Lessons Learned from Operation Planning and Preparation for EQUULEUS Launched Toward the Moon by SLS Artemis-1

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ABSTRACT

EQUULEUS (EQUilibriUm Lunar-Earth point 6U Spacecraft) will be the world's smallest spacecraft to explore around the Earth–Moon Lagrange point, which was launched on November 16, 2022, by NASA's SLS (Space Launch System) Artemis-1. The primary mission of spacecraft is a trajectory control experiment, and its objective is to develop and demonstrate trajectory control techniques within the Sun-Earth-Moon region by flying to a libration orbit around the Earth-Moon Lagrange point L2 (EML2) along a low-energy transfer. EQUULEUS must perform a maneuver before the lunar flyby to stay within the Sun-Earth-Moon region. To perform DV1, we need to calculate and optimize the trajectory from launch to EML2. In addition, it is necessary to optimize the operation plan until the first lunar flyby, which is less than a week after launch. The reason for this is that the EQUULEUS trajectory will be significantly changed by the first lunar flyby, so appropriate trajectory control must be performed by that time. This paper presents the lessons learned in the operational preparation of EQUULEUS and those that should be applied to future missions to explore deep space, including the Moon and planets, by small and micro-satellites.

INTRODUCTION

Lunar and planetary exploration by micro spacecraft is gradually expanding: the launch of PROCYON[1] in 2014 demonstrated the possibility of interplanetary exploration by micro spacecraft, and MarCO[2] demonstrated the possibility of interplanetary exploration by CubeSat. The use of micro spacecraft is not only as child spacecraft or as an assistant of the main mission, but it is also becoming possible for them to explore on their own.

In addition to unmanned exploration, the Artemis program is underway as a manned lunar exploration and development. As a first step in this direction, the first flight of NASA's the Space Launch System (SLS) was conducted in November 2022. In the first flight, in addition to the lunar return experiment of ORION spacecraft, ten 6U CubeSats were launched. From Japan, two missions, EQUULEUS[3] and OMOTENASHI[4], were selected and launched.

Therefore, it is assumed that the number of launch opportunities around the Moon will increase in the future in connection with the Artemis program, and by utilizing the trajectory control technology established with EQUULEUS, it will be possible to take advantage of launch opportunities around the Moon to explore various objects such as temporarily captured orbiter (TCOs). This paper introduces Lessons Learned in the operational preparation of EQUULEUS, and describes what will be useful for similar missions in the future.

OVERVIEW OF EQUULEUS MISSION

The primary mission of EQUULEUS is a trajectory control experiment, and its objective is to develop and demonstrate trajectory control techniques within the Sun-Earth-Moon region by flying to a libration orbit around the Earth-Moon Lagrange point L2 (EML2) along a low-energy transfer. Figure 1 and Figure 2 show the illustrative example of EQUULEUS trajectory. EQUULEUS and other CubeSats launched by SLS Artemis-1 were deployed from the Orion Stage Adapter (OSA) after the SLS Interim Cryogenic Propulsion Stage (ICPS) performed a disposal maneuver. This ICPS disposal trajectory targets a heliocentric orbit via lunar flyby in less than one week after launch, so EQUULEUS must perform a maneuver before the lunar flyby to stay within the Sun-Earth-Moon region. This maneuver, called DV1, is the most important and critical part of our initial operations.

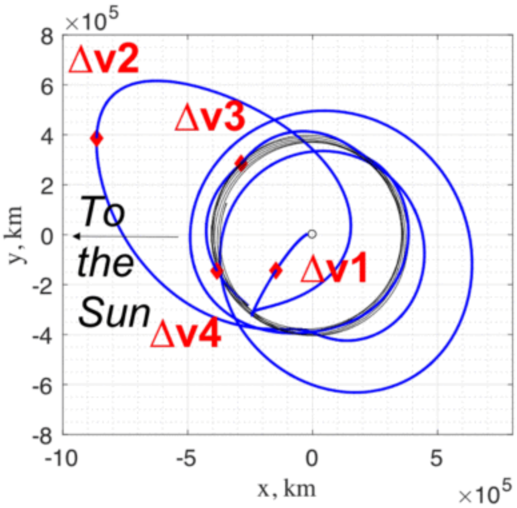

Figure 1: Illustrative example of notional EQUULEUS trajectory in the Sun–Earth rotating frame. [3]

