EQUULEUS: Artemis-1 CubeSat to Successfully Demonstrate Trajectory Control Techniques Within the Sun—Earth—Moon Region to Enable Future Deep Space Missions by Small Satellites

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ABSTRACT

EQUULEUS is a 6U CubeSat jointly developed by Japan Aerospace Exploration Agency and the University of Tokyo. Its mission is to demonstrate efficient orbital maneuvering technology in the Sun—Earth—Moon region by a CubeSat, aiming to enable a CubeSat-class spacecraft to reach deep space on its own propulsion system. EQUULEUS was launched into a lunar transfer orbit on November 16, 2022, aboard the first flight of NASA's SLS launch vehicle. Immediately after separation, all bus functions of the spacecraft, including the propulsion system, were successfully checked out, completing preparations for orbital maneuver operations for the lunar swing-by in less than a week. EQUULEUS achieved an acceleration of about 6.5 m/s during the first orbital maneuver operation (DV1), followed by precise orbit determinations and two trajectory correction maneuvers before and after the timing of the lunar closest approach, which successfully inserted the spacecraft into a nominal orbit toward the second Earth—Moon Lagrange point (EML2) via lunar swing-by. EQUULEUS is equipped with a resistojet propulsion system that uses water as a propellant, and became the first spacecraft in the world to successfully transfer its orbit using water beyond low Earth orbit. EQUULEUS has successfully completed a total of 14 Delta-V operations, including orbital maneuver and trajectory correction maneuvers during its first lunar swing-by, which demonstrated the precise and highly fuel-efficient guidance, navigation, and control technology in the Sun-Earth-Moon region for a CubeSat-class spacecraft. This achievement is expected to enable small satellites released from lunar transfer orbit or lunar gateway to reach deep space using their own propulsion systems with limited propellant and to conduct deep space exploration missions with high frequency, taking advantage of the increasing logistics in the vicinity of the Moon in the future.

1 INTRODUCTION

Deep space exploration, previously carried out by space agencies, is now within the reach of research institutes and private companies through the emergence of small satellites. One of the pioneering efforts in deep space exploration using small satellites was PROCYON (PRoximate Object Close flYby with Optical Navigation), which aimed to demonstrate deep space bus technology using 50 kg-class microsatellites.[1] PROCYON was jointly developed by the University of Tokyo and JAXA and launched in December 2014 together with JAXA's asteroid sample return mission Hayabusa-2. During its one-year flight in deep space, PROCYON successfully demonstrated a 50 kg class deep space exploration bus, including the demonstration of a small deep space communication system[2] and a small Xe-based propulsion system integrating an RCS and ion engine[3], as well as successful scientific observations in deep space[4][5]. This success demonstrated that small satellites are a viable option for deep space exploration. Deep space exploration with smaller CubeSats was demonstrated with two 6U CubeSats, MarCO-A and B.[6] MarCO was launched with the Insight Mars landing mission in 2018 and successfully relayed data to Earth during the landing operation.

For launches to the Moon, a little closer than deep space, more and more launches have been carried out or are planned in recent years. 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 10 x 20 x 30cm and weight is limited to 14kg. JAXA provided two 6U CubeSats named EQUULEUS (EQUilibriUm Lunar-Earth point 6U Spacecraft)[7] and OMOTENASHI (Outstanding MOon exploration TEchnologies demonstrated by NAno Semi-Hard Impactor)[8] respectively. This paper provides an overview of the EQUULEUS mission, the spacecraft design and development results, and the operation results with special emphasis on its precise orbit determination, guidance, and control experiment results.

2 MISSION OVERVIEW

The primary mission of EQUULEUS is the demonstration of trajectory control technology in the Sun-Earth-Moon region for the first time by a nano-spacecraft.[9] In this region, by utilising lunar swing-by (or gravity assist) and solar tidal forces through high-precision guidance navigation and control, spacecraft with limited propulsion capabilities such as CubeSat are expected to be able to conduct various missions in the vicinity of the Moon or reach deep space. This technology is an important technology that should be acquired in order to conduct more frequent exploration of the Moon and deep space, making use of the increasing logistics in the vicinity of the Moon in the future.

