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Launch and Early Operation of Korea Pathfinder Lunar Orbiter

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Abstract

KPLO was launched on August 5, 2022 from the Cape Canaveral Space Force Station in the US using a Falcon-9 launch vehicle. KPLO was separated from the launch vehicle about 40 minutes after launch, injected to the ballistic lunar transfer trajectory. The separation waked-up the on-board computer and automated initial operation was started by the flight software. All heater groups were set-up from the launch configuration to the safe mode configuration. S-band transmitter was turned on and started to send telemetry through the low gain antenna. Two solar panels were deployed one by one, sun pointing attitude control by attitude control thrusters was started. When the automated initial operation was completed, ground station could acquire signal from KPLO. The initial acquired telemetry showed overall status of KPLO was normal, and initial operation was completed without any anomaly. By deploying a high gain antenna and KPLO magnetometer boom, KPLO became the complete flight configuration. Then we activated reaction wheels and star trackers for 3 axis attitude determination and control in normal mode configuration. After orbit upload which was generated using separation information, we changed the S/C operation mode to the normal mode. After 24 hours from launch, the high gain antenna was started to use for S-band and X-band communication. The high gain antenna pointed the ground station accurately, and we could receive the first playback data which was stored in the on-board computer. Two days after launch, the first trajectory correction maneuver for LV dispersion correction was successfully performed. Then the trans-lunar cruise phase for 4.5 months was started. During the TLC phase, 4 trajectory correction maneuvers were performed, and several Earth and Moon Images were taken by lunar terrain imager, called LUTI which is high resolution camera of KPLO, and 16 times of wheel off-loading were performed. The late cruise phase was started on December 1, 2022. KPLO was started to be affected by lunar gravity. In the late cruise phase, while maintaining the trajectory, we prepared the lunar orbit insertion maneuvers. The first LOI maneuver was successfully performed on December 16, 2022 and KPLO was captured in the lunar orbit. By the second and third LOI maneuver on December 21 and 26, 2022, KPLO entered into the lunar mission orbit. In the following commissioning phase, S/C operation mode changed from the sun pointing mode to nadir pointing mode and mission operation was started.

Acronyms/Abbreviations

ACT	=	Attitude Control Thruster
BLT	=	Ballistic Lunar Transfer
DSN	=	Deep Space Network
DTNPL	=	Disruption Tolerant Network Experiment Payload
HGA	=	High Gain Antenna
IAC	=	Initial Activation and Checkout
KARI	=	Korea Aerospace Research Institute
KGRS	=	KPLO Gamma Ray Spectrometer
KMAG	=	KPLO Magnetometer
KPLO	=	Korea Pathfinder Lunar Orbiter
LGA	=	Low Gain Antenna
LOI	=	Lunar Orbit Insertion
LUTI	=	Lunar Terrain Imager
LV	=	Launch Vehicle
OMT	=	Orbit Maneuver Thruster
PolCam	=	Wide-angle Polarimetric Camera
RTCS	=	Relative-Timed Command Sequence
RU	=	Reconfiguration Unit

S/C	=	Spacecraft
SADA	=	Solar Array Driving Assembly
SBMU	=	Standard Bus Management Unit
SOH	=	State of Health
TCM	=	Trajectory Correction Maneuver
TCTM	=	Tele-command Telemetry Module
TLC	=	Trans-lunar Cruise
TSH	=	Thruster-based Safe Hold

1. Introduction

KPLO, also called Danuri is Korea's first lunar mission which was launched on August 5, 2022 from the Cape Canaveral Space Force Station in the US using a Falcon-9 launch vehicle. KPLO was designed, built and operated by Korea Aerospace Research Institute in Daejeon, South Korea. Fig. 1 shows KPLO flight configuration including spacecraft bus units and payloads.

