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Challenges and operations to re-establish communications with EQUULEUS after loss of contact during its cruise to the Earth-Moon L2 Point

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ABSTRACT

EQUULEUS (EQUilibriUm Lunar-Earth point 6U Spacecraft) is a 6U CubeSat developed by the University of Tokyo and JAXA. It was launched on November 16, 2022, aboard NASA's SLS Artemis-1 with the objectives of demonstrating orbital maneuvering capabilities in the cis-lunar environment and observing Earth's magnetosphere plasma. After completing its major orbital maneuvers and achieving full mission success, communication with EQUULEUS was lost in 18th May 2023. Rapid fault tree analysis and optical observations using large telescopes indicated the spacecraft was likely in an uncontrolled tumbling state. Recovery operations were planned to re-establish communication by identifying potential times for sufficient solar power generation. This paper describes the details of EQUULEUS's recovery operation.

INTRODUCTION

EQUULEUS (EQUilibriUm Lunar-Earth point 6U Spacecraft) is a 6U CubeSat developed by the University of Tokyo and the Japan Aerospace Exploration Agency (JAXA). The spacecraft was launched on November 16, 2022 as one of the ten secondary payloads onboard NASA's SLS Artemis-1. EQUULEUS has two mission objectives for full success: 1) demonstration of the orbital maneuvering capabilities of a CubeSat in the cis-lunar environment during a cruise to an Earth-Moon L2 (EML2) near-rectilinear quasi-Halo orbit, 2) observation of the magnetosphere plasma of the Earth.[1, 2]

While cruising towards the quasi-Halo orbit, EQUULEUS completed the major orbital control maneuvers necessary for its journey to EML2 and observed the magnetosphere plasma, which resulted in the achievement of full success. On the other hand, after the full success achievement, we were unable to acquire a signal in the middle of May 2023, which means that communication with EQUULEUS was lost. Generally, re-establishing communication with spacecraft is challenging because we cannot use telemetry data for troubleshooting and recovery.

Rapid estimation and identification of the spacecraft's status to re-establish communication is essential for seizing recovery opportunities. After losing communication, a prompt fault tree analysis was made from various aspects such as attitude, orbit, propulsion, power, and onboard software to estimate the EQUULEUS condition. Although radio communication using ground stations was not available during the communication failure, fortunately, we had the last close approach of EQUULEUS to Earth before reaching EML2 shortly after the communication loss. Thus, we called for cooperation from large astronomical telescopes around the world. As a result, optical observation of EQUULEUS was performed successfully by several large telescopes including the Subaru telescope. The observation results, showing the reflection and flickering of light from EQUULEUS, matched well with the tumbling period predicted by attitude simulations, suggesting that EQUULEUS is likely in an uncontrolled tumbling state. Based on the possible orientation of EQUULEUS's solar panels and attitude patterns, there are several candidates of the timings for communication through enough solar power generation. The recovery operation needs to re-establish communication without missing these opportunities and make the satellite to a proper state.

Accounting for the rotation frequency of EQUULEUS, the operational plan for the recovery is considered so that EQUULEUS can receive commands and send telemetry synchronously. Main commands include turning on the communication system components, switching antennas, and changing attitude modes. Uncertainties in satellite position and velocity from orbital determination, as well as solar radiation pressure (SRP), were considered for tracking, and a Monte Carlo method was used to search the region efficiently where the satellite could be.

This paper will report on the estimation of the problem after losing communication, the overview of the recovery operation, and the lessons learned. This study offers valuable insights into identifying causes and making communication recovery procedures for a relatively common failure mode of communication loss, contributing to troubleshooting for other satellite missions.

