

## Lunar Eclipse Operation Plan and Results of Korea Pathfinder Lunar Orbiter

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### Abstract

The Korea Pathfinder Lunar Orbiter (KPLO) successfully completed its planned one-year primary mission in 2023 and has been conducting an extended mission since January 2024. The spacecraft was designed for a one-year mission, and all onboard units operated nominally during this period. However, due to the battery capacity being optimized for the one-year mission to minimize weight, it is crucial to assess its performance during the extended mission period. Particularly in 2025, KPLO will experience two total lunar eclipses, it has not encountered before. During each approximately 3.5-hour eclipse period, the KPLO will rely solely on stored battery energy as solar power generation will be unavailable.

Preliminary analysis indicated that operating in a typical standby mode during these eclipses would result in complete battery depletion. Therefore, measures to minimize power consumption during the eclipse periods are essential. First, all non-essential units will be powered down, and the spacecraft will switch to a power-saving mode. Second, the thermal control system will preheat the spacecraft components to the highest operational temperature before entering the eclipse, reducing the need for heater operation during the eclipse.

These two strategies, incorporated during KPLO's design phase, ensured that the battery would not be depleted even if a total lunar eclipse occurred during the nominal mission phase. However, with the mission extended to two years, the battery's performance degradation due to prolonged charge-discharge cycles raises concerns. Even with the two previously mentioned measures, battery depletion is estimated to reach 95% during the eclipse period after two years in orbit.

To address this issue, an additional strategy, inspired by NASA's Lunar Reconnaissance Orbiter (LRO) operations, was developed. While the first two strategies focus on minimizing power consumption, the third strategy aims to maximize power generation. This involves adjusting the orbit's phasing through a Phasing Maneuver to maximize sunlight exposure before and after the eclipse. By implementing a minor velocity change of about 1 m/s three weeks prior to the eclipse, a phase shift of approximately 180 degrees from the original orbit can be achieved. This adjustment can reduce the maximum depth of battery discharge from 95% to around 70%.

This paper describes KPLO's operational plans for the total lunar eclipse periods and presents the results of the first total lunar eclipse on March 14, 2025, experienced by KPLO.

**Keywords:** KPLO, Danuri, Lunar Eclipse, Pre-heating, Phase Adjustment Maneuver, Power Saving Mode

### Acronyms/Abbreviations

AOCS	=	Attitude and Orbit Control Subsystem
AOL	=	Argument of Latitude
APEU	=	Antenna Pointing Electronics Unit
ATC	=	Absolute-Timed Command
DoD	=	Depth of Discharge
GRAIL	=	Gravity Recovery and Interior Laboratory
HGA	=	High Gain Antenna
ISRO	=	Indian Space Research Organization
JAXA	=	Japan Aerospace Exploration Agency
JPL	=	Jet Propulsion Laboratory
KARI	=	Korea Aerospace Research Institute
KPLO	=	Korea Pathfinder Lunar Orbiter
LGA	=	Low Gain Antenna
LRO	=	Lunar Reconnaissance Orbiter
NASA	=	National Aeronautics and Space Administration
RFDU	=	Radio Frequency Distribution Unit
SADA	=	Solar Array Drive Assembly

SADE	=	Solar Array Drive Electronics
TCS	=	Thermal Control Subsystem
TP	=	Target Pointing
TSH	=	Thruster-based Safe Hold
VDE	=	Valve Driving Electronics

## 1. Introduction

One of the critical considerations in designing a lunar orbiter mission is lunar eclipses. As the Moon orbits the Earth, it periodically aligns in the Sun-Earth-Moon configuration, resulting in an eclipse approximately twice a year when the Moon enters the Earth's shadow. There are three types of lunar eclipse: a total lunar eclipse, when the Moon is completely covered by the Earth's shadow; a partial lunar eclipse, when only part of the Moon is covered by the Earth's shadow; and a penumbral lunar eclipse, when the Moon is covered by the Earth's penumbra. Since most lunar orbiters rely on solar panels to generate power, their design must ensure that the battery does not deplete during eclipse periods when solar power generation is temporarily unavailable. Given that total, partial, and penumbral lunar eclipses differ in solar power generation characteristics, mission designers must anticipate the types of eclipses that will occur and accordingly design solar panel size, battery capacity, operational configurations, and operation modes.