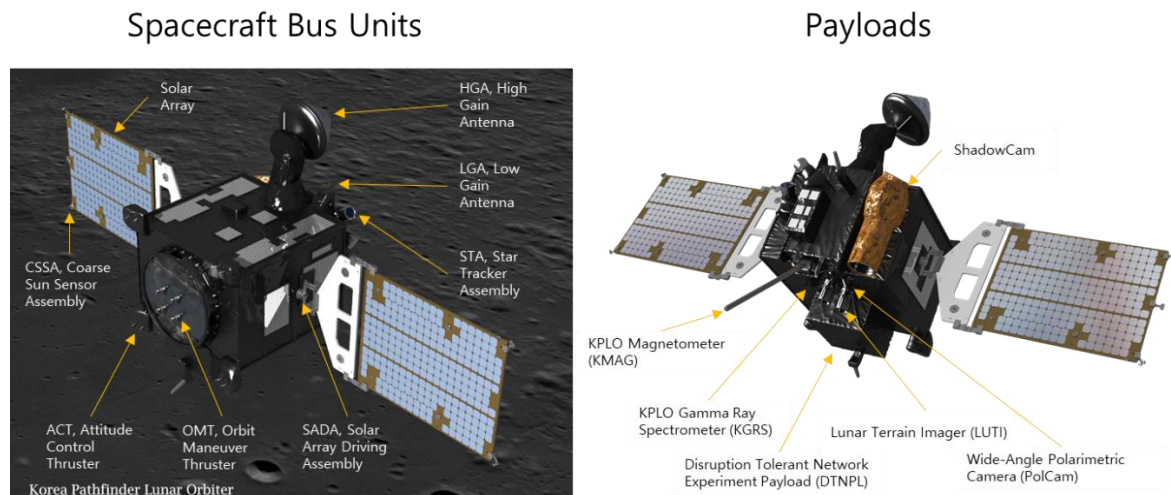


Fig. 1. KPLO Flight Configuration

KPLO spacecraft bus is equipped with four 30N thrusters for orbit maneuver, eight 4.5N thrusters for attitude control and orbit maintenance, two star-trackers and gyros for attitude determination, four reaction wheels for precise attitude control, ten sun sensors for attitude determination in safe mode. A high gain antenna is used for s-band and x-band communication, and two low gain antennas are used for s-band communication. Two solar arrays can be rotated by solar array driving assembly to track the Sun. KPLO accommodates 6 payloads including LUTI [1], PolCam [2], KGRS [3], KMAG [4], DTNPL [5], and ShadowCam [6].

The Falcon-9 separated the KPLO to enter the lunar transfer orbit which is BLT trajectory [7]. When the KPLO was separated from the launch vehicle, the onboard computer which is called SBMU started to boot-up. SBMU started the deployment process by automatically executing Start-up RTCS after a booting and initialization process for about 10 seconds [8]. In Start-up RTCS, devices necessary for TSH Submode operation were turned on and solar array deployment was performed. When solar array deployment was complete, TSH submode control was started, maintained the sun-oriented attitude, and waited for control by ground station. We performed Initial Activation and Checkout procedures after determining that the solar panels were successfully deployed. In Bus IAC performed in the Early Cruise phase, the procedure to change the spacecraft operation mode to the normal mode was performed. The set point for the heater control was changed for normal mode thermal control. Reaction wheels, star trackers, and high gain antenna were activated and checked for normal operation. After entering the SP submode, spacecraft performance was checked such as attitude maneuver and orbit maintenance through the In-Orbit Test. In the Trans-lunar Cruise Phase, several trajectory correction maneuvers [9] were performed to maintain the designed trajectory. In the late cruise phase, the reference coordinate system of the spacecraft was changed from the Earth-centered inertial frame to the Moon-centered inertial frame, and a plan for LOI was established. In all mission phases after launch, orbit determination through ranging and doppler measurement was repeatedly performed. In the Lunar Orbit Acquisition phase, lunar orbit insertion maneuvers [10] to enter the lunar orbit were performed three times. Upon

entering the mission orbit, the Commissioning phase was started and normal mission operation was prepared through in-orbit testing of the spacecraft bus and calibration of payloads. Fig. 2 summarizes mission timeline of KPLO.

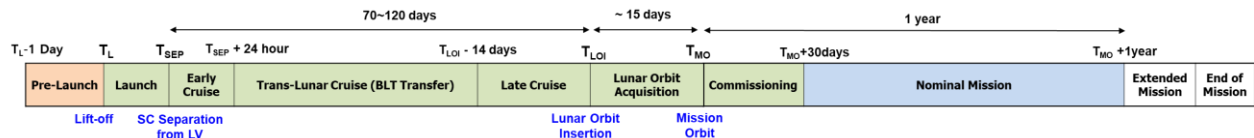


Fig. 2. Mission timeline of KPLO

In this paper, the launch and early operation of KPLO is introduced and the results of the operation are shown. Launch and Early Operation Phase consists of Launch Phase, Initial Activation and Checkout in Early Cruise Phase, In-orbit Test and Trajectory Correction Maneuvers in Trans-lunar Cruise Phase, Late Cruise Phase, LOI Maneuvers in Lunar Orbit Acquisition Phase and In-Orbit Test and Calibration operation in Commissioning Phase. After all initial operations were successfully completed, normal mission operation was started.

2. KPLO Launch and Early Operation Results

2.1 Launch Phase

The launch phase was started with lift-off of the launch vehicle. At the moment, the spacecraft configuration was the launch configuration which the power source for the spacecraft bus was switched from the launch vehicle to the spacecraft battery. In this configuration, PCDU, some critical modules in SBMU which are TCTM and RU, and S-band receiver were turned on. The launch heaters were also turned on to maintain temperature of spacecraft units within survival temperature range. The launch vehicle had been controlled in roll axis for sun avoidance of three optical instruments on KPLO. The launch phased was ended with separation. After 40 min and 15 sec from the launch, KPLO was separated from the launch vehicle at an altitude of about 703 km at 10.15 km/sec.

2.2 Early Cruise Phase

The early cruise phase was started when KPLO was separated from the launch vehicle. The on-board computer was started to wake-up after detection of break-wire open signal. After wake-up, automated initial operation was started which is called start-up RTCS. The start-up RTCS turned on heater groups for safe hold mode thermal control. The s-band transmitter was turned on and started to send telemetry through a low gain antenna. Two solar arrays were sequentially deployed and Sun sensors on the edge of the solar panels were started to measure the Sun. After gyro was selected for attitude determination in safe hold mode, valves for attitude control thrusters were activated. The last part of the start-up RTCS was activation of attitude control using thrusters. By analyzing the SOH playback data, we could conclude the initial operation was successfully performed without any anomaly. Fig. 3 shows change of power generation and power consumption during initial automated operation. The power profile shows successful sun pointing control and unit activation.

