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Preparation of Contingency Trajectory Operation for the Korea Pathfinder Lunar Orbiter

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The Korea Pathfinder Lunar Orbiter (KPLO), also known as Danuri, successfully entered its mission orbit on December 27, 2022 (UTC), and is currently performing its mission smoothly. To mitigate potential contingencies during the flight and to navigate the spacecraft into the desired lunar orbit, the KPLO flight dynamics (FD) team analyzed major trajectory-related contingencies that could lead to the violation of mission requirements and prepared operational procedures from the perspective of trajectory and FD. This paper presents the process of preparing contingency trajectory operations for the KPLO, including the identification of trajectory contingencies, prioritization results, and the development of recovery plans and operational procedures. The prepared plans were successfully applied to address minor contingencies encountered during actual operations. The results of this study will provide valuable insights to FD engineers preparing for space exploration mission operations.

Keywords: Korea Pathfinder Lunar Orbiter, Danuri, contingency, trajectory operation

1. INTRODUCTION

The Korea Pathfinder Lunar Orbiter (KPLO), also known as Danuri, achieved a major milestone on December 27, 2022 (UTC), when it entered its planned mission orbit to start exploring the Moon. After launch on August 4, 2022 (UTC), the KPLO was successfully inserted into a ballistic lunar transfer (BLT) trajectory and began a 4.5-month cruise to the Moon (Song et al. 2023a). The KPLO flight dynamics (FD) team monitored the spacecraft's trajectory every business day and decided to perform four trajectory correction maneuvers (TCMs) to correct errors during its flight (Bang et al. 2022a; Bae et al. 2023). During the lunar orbit acquisition (LOA) phase, significant adjustments were made to the trajectory plan, leading to execute three lunar orbit insertion (LOI) maneuvers instead of the originally planned five LOI maneuvers and one orbit trim maneuver (OTM) (Song et al. 2023b, 2023c). Despite these changes, all mission orbit requirements were successfully met and the KPLO began operating nominally in a 100 km lunar polar orbit. To ensure the KPLO remains in its designated mission orbit, regular orbit maintenance maneuvers (OMMs) were performed and are scheduled in the future (Hong et al. 2023).

Space exploration missions inherently involve numerous expected and unexpected challenges. Since the KPLO mission is Korea's first space mission outside Earth's orbit and the BLT trajectory is challenging for beginners in space exploration, the KPLO FD team made a significant effort in preparing FD operations for both nominal and off-nominal situations. The trajectory design system and the FD subsystem were developed separately to achieve a flexible FD operation while reflecting the characteristics of BLT trajectory (Song et al. 2021; Bang et al. 2022b). Both systems were tested and validated through numerous simulations and rehearsals using realistic blind datasets (Song et al. 2022). Furthermore, cooperation with other entities was

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also prepared. Interfaces with National Aeronautics and Space Administration (NASA)'s Deep Space Network were established to facilitate the gathering of tracking data, as well as spacecraft's telemetry and command (Song et al. 2023d). Collaborative efforts between Korea Aerospace Research Institute (KARI) FD team and NASA Johnson Space Center Flight Operations Directorate were made to compare orbit determination (OD) and maneuver planning (MP) solutions. A number of test and joint rehearsals were conducted to validate all operational concept, procedures, and timelines (Song et al. 2023e).

Preparing contingency trajectory operation is essential for the success of space exploration mission. In many previous lunar missions, a number of studies have been conducted on the recovery trajectories for off-nominal situations such as trans-lunar injection failure and LOI maneuver failure (Lozier et al. 1998; Beckman 2007; Kawakatsu et al. 2007; Genova 2014; Liu et al. 2015; Harpold et al. 2023). For the KPLO mission, LOI-related contingencies were analyzed under the phasing-loop transfer strategy, which was the strategy before adopting the BLT trajectory (Bae et al. 2017; Song et al. 2017). After the confirmation of the BLT trajectory, a comprehensive contingency analysis was performed across all mission phases, leading to the development of mitigation plans for each trajectory contingency case (West et al. 2022; Bang et al. 2023). Note that most studies have primarily focused on how to mitigate specific contingencies and design recovery trajectories. Unlike previous references, this paper encompasses the entire contingency preparation process, from identifying and prioritizing trajectory contingencies to developing mitigation plans and operational procedures. This thoroughly prepared contingency trajectory operation plan enabled KPLO to successfully overcome not only minor contingencies during actual operations but also significant and sudden changes in the trajectory plan during the LOA phase through flexible operation.

