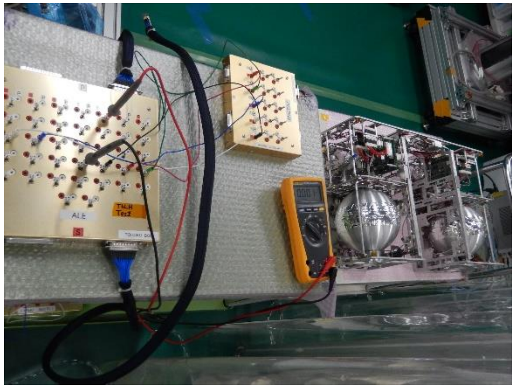
Altitude ascension is **1.342 km/month** against decay due to atmospheric drag

#	Date	Thrust	Operation Time	Altitude Change	Effici-ency
(1)	Oct. 19, 2020	2.1 mN	22.5 min.	+156 m	85.5%
(2)	Oct. 21, 2020	2.1 mN	45 min.	+282 m	76.9%
(3)	Oct. 29, 2020	2.1 mN	45 min.	+294 m	80.3%
(4)	Nov. 4, 2020	3.75 mN	45 min.	+368 m	56.2%
(5)	Nov. 16, 2020	5.85 mN	35 min.	+442 m	55.7%

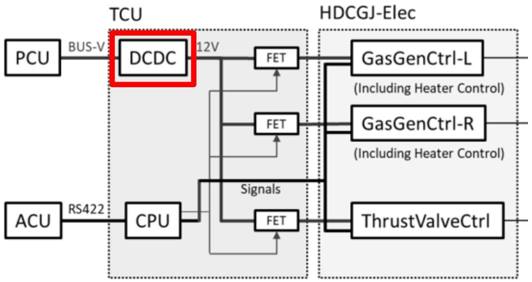
5. Lessons Learned

■ Lessons Learned – Abnormal stoppage of RCS

Insufficient electrical tests in ground



❌ DC/DC has caused serious trouble in orbit.



Anomalies

- **RCS power failure** during eclipse area
- **RCS logic circuit operation stop** when the load on the power supply is too large (high switching frequency of valves)

Cause

- When **the battery voltage is below 12V** or **the repetitive inrush current occurs**, the boost circuit by DC/DC converter may not work.
- Could not identify it due to **lack of ground tests**.

Countermeasures and Effect

- Limit the use of RCS: only sunshine area, low switching frequency → **Change of operation sequence**
- Although the total ΔV decreased, stable control was established.

5. Lessons Learned

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Lessons Learned – Application of FDIR function

– Operates properly and protests the RCS from various anomalies

Abnormal Events

A) Attitude sensor measurement error
B) Attitude calculation logic error
C) Valve open/close operation failure
D) RCS electric board operation stop
E) Satellite OBC operation stop
F) Overcurrent

Detection ←

Anomalous Status Monitoring

A) Anomalous gyro sensor values
B) Increase in attitude determination error (approx. >5°)
C) Rapid increase in angular velocity (approx. >2°/s)
D) Interruption of Housekeeping data from RCS electric board
E) Activation of watch dog timer of OBC
F) Activation of circuit breakers

Isolation & Recovery

RCS Shut-down Process

- Valve all closed
- Gas generation stopped
- Heater stopped
- Interruption of thruster main power supply

6. Conclusion

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Achievement

- In order to solve the problem of the power supply system of the RCS, we devised the operation sequence and changed the parameters appropriately. As a result, we succeeded in adding **an orbit altitude change of up to ±0.4 km** by continuously maneuver halfway around the orbit in the daylight area.
- Although the number of orbits using thrusters was increased, the original objectives of **extending the orbit life by approx. one year** and **adjusting the satellite pass position by ±1300 km** were expected to be feasible.
- The **FDIR function worked effectively** against repeated failures during operation, ensuring a high level of operational safety.

Future Perspectives

- Continue to perform the orbit maintenance control — hoping for the recovery of the meteor ejection system
- Utilize the operational data for further improvement of RCS performance
- Proceed to design the next satellite