Results and Lessons Learned from In-Orbit Thruster Control Demonstration of Microsatellite ALE-2 with a Small Propulsion System

Takumi Saito[1], Shinya Fujita[1], Toshinori Kuwahara[1], Yoshihiko Shibuya[2], Hiromune Ishii[2], Lena Okajima[2], and Junichiro Kawaguchi[3]

[1]Tohoku University
Aoba 6-6-11, Aramaki Aza, Sendai, 980-8579, Japan
Phone: +81 22 795 5082, Mail: saito.takumi.t7@dc.tohoku.ac.jp

[2]*ALE Co., Ltd.*
2-10-1 Shiba Koen, Minato-ku, Tokyo 105-0011, Japan
Phone: +81 3 6441 3312, Mail: info@star-ale.com

[3]Australian National University
School of Engineering, College of Engineering and Computer Cybernetics, Birch Building 35, Science Road, Acton, 2600, Australian Capital Territory, Australia
Mail: junichiro.kawaguchi@anu.edu.au

Abstract: Tohoku University has developed over a dozen microsatellites and has performed earth observation demonstrations in LEO and ALE Co., Ltd, a Japanese space venture aiming to elucidate the physical phenomenon during atmospheric re-entry by releasing the artificial meteor from a microsatellite, try to realize artificial meteor-generating events as space entertainment. To achieve this purpose, the research group has corporately developed a microsatellite ALE-2. This satellite has a cold gas propulsion system newly developed by Patchedconics, LLC., Otherwise, microsatellites generally have only performed passive orbital control. However, the thruster system enables the satellite to perform active orbital control and observe the artificial pellets at any point on the ground. The thruster demonstration was performed approximately 100 times in orbit without happening critical hazards, and the satellite almost finished consuming the fuel installed. Unfortunately, the system to release the artificial pellets had some hardware troubles; as a result, the demonstration of releasing the artificial meter has not been performed. Nevertheless, our research group established the thruster development and control technology for microsatellites through the thruster operations. This paper introduces the results and lessons learned from the thruster operation of ALE-2.

1. INTRODUCTION

The Space Robotics Laboratory (SRL) of Tohoku University has developed and demonstrated more than a dozen microsatellites, which are 50 kg class. They have been utilized as an opportunity for various technological challenges because of their advantages of lower cost and a shorter development period than conventional satellites [1]– [4]. In recent years, our research team has conducted observation missions by RISESAT, a high-resolution multispectral earth observation microsatellite. This satellite tested the high-precision attitude control technology. Recently, the joint development projects of microsatellites have corporately proceeded with the private company. One is the two microsatellites ALE-1 and ALE-2, shown in Figure 1, developed with the Japanese space venture ALE Co., Ltd. This business has the world's first aim of realizing space entertainment due to releasing artificial meteors from them and has developed demonstration satellites. The first satellite, ALE-1, was launched to an altitude of 500 km by an Epsilon rocket in January 2019. In this satellite case, the altitude was lowered to 400 km or less to avoid a collision between the International Space Station (ISS) and artificial pellets. The de-orbit method of nearly 100 km was achieved by carrying a membrane deployment structure, called a DOM, developed by our research group. The deployment succeeded in the orbit and increased the satellite’s acceleration rate drastically. This operation established a passive orbital control method using the micro atmosphere around the Earth. ALE-2, developed as the successor model of ALE-1, was launched by the Electron of RocketLab in December 2019 at an altitude of 400 km. It did not have a DOM mechanism because the de-orbit requirement was not imposed. On the other hand, a reaction control system (RCS) due to cold gas propulsion for microsatellites has been newly developed by Patchedconics, LLC. and installed on the satellite to enable active orbital maneuver [5]. The RCS technology enables high-speed orbital transition, which has been difficult with conventional microsatellites. It also allows the release point to design accessible, making it possible to observe shooting meteors at any location on the ground. Unfortunately, ALE-1 and ALE-2 have been unable to release meteors in orbit due to a defect in the meteor release mechanism. However, they have achieved new technological demonstrations on microsatellites and essential contributions to satellite development. This paper illustrates the thruster operations results performed by ALE-2 and lessons learned for future microsatellite development.