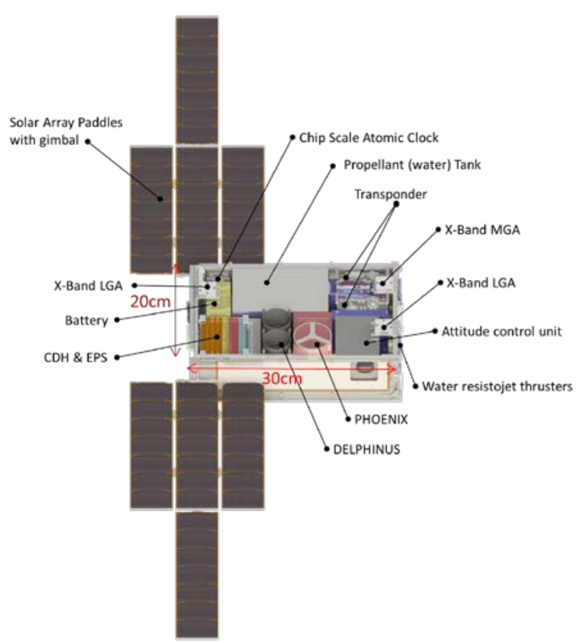

Figure 1: Schematic view of EQUULEUS

Table 1: EQUULEUS Specifications

Function	Detail
Mechanical& Structure	- 6U, with two wings of 4 SAPs(with gimbaling) - 10.26 kg (wet)
Propulsion	- Water Resistojet thrusters 0.64mN/59.8s x4 (RCT), - 4.09 mN/68.5s x2 (DVT)
Electrical Power System	- 50W@1AU, BOL,70degC - Li-ion, 31 Wh
Telecom	- X-band MGA x 1 - X-band LGA x 5 - Chip Scale Atomic Clock x 1
Attitude Control System	- Reaction Wheel x 3 - 3-axis MEMS Gyro - Sun Aspect Sensor x 4 - Star Tracker x 1

SPECIFICATION OF EQUULEUS

Figure 1 illustrates the schematic view of EQUULEUS. The specifications of the satellite are listed in Table 1. EQUUELUS has the fundamental functions for the deep space exploration. During its cruising, the attitude mode of EQUULEUS is three axis stabilized attitude control mode by using the attitude control unit provided by BCT. The propulsion performance is based on the flight results in the table.[4] EQUULEUS's trajectory control consists of Delta-V Thruster (DVT) operation and unloading by RCT. Then, the actual / average thrust magnitude is lower than the thrust performance of DVT. The Solar Array Panel (SAP) provided by MMA Design can rotate on a single axis and its rotation angle may change in response to unforeseen circumstances in terms of FDIR.

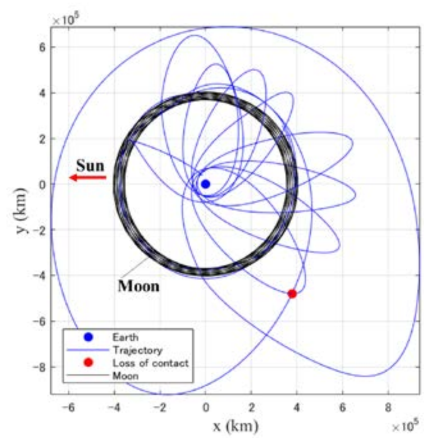

Figure 2: Nominal trajectory in Sun-Earth rotating frame

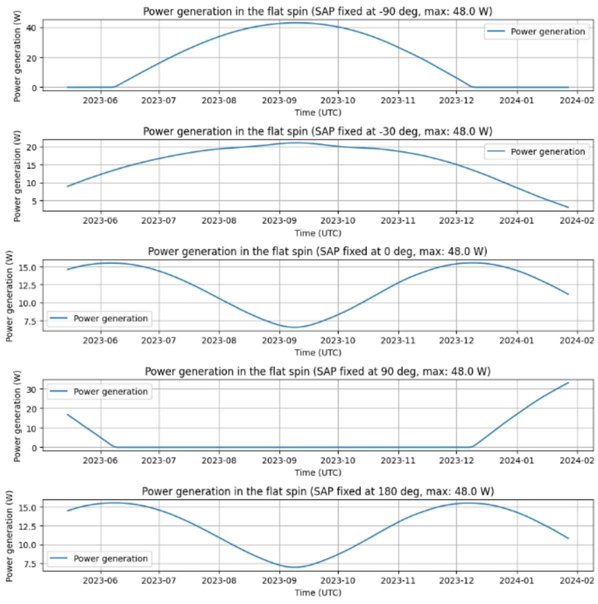

Figure 3: Power generation scenarios for the flat spin

RECOVERY OPERATIONS

Investigating cause of communication loss

We could not communicate with EQUULEUS for the operation on May 18, 2022. Figure 2 shows the nominal trajectory in the Sun-Earth fixed rotating frame. The orbital position is just before the last closest approach to Earth.