NASA's Lunar Reconnaissance Orbiter (LRO), launched in 2009 and still operational as of 2025, implemented thorough eclipse preparation. Although there were no total lunar eclipses during its primary mission, the spacecraft was designed to withstand such events in anticipation of mission extensions [1]. During a total lunar eclipse, LRO minimized power consumption by shutting down non-essential instruments and switching to safe mode operations. Additionally, a phasing maneuver was executed several weeks in advance to optimize solar exposure [2]. The navigation team provided solar intensity predictions for various phase conditions, allowing the system engineering team to analyze power availability, determine the minimum battery voltage and state of charge, and establish acceptable phase conditions for executing the phasing maneuver.

NASA's GRAIL mission was designed to avoid the period of the lunar eclipse when designing the mission. The time of entry into the lunar orbit was set for December 28, 2011, avoiding the total lunar eclipse that will occur on December 10, 2011, and the partial lunar eclipse that will occur on June 4, 2012. It was designed to perform its mission in the lunar orbit until 29 May 2012 and end its mission by colliding with the lunar surface on 4 June [3]. Survival during the lunar eclipse was not reflected in the design. However, despite the original plan to avoid lunar eclipse operations, GRAIL successfully survived the partial lunar eclipse on June 4, 2012, and continued its extended mission, ultimately deorbiting and impacting the lunar surface on December 17, 2012 [4].

Partial or penumbral lunar eclipses are shorter in duration than total lunar eclipses and may not require special operations such as safe mode operation. If power availability is not a concern, these eclipse periods can even be utilized for specialized observations. For example, Japan's KAGUYA spacecraft captured images of the gradual emergence of the Sun from behind the Earth's shadow during the penumbral lunar eclipse on February 10, 2009 [5]. These historical examples highlight that while lunar eclipses present survival challenges for orbiters, they also offer unique scientific opportunities.

The Indian Space Research Organization (ISRO)'s Chandrayaan-2 Orbiter implemented an orbit tuning strategy to optimize power generation during total lunar eclipses [6]. Similar to the phasing maneuver used by NASA's Lunar Reconnaissance Orbiter (LRO), this approach adjusted the Argument of Perigee (AOP) and True Anomaly (TA) to maximize solar exposure before and after the eclipse. These parameters were tuned through orbit maneuvers to prevent deep battery discharge and ensure mission continuity. Additionally, satellite load management was carried out to further protect the battery. By implementing these measures, Chandrayaan-2 Orbiter successfully survived multiple total lunar eclipses despite the extended duration of power unavailability.

The Korea Pathfinder Lunar Orbiter (KPLO), operated by the Korea Aerospace Research Institute (KARI), also experienced lunar eclipses twice a year during its mission. In 2023, during the nominal mission phase, and in 2024, during the first year of its extended mission, KPLO only encountered partial and penumbral eclipses, which did not necessitate special operational procedures, as power supply remained stable. However, the total lunar eclipse on March 14, 2025, posed a significant risk to power availability, requiring special eclipse operations to prevent battery depletion.

Although KPLO's initial design accounted for total lunar eclipses in terms of battery capacity and operational modes, these considerations assumed a one-year mission duration. By 2025, KPLO had been operating in an extended mission for two years, and its battery capacity had degraded beyond the original design assumptions. To ensure survival during the total lunar eclipse, two major operational strategies were developed: (1) maximizing power generation through orbit adjustment and (2) minimizing power consumption using Power Saving Mode. These strategies were refined, verified through in-orbit test, and applied during the lunar eclipse. This paper describes the eclipse operation plan, the detailed procedures prepared, and the results of the March 14, 2025, total lunar eclipse.