The remainder of this paper is structured as follows. Section 2 provides an overview of KPLO's nominal trajectory and mission orbit. Section 3 presents the methodologies and results related to the identification and prioritization of trajectory contingencies. Preparation of recovery plans and operational procedures for contingency trajectory operation are introduced in Section 4. Finally, Section 5 provides the conclusions.

2. TRAJECTORY AND MISSION ORBIT OVERVIEW

The KPLO utilized a BLT trajectory to reach the Moon. The trajectory was designed to ensure consistent lunar arrival conditions, regardless of the launch date. Prior to launch, the KPLO FD team prepared reference trajectories corresponding to each launch date within the 7-day launch period. During the trans-lunar cruise (TLC) phase, a total of nine TCMs, namely TCM1 through TCM9, were scheduled to correct any errors during the flight. TCM1 serves the dual purpose of addressing launch errors and testing the orbit maneuver thruster (OMT), which is a newly developed propulsion system. TCM3 is the only deterministic maneuver with a non-zero magnitude and direction for the purpose of manifold transition. The others are statistical maneuvers that can be performed when the spacecraft is expected to fail to achieve the desired lunar arrival conditions. Fig. 1 illustrates the nominal KPLO trajectory for the August 4, 2022 launch case, including the locations where TCMs are scheduled.

The LOA phase originally included five LOI maneuvers and one OTM, namely LOI1 through LOI5 and OTM1, respectively. Each LOI maneuver is an anti-velocity burn executed at the perilune to reduce the orbit period. OTM1 consists of a pair of maneuvers designed to strictly match a 100 × 100 km circular orbit at the end of the LOA phase. The commissioning phase was scheduled after the LOA phase to check the operability of science payloads. One additional OTM, OTM2, was planned during the commissioning phase to achieve mission orbit requirements: 100 ± 30 km of lunar altitude and 90 ± 0.25 deg of mean inclination during the 1-year mission period. After the beginning of the nominal mission phase, regular OMMs were planned to maintain the KPLO's orbit. Each OMM is composed of a pair of maneuvers that adjust eccentricity and argument of periapsis simultaneously.

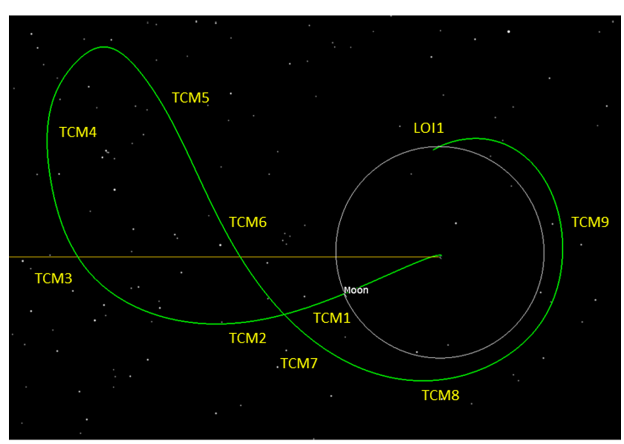


Fig. 1. Korea Pathfinder Lunar Orbiter trajectory and TCM locations represented in Sun-Earth rotating frame. TCM, trajectory correction maneuver; LOI, lunar orbit insertion.

During the actual operation of KPLO, especially in the LOA phase, the trajectory plan has been significantly revised regarding many real-world operational constraints (Song et al. 2023c). Note that the results in this paper are based on the reference trajectory generated prior to launch.

3. TRAJECTORY CONTINGENCY

3.1 Identification

The first step in preparing for contingency trajectory operations is to identify all off-nominal situations that could impact the KPLO's trajectory. Table 1 provides a summary of the predicted performance of the launch vehicle and KPLO thrusters, namely OMT and attitude control thruster (ACT), which were received prior to launch. Based on these values, the KPLO FD team conducted dispersion analysis and prepared the delta-V budget to account for expected errors during launch and maneuver executions.