For this demonstration mission, the final destination of EQUULEUS is set as the Earth—Moon second Lagrange point (EML2), and we aim to perform the guidance navigation and control experiments described above during the flight to the periodic orbit around EML2.[10] Figure 1[11] shows an example of the trajectory design to EML2, which includes three orbit transfer operations (DV1, 2 and 3) and three lunar gravity assists (LGA1, 2 and 3), requiring highly accurate guidance navigation and control to fly such a trajectory.

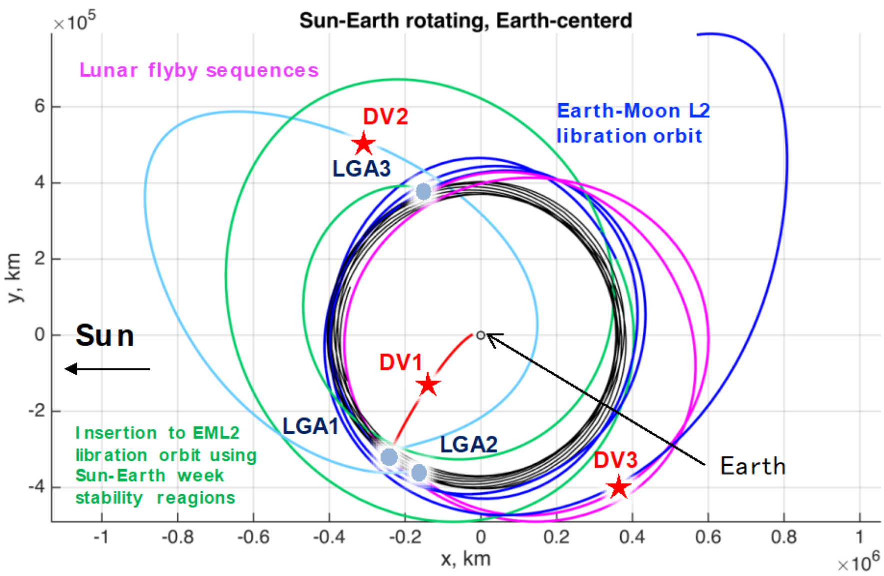

Figure 1. Illustrative example of EQUULEUS trajectory design to EML2.

In addition to the engineering demonstration mission, EQUULEUS carries three scientific observation missions[12]: imaging of Earth's plasmasphere by extreme UV wavelength, lunar impactflash 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 in the cis-lunar region. These observations are performed during the flight to EML2 and after arrival at EML2.

3 SPACECRAFT SYSTEM OVERVIEW

Figures 2 and 3 show the exterior and internal structure of the spacecraft. The spacecraft system was developed jointly by the University of Tokyo and JAXA. Much of the equipment was developed using the heritage of PROCYON and its predecessor (microsatellites in LEO). In particular, the small deep space transponder, which successfully communicated with the Earth and performed orbit determination from a distance of 60 million km for PROCYON, was further miniaturised and adapted to the CubeSat form factor.