To investigate the cause of the communication failure with the satellite, we conducted a Fault Tree Analysis (FTA). As a result, it was determined that the failure might be due to issues with the H/W UVC or the power supply circuit. If the communication loss was caused by the H/W UVC, it would mean that communication cannot be done until the satellite's power is satisfied. On the other hand, if the power supply circuit is at fault, there is no prospect of recovery. Therefore, the recovery operations for EQUULEUS were conducted under the assumption that the H/W UVC might be the cause, as there is a possibility of recovery.

Based on the angular momentum information from the last telemetry, Figure 3 shows the predicted changes in power generation if tumbling occurs around the principal axis of maximum inertia. As previously mentioned, the SAP may change its rotation angle depending on the situation due to FDIR, so the results for each pattern are shown. The polarity of the tumbling rotation axis is not considered here. From these results, it is clear that the timing of when the satellite can achieve a power balance varies depending on its attitude. Therefore, it is necessary to attempt recovery operations at times of sufficient power generation. Aiming for recovery at each potential timing, long-term recovery operations for EQUULEUS were conducted continuously.

Optical observation from the Earth

As described earlier, we have the EQUULEUS's closest approach to the Earth just after the communication loss. This was the last opportunity to confirm our assumption of EQUULEUS's tumbling by optical observations. Therefore, we contacted as many observatories and institutions as possible within our reach to request their cooperation in the optical observation of EQUULEUS. We were grateful for the cooperation of many institutions. Table 2 summarizes the results of these optical observations. Due to factors such as the observable time window and weather conditions, there were many instances where EQUULEUS could not be observed. However, we were able to successfully observe EQUULEUS with telescopes at three locations.

Figure 4 illustrates an example of the observation results, where the obtained data indicated a 76 second periodic blinking. This suggests that EQUULEUS is tumbling. This result matches the predicted rotation period of 75 seconds for an uncontrolled state, which was one of the anticipated scenarios. These corporations provided a important opportunity to confirm the status of EQUULEUS from a different perspective. In addition, the order of the error between the optical observation results and the orbit prediction direction using the orbit determination result is about 1/1000 degree. Therefore, we could eliminate concerns about propulsion system leaks.

Table 2: Optical Observation summary

Telescope	Observation details
Subaru Telescope	Detected
Lowell Observatory	Detected
Telescopes of CNES	Not detected
Seimei telescope	Detected
Bisei Astronomical Observatory	Not detected
Kiso Observatory	Not detected
Nishi-Harima Astronomical Observatory	Not detected
Mt. Nyukasa Astronomical Observatory	Not detected
Siding Spring Observatory	Not detected

Figure 4: Observation results from Lowell Observatory

Commands for recovery operation

It is necessary to determine the commands to be sent by assuming the state of the satellite. Based on the results of the attitude analysis and optical observation, we assumed that the satellite is rotating with a period of about 75 seconds and spaced out the command intervals. The transmitted commands primarily included XTx ON commands, switching of antennas mounted on the Y and Z planes, and the transition to sun pointing mode. To increase the probability that the X-band transponder could lock onto and receive the uplink signal, communication establishment procedures such as uplink sweep were executed with each set of commands.

In addition, when the UDCS is used, special commands could be utilized. These are commands that can be interpreted by the TRP without the MOBC. We could send commands to turn on XTx and reset the PCU.

ERROR PROPAGATION

Simulation conditions and Results

Table 3 shows the conditions for the trajectory propagation. The recovery operations primarily utilized Japanese ground stations (UDSC, USC, and MDSS). These operations were conducted 2-3 times a week, for about 4-5 hours each session.