A contingency can be simply considered as any situation outside of the expected performance and the established delta-V budget. During the launch phase, a total of six contingencies were identified as presented in Table 2. Given the instantaneous launch window for the KPLO trajectory on each launch date, the launch time error can impact the trans-lunar trajectory insertion performance. Low C3 and high C3 energy cases were separately considered. If the launch vehicle fails to produce sufficient C3 energy, there is a risk that the KPLO will return to Earth's orbit. On the other hand, if the launch vehicle generates excessive C3 energy, the KPLO may fly towards the Sun instead of the Sun-Earth L1 point. Contingencies in KPLO's trajectory also arise when errors in right ascension of the injection orbit apoapsis vector (RAV) and declination of the injection orbit apoapsis vector (DAV) exceed the expected boundaries. Additionally, the risk of collision with any satellites orbiting in Earth's orbit was considered as a potential contingency.

Table 1. Expected performance of launch vehicle and KPLO thrusters

Launch vehicle accuracy (3σ)	
C3	0.15 km^2/s^2
RAV	0.2°
DAV	0.2°
Maneuver magnitude accuracy (3σ)	
OMT	4%
ACT	4%
Maneuver pointing accuracy (3σ)	
OMT	1.27°
ACT	2.5°

KPLO, Korea Pathfinder Lunar Orbiter; C3, launch injection energy per unit mass; RAV, right ascension of the injection orbit apoapsis vector; DAV, declination of the injection orbit apoapsis vector; OMT, orbit maneuver thruster; ACT, attitude control thruster.

In the TLC phase, contingencies can be categorized into two cases: those occurring before and after TCM execution. When planning a TCM, not only the upcoming maneuver but also all remaining TCMs until lunar arrival are comprehensively considered to predict the remaining fuel after the TLC phase. If the expected fuel consumption exceeds the assigned fuel budget, there is a risk of violating the mission orbit requirements. One critical contingency associated with TCMs is the failure to execute a planned TCM. Since TCM3 is an essential maneuver for lunar approach, missing its execution could result in a lunar approach failure. Execution failures in other statistical TCMs and unexpected errors in magnitude, attitude, and burn time could lead to off-nominal trajectories.

Before the LOA phase, contingencies related to errors in lunar arrival conditions following the final TCM, TCM9, were identified. These errors include lunar arrival epoch, altitude, and inclination, all of which can impact the trajectory during the LOA phase. Similar to TCM planning, when planning a LOI maneuver, all remaining maneuvers until the end of the LOA phase are planned together to predict fuel consumption. A lack of remaining fuel could lead to a failure in achieving the mission orbit requirements. The conjunction risk with other lunar orbiters including the Lunar Reconnaissance Orbiter (LRO) and Chandrayaan-2 was considered as a contingency case that requires special operations. The first LOI maneuver, LOI1, is responsible for capturing the KPLO in lunar orbit. Failure to execute LOI1 or a significant partial burn during LOI1 could result in a failure in lunar capture. Execution errors that exceed the predicted values in magnitude, attitude, and burn time during the LOA phase could lead to off-nominal orbits.

The purposes of OTMs and OMMs are to ensure that the KPLO remains within the mission orbit requirements: an altitude of 100 ± 30 km and a mean inclination of 90 ± 0.25 deg during the 1-year mission period. Failures in executing these maneuvers or unexpected execution errors in magnitude, attitude, and burn time may result in a violation of the mission orbit requirements.

3.2 Prioritization

After identifying trajectory contingencies, the KPLO FD team prioritized them to efficiently prepare recovery plans. The prioritization was based on evaluating likelihood and consequence, which are widely used method in risk analysis. Likelihood refers to the probability of a contingency case occurring and was scored on a 5-point scale in this study: 1)

Table 2. List of trajectory contingencies and prioritization result (continued on the next page)