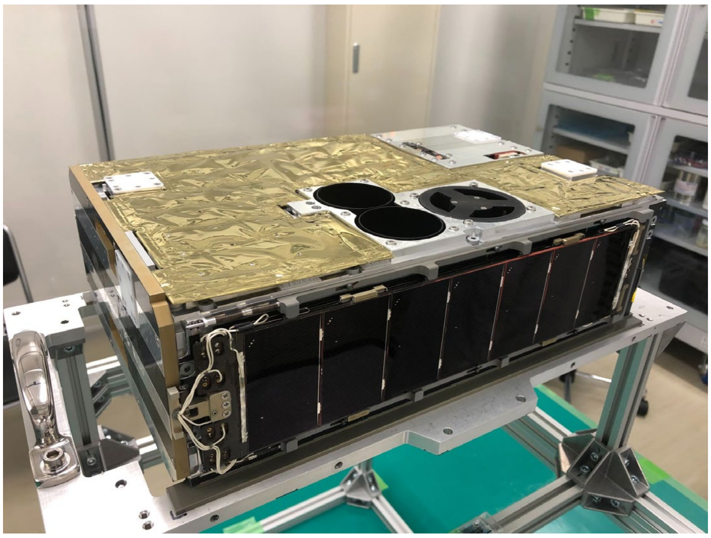

Figure 2. External outlook of EQUULEUS.

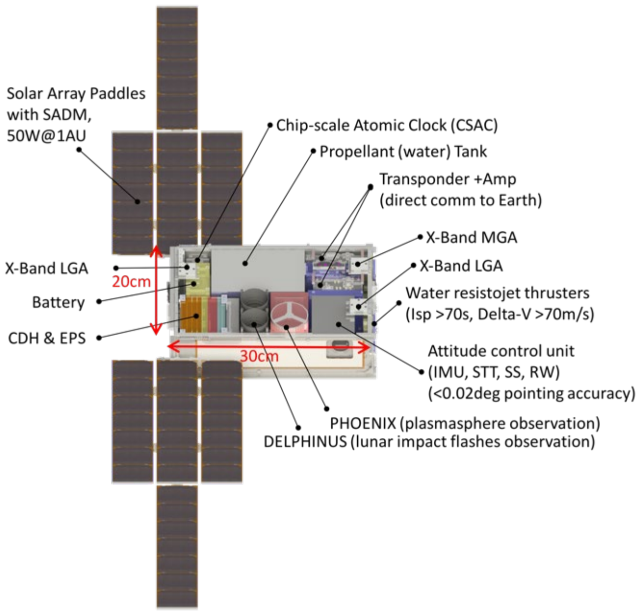

Figure 3. Internal configuration of EQUULEUS.

Many COTS components were also utilised, with the solar array paddles with gimbals being procured from MMA Design and the attitude control unit from Blue Canyon Technologies.
As a propulsion system for orbit and attitude control, we have developed a new propulsion system, AQUARIUS (AQUA ResIstojet propUlsion System)[13], which uses water as propellant. AQUARIUS has a specific impulse of 70s and provides EQUULEUS with an orbit transfer capability of approximately 70 m/s, enabling EQUULEUS to fly to EML2 and stay in the vicinity of EML2 for several months or more thereafter.
Development of the spacecraft officially started in 2016, with the PDR completed in September 2016, the CDR in June 2018 and the PQR in December 2020, and the spacecraft was finally delivered to SLS at NASA KSC in July 2021.

4 OPERATION RESULTS

4.1 Initial Operation Results

After two failed launch attempts, EQUULEUS was finally launched on November 16, 2022. The initial operations immediately after launch are shown in Table 1[14] as a timeline of events. It reflects the actual operational results. The most challenging aspect of this launch was the fact that if EQUULEUS flew in its released trajectory, it would go through its first lunar flyby and escape into deep space. To avoid this and to inject the spacecraft into a nominal orbit to EML2, the first orbit maneuver (DV1) had to be accomplished before the first lunar flyby, and the maneuver had to begin the day after the release due to spacecraft propulsion limitations and orbital dynamics. This required the spacecraft operations team to complete the checkout of the bus functions, including the newly developed propulsion system, on the day of the launch. Although the operations team had improved their skills to deal with various situations through pre-launch operations training, such time-critical operations are not typically experienced in normal CubeSat rideshare missions to LEO, and are considered a unique challenge for a rideshare launch opportunity to the Moon. The initial 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[15].

