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EQUULEUS: Initial Operation Results of an Artemis-1 CubeSat to the Earth―Moon Lagrange Point

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ABSTRACT

EQUULEUS is a 6U CubeSat developed by the Japan Aerospace Exploration Agency (JAXA) and the University of Tokyo, aiming to reach the Earth-Moon second Lagrange point (EML2) and perform scientific observations there. After being inserted into a lunar transfer orbit by SLS Artemis-1 on November 16, 2022, the spacecraft completed checkout operations and successfully performed a delta-V maneuver and subsequent trajectory correction maneuver. This enabled a precise lunar flyby as planned and successful insertion into the orbit toward EML2, which will take advantage of multiple lunar gravity assists and the gravity of the Sun. EQUULEUS is equipped with a water propulsion system newly developed by the University of Tokyo, and became the first spacecraft in the world to successfully control its orbit beyond low Earth orbit using water propulsion. The successful precise orbit control in the Sun–Earth–Moon region by EQUULEUS, a 6U CubeSat weighing only 10kg, has opened the possibility of full-scale lunar and planetary exploration by CubeSats. This paper describes the early operational results of EQUULEUS during its flight to EML2, with special emphasis on its precise orbit determination, guidance, and control results.

INTRODUCTION

In recent years, there have been efforts to perform deep space exploration using nano-satellites (1–10 kg) and micro-satellites (~50 kg), which are much smaller than conventional spacecraft.[1,2] These activities are being conducted not only by space agencies but also by universities and private companies. As the first step of these attempts, the University of Tokyo and the Japan Aerospace Exploration Agency (JAXA) jointly developed and launched the 50-kg-class deep space exploration micro-spacecraft PROCYON (PRoximate Object Close flYby with Optical Navigation) in December 2014, which became the world's smallest full-scale deep space probe at the time of its operation. During its one-year flight in deep space, PROCYON successfully demonstrated a 50-kg-class deep space exploration bus system and performed scientific observations in deep space.[3,4,5] This success demonstrated that deep-space exploration with ultra-small spacecraft was viable and that it could be a useful tool for future deep-space exploration. Since then, there has been a trend to challenge deep space exploration with smaller spacecraft, or CubeSat, and two 6U CubeSats MarCO-A and MarCO-B, launched with InSight Mars mission in 2018, became the first CubeSat to successfully operate in the vicinity of Mars.[6]

Recently, more and more small deep space missions using CubeSats are being planned. 10 CubeSats were launched as secondary payloads onboard the first flight of NASA's SLS (Space Launch System) in November 2022. SLS is NASA's next-generation heavy launch vehicle to carry astronauts beyond Earth's orbit to the Moon and eventually to Mars. The first flight, called "Artemis-1" provided accommodations for a maximum of thirteen 6U CubeSats into a lunar flyby trajectory, whose size are about 10x20x30cm and weight is limited to 14kg. JAXA provided two 6U CubeSats named EQUULEUS (EQUilibriUm Lunar-Earth point 6U Spacecraft) and OMOTENASHI (Outstanding MOon exploration TEchnologies demonstrated by NAno Semi-Hard Impactor) respectively. This paper provides an overview of the EQUULEUS mission, the spacecraft design and development results, and the initial operation results of its mission to the Earth–Moon Lagrange point with special emphasis on its precise orbit determination, guidance, and control results.

MISSION OVERVIEW

The primary objective of the mission is the demonstration of the trajectory control techniques within the Sun–Earth–Moon region (e.g. low-energy transfers using weak stability regions) for the first time by a nano-spacecraft. For this purpose, the spacecraft will fly to a libration orbit around the Earth–Moon L2 point (EML2) by using multiple lunar gravity assists (LGAs).[7,8] An illustrative example of the trajectory design is shown in Figure 1[9], which includes three orbital maneuvers (DV1, 2 and 3) and three lunar gravity assists (LGA1, 2 and 3).