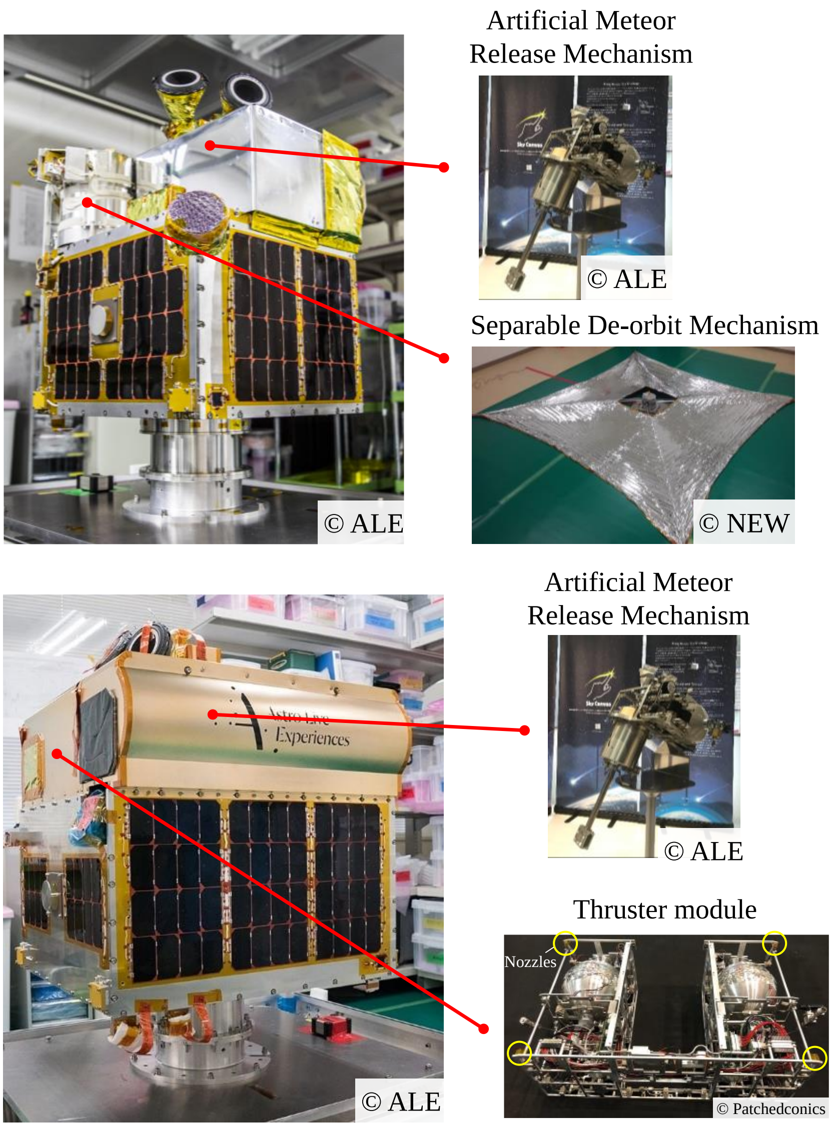


Figure 1. Flight model of ALE satellites (top: ALE-1, bottom: ALE-2).