## 2. Lunar Eclipse Operation Plan

### 2.1 Orbit Adjustment to Maximize Power Generation

The duration and characteristics of a lunar eclipse experienced by an orbiter depend on its orbit, independent of when the Moon enters and exits the Earth's shadow. By adjusting the timing of when the orbiter enters and exits both the Earth's and the Moon's shadow, it is possible to create more favorable conditions for solar power generation. This can be expressed in terms of Argument of Latitude (AOL) at a given point in time, and power characteristics can be predicted for 12 orbits with AOLs spaced 30 degrees apart, as shown in Figure 1. Figure 2 shows the Solar Intensity for the orbit corresponding to each AOL. The sun exposure time is relatively longer around AOL 0 degrees and shorter around AOL 180 degrees. The predicted solar intensity is used as input data for power simulations. Figure 3 shows the power simulation results.

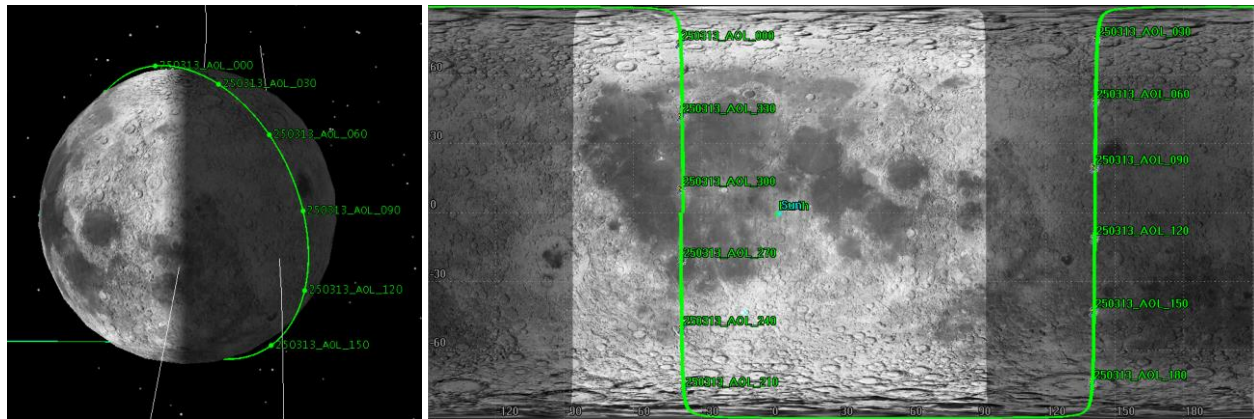


Fig. 1. 12 orbits with different AOLs

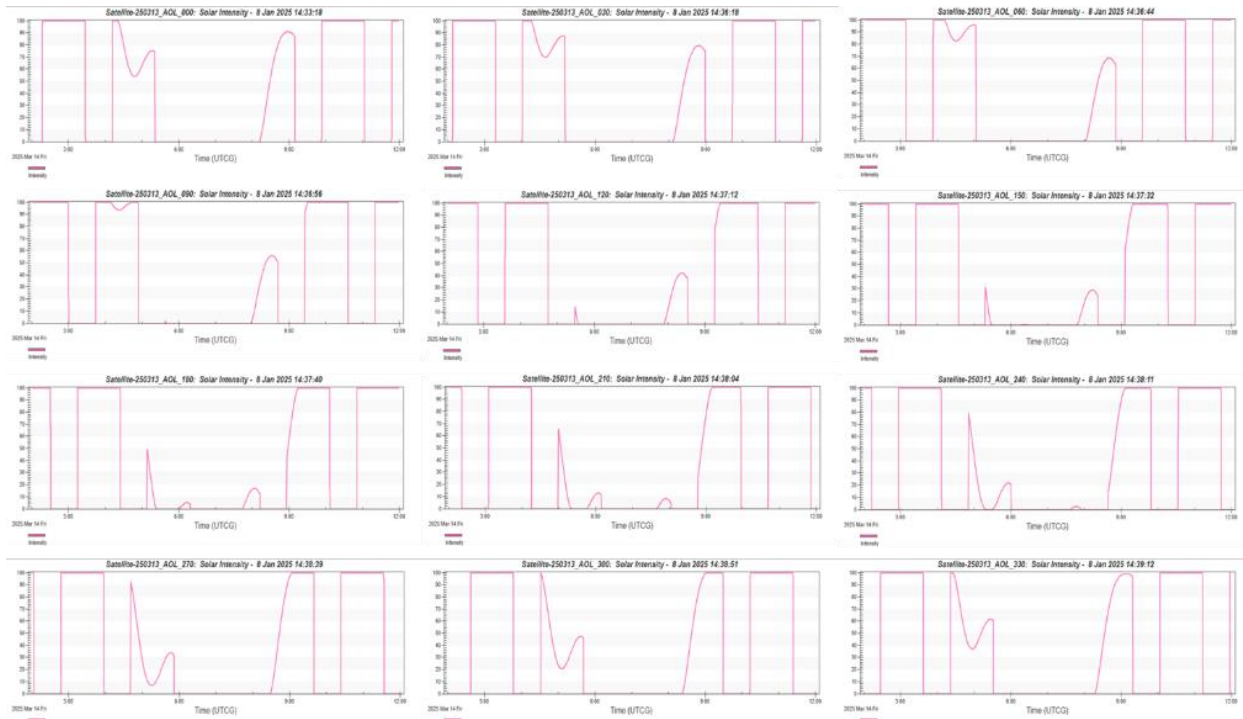


Fig. 2. Solar Intensity for the orbit corresponding to each AOL

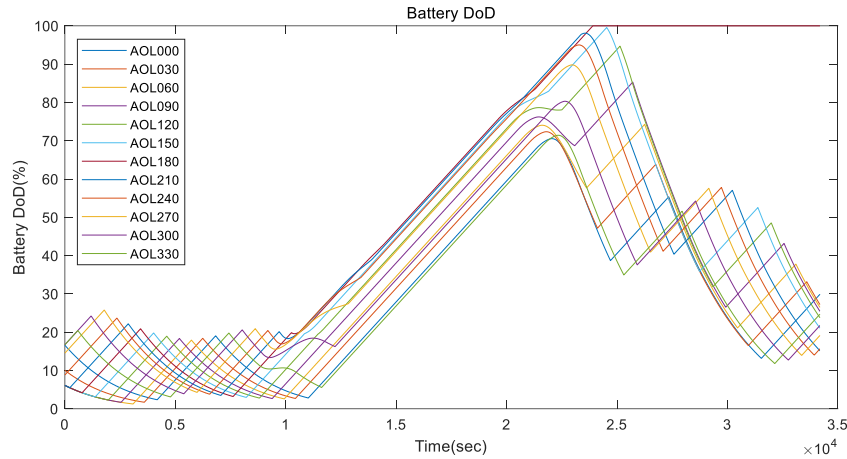


Fig. 3. Power Simulation Results (Battery DoD Profile)

