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The Epsilon Guidance and Control System Contributing to the High Accuracy Injection into the Orbit of the Flights

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Abstract
The fourth flight of the Epsilon launch vehicle was successfully conducted in January, 2019. The Epsilon successfully delivered a total of seven satellites into Sun Synchronous Orbit (SSO) as its first rideshare mission. In order to correspond to this mission, a new Guidance and Control (G&C) system was developed. This paper first introduces the outline of G&C system of the Epsilon. Then, we describe newly developed G&C system for the rideshare option. Finally, we describe the flight result of the fourth Epsilon.

1. Introduction

In January 2019, the fourth Epsilon launch vehicle successfully launched from Uchinoura Space Center (USC) in Kagoshima, Japan and carried a total of seven satellites into the individual orbits. It was the first multiple payload mission for the Epsilon since its first launch in September, 2013.

The Epsilon launch vehicle was developed by Japan Aerospace Exploration Agency (JAXA), and IHI AEROSPACE Co., Ltd. (IA) functioned as the rocket system integrator. The Epsilon is a three-stage solid propellant launch vehicle, which has technology inherited from two Japan's launch vehicles, H-IIA launch vehicle and M-V launch vehicle. After its first launch, JAXA developed the Enhanced Epsilon, which has enlarged payload usable volume of a satellite and improved launch capability, in order to respond to the needs for satellites.

The Epsilon has three features for payload-friendliness: high injection accuracy, comfortable environmental conditions and short launch campaign. Firstly, the Epsilon could inject its payload into the orbit with high accuracy equivalent to the liquid propellant rocket because of the Post Boost Stage (PBS), an optional liquid stage equipped upon the third stage. The PBS has conventional hydrazine thrusters for 3-axis attitude control and orbit maneuvering. Secondly, the Epsilon has comfortable environmental conditions for satellites because of its low sinusoidal vibration with newly designed Payload Attach Fitting (PAF) and low acoustic vibration by modified launch facilities and soundproof blanket inside the payload faring. Thirdly, the launch campaign period is shortened by an automatic checking system. The basic concept of this system is to prevent serious accidents with a computer detecting any human errors. Furthermore, it contributes to decreasing the campaign period.

The first Epsilon was launched with "HISAKI" on September 14, 2013. HISAKI was successfully injected into Low Earth Orbit (LEO, 950 km x 1150 km and 29.7° of inclination) with high accuracy of +6.87 km for apogee altitude, +4.05 km for perigee altitude and +0.0 degrees for inclination. The second flight of the Epsilon was conducted in 2016 and "ARASE" was injected into elliptical orbit (219 km x 33200 km and 31° of inclination) without PBS. In 2018, the third Epsilon was launched and delivered "ASNARO-2" into 500 km SSO with high accuracy of +1.545 km for semi-major axis, and -0.033° for inclination. In this way, the past three Epsilons has demonstrated three features above, especially its capability of accurate injection of a payload into the orbit, but those launches were only for a single payload.

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The rapid technological improvements caused more and more start-up companies or universities to develop their own satellites, which increased demand for more launch opportunities for smaller satellites. In this situation, JAXA planned to develop a rideshare configuration of the Epsilon in order to respond to those demand for launch and to provide a high accuracy injection and comfortable environmental condition for smaller satellites.

This paper first introduces the outline of Guidance and Control (G&C) system of the Epsilon. Then, we describe newly developed G&C system for the rideshare option. Finally, we describe the flight result of the fourth Epsilon.

Figure 1: Fourth Epsilon launch vehicle

2. Outline of the Epsilon launch vehicle

Outline of the Epsilon launch vehicle is shown in Table 1. The Epsilon is the three-stage solid propellant launch vehicle, and has optional liquid stage, PBS. The enhanced Epsilon, the second launch and later, has the capability of carrying payloads up to 590 kg in SSO and 365 kg in elliptical orbit.
Figure 2 shows the flight sequence of the optional configuration (with PBS).