Phase	Contingency	Condition	L	C	L × C	Priority	Complexity
Launch	Launch time	Off-nominal trajectory	2	3	6	3	Low
	Low C3 energy	Earth return	2	4	8	2	Medium
	High C3 energy	Heliocentric escape	1	4	4	3	Medium
	RAV error	Off-nominal trajectory	2	3	6	3	Low
	DAV error	Off-nominal trajectory	2	3	6	3	Low
	Col. avoidance	High probability conjunction	1	4	4	3	Medium
Planning TCM	Over budget	Fail to achieve mission orbit requirements	2	3	6	3	Medium
TCM3	No burn	Fail to approach Moon	3	4	12	2	Medium
	Partial burn	Off-nominal trajectory	3	1	3	3	Low
	Over burn	Off-nominal trajectory	2	1	2	3	Low
	Delayed start	Off-nominal trajectory	2	1	2	3	Low
	Early start	Off-nominal trajectory	2	1	2	3	Low
	Az. pointing error	Off-nominal trajectory	2	1	2	3	Low
	El. pointing error	Off-nominal trajectory	2	1	2	3	Low
TCMX	No burn	Off-nominal trajectory	2	3	6	3	Medium
	Partial burn	Off-nominal trajectory	3	2	6	3	Low
	Over burn	Off-nominal trajectory	3	2	6	3	Low
	Delayed start	Off-nominal trajectory	2	1	2	3	Low
	Early start	Off-nominal trajectory	2	1	2	3	Low
	Az. pointing error	Off-nominal trajectory	2	1	2	3	Low
	El. pointing error	Off-nominal trajectory	2	1	2	3	Low
Planning LOI	LOI Epoch error	Off-nominal trajectory	3	3	9	2	Medium
	LOI altitude error	Off-nominal altitude	3	3	9	2	Medium
	LOI inclination error	Off-nominal inclination	3	3	9	2	Medium
	Over budget	Fail to achieve mission orbit requirements	2	3	6	3	Medium
	Col. avoidance	High probability conjunction	1	5	5	3	Medium
LOI1	No burn	Fail to capture	3	5	15	1	High
	Partial burn	Fail to capture	4	5	20	1	High
	Partial burn	Off-nominal orbit, T > 12 h	4	4	16	1	Medium
	Over burn	Off-nominal orbit, T < 12 h	1	1	1	3	Low
	Delayed start	Off-nominal orbit	2	2	4	3	Low
	Early start	Off-nominal orbit	2	2	4	3	Low
	Az. pointing error	Off-nominal inclination	2	4	8	2	Medium
	El. pointing error	Off-nominal orbit	2	1	2	3	Low
LOI2	No burn	Remain in 12 h orbit	3	4	12	2	Low
	Partial burn	Off-nominal orbit, T > 5.75 h	4	3	12	2	Low
	Over burn	Off-nominal orbit, T < 5.75 h	1	1	1	3	Low
	Delayed start	Off-nominal orbit	2	1	2	3	Low
	Early start	Off-nominal orbit	2	1	2	3	Low
	Az. pointing error	Off-nominal inclination	2	4	8	2	Medium
	El. pointing error	Off-nominal orbit	2	1	2	3	Low
LOI3	No burn	Remain in 5.75 h orbit	2	4	8	2	Low
	Partial burn	Off-nominal orbit, T > 3.60 h	3	3	9	2	Low
	Over burn	Off-nominal orbit T < 3.60 h	1	1	1	3	Low
	Delayed start	Off-nominal orbit	2	1	2	3	Low
	Early start	Off-nominal orbit	2	1	2	3	Low
	Az. pointing error	Off-nominal inclination	2	4	8	2	Medium
	El. pointing error	Off-nominal orbit	2	1	2	3	Low
LOI4	No burn	Remain in 3.60 h orbit	2	4	8	2	Low
	Partial burn	Off-nominal orbit, T > 2.58 h	3	3	9	2	Low
	Over burn	Off-nominal orbit T < 2.58 h	1	1	1	3	Low
	Delayed start	Off-nominal orbit	2	1	2	3	Low
	Early start	Off-nominal orbit	2	1	2	3	Low
	Az. pointing error	Off-nominal inclination	2	4	8	2	Medium
	El. pointing error	Off-nominal orbit	2	1	2	3	Low

(**Table 2.** Continued)