2. SPECIFICATIONS

The Attitude Control Unit (ACU) system of ALE-2 is described; the ACU performs attitude and orbit calculations by the onboard computer and manages the power supplied by the Power Control Unit (PCU). The Thruster Control Unit (TCU) handles power and communication interactions between the ACU and the thruster modules. Figure 2 shows an overview of the satellite and its coordinate system definition. For the thruster module, the liquid propellant is loaded in the main tank, which is self-pressurized to generate gas, and the gas enables constant pressure in the buffer tank. The module has functions of temperature and pressure control; the heater of the heat exchanger is of PWM specification that can be automatically controlled to the target temperature only during pressure control. The pressure control logic is based on setting the lower and upper-pressure limits and automatically opening the valve when the pressure falls below the lower limit and closing the valve when the pressure rises above the upper limit. The pressure control can generate a thrust of 3–10 mN per unit. The thruster control algorithm uses a table lookup method with a quaternion feedback regulator shown in Figure 3 [6]– [7]. First, highly accurate attitude determination is performed using an Extended Kalman Filter (EKF) based on the inputs from the geomagnetic and gyro sensors. The error between the current and the target attitude is calculated, and the attitude maneuver for the next step is determined based on the attitude error. To eliminate control instability, a Schmitt trigger function with hysteresis characteristics applies to $\boldsymbol{T}_t$ values. Selects the thruster combination from a table that achieves the required attitude maneuver. The torque is derived from the thruster's position and thrust vector. When the thruster controls, the reaction wheels do not operate from a power aspect of the satellite battery. Only four thrusters can perform three-axis attitude control by tilting 15 degrees against the x-axis in the body coordinate system. The target attitude is defined to be geocentrically oriented so that the -Xb direction in the body coordinate system faces the flight direction. Because of simple implementation, this is based on the Local Vertical, Local Horizontal (LVLH) attitude. By maintaining this attitude and injecting the opposite to the flight direction, the semi-major axis of the satellite can be increased. Also, the satellite's orbital period can be extended. There are two types of in-planes and out-of-plane for orbital control. In this study, only in-plane control is used for trajectory change to facilitate operation as planned.

Size	W 555.7 × D 656.2 × H 707.0 mm	
Weight	75 kg	
Orbit	Sun-synchronous Orbit, 400 km	
Sensor	Star tracker × 3, Gyroscope × 3, Sun Sensor × 3 Geomagnetic Sensor × 2, GPS Receiver × 2	
Actuator	Reaction Wheel × 3 , Magnetorquer × 3 Thruster module	
Thruster module	Size	485 × 485 mm
	Weight	9.3 kg (Wet), 7.3 kg (Dry)
	Propellant	R600a (2 kg)
	Number of nozzles	4
	Total Impulse	1400 Ns
	Operation Temperature	0-60 ℃
	Power Consumption	~1.1 W

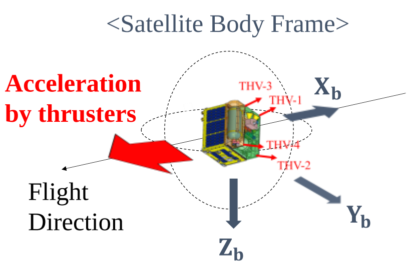
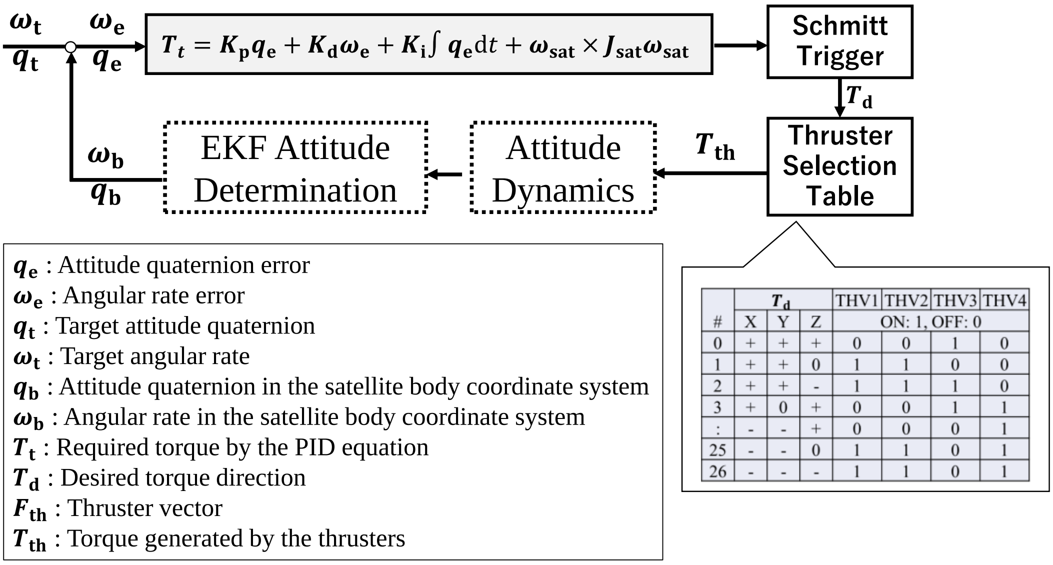


Figure 2. Components and satellite coordinate system.