### 2.2 Power Saving Mode to Minimize Power Consumption

KPLO uses different types of devices depending on its operation mode, and the attitude of the spacecraft also changes. In normal operation mode, which performs scientific missions in the lunar orbit, the payload is oriented towards the Moon in a nadir-pointing attitude, and various instruments, communications, and attitude control devices remain active. The attitude control system employs star trackers as sensors and reaction wheels as actuators. In contrast, the safe mode utilizes sun sensors and thrusters for attitude control. Additionally, the heater set points in safe mode are lower than in normal operations, resulting in reduced power consumption.

Power saving mode is a mode in which attitude control is suspended in the safe mode operation configuration and the power of the devices required for the thruster operation, i.e. the Valve Driving Electronics (VDE) and the Cat. Bed Heater is turned off. The thermal control set point is the survival range, and the pre-heating mode is applied to raise the temperature of all parts of the spacecraft to the highest operational temperature 10 orbits before entering the lunar eclipse and until just before entering the lunar eclipse to minimize the operation of the heater.

### 3. Lunar Eclipse Operation Procedures

Figure 4 presents the operational timeline before and after the lunar eclipse. The lunar eclipse operation is divided into four phases: (1) 10 orbits before the eclipse, (2) 1 orbit before the eclipse, (3) eclipse phase, and (4) post-eclipse recovery.