Phase	Contingency	Condition	L	C	L × C	Priority	Complexity
LOI5	No burn	Remain in 2.58 h orbit	2	4	8	2	Low
	Partial burn	Off-nominal orbit, T > 1.99 h	3	3	9	2	Low
	Over burn	Off-nominal orbit, T < 1.99 h	1	1	1	3	Low
	Delayed start	Off-nominal orbit	2	1	2	3	Low
	Early start	Off-nominal orbit	2	1	2	3	Low
	Az. pointing error	Off-nominal inclination	2	4	8	2	Medium
	El. pointing error	Off-nominal orbit	2	1	2	3	Low
OTM1	No burn	Off-nominal orbit	2	1	2	3	Low
	Partial burn	Off-nominal orbit	2	1	2	3	Low
	Over burn	Off-nominal orbit	1	1	1	3	Low
	Delayed start	Off-nominal orbit	1	1	1	3	Low
	Early start	Off-nominal orbit	1	1	1	3	Low
	Az. pointing error	Off-nominal inclination	2	1	2	3	Low
	El. pointing error	Off-nominal orbit	2	1	2	3	Low
OTM2	No burn	Off-nominal orbit	2	1	2	3	Low
	Partial burn	Off-nominal orbit	2	1	2	3	Low
	Over burn	Off-nominal orbit	1	1	1	3	Low
	Delayed start	Off-nominal orbit	1	1	1	3	Low
	Early start	Off-nominal orbit	1	1	1	3	Low
	Az. pointing error	Off-nominal inclination	2	1	2	3	Low
	El. pointing error	Off-nominal orbit	2	1	2	3	Low
OMM	No burn	Off-nominal orbit	2	1	2	3	Low
	Partial burn	Off-nominal orbit	2	1	2	3	Low
	Over burn	Off-nominal orbit	1	1	1	3	Low
	Delayed start	Off-nominal orbit	1	1	1	3	Low
	Early start	Off-nominal orbit	1	1	1	3	Low
	Az. pointing error	Off-nominal inclination	2	1	2	3	Low
	El. pointing error	Off-nominal orbit	2	1	2	3	Low

L, likelihood; C, consequence; TCM, trajectory correction maneuver; LOI, lunar orbit insertion; OTM, orbit trim maneuver; OMM, orbit maintenance maneuver; C3, launch injection energy per unit mass; RAV, right ascension of the injection orbit apoapsis vector; DAV, declination of the injection orbit apoapsis vector; Col, collision; Az, azimuth; El, elevation.

least likely, 2) unlikely, 3) moderate, 4) likely, and 5) most likely to happen. Consequence represents the impact when a contingency occurs and was also assessed on a 5-point scale: 1) minor impacts requiring additional analysis, 2) mild impacts that can lead to a change in mission timeline, 3) moderate impact that can lead to a reduction of mission lifetime, 4) significant impacts that can lead to the loss of one or more science objectives, and 5) severe impacts that can lead to the loss of mission. Each team member qualitatively evaluated the likelihood and the consequence for each contingency case, and the average values were used for prioritization, as presented in Table 2. In addition, the complexity of preparing recovery plan for each contingency was also evaluated to consider the practical timeline and ensure completion of the preparation process before launch.

All contingencies were categorized into three priority groups based on the multiplication of likelihood and consequence (L × C) scores: 1) 15–25, 2) 8–14, and 3) 1–7. Priority 1 group includes three contingencies associated with LOI1. Since the LOI1 maneuver is the most critical maneuver for lunar capture, any failure or partial burn during the maneuver could directly result in a loss of mission. Therefore, a mitigation plan for these contingencies should be prepared as a top priority based on in-depth analysis results. Priority 2 group consists of four categories: low C3 energy during launch, execution failure of TCM3, errors in lunar arrival, and azimuth pointing errors during LOA phase. These contingencies have non-negligible likelihood and consequence that could lead to a loss of science objectives or a reduction of mission lifetime. Azimuth-directed pointing errors are more significant than elevation-directed errors because the KPLO has a strict inclination requirement to observe the Moon's south pole. Other contingencies were classified as Priority 3, which have a low probability or minor impacts on KPLO's trajectory.

4. CONTINGENCY TRAJECTORY OPERATION PLAN

4.1 Recovery Planning

The KPLO FD team developed mitigation plans for each trajectory contingency based on their assessed priorities. High-priority and complex contingencies were analyzed before other cases. For each contingency case, a sensitivity analysis was conducted to quantitatively assess the resulting trajectories depending on the severity of the contingency. In general, there are several viable options for addressing trajectory contingencies, such as rescheduling a maneuver, adding one or more recovery maneuvers to follow the reference trajectory, or revising the reference trajectory itself. The KPLO FD team determined the most preferable and effective option for each case and prepared corresponding mitigation strategies.