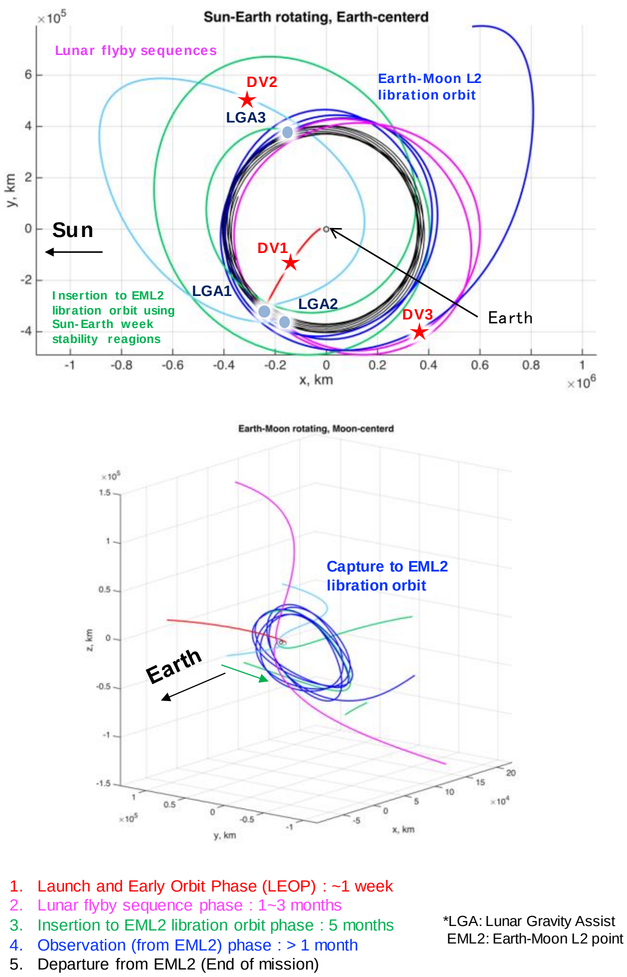

Figure 1: Illustrative example of EQUULEUS trajectory design to EML2.

After the spacecraft is injected into the lunar transfer orbit by the launch vehicle, it must perform the first orbital maneuver operation (DV1) to raise the perilune altitude and remain in the Earth–Moon system after the first lunar flyby. Otherwise, the spacecraft will escape into deep space via the lunar swing-by. After successfully completing this most critical orbit maneuver operation, the spacecraft will fly within the Earth–Moon system, occasionally performing orbital maneuvers, to reach a libration orbit around EML2.[10] After performing various scientific observation missions in EML2, the spacecraft will leave the Earth–Moon system to complete the mission.

In addition to the engineering demonstration mission, EQUULEUS carries three scientific observation missions[11]: imaging of Earth's plasmasphere by extreme UV wavelength, lunar impact-flash observation on the far side of the moon, and micrometeoroid flux measurements in the cis-lunar region. While all these missions have their own scientific objectives, they will also contribute to future human activity and/or infrastructure in the cis-lunar region. These observations are performed during the flight to EML2 and after arrival at EML2.

SPACECRAFT SYSTEM DESIGN AND DEVELOPMENT RESULTS

Figure 2 and Figure 3 show the exterior and interior views of the spacecraft.

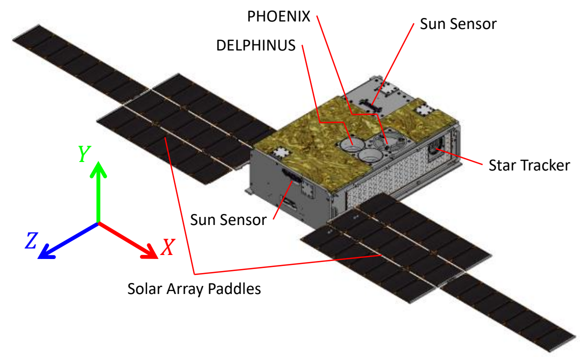

Figure 2: External view of EQUULEUS.

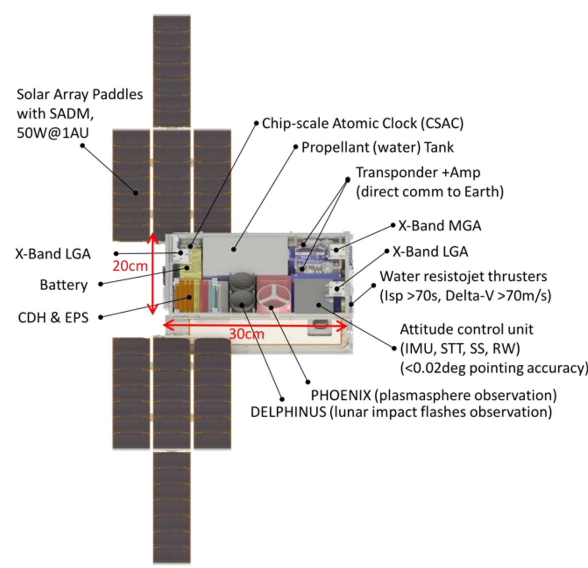

Figure 3: Internal configuration of EQUULEUS.