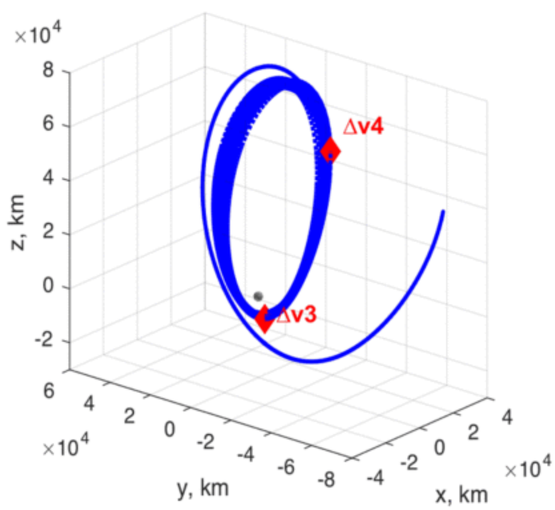

Figure 2: Illustrative example of arrival and science orbit in the Earth–Moon rotating frame. [3]

In addition, EQUULEUS equips three science instruments: the extreme UV telescope for imaging of Earth's plasmasphere (PHOENIX), the visible telescope for lunar impact-flash observation on the far side of the moon (DELPHINUS), and micrometeoroid flux measurements in the cis-lunar region (CLOTH).

OPERATION PLAN OF EQUULEUS

The overall operation plan of EQUULEUS is shown in Figure 3, which is divided into four phases: an initial phase of two weeks after launch (Launch and Early Operation Phase: LEOP), a phase to repeat the lunar swing-by, a phase to navigate the transfer orbit to EML2, and a phase after arrival at EML2.

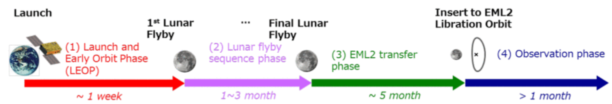

Figure 3: Overview of EQUULEUS operation phase: the period of each phase is just an example.[3]

Launch and Early Operation Phase (LEOP)

EQUULEUS will perform a lunar swing-by within a week of its launch by SLS. CubeSats, including EQUULEUS, will be released after ICPS disposal maneuver, so if trajectory control is not performed before the lunar swing-by, EQUULEUS will not be able to stay in the Earth-Moon region and will escape into deep space. Therefore, the objective of LEOP is to inject the spacecraft into a trajectory that will allow it to reach EML2, with the minimum goal of remaining in the Earth-Moon region. To achieve this objective, the first trajectory control, named DV1, is scheduled for approximately 40 hours after launch, and the operation plan is to perform trajectory correction maneuvers (named TCM1 and TCM2) before and after the lunar flyby. In order to implement these maneuvers, the propulsion system checkout must be performed immediately after launch in addition to the bus system checkout as soon as possible. Since this LEOP is a series of time-critical operations, operational milestones were set for each day, and operational items were determined in detail for each pass. The strategy to cope with this difficulty was to set critical operational items during the visible hours of the JAXA deep space stations, when sufficient operation time is likely to be available, and to conduct necessary operational items in the DSN station in between them.

Lunar flyby sequence phase and EML2 transfer phase

During the lunar swing-by and transition orbit navigation phase to EML2, periodic orbit determination and trajectory correction control based on this determination will be performed. Trajectory control planned in advance will also be performed. In addition to the above, science observations will be made by the onboard scientific instruments. The science observations to be conducted in this phase are imaging of the Earth's plasmasphere by PHOENIX and micrometeoroid observations by CLOTH. During these operation periods, the plan is to secure enough operation time to ensure orbit determination accuracy necessary to maintain the trajectory toward EML2, as well as the necessary timing and duration for scientific observations, etc., if needed. To achieve both of these goals, the operation time is planned to be 5 hours three times a week as the nominal operation time.