Figure 5 shows the maximum angular deviation from the nominal trajectory direction of EQUULEUS after losing communication. These results were calculated using a Monte Carlo simulation based on 10,000 cases. The initial conditions were based on the last orbit determination values and its error covariance matrix. It is assumed that the satellite is tumbling, and the uncertainty of the Solar Radiation Pressure (SRP) was set to 0.2 (1σ). Initially, when the communication was lost, the orbit error was small, and we explored a wide area by tripling the covariance matrix errors. However, as the orbit error expanded, we set more realistic values due to the increasing exploration time required. Figure 6 describes an example of the angular deviation from the nominal trajectory during a specific operation. Since the satellite does not approach celestial bodies like the moon until it is inserted into EML2, the orbit error does not significantly expand, and the search essentially follows a straight line. The spread of errors was fitted with a linear function. Based on this, the antenna direction was adjusted every 12 to 15 minutes during operations.

Figure 7 shows an example of the error spread after the satellite approaches the moon, associated with the timing of the insertion into EML2. If the error spreads to this extent, it becomes impossible to explore the entire area in a single operation. Therefore, we considered sweeping the antenna direction to encompass the area covered by 10,000 propagated trajectory samples with the error described earlier. The areas already searched were distinguished for each sample to avoid overlapping explorations. In the figure, the white area at the bottom indicates the regions that have already been searched. Figure 8 shows the further expansion of the error after trajectory propagation until various timing in 2024. Considering that each direction's recovery operation takes 12-15 minutes, it becomes impractical to search all areas. Consequently, the recovery operations for EQUULEUS were terminated.

Table 3: Simulation conditions

Name	Setting
Celestial body	**Sun, Mercury, Venus, Earth, Moon, Mars, Jupiter, Saturn, Neptune, Uranus, Pluto (JPL DE440)**
Spherical harmonics (Trajectory design after launch)	**Earth: 50 x 50 (JGM3)**
	Moon: 100 x 100 (GL900D)
Solar radiation pressure	**Canon ball model**