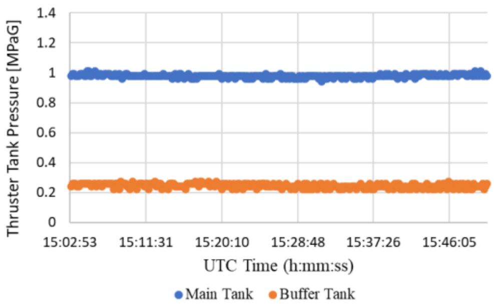
#	T_d			THV1	THV2	THV3	THV4
	X	Y	Z	ON: 1, OFF: 0			
0	+	+	+	0	0	1	0
1	+	+	0	1	1	0	0
2	+	+	-	1	1	1	0
3	+	0	+	0	0	1	1
:	-	-	+	0	0	0	1
25	-	-	0	1	1	0	1
26	-	-	-	1	1	0	1

Figure 3. Thruster control algorithm.

3. THRUSTER CONTROL IN NOMINAL

This chapter describes the thruster control operation strategies [8]– [9]. In order to reduce the load on the power supply of the satellite bus system due to power consumption while using the thruster, the thruster operation is limited to when the satellite is in the sunshine. After ending up in the eclipse, the satellite must set intervals to charge the battery. The charging is generally completed in approximately ten minutes. After charging the battery, the thruster control starts to maneuver to the target attitude, and the attitude control by only the thrusters is completed within ten minutes. The operation does not perform an active attitude maneuver using the reaction wheels to reduce unnecessary power consumption during battery charging. The attitude maneuver is completed, and orbital control is performed while the satellite is in the sunset. The duration of orbital control performs for 35 minutes to prevent the satellite from using the thruster not to start the eclipse. The thrust level is proportional to the pressure adjustment value of the pressure in the buffer tank. The satellite consumes the propellant in the main tank, which stores as a liquid and vaporizes it when the thruster uses. As long as a liquid remains in the main tank, the pressure of the main tank shows a constant value of the vapor pressure of the propellant. This paper defines the state where liquid remains in the main tank as the nominal state. The operation result in the nominal state shows in Figure 4. This figure shows the operational conditions, the attitude control error, the angular rate error, the main and buffer tank pressure and the temperature, thruster injection time, the number of opening valves, and the amount of altitude ascending while the orbital control performs three times. During orbital control, the satellite can control the attitude and angular rate. The pressure history shows that the thrust level is constant, and the propellant remains. The history of injection times for each thruster shows a bias toward THV-3, and this is due to the position error of the center of gravity. The maximum number of opening valves is set to two simultaneously to reduce the power load. Concerning the constraints, the thruster table is designed. The fraction of opening one valve accounts for close to 50 % of the total, and two valves are used at approximately 25 percent, and the remaining 25 % when thrusters are not injected. The amount of the altitude ascending can calculate based on the Two-Line Elements (TLE) provided by the Combined Space Operation Center (CSpOC). As a result, the satellite altitude can increase an approximately 150 m in 35 minutes at an altitude of around 393 km. Next, the thrust efficiency in each operation is derived. Assuming a Hohmann orbit transfer, the efficiency can be estimated from the relationship between the amount of velocity change required to increase 1 km from an altitude of 393 km and the amount of altitude change based on the TLE. The efficiency was estimated to be 50–60 %, contributing to the velocity change.