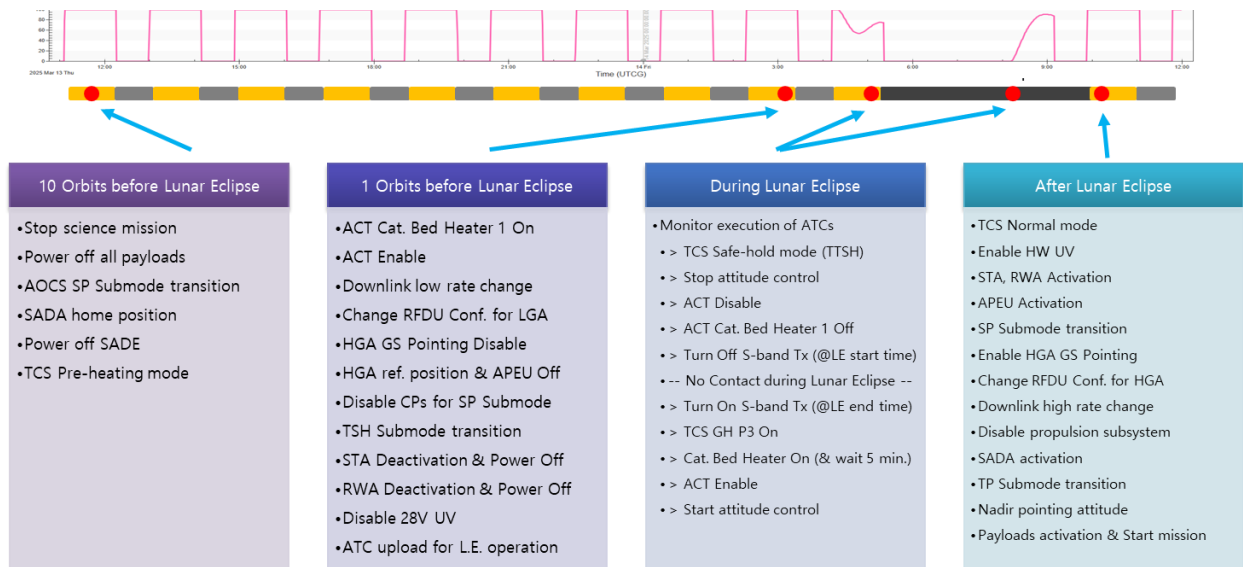


Fig. 4. Lunar Eclipse Operation Timeline

### *3.1 Procedures 10 Orbits Before the Eclipse*

All scientific operations conducted in normal operation mode are suspended, and all payloads are powered down. The spacecraft attitude is switched from a nadir-pointing attitude to a Sun-pointing attitude to optimize the solar panel's incidence angle to 0 degrees for maximum power generation. This transition is achieved by switching the Attitude and Orbit Control Subsystem (AOCS) submode from TP Submode to SP Submode. Subsequently, the Solar Array Drive Assembly (SADA) is fixed in the home position, and the SADE power is turned off. The Thermal Control Subsystem (TCS) mode is changed from Normal mode to Pre-heating mode, raising all heater set points to the highest operational temperature. Over the course of 10 orbits (approximately 20 hours), the spacecraft components gradually heat up, maintaining a high temperature until just before the eclipse.

### *3.2 Procedures 1 Orbit Before the Eclipse*

One orbit before entering the lunar eclipse, the spacecraft transitions into Safe Mode. The Attitude Control Thruster (ACT) is activated for safe mode attitude control, and the downlink rate is switched to a low rate. The configuration of the RFDU is modified to change the S-band downlink path from the High Gain Antenna (HGA) to the Low Gain Antenna (LGA). The HGA is no longer pointed at the ground station and is moved to the reference position before turning off the APEU. The AOCS submode is switched from SP Submode to TSH Submode. In TSH Submode, star trackers and reaction wheels are deactivated and powered down. The bus voltage monitoring logic is disabled to prevent automatic responses to battery voltage drops caused by power depletion. Finally, the Absolute-Timed Command (ATC) for the total lunar eclipse phase is uploaded, ensuring that the commands are executed at the planned time, even if real-time ground communication encounters difficulties.