Fig. 2 illustrates the off-nominal trajectory and the recovery trajectory for the case of LOI1 maneuver execution failure. In the event of a failed LOI1 execution, the KPLO would arrive at the next perilune with a significantly different altitude and inclination than the desired conditions, ultimately escaping the Moon as depicted by the red trajectory in Fig. 2. Simply adding a recovery LOI (rLOI) maneuver at the next perilune, as a substitute for the original LOI1, requires enormous delta-V for inclination correction. To reduce the required delta-V, a recovery TCM (rTCM) is also included ahead of the rLOI to achieve the desired altitude and inclination at the perilune. The location of the rTCM is strategically determined at the apolune to ensure sufficient time for OD and MP for both maneuvers. Consequently, the KPLO can be captured into the desired lunar orbit with an additional delta-V of approximately 85.75 m/s. Similar to this case, recovery plans were prepared for all identified trajectory contingencies based on the results of contingency analysis and practical considerations,

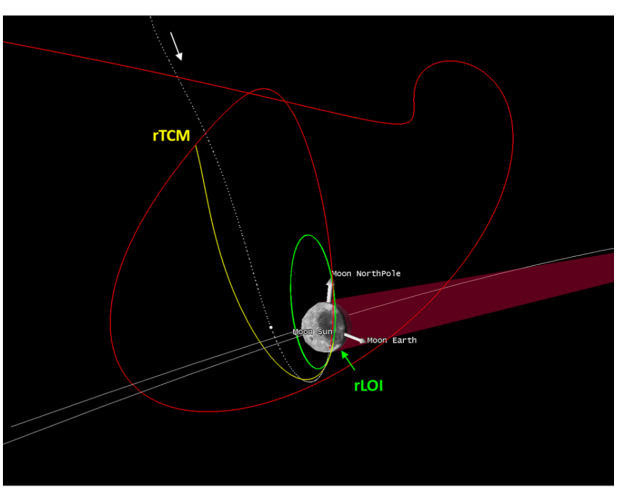


Fig. 2. Trajectory after missing LOI1 (red), recovery trajectory after rTCM (yellow), recovery trajectory after rLOI (green) represented in Moon inertial frame. rTCM, recovery trajectory correction maneuver; rLOI, recovery lunar orbit insertion.

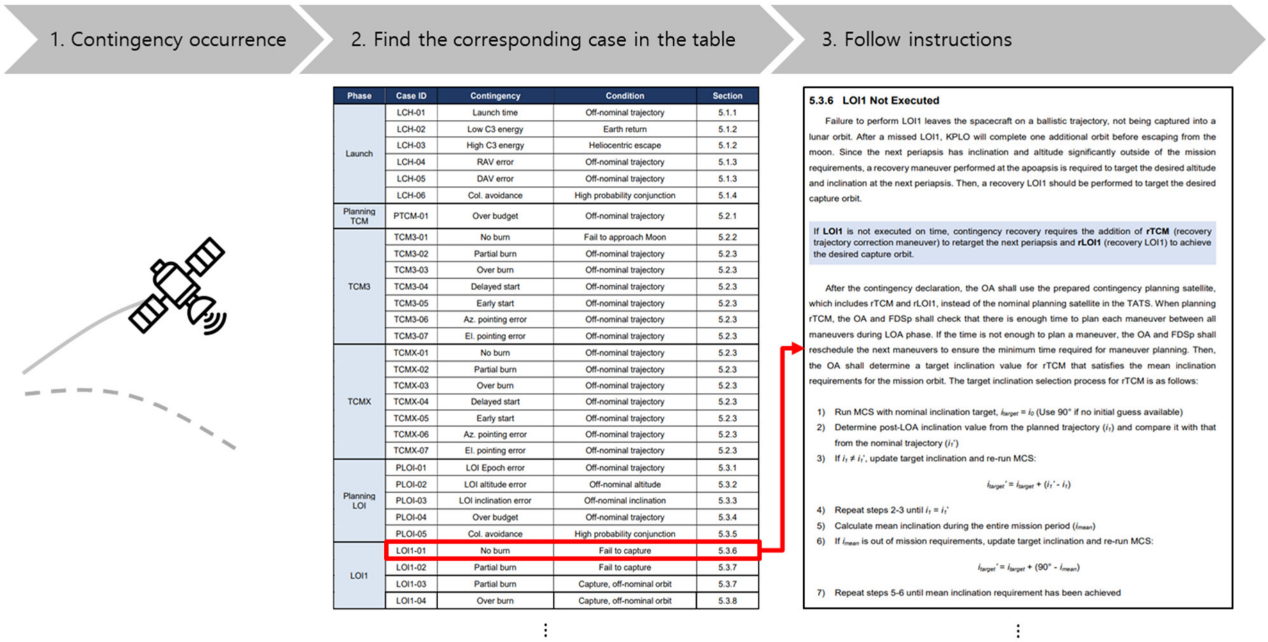
including operational timelines.

