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Flight Model Design and Development Status of the Earth—Moon Lagrange Point Exploration CubeSat EQUULEUS Onboard SLS EM-1

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ABSTRACT

EQUULEUS (EQUilibriUm Lunar-Earth point 6U Spacecraft) will be the world's smallest spacecraft to explore the Earth—Moon Lagrange point. The spacecraft is being jointly developed by JAXA and the University of Tokyo and will be launched by NASA's SLS (Space Launch System) EM-1 (Exploration Mission-1). The spacecraft will fly to a libration orbit around the Earth—Moon Lagrange point L2 (EML2) and demonstrate trajectory control techniques within the Sun-Earth-Moon region for the first time by a nano spacecraft. This spacecraft also carries several scientific observation missions which will be conducted during and after the flight to EML2; imaging of the entire Earth's plasmasphere by extreme UV wavelength, observation of the space dust flux in the cis-lunar region, and observation of the lunar meteor impact flashes at the far side of the moon from EML2. The development of the spacecraft started in the summer of 2016 and the engineering model integration and testing was completed by the end of 2017. The design of the flight model was completed based on the engineering model test results. The integration and testing of the flight model will be completed by the end of 2018, to be ready for the launch by SLS' first flight in 2019.

INTRODUCTION

Space agencies, private companies, and universities have been recently planning to build nano-satellites (1–10 kg) and micro-satellites (~50 kg) for deep space exploration.[1,2] 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 ever. During its one-year flight in deep space[3], PROCYON succeeded in its primary mission (the demonstration of a 50-kg-class deep space exploration bus system), and also achieved some of its optional missions, which are the demonstration of advanced deep space exploration technologies and scientific observations.[4,5] These successes demonstrated the capability of the ultra-small spacecraft for performing a deep space mission by itself and also demonstrated that it can be a useful tool for deep space exploration. After that, the size of the deep space probe has been becoming smaller and smaller, and the world's first deep space CubeSat "MarCO" was successfully launched in 2018 together with the “InSight” Mars mission.[6]

Recently, more and more small deep space missions are being planned over the world, and a bunch of CubeSats will fly as secondary payloads onboard the first flight of NASA’s SLS (Space Launch System) in 2019. SLS is NASA’s next-generation heavy launch vehicle to carry astronauts beyond Earth’s orbit to an asteroid and eventually to Mars. The first flight, called “EM-1” (Exploration Mission-1) will provide accommodations for thirteen 6U CubeSats into a lunar flyby trajectory, whose size are about 10x20x30cm and weight is limited to 14kg. JAXA and the University of Tokyo will provide two 6U CubeSats named EQUULEUS (EQUilibriUm Lunar-Earth point 6U Spacecraft) and OMOTENASHI (Outstanding MOon exploration TEchnologies demonstrated by NAno Semi-Hard Impactor).[7] This paper describes EQUULEUS’ mission outline, spacecraft system design, and spacecraft development status as of June 2018.

MISSION OVERVIEW

The ride-share opportunity on SLS EM-1 was called to the international partners by NASA to select payloads which will contribute to the future space exploration scenario. The concept of EQUULEUS mission was developed to fit the requirement.

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). Figure 1 shows the current baseline trajectory, which includes three deterministic trajectory correction maneuvers (TCMs) and three LGAs. After deployment into a lunar flyby trajectory, EQUULEUS will perform a deterministic TCM of 10-20 m/s to increase the perilune altitude and target an Earth-bound, Moon-return trajectory. The first LGA occurs about a week after launch, then a sequence of lunar flybys is used to enable a low-energy transfer to an EML2 libration orbit. The sequence of lunar flybys can last several months and include one to four additional LGAs. At the end of this sequence, the spacecraft reaches the EML2 libration orbit. Finally, after completing the observation mission at EML2, the spacecraft leaves the Earth system on an escape orbit shortly before the completion of the onboard propellant. This engineering mission will demonstrate part of the future scenario of the utilization of the deep space port around the moon and its Lagrange points.

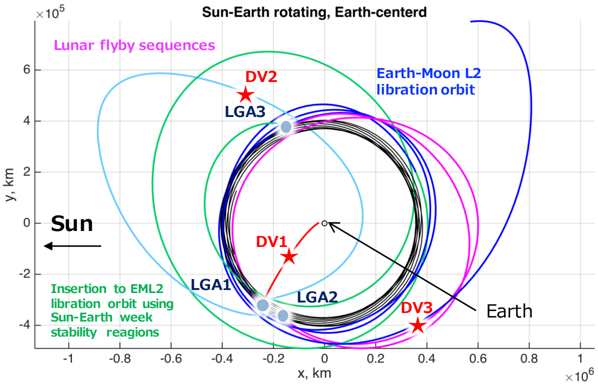

Figure 1: Current baseline trajectory of EQUULEUS from the launch to EML2.