Table 1: Outline of the Epsilon

	The Enhanced Epsilon
Height	26 m
Diameter	2.6 m
Mass	95.4 ton
Configuration	three-stage solid propellant motor & optional Post Boost Stage (PBS)
Launch capability	590 kg (SSO 500 km) 365 kg (Elliptical orbit 200 km x 30000 km)

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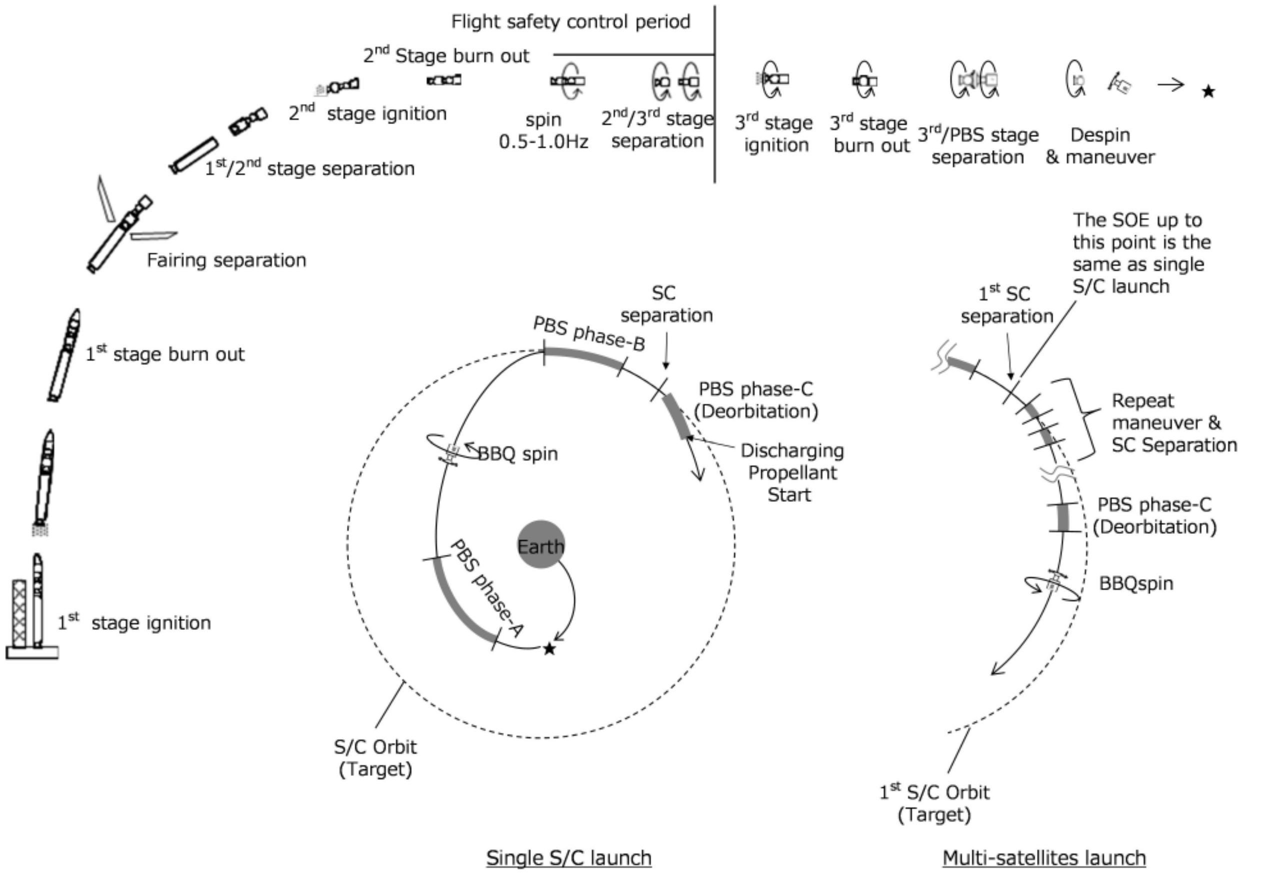

Figure 2: Flight sequence of the optional configuration (with PBS)

3. Guidance and Control System

3.1 Outline of Guidance and Control System of the Epsilon

The G&C system of the Epsilon is summarized in Figure 3 and Table 2. The first and the second stage are solid rocket motors with Movable Nozzle Thrust Vector Control (MNTVC) system. The third stage is a solid rocket motor not with MNTVC but with spin stabilizing. The optional fourth stage is the PBS, which has conventional hydrazine thrusters to compensate the orbit error in the solid phase.