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

Thanks to preparation through pre-launch operational training, checkout operations immediately after release proceeded almost flawlessly. The spacecraft exhibited slightly higher-than-expected temperatures and deviated from the allowable temperature range of some components of the propulsion system in some attitudes, but this was resolved by devising the sequence of attitudes for operating the propulsion system and the start-up procedure for the equipment until the start of the propulsive maneuver. The performance of the propulsion system satisfied the design requirements[16]. The performance of all other bus equipment was normal, and all preparations for DV1 operations were completed as planned with two DSN passes immediately after launch, a subsequent JAXA station pass, and one subsequent DSN pass.
The DV1 operation was executed smoothly, achieving an acceleration of 6.48 m/s, slightly exceeding the target of 6.39 m/s. In addition to onboard predictions calculated from the propulsion system pressure and temperature, the achieved acceleration was monitored by the range rate (Doppler shift), because the DV1 operation was carried out within visible time from the ground station.
After DV1, the spacecraft trajectory after DV1 and the amount of acceleration achieved by DV1 were precisely evaluated through precise orbit determination operations via DDOR (Delta-Differential One-Way Range) using JAXA and DSN stations, and the first trajectory correction maneuver (TCM1) was performed on the fourth day. TCM1 achieved an acceleration of 87 cm/s almost exactly compared to the target acceleration of 84 cm/s. As a result, according to the subsequent orbit determination, we were able to fly the spacecraft within a few kilometers of accuracy on the B-plane during the lunar flyby, successfully injecting it into a nominal orbit to EML2. The small error caused by the lunar flyby was cancelled by TCM2 immediately afterward, and the spacecraft was confirmed to be precisely injected into the nominal orbit to EML2.
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[17]). The captured area of the lunar surface was as expected, indicating that the spacecraft's orbit and attitude were precisely controlled.

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).

4.2 Trajectory Control Experiment Results

Figure 5 shows the trajectory plan of EQUULEUS towards EML2 in the Sun-Earth fixed rotational frame. In this trajectory, the spacecraft can reach EML2 after three relatively large (more than a few m/s) orbital maneuver operations (which we call "DV" operations). During the periods outside of the DV operations, smaller orbit maneuver operations (which we call TCM operations) are carried out to cancel errors from the nominal planned trajectory. After completing the first lunar flyby on 22 November 2022 with DV1, TCM1 and 2, two DV operations and eight TCM operations were carried out as planned until April 2023. The orbit control accuracy was very high, on the order of mm/s to cm/s or better. It was also confirmed that no further DV operations were required to reach EML2.The total delta-V by these operations were approximately 18 m/s. After evaluating the results so far, the project team declared the trajectory control experiment mission in the Earth—Moon region to be successful.

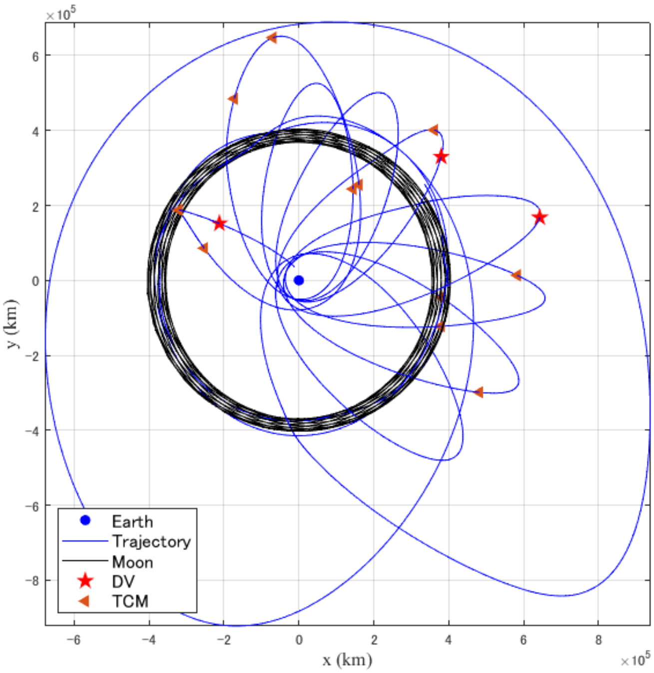

Figure 5. Trajectory of EQUULEUS towards EML2 in the Sun-Earth fixed rotating frame.