EQUULEUS carries three scientific observation instruments. The first one, named PHOENIX (Plasmaspheric Helium ion Observation by Enhanced New Imager in eXtreme ultraviolet) (Figure 2), will conduct the imaging of the Earth's plasmasphere by extreme UV wavelength. The observation will be conducted throughout all mission phases and enhance the geospace in-situ observation conducted by the ERG (JAXA's small space science mission launched in 2016) and NASA’s Van Allen probe missions. As a result, we can improve our understanding of the radiation environment around the Earth, which is one of the critical issues for future human cis-lunar exploration.

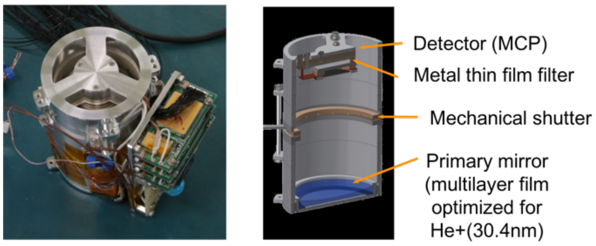

Figure 2: PHOENIX (EM) for the Earth plasmasphere imaging observation.

The second scientific observation instrument named CLOTH (Cis-Lunar Object detector within THermal insulation) will detect and evaluate the meteoroid impact flux in the cis-lunar region by using dust detectors. The goal of this mission is to understand the size and spatial distribution of solid objects in the cis-lunar space.

The third scientific observation instrument named DELPHINUS (DEtection camera for Lunar impact PHenomena IN 6U Spacecraft) (Figure 3) will observe the impact flashes at the far side of the moon from EML2 for the first time.[8] This observation will characterize the flux of impacting meteors, and the results will contribute to the risk evaluation for future human activity and/or infrastructure on the lunar surface.

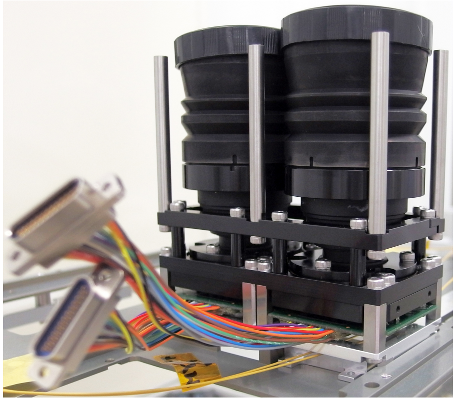

Figure 3: DELPHINUS (EM) for the lunar impact flashes observation.

SPACECRAFT SYSTEM DESIGN

Figure 4 shows the external view of EQUULEUS. Figure 5 shows the internal configuration of the spacecraft.

The cold gas propulsion system, named AQUARIUS (AQUA ResIstojet propUlsion System), for both trajectory control and attitude control was newly developed for EQUULEUS mission.[9] Water is used as the propellant as it is the most "green" propellant.

Most of the other part of the spacecraft utilizes commercial off-the-shelf (COTS) components or are designed based on the experiences on the various past space missions. We employed COTS components for the attitude control system and the solar array paddles. XACT-50 from Blue Canyon Technologies, which is an integrated unit of IRU, STT, RWs, is used for the three-axis attitude control system, and HaWK from MMA, LLC, which is solar array paddles with one-axis gimbal, is used with some customization for the EQUULEUS mission.

Most of the bus components are based on the design of PROCYON and other 50-kg-class Earth-orbiting micro-satellites. Electronics boards were redesigned to fit within the "CubeSat form factor". For example, the deep space X-band transponder[10] which had been demonstrated on PROCYON was redesigned to significantly reduce its volume to fit within the CubeSat envelope (Figure 6).

The design of the mission instruments utilizes the experiences on the past space missions. The design of PHOENIX was optimized for EQUULEUS based on instruments onboard the previous space missions such as UPI on Kaguya[11], IMAP on ISS[12], and EXCEED on Hisaki[13]. Electronics board of CLOTH was designed based on the ALDN[14] onboard the IKAROS solar sail demonstration mission. The image processing unit for DELPHINUS mission utilizes the image feedback control unit for the asteroid detection telescope for PROCYON.[15]

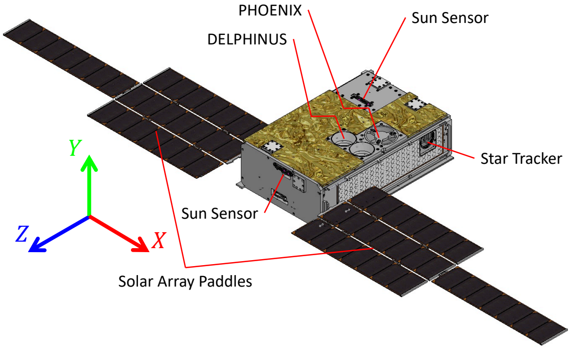

Figure 4: External view of EQUULEUS.