The spacecraft system was developed jointly by JAXA and the University of Tokyo.[7] The attitude control system and solar array paddles were procured from Blue Canyon Technologies (BCT) and MMA Design, respectively, with slight customizations to their off-the-shelf products. Most of the other onboard components were developed using COTS parts, leveraging the heritage of PROCYON and other 50 kg class LEO missions. The deep space X-band transponder which had been demonstrated on PROCYON[12] was redesigned to significantly reduce its volume to fit within the CubeSat envelope. The propulsion system had to be developed almost entirely from scratch. AQUARIUS (AQUA ResIstojet propUlsion System), a resistojet propulsion system using water as a propellant, was developed to satisfy the EQUULEUS mission requirements while using a safe propellant.[13]

Development of the spacecraft began in 2016, with PDR completed in September 2016, CDR in June 2018, and PQR in December 2020, and the completed spacecraft was delivered to NASA in July 2021.

INITIAL OPERATION RESULTS

After EQUULEUS was delivered to NASA in 2021, troubles with the launch vehicle, SLS, and weather problems caused the launch attempts on August 29 and September 3, 2022, to be postponed, with the final launch on November 16, 2022, from the Kennedy Space Center.

Table 1: Critical operation timeline reflecting the actual operation results. The time in the table is in UTC.

Start	End	Station	Operation event
			11/16 6:47 Launch
			11/16 10:28 EQUULEUS separated, automatic sun acquisition control started
11/16 10:33	11/16 13:05	Madrid	Initial checkout (SADA, sun sensor, STT, heater)
11/16 16:50	11/16 18:20	Goldstone	Initial checkout (heater)
11/16 18:25	11/17 4:25	USC(JAXA)	Transition to three-axis attitude control, propulsion system checkout, test maneuvers
		Madrid Goldstone	DV1 preparation (DV1 FDIR parameter adjustment, etc.)
11/17 19:14	11/18 5:11	UDSC (JAXA)	**DV1** (~6.4m/s) (Completed during visible period)
11/18 19:30	11/19 5:11	USC (JAXA)	DELPHINUS checkout
11/19 19:34	11/20 5:20	USC (JAXA)	**TCM1** (~0.84m/s)
11/21 11:00	11/21 13:05	Madrid	Preparation for lunar surface imaging
11/21 16:25		-	closest approach to the moon
11/22 20:48	11/23 5:04	UDSC (JAXA)	**TCM2** (~0.20m/s) **⇒Successful orbit injection toward EML2 confirmed**
11/25 9:35	11/25 22:53	UDSC (JAXA)	CLOTH checkout

Table 1 shows the timeline for the critical operation phase immediately after launch. It reflects the actual operational results. Due to trajectory design constraints, the first orbital maneuver operation (DV1) had to begin approximately one day after launch, and checkout of all necessary functions of the spacecraft, including the newly developed propulsion system, had to be completed by then. Operations were planned to be performed not only from the JAXA deep-space ground stations (UDSC, USC, and MDSS), but also from NASA's DSN during the hours when the spacecraft would not be visible from the JAXA stations, but this operation was still very time-critical.

The project team gained many Lessons Learned from this operational preparation work.[15] Time-critical one-shot events are inevitable for deep space missions. Especially, Artemis-1 launch opportunity was even more challenging since the mission had the critical event (i.e., orbital maneuver) immediately after the launch. In such a case, it is obviously important that the spacecraft hardware and software be fully verified prior to launch, but it is also important (1) to sophisticate the operational scenario by implementing a number of backup plans in case the spacecraft's on-orbit performance or operational progress is not as expected, and (2) to improve the skill of the operation team through repeated operation training. Such extensive preparation is possible only when the launch date is fixed and sufficient time is allowed for launch preparation. However, in our case, it was even more difficult because the launch was postponed several times. Under these circumstances, it was not realistic to prepare perfectly for each postponed launch candidate, but the operations team did their best to be as prepared as possible. Actually, backup procedures were prepared for various anomalies, and a backup trajectory was designed in case the propulsion system did not perform as expected. Also, the operations team conducted many pre-launch operational training to increase their skills and proficiency.

Despite these careful preparations, the checkout operation proceeded very smoothly after the first contact with the spacecraft, and the performance of the propulsion system was confirmed to be as expected, enabling DV1 to be carried out as planned.[16] After DV1, a trajectory correction maneuver (TCM1) was performed after precise orbit determination by DDOR (Delta-Differential One-way Range), and the first lunar flyby was successfully completed with the planned geometric conditions.