5 CONCLUSION

SLS Artemis-1, which launched ten CubeSats into orbit towards the Moon, was a major step towards the full-scale use of CubeSats for deep space exploration. One of the 10 CubeSats, EQUULEUS, was jointly developed by JAXA and the University of Tokyo, and its main mission was to demonstrate high-precision orbit control technology in the Earth-Moon region during its orbit towards EML2.
After EQUULEUS was launched on 16 November 2022, orbital maneuver and the first lunar flyby were carried out as planned, despite the very challenging situation that the first orbital maneuver operation had to be performed the following day. The trajectory control mission was a success, with a total of 14 orbit maneuvers carried out with a very high accuracy of mm/s to less than cm/s. Such orbit control technology is expected to enable future CubeSats released from Gateway or launched into orbit towards the Moon to access deep space with limited fuel, utilising lunar swing-by and solar tidal forces, which will open up the frequent deep space exploration by small satellites.

6 REFERENCES

[1] Ryu Funase, Takaya Inamori, Satoshi Ikari, Naoya Ozaki, Shintaro Nakajima, Hiroyuki Koizumi, Atsushi Tomiki, Yuta Kobayashi and Yasuhiro Kawakatsu, "One-year Deep Space Flight Result of the World's First Full-scale 50kg-class Deep Space Probe PROCYON and Its Future Perspective", SSC16-III-05, 30th Annual AIAA/USU Conference on Small Satellite, Utah, USA, 2016.

[2] Yuta Kobayashi, Atsushi Tomiki, Taichi Ito, Daisuke Kobayashi, Makoto Mita, Taku Nonomura, Hiroshi Takeuchi, Yosuke Fukushima, Ryu Funase and Yasuhiro Kawakatsu, "Low-cost and Ultimately-downsized X-band Deep-space Telecommunication System for PROCYON Mission", IEEE Aerospace Conference, Montana, USA, 2016.

[3] Hiroyuki Koizumi, Hiroki Kawahara, Kazuya Yaginuma, Jun Asakawa, Yuichi Nakagawa, Yusuke Nakamura, Shunichi Kojima, Toshihiro Matsuguma, Ryu Funase, Junichi Nakatsuka, Kimiya Komurasaki, "Initial Flight Operations of the Miniature Propulsion System Installed on Small Space Probe: PROCYON", *Transactions of the Japan Society for Aeronautical and Space Sciences, Aerospace Technology Japan*, Vol.14, No.ists30, pp.Pb_13-Pb_22, 2016.

[4] Yoshiharu Shinnaka, Nicolas Fougere, Hideyo Kawakita, Shingo Kameda, Michael R. Combi, Shota Ikezawa, Ayana Seki, Masaki Kuwabara, Masaki Sato and Makoto Taguchi, "Imaging observations of the hydrogen coma of comet 67P/Churyumov-Gerasimenko in September 2015 by the PROCYON/LAICA", *The Astronomical Journal*, Vol.153, No.2, pp.76-81, 2017.

[5] S. Kameda, S. Ikezawa, M. Sato, M. Kuwabara, N. Osada, G. Murakami, K. Yoshioka, I. Yoshikawa, M. Taguchi, R. Funase, S. Sugita, Y. Miyoshi, M. Fujimoto, "Ecliptic north-south symmetry of hydrogen geocorona", *Geophysical Research Letters*, Vol.44, Issue 23, 2017.

[6] Andrew T. Klesh, John Baker, Joel Krajewski, "MarCO: Flight Review and Lessons Learned", SSC19-III-04, 33rd Annual AIAA/USU Conference on Small Satellite, Utah, USA, 2019.