Operation time	15:07:19 UTC, Apr. 4, 2022
Operation sequence	15:07:19 UTC Start attitude control (10 min) 15:17:19 UTC Switch to orbital ascending control (35min) 15:52:19 UTC Stop thruster control
Thruster gas control	Within 0.223-0.240 MPaG
Thrust level	Approximately 5.45-5.85 mN in each nozzle



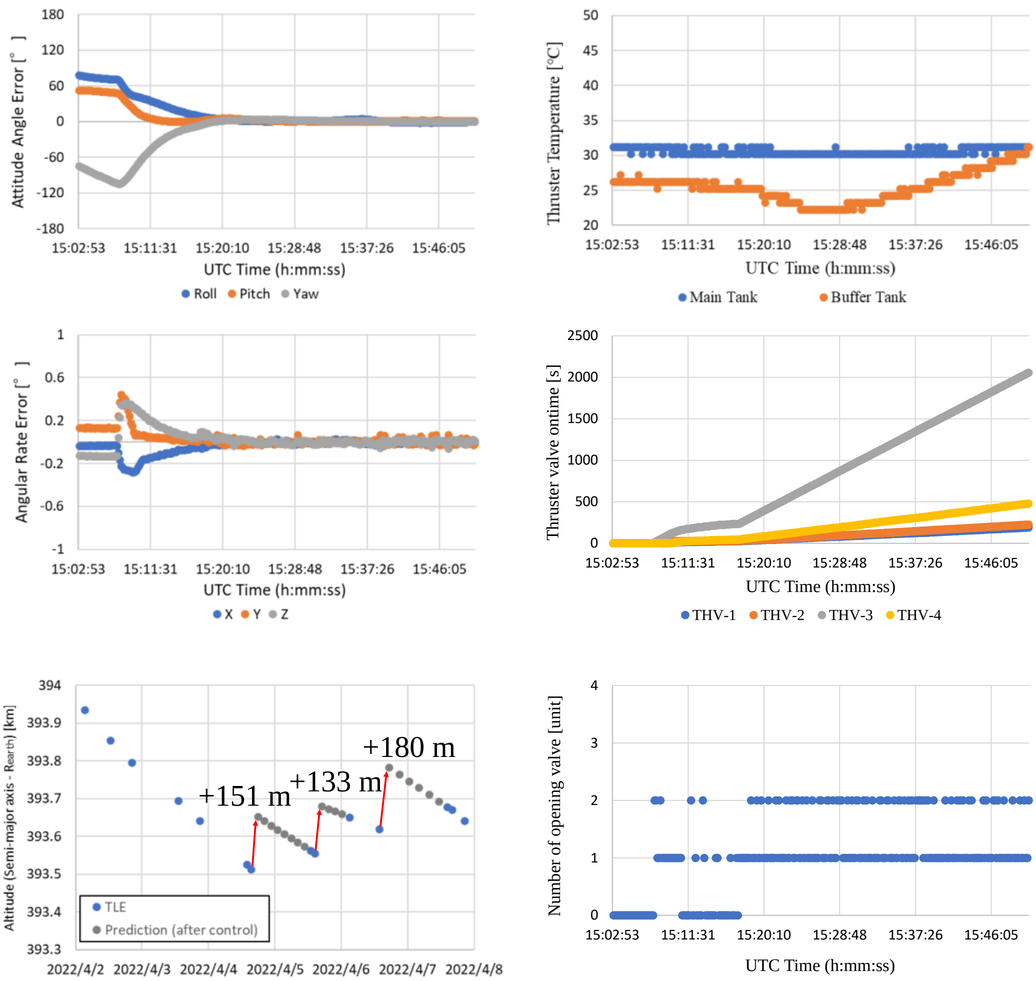
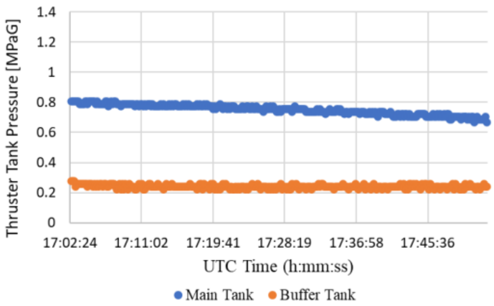


Figure 4. Thruster operation flight data (Nominal state).