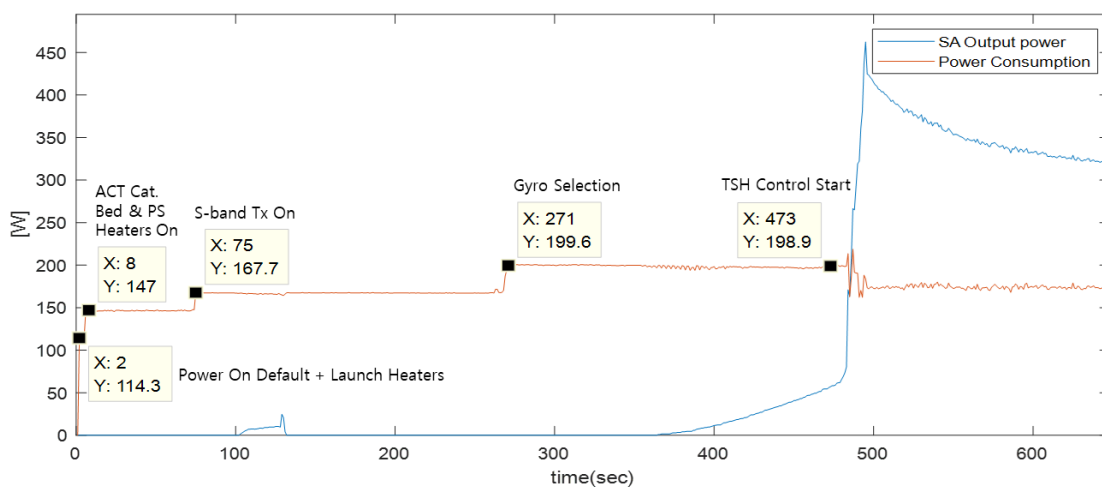


Fig. 3. Power consumption during initial automated operation

After several minutes from the initial operation is completed, the first signal was acquired on the ground station. For the first contact, the Canberra DSN supported KPLO initial acquisition. The contact was established as scheduled, so we could start the spacecraft bus initial activation and checkout (IAC) procedure. The bus IAC was 1-day activity which includes functional checkout of each s/c bus units used for normal mode operation. The uplink rate and downlink rate were changed from default low rate to high rate for normal operation. The on-board time was set to current time roughly. The group heaters were enabled as normal mode configuration and TCS operation mode was changed to a cruise mode. After activation of ranging mode of s-band transponder, the ground station started ranging and doppler measurement. For the normal mode operation, orbit data was necessary for attitude control. We uploaded designed orbit data for the initial orbit data and updated it by orbit determination results after obtaining the separation information from the launch vehicle. The high gain antenna stowed and hold by frangi-bolt was successfully deployed. The KMAG boom was also successfully deployed and started to measure near earth magnetic field. Star tracker assembly was activated and started to provide attitude quaternions. For the reaction wheels activation, we applied run-in time for about two hours. By rotation all wheels at about maximum speed, lubricant in each wheel could be well spread and the reaction wheels could provide full performance. Finally, we changed S/C operation mode from safe mode to normal mode and the early cruise phase was completed. Fig. 4 shows the spacecraft bus initial activation and checkout flow and Fig. 5 shows the spacecraft body rate measured at each activity.