[7] Ryu Funase, Satoshi Ikari, Kota Miyoshi, Yosuke Kawabata, Shintaro Nakajima, et al., "Mission to Earth–Moon Lagrange Point by a 6U CubeSat: EQUULEUS", *IEEE Aerospace and Electronic Systems Magazine*, Vo.35, No.3, pp.30-44, 2020.

[8] Tatsuaki Hashimoto, Tetsuya Yamada, Masatsugu Otsuki, et al., "Nano Semihard Moon Lander: OMOTENASHI", *IEEE Aerospace and Electronic Systems Magazine*, Vo.34, No.9, pp.20-30, 2019.

[9] Stefano Campagnola, Javier Hernando-Ayuso, Kota Kakihara, Yosuke Kawabata, Takuya Chikazawa, Ryu Funase, et al., "Mission Analysis for the EM-1 CubeSats EQUULEUS and OMOTENASHI", *IEEE Aerospace and Electronic Systems Magazine*, Vo.34, No.4, pp.38-44, 2019.

[10] Kenshiro Oguri, Kenta Oshima, Stefano Campagnola, Kota Kakihara, Naoya Ozaki, Nicola Baresi, Yasuhiro Kawakatsu, Ryu Funase, "EQUULEUS Trajectory Design", *The Journal of Astronautical Sciences*, Vol.67, issue 3, pp.950-976, 2020.

[11] Ryu Funase, Satoshi Ikari, Yosuke Kawabata, Shintaro Nakajima, et al., "Flight Model Design and Development Status of the Earth―Moon Lagrange Point Exploration CubeSat EQUULEUS Onboard SLS EM-1", SSC18-VII-05, 32nd Annual AIAA/USU Conference on Small Satellite, Utah, USA, 2018.

[12] Satoshi Ikari, Masahiro Fujiwara, Hirotaka Kondo, Shuhei Matsushita, Ichiro Yoshikawa, Kazuo Yoshioka, et al., "Solar System Exploration Sciences by EQUULEUS on SLS EM-1 and Science Instruments Development Status", SSC19-WKV-04, 33rd Annual AIAA/USU Conference on Small Satellite, Utah, USA, 2019.

[13] Jun Asakawa, Hiroyuki Koizumi, Keita Nishii, Naoki Takeda, Masaya Murohara, Ryu Funase, Kimiya Komurasaki, "Fundamental Ground Experiment of a Water Resistojet Propulsion System: AQUARIUS Installed on a 6U CubeSat: EQUULEUS", *Transactions of the Japan Society for Aeronautical and Space Sciences, Aerospace Technology Japan*, Vol.16, No.5, pp.427-431, 2018.

[14] Ryu Funase, Shintaro Nakajima, Yosuke Kawabata, Ryota Fuse, Hokuto Sekine, Hiroyuki Koizumi, "EQUULEUS: Initial Operation Results of an Artemis-1 CubeSat to the Earth—Moon Lagrange Point", SSC23-WVII-03, 37th Annual AIAA/USU Conference on Small Satellite, Utah, USA, 2023.
[15] Shintaro Nakajima, Yosuke Kawabata, Ryota Fuse, Ryu Funase, "Lessons Learned from Operation Planning and Preparation for EQUULEUS Launched Toward the Moon by SLS Artemis-1", SSC23-WI-09, 37th Annual AIAA/USU Conference on Small Satellite, Logan, Utah, USA, 2023.
[16] Aoma Fujimori, Hokuto Sekine, Yasuho Ataka, Isamu Moriai, Mariko Akiyama, Masaya Murohara, Hiroyuki Koizumi, Ryu Funase, "AQUARIUS: The World's First Water-based Thruster Enabled 6U CubeSat to Complete Lunar Flyby", SSC23-VI-05, 37th Annual AIAA/USU Conference on Small Satellite, Logan, Utah, USA, 2023.
[17] EQUULEUS X (Twitter), https://twitter.com/EQUULEUS_en/status/1595261621454401536 (accessed April 15, 2024)