4. THUSTER CONTOL IN BLOWDOWN

The operation moved to the blowdown state, where the satellite consumed most of the propellant in the main tank through repeated thruster control in the nominal state. Figure 5 shows the flight data of the orbital control in the state. The satellite can establish attitude control; however, accuracy is worse than nominal time. The pressure in the main tank decreased due to the thruster injection, and the temperature in the buffer tank did not decrease because all the liquid in the main tank vaporized. The altitude ascending due to the operation is barely visible in the TLE evaluation method. At around 375 km, the amount of orbital descent due to atmospheric drag is too large, so the altitude ascending by this control is minimal. Increasing the altitude with the thrust level seems complicated if the satellite altitude decreases to approximately 375 km. The main tank pressure drops by about 0.10 MPaG during 35 min of thruster control, which means that the pressure can be estimated to drop to the buffer tank pressure within a few times operations after the start of the blowdown. The satellite enters a blowdown state when approximately 97.5 % of the installed fuel mass is used, based on the relationship between the density property of gas and liquid at a vapor pressure of 0.70 MPa. Therefore, the satellite completed thruster control operations until most of its propellant was consumed.

Operation time	17:07:32 UTC, Oct. 4, 2022
Operation sequence	17:07:32 UTC Start attitude control (10 min) 17:17:32 UTC Switch to orbital ascending control (35min) 17:52:32 UTC Stop thruster control
Thruster gas control	Within 0.223-0.240 MPaG
Thrust level	Approximately 5.45-5.85 mN in each nozzle



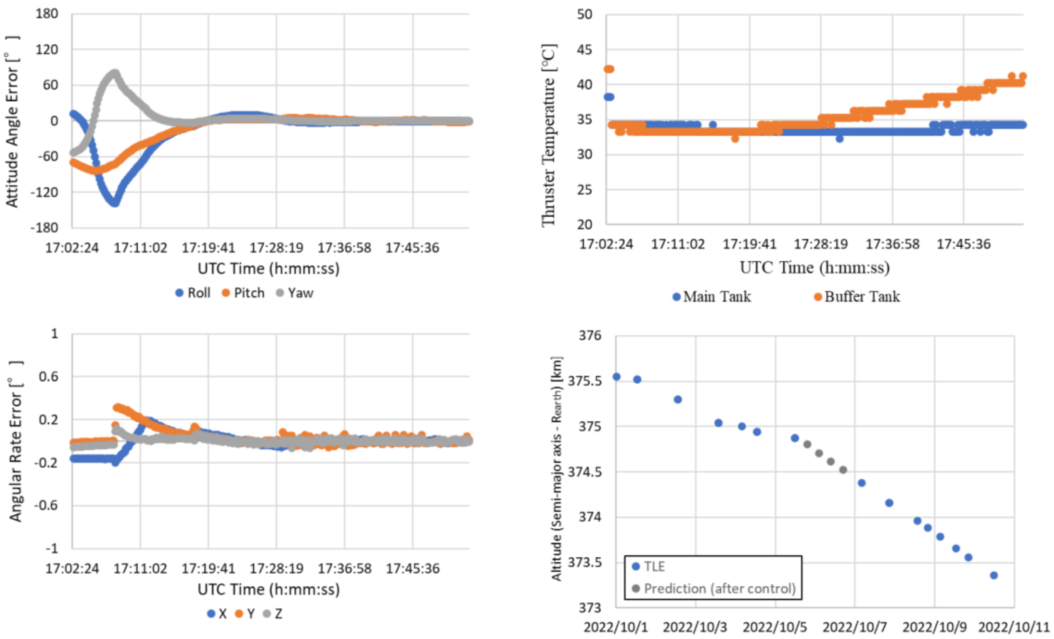


Figure 5. Thruster operation flight data (Blowdown state).