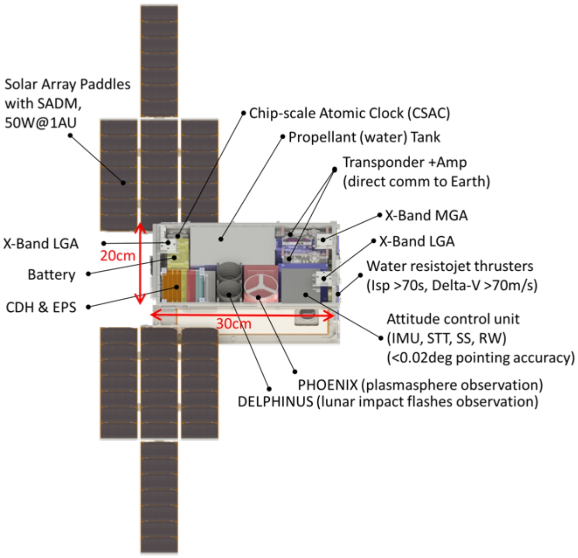

Figure 5: Internal configuration of EQUULEUS.

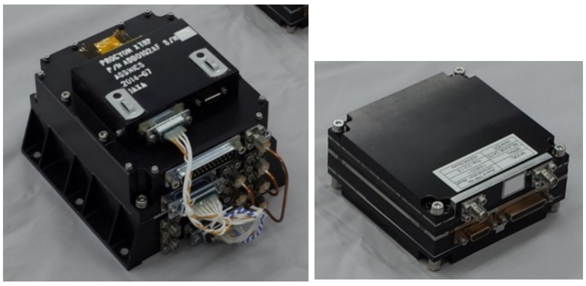

Figure 6: The deep space X-band transponder demonstrated on PROCYON (left) and the newly developed transponder for EQUULEUS to fit within the CubeSat form factor (right). The function of the transponder was divided into multiple slices for the case of EQUULEUS.

DEVELOPMENT STATUS

EQUULEUS was officially selected as one of the thirteen secondary payloads on SLS EM-1 in April 2016.[16] The spacecraft is jointly developed by the University of Tokyo and JAXA. All of the system integration and electrical tests is conducted at the University of Tokyo. Part of the system-level environmental tests such as vibration and thermal vacuum tests are conducted outside of the University of Tokyo, e.g. CENT (the Center for Nanosatellite Testing) at the Kyushu Institute of Technology, which is located in the western part of Japan.

After the official selection, the development of the spacecraft engineering model (EM) started. System level environmental tests were completed by the end of 2017. The flight model (FM) design was made considering the EM test results, and the EQUULEUS project passed the Critical Design Review (CDR) on June 2018. Now the flight model manufacturing and integration is being conducted, aiming at the spacecraft ready for the launch by March 2019.

CONCLUSION

The size of the deep space probe has been becoming smaller and smaller after the success of PROCYON (50kg-class, 2014) and MarCO (6U CubeSat, 2018). The next fleet will be the thirteen 6U CubeSats onboard SLS in 2019. SLS is NASA’s next-generation heavy launch vehicle to carry astronauts beyond Earth’s orbit to an asteroid and eventually to Mars. Its first flight in 2019 will provide accommodations for thirteen 6U CubeSat into a lunar flyby trajectory. JAXA and the University of Tokyo will provide a 6U CubeSat EQUULEUS as one of the thirteen payloads.

The primary mission of EQUULEUS is an engineering mission to demonstrate the trajectory control techniques within the Sun-Earth-Moon region for the first time by a nano-spacecraft. This mission will be accomplished through the flight with a small amount of deterministic Delta-V (10-20 m/s) to a libration orbit around EML2 by using multiple LGAs and low-energy transfers using weak stability regions.

EQUULEUS carries three scientific observation instruments; PHOENIX to conduct the imaging of the Earth's plasmasphere by extreme UV wavelength, CLOTH to detect and evaluate the meteoroid impact flux in the cis-lunar region by using dust detectors, and DELPHINUS to observe the impact flashes at the far side of the moon from EML2 for the first time and characterize the flux of impacting meteors.

Most of the spacecraft utilizes COTS components or are designed based on the experiences on the past space missions such as PROCYON, IKAROS, Kaguya, and Hisaki.

After the official selection as a secondary payload on SLS EM-1 in April 2016, the spacecraft has been jointly developed by JAXA and the University of Tokyo. EQUULEUS passed CDR on June 2018, and its flight model development will complete by March 2019, to be ready for the launch in late 2019.

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