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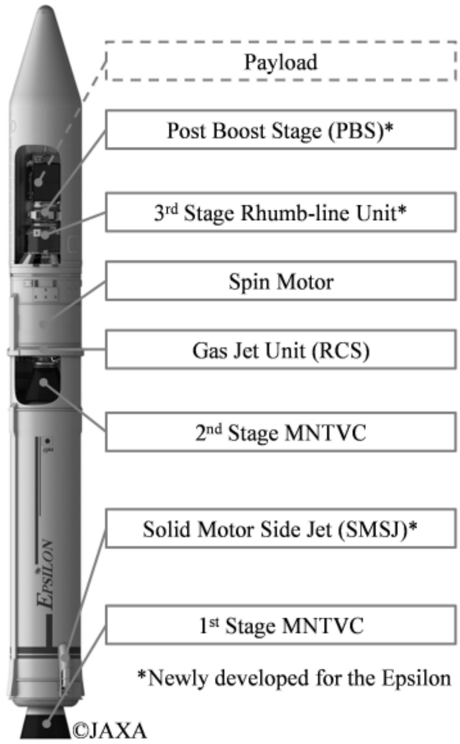

Figure 3: Configuration of Epsilon launch vehicle (G&C system)

Table 2: G&C system of the Epsilon

	Guidance	Attitude Control	
PBS	Explicit guidance	PBS thruster control (R/P/Y)	
third Stage**	Implicit guidance	Rhumb-line control*** (pointing direction)	
second Stage	Implicit guidance	Coasting	RCS (R/P/Y)
		Powered	RCS (R) MNTVC (P/Y)
first Stage	Implicit guidance	Coasting	SMSJ (R/P/Y)
		Powered	SMSJ (R) MNTVC (P/Y)

**Spinning stage
***Optional control system and not equipped second launch and later.

3.2 Solid Motor Side Jet (SMSJ)

M-V launch vehicle had 8 units of Solid Motor for Roll Control (SMRC) & SMSJ equipment which has 2 valves for roll control during powered flight and 3-axis control during coasting phase. On the other hand, SMSJ for the Epsilon has 3 valves (Hot Gas Valve: HGV) in order to reduce the total cost by integrating the functions of SMRC & SMSJ. As a result of that, SMSJ units were reduced from 8 units to 2 units. These SMSJ units are used for roll control during first stage powered flight and for 3-axis control during the coasting phase before first/second stages separation.

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Therefore, its combustion time is very long as over 171 s. Solid propellant of the SMSJ has high level storage property, safeness, and reliability, comparing to liquid propellant.

Figure 4 shows the appearance of the SMSJ of the Epsilon. Figure 5 shows firing of the SMSJ at the launch pad. The Epsilon lifts off 10 s after the SMSJ is ignited in order to confirm normally ignition of the SMSJ. In the past four flights, the SMSJ has demonstrated its high reliability; it worked as expected and flawlessly.

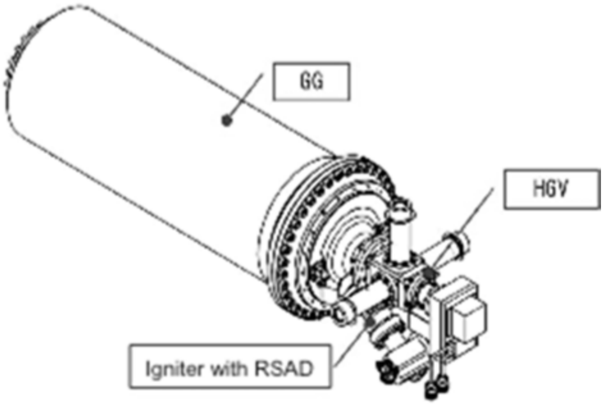

Figure 4: SMSJ of the Epsilon

Figure 5: Firing of SMSJ at the launch pad

3.3 Rhumb-line control system

Figure 6 shows the appearance of the rhumb-line control system, and its control logic. The rhumb-line control is performed after the separation of second/third stages in order to reduce the third stage pointing error. The third stage pointing error is mainly caused by the following factors:

(a) Measurement error of Inertia Measurement Unit (IMU)
(b) Dispersion of spin motor performance

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(c) Disturbance at second/third stages separation
(d) Disturbance at third stage ignition

These factors make influence on the direction of the angular momentum vector of a spinning vehicle. The application of the rhumb-line control contributes to reduce the resulting pointing error by producing compensatory angular momentum. This can be achieved in the way that the rhumb-line thruster ejects an impulsive jet in each spin cycle. As a result, the Epsilon has obtained a capability to inject a satellite into more accurate orbit than M-V launch vehicle.