Observation phase at EML2

After the arrival of EML2, the operation plan will follow the same concept as the previous phase, which is to ensure that there will be enough operation time for orbit determination and orbit correction necessary to maintain the Libration Orbit around EML2, as well as enough operation time for scientific observations to be performed in this orbit. In this phase, in addition to the scientific observations in the previous phase, the lunar impact flash observations by DELPHINUS will be conducted, and if there is an overlap between the DELPHINUS and PHOENIX scientific observations, a meeting will be held to determine which operation will be conducted after confirming the conditions under which each observation can be conducted.

OPERATION PREPARATION

This section describes the preparations made for the actual launch based on the operation plans, especially for the initial operational critical operations.

First, operational procedures for each operation plan were prepared and verified through operational training prior to the delivery of the flight model to NASA. In particular, for the time-critical initial operations, the spacecraft was installed in a vacuum chamber and the propulsion system was actually operated to verify the operation procedures in real time, and if necessary, feedback was provided to the operation plan. After handover of the flight model to NASA in July 2021, we prepared an FM simulator based on the Engineering model, verified the operation procedures, and trained the operation team members. Figure 4 And Figure 5 show the external view of FM simulator and GSEs.

The EQUULEUS flight model had completed environmental tests by the end of 2019, so there was a three-year gap before launch in November 2022. In addition, the development of EQUULEUS was primarily carried out by graduate students at the University of Tokyo, and the turnover of people between the completion of the environmental tests and launch was a major challenge. In order to cope with this turnover of personnel, documents including design documents were prepared in advance, and periodic operational training was conducted after the launch date had been confirmed, so that the new members of the team would be able to operate the spacecraft.

SLS has about two weeks of launch dates approximately every month, shown in Figure 6, with a launch window of about two hours or less on each launch day. To perform DV1 during our initial operations, we need to calculate and optimize the trajectory from launch to EML2 for every launch candidate because the initial conditions of the trajectory will change depending on the launch date. Depending on this trajectory, the visible time from the ground station will change, as well as the attitude and the amount of acceleration of DV1. Related to the change in visibility time, the operational time at the NASA DSN station will change on each launch day. These changes in various operation times and events were reflected in the Sequence of Event (SOE), and scheduling of off-line work to be performed in parallel with the operations was conducted. Because of the huge amount of work involved, it was not possible to perform these tasks for all SLS launch dates. Therefore, these tasks were performed for the most likely launch dates when the launch dates were more certain.

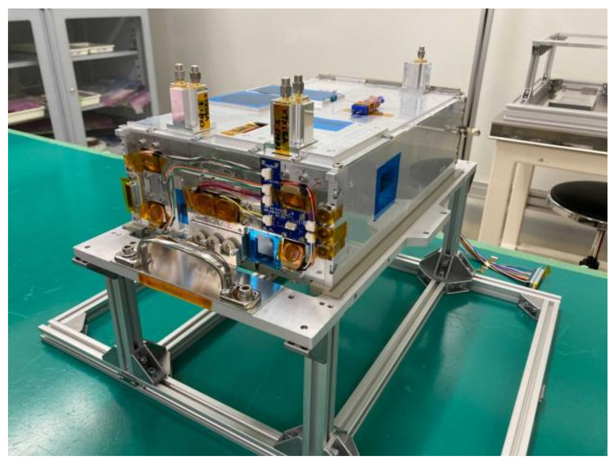

Figure 4: FM simulator of EQUULEUS.

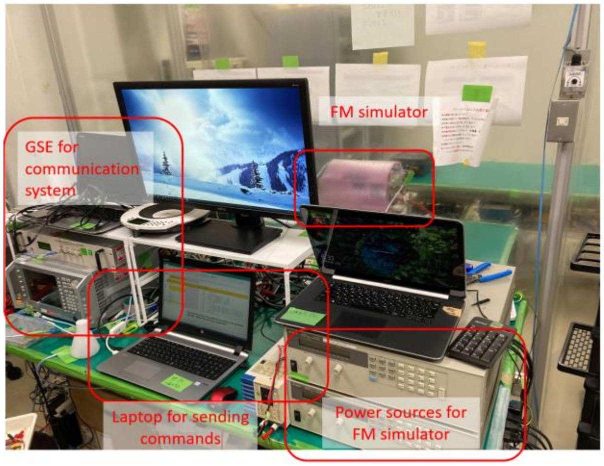

Figure 5: GSEs for operation training.