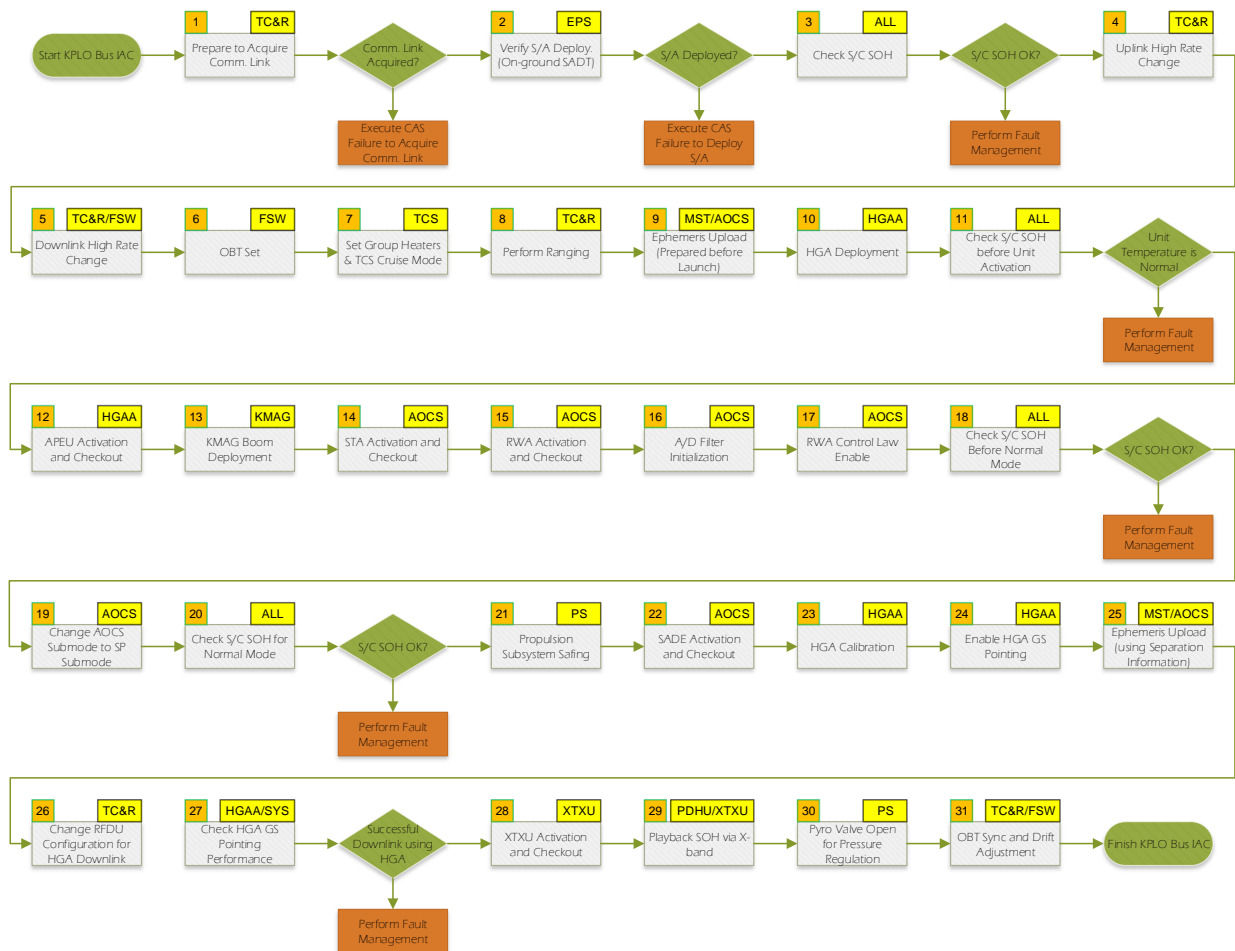


Fig. 4. KPLO spacecraft bus initial activation and checkout flow

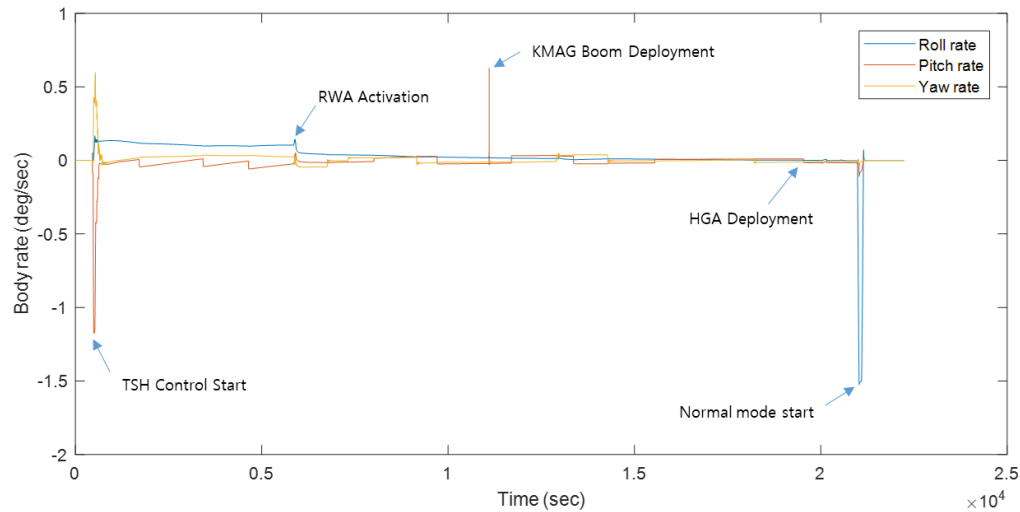


Fig. 5. Spacecraft body rate during initial activation

2.3 Trans-lunar Cruise Phase

The trans-lunar cruise phase was started on August 6, 2022 and finished at the end of November, 2022. Most of the time in this phase, S/C was in normal mode with normal flight configuration. Solar panel was fixed in home position and pointed the Sun by attitude control using reaction wheels. The high gain antenna pointed ground antenna precisely. During this phase, KPL0 traveled following the ballistic lunar transfer trajectory. To maintain the trajectory, four trajectory correction maneuvers (TCM) were performed. We prepared total 9 TCMs including deterministic TCMs and statistical TCMs. Due to successful deterministic TCM results, we could skip 5 TCMs. Fig. 6 represents major events in trans-lunar cruise phase.