In addition to the reducing the pointing error, the rhumb-line control also benefits the PBS phase. Because the orbital error, which is to be corrected in the PBS phase, is reduced by the third stage rhumb-line control, the PBS propellant mass can be saved. This means that the payload capability increases as a result of applying the rhumb-line control.

In this way, more accurate injection and higher launch capability can be achieved with rhumb-line control. However, rhumb-line control needs an additional thruster system and, therefore, has an additional cost. We set rhumb-line control as an option, and can select according to individual mission. In the past four flights, the first Epsilon equipped the rhumb-line control system.

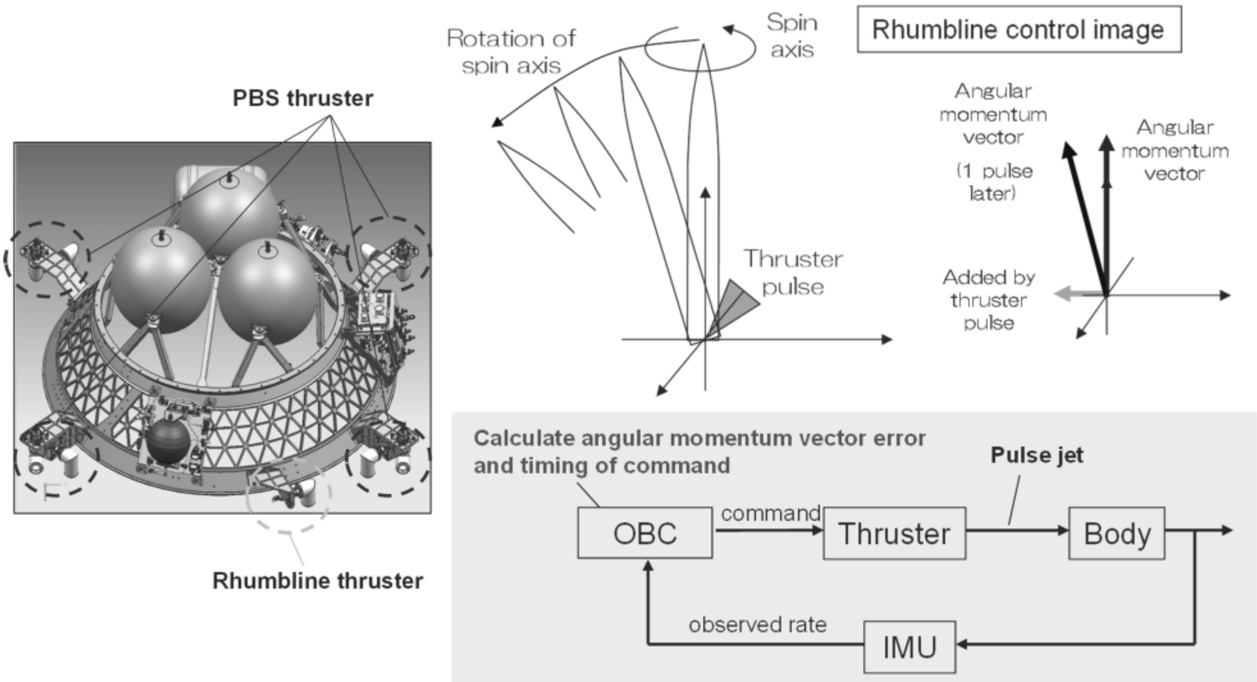

Figure 6: Rhumb-line control system

3.4 PBS guidance system

Figure 7 shows the image of PBS guidance. The guidance is achieved in two steps: phase-A and phase-B. In phase-A, the Epsilon guides into a Hohmann transfer orbit. In phase-B, it guides into the target orbit, in which the satellite is separated.