### *3.3 Eclipse Phase Procedures*

During the eclipse phase, the pre-uploaded commands are automatically executed and monitored. The Pre-heating mode, which had been maintained until the eclipse entry, is deactivated, and the thermal control mode is switched to Safe-Hold mode, changing the set points to the survival range. As a result, the heaters stop operating, and they will only reactivate once the temperature reaches the low limit of the survival range. Just before eclipse entry, attitude control is suspended, the Attitude Control Thruster is deactivated, and the Catalyst Bed Heater power is turned off. Subsequently, the S-band Transmitter is powered down, completing the transition to Power Saving Mode. The spacecraft then remains unmonitored for approximately 3 hours while receiving no sunlight.

When sunlight begins to partially illuminate the spacecraft, the pre-uploaded commands reactivate the S-band Transmitter to resume monitoring. Since the spacecraft was in a Sun-pointing attitude at eclipse entry but had been uncontrolled for 3 hours, attitude errors may prevent power generation even if sunlight is available. Therefore, once partial sunlight returns, the attitude control thrusters are reactivated to restore Sun-pointing attitude control.

### *3.4 Post-Eclipse Recovery Procedures*

Once the eclipse ends and full sunlight returns, recovery procedures commence. The thermal control mode is switched back to Normal mode, and the bus voltage monitoring logic is reactivated. The star trackers and reaction wheels are powered on, and the APEU is reactivated to reestablish communication via the High Gain Antenna (HGA). The spacecraft then transitions back to SP Submode for three-axis attitude control. The HGA is pointed at the ground station, and the S-band downlink path is switched from LGA to HGA. The downlink rate is increased to high rate, completing the transition back to the Sun-pointing normal operation mode. The Attitude Control Thruster, no longer needed, is deactivated, and the solar array drive mechanism is reactivated before switching the spacecraft attitude back to a nadir-pointing orientation. Finally, all payloads are powered on, and scientific operations are resumed, marking the completion of the entire eclipse operation procedure.

## **4. Lunar Eclipse Operation Results**

On February 27, 2025, an in-orbit test was conducted to verify the prepared lunar eclipse operation procedures. Since the primary purpose of the in-orbit test was procedural validation, it was carried out in a fast-tracked manner. During the test, it was observed that power consumption by heaters significantly increased due to Pre-heating Mode, which led to a rapid rise in battery discharge current and battery temperature. As an emergency measure, the Pre-heating Mode was immediately halted, and the thermal control mode was switched to Normal Mode before continuing the test. It was subsequently determined that Pre-heating Mode should be activated only in the sunlit phase of the orbit to ensure safety. In the sunlit phase, even though heater power consumption increases, the higher power generation from solar panels offsets this, preventing excessive battery discharge current and maintaining battery temperature stability. These revised procedures were validated through a Pre-heating Mode temperature characteristic test conducted on March 6, 2025, and were applied in the lunar eclipse operation.

Figure 5 illustrates the results of the lunar eclipse operation. It is evident that solar power generation was entirely suspended for 3 hours. The bus voltage dropped to 28.6V and started recovering as solar power generation resumed. Power consumption during the Pre-heating phase increased to 850W, whereas in the Power Saving Mode during the eclipse, it was maintained at approximately 160W. After entering the eclipse, the temperatures of various spacecraft components gradually declined, and the heaters reactivated after 1.6 hours. This led to a gradual increase in power consumption. The battery Depth of Discharge (DoD) peaked at 61.8% which is lower than expected value 70.4%.