To demonstrate that the lunar flyby was executed as planned, the day-night boundary area on the far side of the Moon was photographed by the onboard camera at the time of the closest approach to the Moon (Figure 4). The captured area of the lunar surface was as expected, indicating that the spacecraft's orbit and attitude were precisely controlled.

The second trajectory correction maneuver (TCM2) was performed immediately after the lunar flyby, and EQUULEUS was confirmed to have been injected into its nominal trajectory toward EML2. To date, EQUULEUS has performed three delta-V maneuvers (DV1, 2 and 3) and eleven trajectory correction maneuvers (TCM1 to TCM11) (Table 2) with a total delta-V of approximately 17 m/s, and no more significant DV is required to reach EML2, which is planned for the end of 2023.

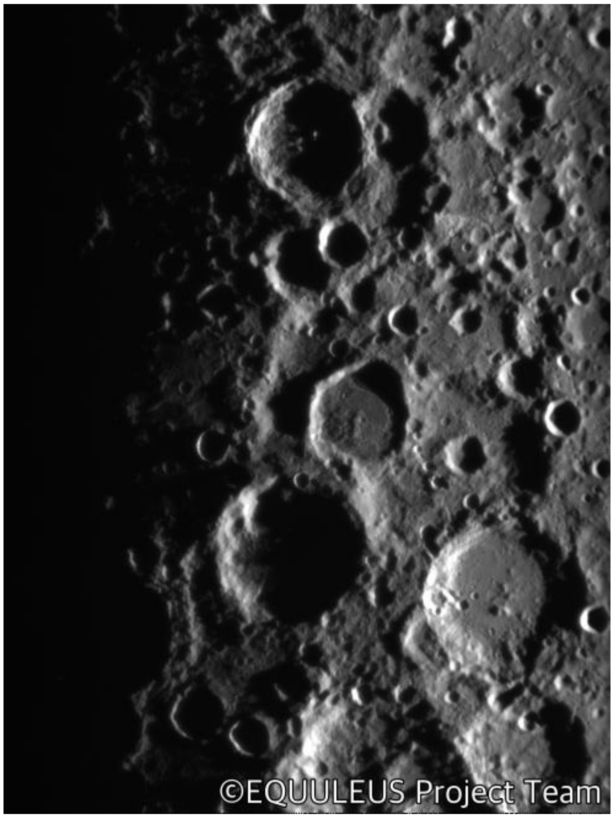

Figure 4: The day-night boundary area of the far side of the moon captured by EQUULEUS at 5:05 p.m. on Nov. 21 UTC during the lunar flyby (5550 km).[14]

Table 2: History of DV and TCM operations conducted to date.

Event	Date and time (yyyy/mm/dd hh:mm UTC)
DV1	2022/11/17 23:14
TCM1	2022/11/20 01:45
TCM2	2022/11/23 00:30
TCM3	2022/11/27 16:30
TCM4	2022/12/09 19:30
TCM5	2022/12/15 21:00
TCM6	2022/12/23 20:45
DV2	2023/02/03 18:30
TCM7	2023/02/07 18:30
DV3	2023/02/27 16:30
TCM8	2023/03/16 15:30
TCM9	2023/03/30 15:30
TCM10	2023/04/13 11:30
TCM11	2023/04/27 14:00

CONCLUSION

Not only space agencies but many research institutes and private companies are trying to explore deep space with nano-/micro-satellites. In this context, 10 6U CubeSats were launched into the lunar transfer orbit by NASA's SLS in November 2022.

One of the 10 CubeSats is EQUULEUS, jointly developed by JAXA and the University of Tokyo, which is flying to the second Earth–Moon Lagrange point (EML2) to demonstrate efficient orbit control technology in the Sun–Earth–Moon region and conduct various scientific observation missions. EQUULEUS' mission is extremely challenging, as the first orbital maneuver must begin approximately one day after launch, but the critical operation of EQUULEUS went very smoothly, and the spacecraft was successfully inserted into its nominal trajectory toward EML2 with extremely high accuracy. EQUULEUS has performed three delta-V maneuvers and eleven trajectory correction maneuvers with a total delta-V of approximately 17 m/s achieved.

The successful precise orbit control in the Sun–Earth–Moon region by EQUULEUS has raised the technological level of nano-/micro-satellites to a higher level, and we believe that more and more advanced exploration missions will be realized by such small satellites in the future.

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