Long-time Velocity Increment Cut-off (LVIC) method derived from conventional VIC method is adopted for PBS with liquid propulsion system. The PBS system is composed of 8 thrusters; 4 thrusters are used for main thrust and pitch/yaw control and the other 4 thrusters are used for roll control. Thrust level is about 50 N per unit. Total main thrust is about 200 N and relatively low. LVIC guidance is suitable for such low thrust and long-time maneuver. This method enabled us to use existing thrusters with low cost and high reliability. This also made it possible for us to share the use of main thrusters with the use of attitude control.

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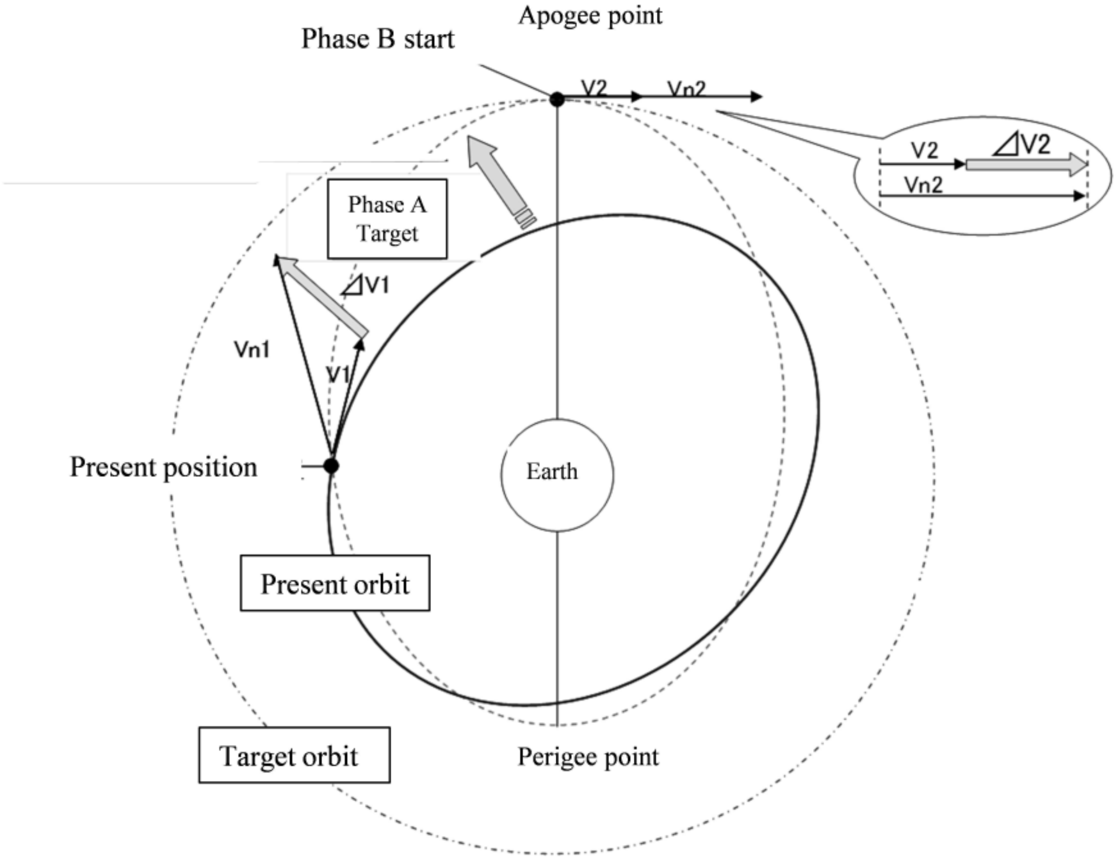

Figure 7: Image of PBS guidance

3.5 Newly developed G&C system

Until the third flight of the Epsilon, single launch missions, the number of the guidance execution in the PBS phase had been fixed to 3 times: Phase-A and Phase-B as described, and Collision and Contamination Avoidance Maneuver (CCAM) after separating a payload.