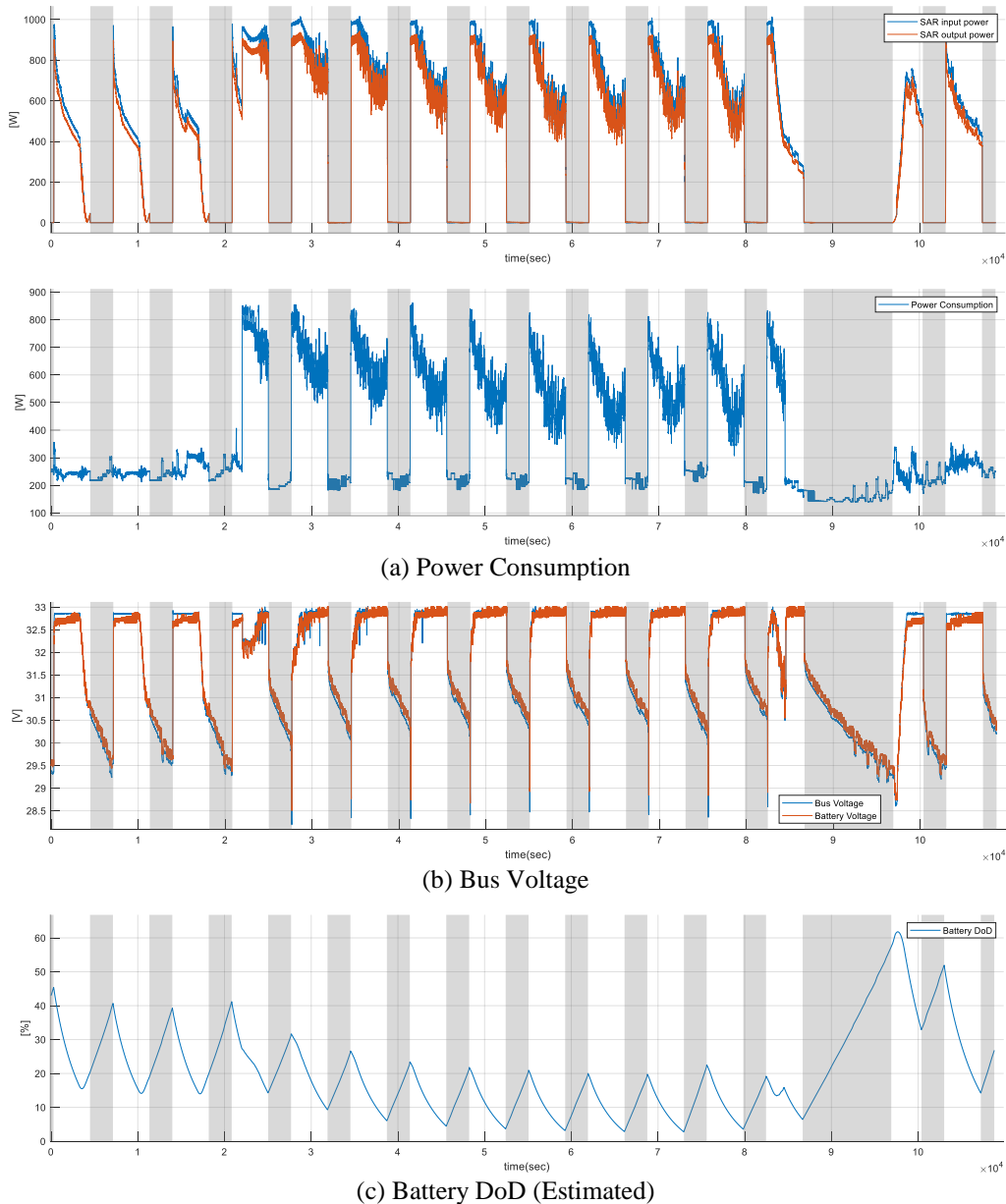


Fig. 5. Lunar Eclipse Operation Results

## 5. Conclusions

This paper presented the operational plan, procedures, and results of KPLO's first total lunar eclipse survival operation. To maximize solar power generation, a phasing maneuver was performed, while Pre-heating Mode and Power Saving Mode were employed to minimize power consumption. The eclipse operation procedures were verified and refined through in-orbit testing in preparation for the total lunar eclipse.

Thanks to thorough preparation and precise execution, KPLO successfully survived the total lunar eclipse. There are three more total lunar eclipses remaining before the end of KPLO's mission. As time progresses, the available

battery capacity is expected to decrease, making future total lunar eclipses more challenging. However, by utilizing this eclipse operation procedure, we expect to be able to survive future eclipses until the end of the mission.

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