5. OPERETION REVIEW

The flight history of ALE-2 is shown in Figure 6. The altitude decreased dramatically after passing 400 km altitude, and the satellite re-entered to the earth on April 18, 2023, according to the TLE information issued. ALE-2 has performed 100 thruster control operations in orbit, injected for 96 hours, and increased an altitude of more than 20 km. The time indicates that ALE-2 can demonstrate the thruster specification in orbit as expected, assuming that 1–2 nozzles were used for thruster control. The operational results were satisfactory as a low-thrust propulsion system for microsatellites and completed more than two years of thruster operation. Finally, we describe the problems that occurred during the operation of the thruster control. The logic circuit unexpectedly drops down when the below events occur.

- Thrusters operate in shaded condition.
- 3-4 thrusters at high frequency and simultaneous injection
- The battery charge rate before the start of thruster control is less than 92 %.

In this satellite, the events could not be anticipated during evaluations on the ground, and they became apparent only after being launched in orbit. This operation trouble had happened at the proportion of one-third of the total operation. However, during an anomaly operation, the autonomous fault detection, isolation, and recovery (FDIR) function worked properly to shut down the thruster power supply and prevent a critical hazard with the thruster system. By turning the thruster power on again when the next operation performs, the operation could be carried out promptly. A lesson learned for future microsatellite development is to be able to restart the power supply after thruster trouble happens automatically. In ALE-2, if the power supply goes down due to an anomaly, it is impossible to continue the thruster control afterward unless the operator is commanded from the ground. Given that the number of operation times per day is limited, consecutive control failures will lead to failure to transit the satellite into the desired orbit, which is a disadvantage for active orbital control. Based on this experience, autonomous thruster operation will be essential.

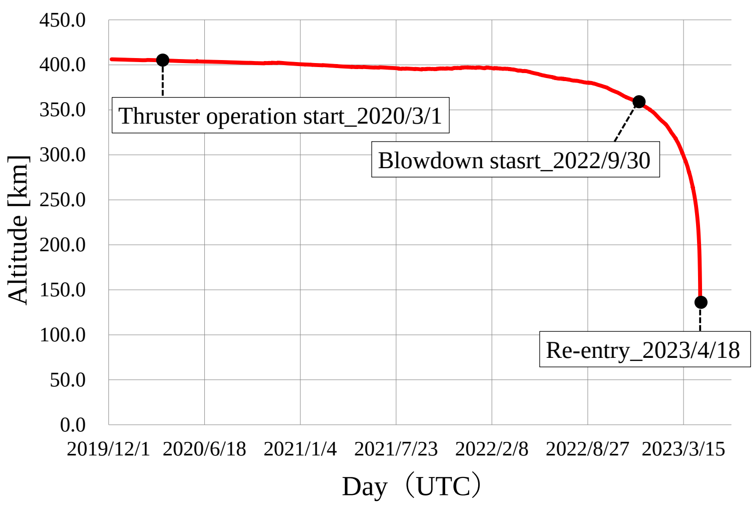


Figure 6. Flight history of ALE-2 based on TLE.

6. CONCLUSIONS

This paper reported in-orbit operation results using a newly developed thruster system for microsatellite ALE-2, developed at Tohoku University and ALE Co., Ltd. to demonstrate released artificial meteors. Both attitude and orbital control of the satellite using the thruster system, which Patchedconics developed, LLC., worked adequately in orbit. It was shown that the satellite's orbit could be changed freely. Next, it was confirmed that the thruster status had shifted to the blowdown state after the installed propellant was almost consumed. Furthermore, operational troubles that became apparent in orbit did not lead to fatal problems in both the satellite and thruster systems. This thruster operation could be continued by simply revising the operation plan. Unfortunately, the meteor-releasing demonstrations from this satellite could not be realized due to hardware troubles. However, the thruster control operation was successful nearly 100 times before the satellite re-entered the earth, and the thruster performance similar to the ground was illustrated. In conclusion, the development and operation results for ALE-2 significantly contributed to establishing orbital control technologies for microsatellites. In the future, based on the knowledge obtained from this development, our research group will improve the system for autonomous control of the thrusters and challenge the thruster technology that has been proven in the microsatellites to the CubeSat class satellites, aiming at diversification of their missions by active orbital control.

7. REFERENCES

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