For the rideshare mission, Flight Software (FSW) was improved so that number of guidance steps can be chosen in order to inject each payloads into individual orbits. Moreover, the newly developed guidance mode, the relative altitude guidance mode, was applied to the fourth Epsilon. This guidance mode is used to change each separation altitude relative to the previous orbit in order to avoid collision with the satellite separated earlier. Depending on the mission, either the relative altitude guidance mode or conventional absolute altitude guidance mode could be chosen.

As for control, the improved control method can deal with changes in the inertia and the center of gravity, which is caused by step-by-step separation of the payloads.

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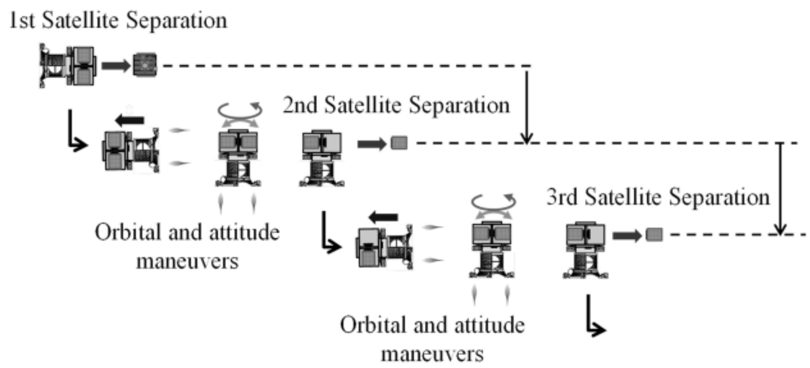

Figure 8: Sequence of multiple orbit injection

4. Flight Result of the fourth Epsilon

The fourth Epsilon was launched on January 18, 2019 and carried multiple satellites selected by Innovative Satellite Technology Demonstration Program into desired orbits. This program aims to provide opportunities for the demonstration of equipment, parts, spacecraft and CubeSats developed by start-up companies, universities, etc. Seven satellites shown in Table 3 were selected for this program.

Table 3: Satellites selected by JAXA's Innovative Satellite Technology Demonstration Program

Satellite	Size	Mission(s)
RAPIS-1	200 kg class	Perform orbital demonstration of the components and equipment selected in the Innovative Satellite Technology Demonstration Program
MicroDragon	60 kg class	Earth observation for expanding satellite usage
RISESAT	60 kg class	High-resolution/multi-spectrum earth observation
ALE-1	60 kg class	Verifying the feasibility of generating man-made meteor showers
OrigamiSat-1	3U	On-orbit demonstration of Multi-Functional Deployable Membrane Structure
Aoba VELOX-IV	2U	On-orbit demonstration of the attitude/orbit control and low-light camera
NEXUS	1U	On-orbit demonstration of next generation amateur satellite communication technology

Figure 9 shows the flight path of the fourth Epsilon. The Epsilon flew as expected and injected all seven satellites into the orbit. The difference in the duration of the first PBS maneuver is a result of the error in the solid phase, which is corrected in the PBS phase.

Figure 10 shows the results of injection accuracy for all seven satellites. As this graph shows, the newly developed relative altitude guidance mode and improved control method were well functioned.