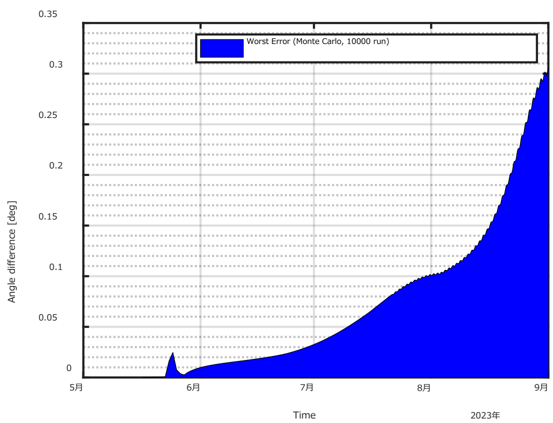

Figure 5: Angle difference from nominal trajectory

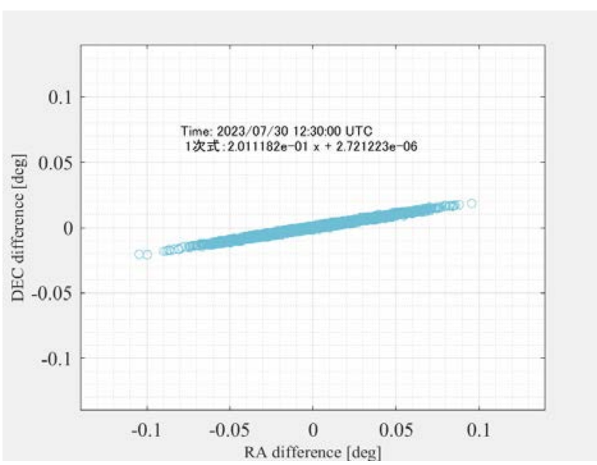

Figure 6: Example of trajectory dispersion before EML2 approach

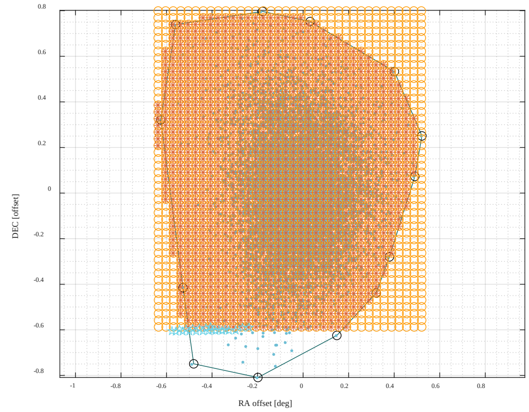

Figure 7: Example of trajectory dispersion after LFB

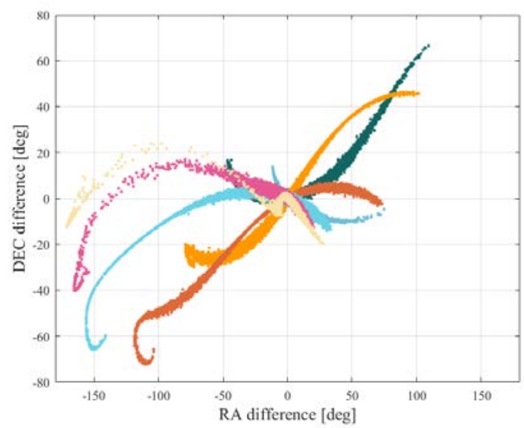

Figure 8: Example of trajectory dispersion after EML2 approach in different time frame

LESSONS LEARNED

Through the recovery operations of EQUULEUS, we have identified several important lessons learned that we would like to share. We hope these insights will be useful in similar situations.

Firstly, although it is not commonly considered in the operations of typical deep space probes, optical observations from ground-based telescopes can be extremely valuable for assessing the status of a satellite, especially when it is making a close approach to Earth. These optical observations provide an alternative means to radio signals for monitoring the satellite.

Secondly, considering the possibility that EQUULEUS might not be found quickly due to its attitude and power conditions, we planned our operations with a focus on maintaining long-term motivation and reducing effort.

Specifically, we ensured that key personnel were available for contact and participated only at the beginning of each operational pass. If no signal was detected after following typical procedures several times, we would release student subsystem participants. This approach helped maintain motivation throughout the prolonged recovery operations.

Lastly, although it was not an issue for EQUULEUS due to past mission experience, we operated with a keen awareness of orbit determination accuracy. This is particularly important for microsatellites developed by universities, which may underestimate the importance of precise orbit determination. By conducting sufficient observations for orbit determination during regular operations, it is possible to keep error growth within realistic limits, even if communication with the satellite is lost for an extended period due to unforeseen circumstances.

CONCLUSION

EQUULEUS is a 6U CubeSat developed by the University of Tokyo and the Japan Aerospace Exploration Agency (JAXA). The spacecraft was launched on November 16, 2022 as one of the ten secondary payloads onboard NASA's SLS Artemis-1. The mission achieved full success by completing the demonstration of orbit control technology and other objectives. However, since the operation on May 18, 2023, we have been unable to communicate with EQUULEUS. This paper primarily described the recovery operations for EQUULEUS after the loss of communication. Through ground-based analysis and the cooperation of various institutions, we obtained optical observations from ground-based telescopes, revealing that EQUULEUS was in a tumbling state. The direction of the SAP might change in terms of FDIR, leading to different potential recovery times based on power availability. Therefore, we conducted long-term recovery operations. As EQUULEUS approached the moon around its insertion into EML2, the trajectory error expanded significantly. It made the spread of the error unrealistic to continue the recovery operations. Consequently, we regret to report that the recovery operations for EQUULEUS have ended, and we were unable to re-establish communication with the satellite.

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- Subaru Telescope

- Lowell Observatory

- Telescopes of CNES

- Seimei Telescope

- Bisei Astronomical Observatory

- Kiso Observatory

- Nishi-Harima Astronomical Observatory

- Mt. Nyukasa Astronomical Observatory

- Siding Spring Observatory

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