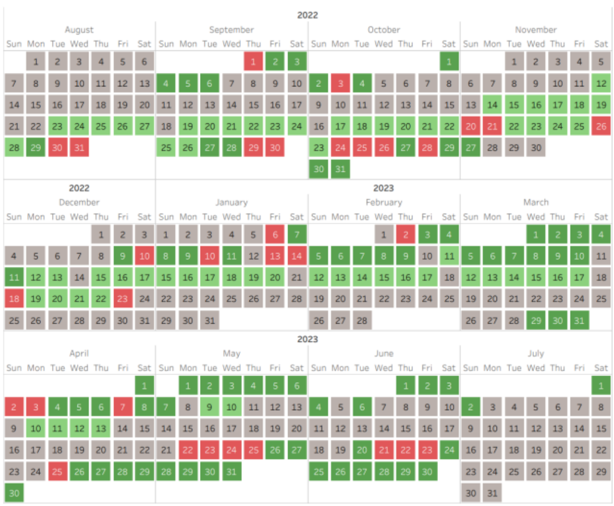

Figure 6: Artemis-1 mission availability, which is equal to SLS launch candidate.[5]

LESSONS LEARNED FROM OPERATION PREPARATION AND ACTUAL OPERATION

In this section, we present the lessons learned from the operational preparations and actual operations described in the previous sections.

In terms of operational preparation, the preparation for each SLS launch date was very hard. Full-scale operational preparations were made for two launch windows: the August 2022 launch window (LP-25) and the November 2022 launch window (LP-28). For LP-25, the launch date was initially announced as August 29 with backup dates of September 2 and September 5 [6]. As mentioned in the previous section, a lot of work was required for each launch date, so preparations were made for these dates. As you know, the August 29 launch was scrubbed and the next launch date was announced as September 3. For LP-28, preparations were made for a backup date other than the November 16 launch date set for Nominal, but the SLS was ultimately launched on Nominal's November 16 date.

The difficulties involved in preparing for these operations suggest that it is desirable to automate as much of the preparation per launch day as possible. In the case of the EQUULEUS operation plan, the trajectory design was so difficult that it could not be fully automated, and the people in charge of trajectory design became exhausted. In the case of future missions using similar orbit control technology, it is desirable to make the mission design a little more robust or to establish a system that enables full automation of the orbit design.

In order to visualize the actual operations and off-line works and the interfaces between each operation in chronological order, EQUULEUS team created an SOE using Excel. Although this SOE was useful in terms of visualizing the work and interfaces, it was difficult to re-create it every launch day. We believe this point can be improved by using more appropriate tools.

In terms of operational preparation, we believe that our strategy of setting a critical event at a visible location in Japan where we can ensure operational time, and using that as a milestone to plan operations in the intervening days worked very well. This strategy has allowed us to minimize changes in operational procedures in response to changes in launch dates. On the other hand, this strategy was only possible because JAXA was able to ensure the availability of the JAXA deep space stations, and we believe that a more robust method needs to be considered if more universities and institutions are to conduct planetary exploration using micro-exploration spacecraft.

CONCLUSION

This paper describes the operational planning and operational readiness strategy for EQUULEUS and its lessons learned, particularly with respect to the initial critical operations (LEOPs). EQUULEUS was launched on SLS and then used multiple lunar swing-bys and solar tidal forces to efficiently control its trajectory to EML2. Since there were multiple launch day candidates for SLS, a rough operational plan was made in advance and operational procedures were prepared, and more detailed operational preparations were carried out once the launch date was more certain. In addition, since there was a gap of nearly three years between the flight model environmental test and the launch, operational training was intensively conducted prior to the launch in order to cope with the change of members. The strategy of setting a critical event in the visibility of the JAXA deep space stations where the operation time can be ensured and planning the operation between the critical events as a milestone worked very well, but a more robust operation planning method and labor-saving work for each launch day are needed for similar missions in the future. However, for similar missions in the future, a more robust operational planning method and labor saving for each launch day will be necessary.

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