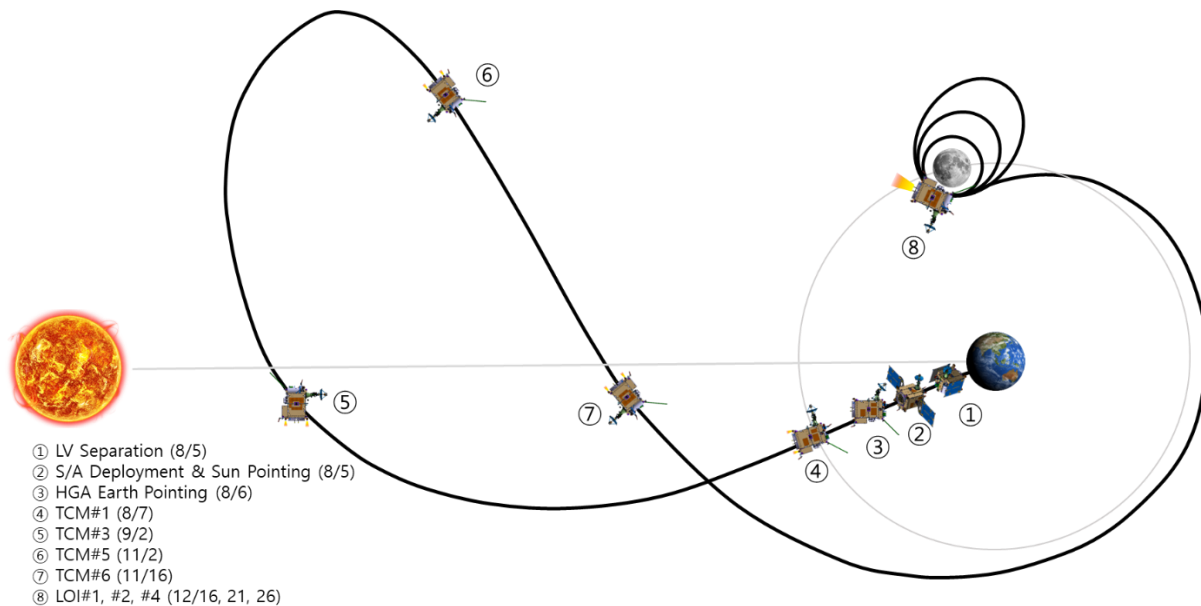


Fig. 6. Major events in trans-lunar cruise phase

Both of orbit maneuver thruster (OMT) and attitude control thruster (ACT) could be used as a main thruster for each TCM. For TCM#1 and TCM#3, OMT was used for DV burn and ACT was used for attitude control. For TCM#5 and TCM#6 which were small burns, ACT was used for DV burn and attitude control. Fig. 7 shows four types of TCM categorized by thruster for DV burn and antenna for communication. TCM#1 and TCM#3 were type 3), whereas TCM#5 and TCM#6 were type 1).

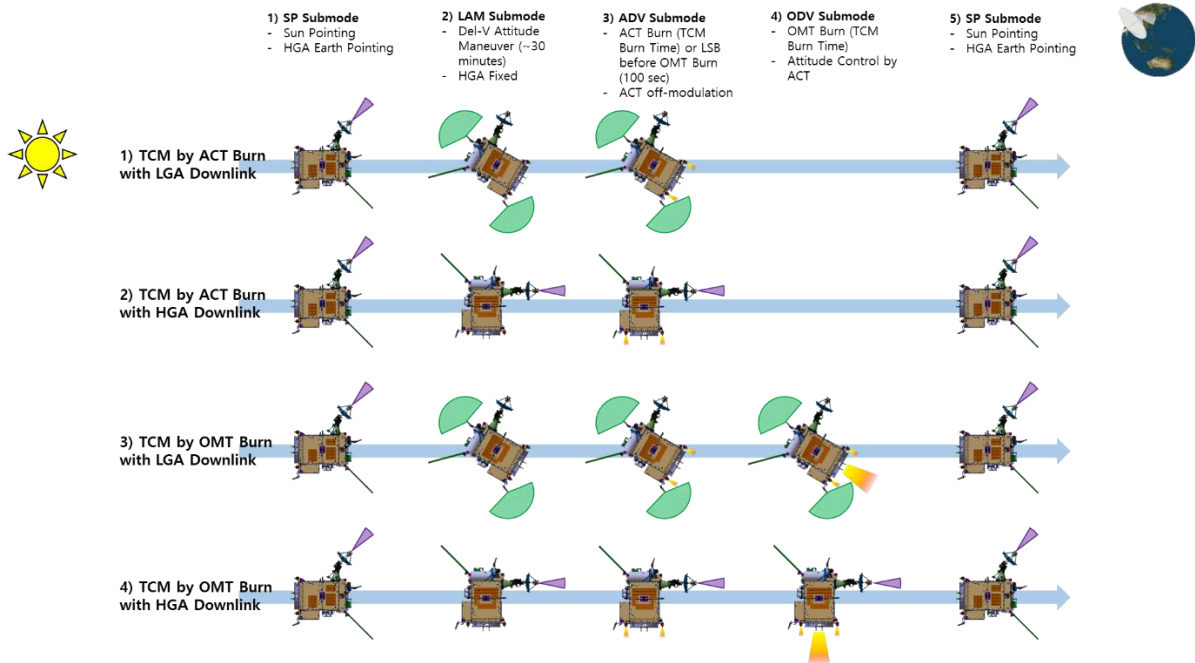
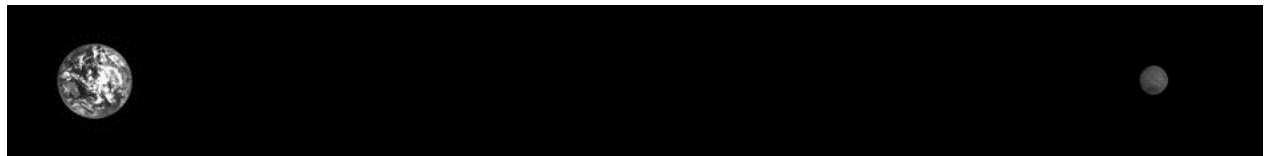