4.2 Contingency Operational Procedure Preparation

To ensure smooth and immediate trajectory operations in the event of trajectory contingencies, the KPLO FD team developed a document titled "Trajectory Contingency Playbook" (Bang 2022c). This document provides not only the list of trajectory contingencies identified in Section 3, but also detailed operational procedures based on the prepared recovery plans. Fig. 3 outlines the workflow for contingency trajectory operations. When an off-nominal situation occurs, FD operators can find the corresponding case ID and section numbers in the contingency list. Each section contains checklists or guidelines that FD operators can intuitively follow. As a brief example, if the LOI1 maneuver fails to execute as planned, FD operators are instructed to: 1) replace the nominal template scenario with the contingency scenario, which includes rTCM and rLOI, 2) check the feasibility of executing rTCM on time, 3) check that there is enough time to plan a maneuver between all maneuvers during the LOA phase, and 4) determine a target inclination value for rTCM that meets the mean inclination requirements as per step-by-step instructions. The procedure was validated through simulations performed prior to launch and remains revisable to address any unexpected issues that may arise during the mission.

5. CONCLUSIONS

This paper provides a comprehensive overview of the process of preparing contingency trajectory operations for the KPLO. To ensure the success of the mission and to account for potential off-nominal situations, the KPLO FD team conducted a thorough analysis of trajectory-related contingencies across all mission phases, including launch, TLC, LOA, commissioning, and nominal mission. The team's initial step involved identifying a wide range of potential trajectory contingencies, drawing from the expected performance of the launch vehicle and KPLO thrusters. The application of likelihood and consequence assessment allowed the team to prioritize trajectory contingencies effectively. High-priority cases, particularly those related to LOI1, were addressed with in-depth analysis due to their critical impact on the mission's success. The paper outlines the development of mitigation plans and recovery strategies for each trajectory contingency. These strategies encompass various options, such as rescheduling maneuvers, adding recovery maneuvers, or modifying the reference trajectory.



Phase	Case ID	Contingency	Condition	Section
Launch	LCH-01	Launch time	Off-nominal trajectory	5.1.1
	LCH-02	Low C3 energy	Earth return	5.1.2
	LCH-03	High C3 energy	Heliocentric escape	5.1.2
	LCH-04	RAV error	Off-nominal trajectory	5.1.3
	LCH-05	DAV error	Off-nominal trajectory	5.1.3
	LCH-06	Col. avoidance	High probability conjunction	5.1.4
Planning TCM	PTCM-01	Over budget	Off-nominal trajectory	5.2.1
TCM3	TCM3-01	No burn	Fail to approach Moon	5.2.2
	TCM3-02	Partial burn	Off-nominal trajectory	5.2.3
	TCM3-03	Over burn	Off-nominal trajectory	5.2.3
	TCM3-04	Delayed start	Off-nominal trajectory	5.2.3
	TCM3-05	Early start	Off-nominal trajectory	5.2.3
	TCM3-06	Az. pointing error	Off-nominal trajectory	5.2.3
	TCM3-07	El. pointing error	Off-nominal trajectory	5.2.3
TCMX	TCMX-01	No burn	Off-nominal trajectory	5.2.3
	TCMX-02	Partial burn	Off-nominal trajectory	5.2.3
	TCMX-03	Over burn	Off-nominal trajectory	5.2.3
	TCMX-04	Delayed start	Off-nominal trajectory	5.2.3
	TCMX-05	Early start	Off-nominal trajectory	5.2.3
	TCMX-06	Az. pointing error	Off-nominal trajectory	5.2.3
	TCMX-07	El. pointing error	Off-nominal trajectory	5.2.3
Planning LOI	PLOI-01	LOI Epoch error	Off-nominal trajectory	5.3.1
	PLOI-02	LOI altitude error	Off-nominal altitude	5.3.2
	PLOI-03	LOI inclination error	Off-nominal inclination	5.3.3
	PLOI-04	Over budget	Off-nominal trajectory	5.3.4
	PLOI-05	Col. avoidance	High probability conjunction	5.3.5
LOI1	LOI1-01	No burn	Fail to capture	5.3.6
	LOI1-02	Partial burn	Fail to capture	5.3.7
	LOI1-03	Partial burn	Capture, off-nominal orbit	5.3.7
	LOI1-04	Over burn	Capture, off-nominal orbit	5.3.8