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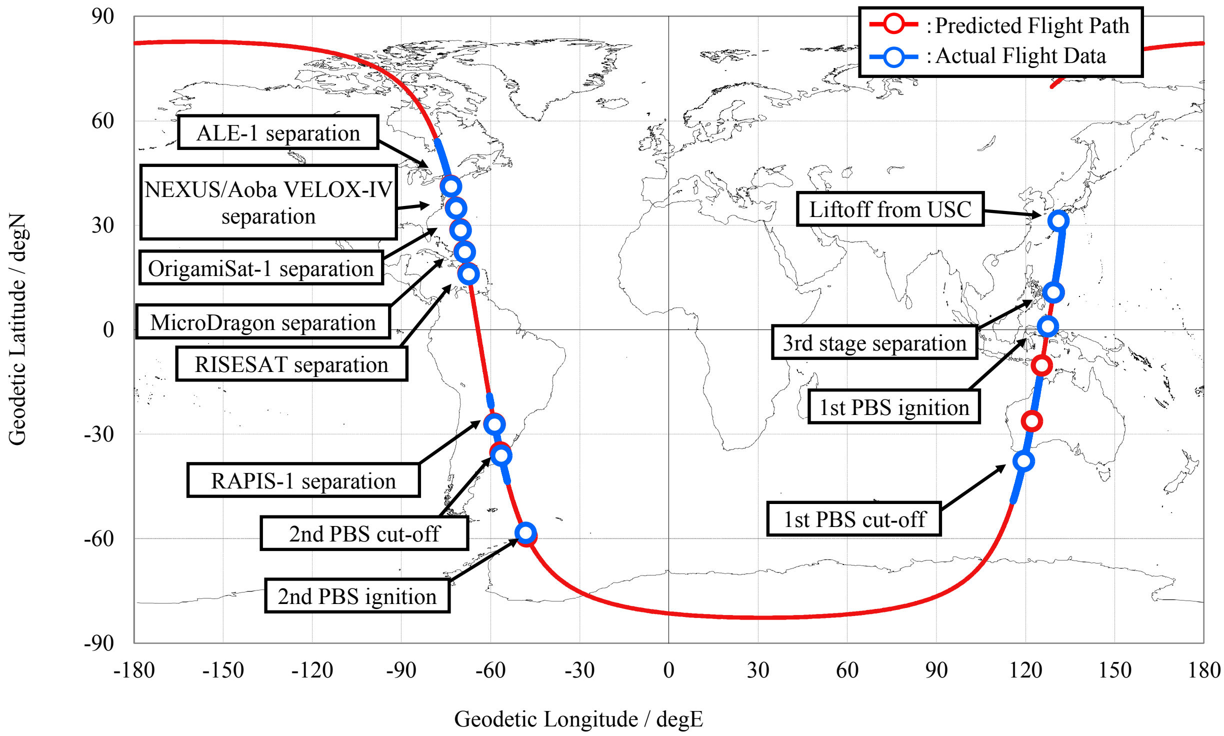

Figure 9: Flight path of the fourth Epsilon

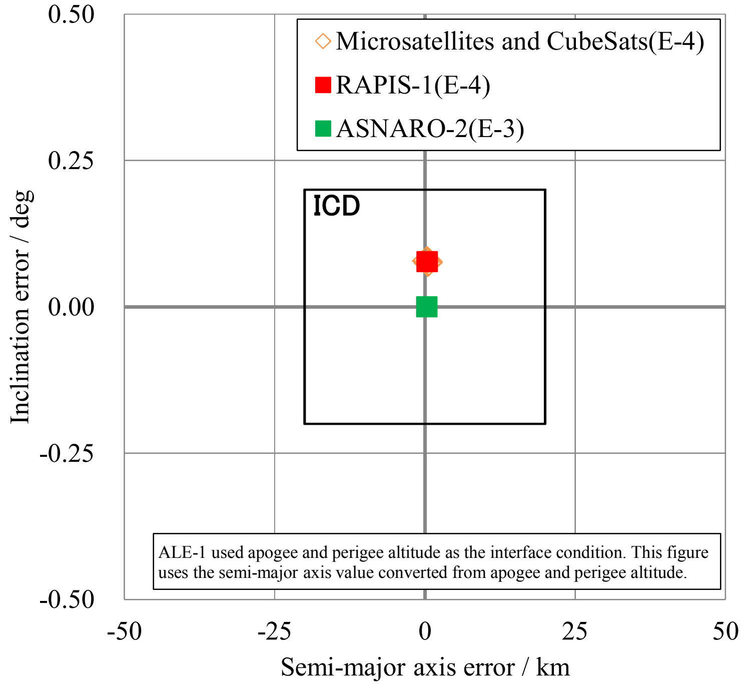

Figure 10: Injection accuracy of the third and the fourth Epsilon

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5. Conclusion

A new guidance method was applied to the fourth Epsilon in order to respond the increasing demand for rideshare mission. The relative altitude guidance mode is used to change each separation altitude relative to the previous orbit in order to avoid collision with the satellite separated earlier.

The first rideshare mission for the Epsilon was successfully conducted. A total of seven satellites were injected into their planned orbit with high injection accuracy. This indicates that the newly developed G&C methods were well functioned.

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