Fig. 7 Four types of TCM

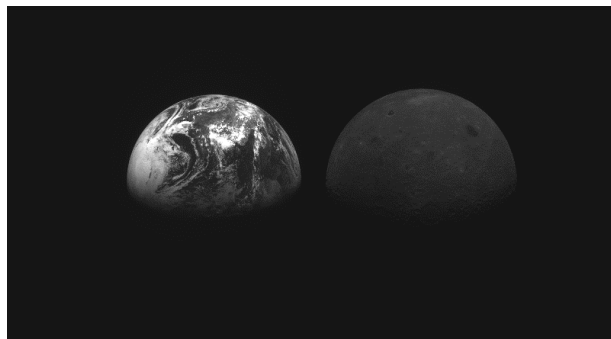
On the reaction wheels, the external disturbance was accumulated to momentum as expected before launch. Therefore, wheel off-loading was required every week in trans-lunar cruise phase. We executed 16 wheel off-loadings in this phase. At first, wheel off-loading was executed at the sun pointing attitude without any attitude maneuver. From the wheel off-loading#6, we applied special attitude which help maintain the designed trajectory. Utilizing small DVs generated by wheel off-loadings, we could cancel small statistical TCMs such as TCM#7~9. During the journey to the moon, we tried to take special images of the Earth and the Moon. Fig. 8 shows the images taken by LUTI in the trans-lunar cruise phase.



(a) First image of the Earth and Moon taken by LUTI on Aug. 26



(b) Combined Image of the Moon orbiting the Earth for 1 month from Sep. 15 to Oct. 15



(c) Image of the Earth and Moon which are close and similar size on Nov. 28
 Fig. 8. Image of the Earth and the Moon taken by LUTI in trans-lunar cruise phase

The trans-lunar cruise phase was successfully completed at the end of November.

2.4 Late Cruise Phase

The late cruise phase started on 1 December, 2022 and finished 15 December, 2022. The reference frame for the on-board orbit was changed from the Earth-centered ICRF to the Moon-centered ICRF. During the late cruise phase, lunar orbit insertion maneuvers were prepared and wheel off-loading was performed three times.

2.5 Lunar Orbit Acquisition Phase

The lunar orbit acquisition phase was started with the first lunar orbit insertion (LOI) maneuver on December 16, 2022. The original LOI plan consists of five LOI maneuvers. The LOI#1 was for capture of KPLO in the Moon orbit. The second to the fifth maneuver which have similar delta-v were for orbit period reduction. After successful LOI#1, we merged LOI#3 into LOI#2 and LOI#5 into LOI#4. This change provided more time to prepare the next burn for both of the mission support team (navigation team) and flight support team (spacecraft specialists). Fig. 9 shows the LOI operation sequence.