⋮

5.3.6 LOI1 Not Executed

Failure to perform LOI1 leaves the spacecraft on a ballistic trajectory, not being captured into a lunar orbit. After a missed LOI1, KPLO will complete one additional orbit before escaping from the moon. Since the next periapsis has inclination and altitude significantly outside of the mission requirements, a recovery maneuver performed at the apoapsis is required to target the desired altitude and inclination at the next periapsis. Then, a recovery LOI1 should be performed to target the desired capture orbit.

If **LOI1** is not executed on time, contingency recovery requires the addition of **rTCM** (recovery trajectory correction maneuver) to retarget the next periapsis and **rLOI1** (recovery LOI1) to achieve the desired capture orbit.

After the contingency declaration, the OA shall use the prepared contingency planning satellite, which includes rTCM and rLOI1, instead of the nominal planning satellite in the TATS. When planning rTCM, the OA and FDSp shall check that there is enough time to plan each maneuver between all maneuvers during LOA phase. If the time is not enough to plan a maneuver, the OA and FDSp shall reschedule the next maneuvers to ensure the minimum time required for maneuver planning. Then, the OA shall determine a target inclination value for rTCM that satisfies the mean inclination requirements for the mission orbit. The target inclination selection process for rTCM is as follows:

1) Run MCS with nominal inclination target, $i_{target} = i_0$ (Use 90° if no initial guess available)
2) Determine post-LOA inclination value from the planned trajectory (i_1) and compare it with that from the nominal trajectory (i_1')
3) If $i_1 \neq i_1'$, update target inclination and re-run MCS:

$$i_{target}' = i_{target} + (i_1' - i_1)$$

4) Repeat steps 2-3 until $i_1 = i_1'$
5) Calculate mean inclination during the entire mission period (i_{mean})
6) If i_{mean} is out of mission requirements, update target inclination and re-run MCS:

$$i_{target}' = i_{target} + (90° - i_{mean})$$

7) Repeat steps 5-6 until mean inclination requirement has been achieved

⋮

Fig. 3. Contingency trajectory operation workflow based on the prepared operational procedure.

To ensure swift and well-coordinated trajectory operations in the event of contingencies, the KPLO FD team developed a document for contingency trajectory operations. This document contains detailed operational procedures, checklists, and guidelines for FD operators, facilitating a systematic approach to address specific contingency scenarios.

In summary, this study offers valuable insights for FD engineers and mission planners engaged in space exploration missions, emphasizing the importance of a proactive approach to contingency planning. The preparation process, from identification and prioritization of trajectory contingencies to the development of mitigation plans and operational procedures, serves as a comprehensive guide for ensuring the success of future space exploration missions. Fortunately, the KPLO mission encountered no serious contingencies. Two minor contingencies were effectively addressed using prepared plans: the over burn during TCM5 was corrected with TCM6, and the conjunction risk with Chandrayaan-2 was mitigated through a collision avoidance maneuver. Furthermore, the experience and know-how gained from the preparation process allowed flexible operations, even when significant adjustments were required to the trajectory plan during the LOA phase. The KPLO mission's achievements provide an excellent example of how diligent preparation can lead to mission success even in the face of unexpected challenges.

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