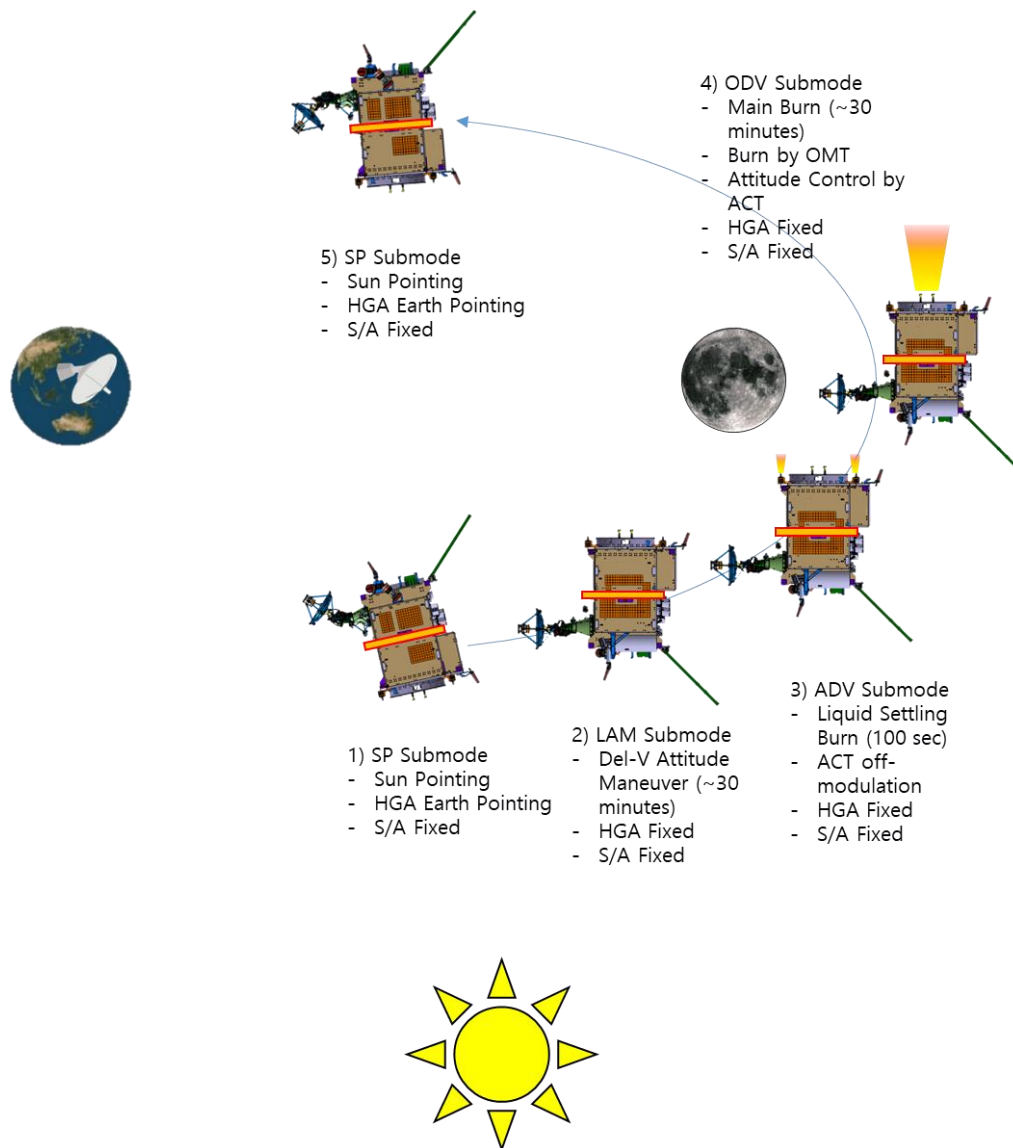


Fig. 9. LOI Operation Sequence

At first, the high gain antenna was hold in the reference position and spacecraft attitude was changed to LOI burn attitude. The burn attitude was cautiously selected to satisfy several constraints such as sun avoidance of all optical

payloads, thermal constraints and antenna coverage for communication during burn. Fig. 10 shows KPLO burn attitude generation software (KBAGS) which is an in-house tool to generate burn attitude satisfying the constraints. After attitude maneuver was completed, a liquid settling burn (LSB) was started and settled down the propellant to the bottom of the propellant tank. Only after LSB, the dynamic model of whole spacecraft including propellant sloshing, solar array flexible mode could be applied to attitude controller for the LOI burn. After the LSB for 100 seconds, the OMT burn was executed for the LOI burn duration. When the burn was finished, spacecraft waited for 2 minutes in the same attitude while controlling the attitude using ACT. This is for reducing disturbance from propellant motion to the reaction wheels after OMT burn. After this waiting time, the spacecraft operation mode was changed back to the sun pointing mode which the reaction wheels are used for attitude control.

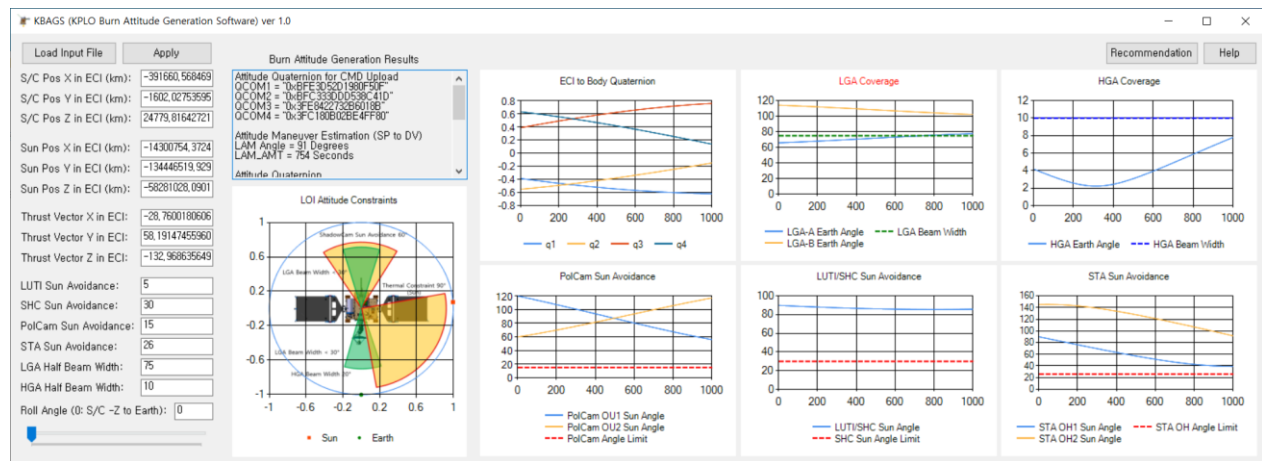


Fig. 10. KPLO burn attitude generation software (KBAGS)

The deep space network (DSN) continuously supported KPLO mission for the lunar orbit acquisition phase from December 16, 2022 to December 31, 2022. All three LOI maneuvers were completed successfully, and KPLO entered into lunar mission orbit. After LOI#2, KPLO took an image of the Earth and the Moon as shown in Fig. 11 on December 24, 2022 which is called the Earth Rise.

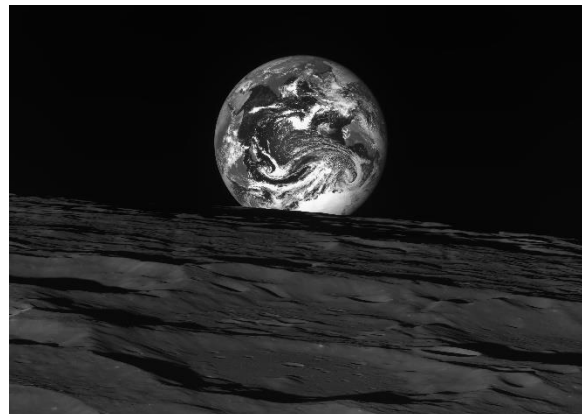


Fig. 11. Earth Rise Image taken by LUTI after LOI#2

2.6 Commissioning Phase

The commissioning phase was started earlier than original plan. After LOI#4, the spacecraft was still in sun pointing mode. The flight support team found there were temperature increase of some units. This was because the spacecraft was affected by direct sunlight and reflected sunlight from the lunar surface. The spacecraft thermal design was optimized to the nadir pointing attitude, so we decided to start commissioning phase as soon as possible. So, a day after LOI#4, the commissioning phase was started. The solar array driving assembly (SADA) was turned on and started to track the Sun. The spacecraft attitude was changed from the sun pointing attitude to the nadir pointing attitude. The reference frame for attitude control was changed from inertial frame to LVLH frame. Fig. 12 shows the spacecraft attitude and solar array operation in the mission orbit. The nadir pointing attitude is an attitude

rotated 45 degrees in yaw axis. This attitude can provide power generation capability under any Sun beta angle condition [11].

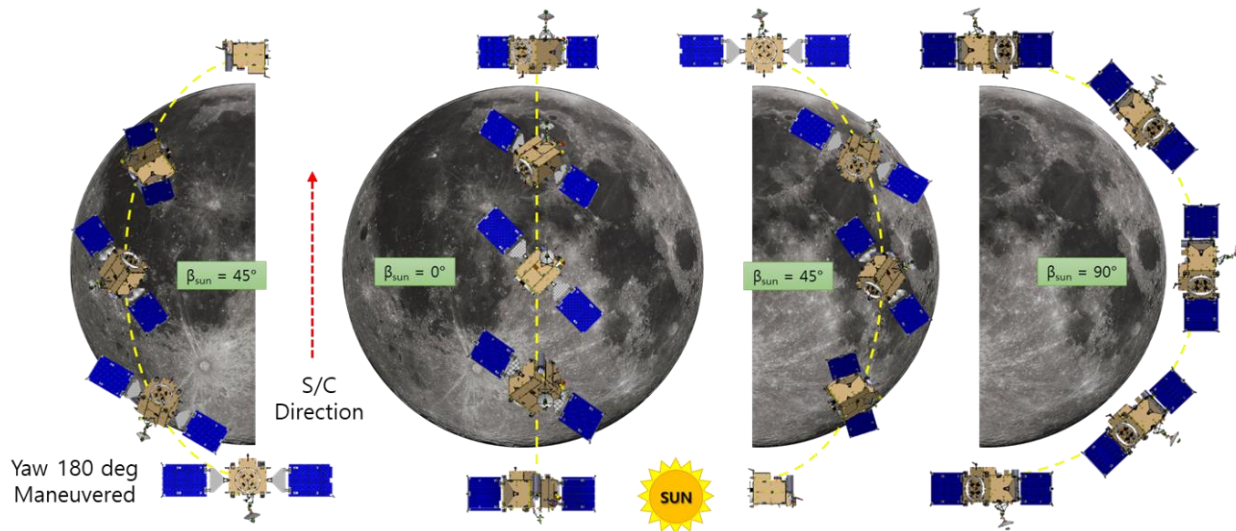


Fig. 12. Spacecraft attitude and solar array operation in the mission orbit

After an attitude maneuver test and a wheel off-loading test in LVLH frame, the spacecraft bus in-orbit test in commissioning phase was finished. Then the payload operation in commissioning phase was started. All payloads successfully performed commissioning. Ground system functions for nominal routine operation were stabilized during the commissioning phase.

The orbit trim maneuver for precise maintenance of mission orbit was performed on January 16, 2023. A pair of two burn were executed for the orbit trim maneuver. To maintain the mission orbit, orbit maintenance maneuvers will be performed every two months.

3. Conclusions

In this paper, we showed the launch and early operation results of KPLO. From the launch to the commissioning, all operations were successfully performed as planned. All bus and payload units were activated and checked without any anomaly. The spacecraft operation mode was changed to normal mode smoothly. The thruster's characteristics were as expected, so we could skip the four statistical TCMs and merge 5 LOI burns to 3 LOI burns. During the cruise, KPLO took several special images of the Earth and the Moon using LUTI. KPLO will continue routine operation for the mission lifetime until the end of 2023. When the one-year mission operation is finished, we will discuss about the possible extended mission.

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