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Korea Pathfinder Lunar Orbiter Flight Dynamics Simulation and Rehearsal Results for Its Operational Readiness Checkout

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Korea Pathfinder Lunar Orbiter (KPLO), also known as Danuri, was successfully launched on 4 Aug. from Cape Canaveral Space Force Station using a Space-X Falcon-9 rocket. Flight dynamics (FD) operational readiness was one of the critical parts to be checked before the flight. To demonstrate FD software's readiness and enhance the operator's contingency response capabilities, KPLO FD specialists planned, organized, and conducted four simulations and two rehearsals before the KPLO launch. For the efficiency and integrity of FD simulation and rehearsal, different sets of blind test data were prepared, including the simulated tracking measurements that incorporated dynamical model errors, maneuver execution errors, and other errors associated with a tracking system. This paper presents the simulation and rehearsal results with lessons learned for the KPLO FD operational readiness checkout. As a result, every functionality of FD operation systems is firmly secured based on the operation procedure with an enhancement of contingency operational response capability. After conducting several simulations and rehearsals, KPLO FD specialists were much more confident in the flight teams' ability to overcome the challenges in a realistic flight and FD software's reliability in flying the KPLO. Moreover, the results of this work will provide numerous insights to the FD experts willing to prepare deep space flight operations.

Keywords: Danuri, Korea Pathfinder Lunar Orbiter, flight dynamics, simulation & rehearsal

1. INTRODUCTION

Korea's first lunar mission, Korea Pathfinder Lunar Orbiter (KPLO), was successfully launched on Aug. 4, 2022, at 23:08:48 (UTC) using Space-X Falcon-9 launch vehicle. To date, all KPLO systems are operating normally (Bae et al. 2022a; Hong et al. 2022a; Jeon & Cho 2022a, b; Kim et al. 2022; Yim 2022). The original KPLO transfer trajectory was the 3.5 phasing loop to reach the Moon. However, the weak stability boundary (WSB)/ballistic lunar transfer (BLT) method was finally selected due to its dry mass growth problem. At Sep. 2, the KPLO successfully executed the 3rd trajectory correction maneuver (TCM) to change its trajectory heading back to the Moon. The KPLO is cruising about 118 million km away from the Earth with about 472 m/s velocities as of Nov. 2, 2022.

For the successful flight dynamics (FD) operation of the KPLO, Korea Aerospace Research Institute (KARI) KPLO FD specialist designed, developed, and validated FD-related ground operation systems. The KPLO deep-space ground system (KDGS) consists of the 35 m aperture Korea Deep-Space Antenna (KDSA) and five major subsystems with each unique functionality. Among the five major subsystems, the trajectory design system (TDS) and flight dynamics subsystem (FDS) are the subsystems that are directly related to FD ground operation. Despite numerous past development and successful operational experiences on low Earth orbit and geostationary missions, the FD team had to newly design, develop and validate every functionality and associated workflow of TDS and FDS. This was due to the FD operational uniqueness of the lunar mission, especially even more unique when using WSB/BLT methods. Before

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integrating all of the KDGS subsystems, several times of TDS and FDS internal validation and verifications test were conducted. Internal validation and verification test include the tests on functionalities, workflows, internal and external interfaces, and operational procedures with contingency cases. The very recent efforts made to design, implement, validate the KPLO mission trajectory as well as TDS and FDS can be found on Refs. (Bae et al. 2020a, b, c; Hong et al. 2020a, b; Kim et al. 2020a, b, c; Lee et al. 2020a, b, c; Song et al. 2020; Bae et al. 2021a, b; Kim et al. 2021; Song et al. 2021a, b; Bae et al. 2022b; Bang et al. 2022a, b; Hong et al. 2022b; Song et al. 2022).

After the completion of internal verification and validation tests, final operational readiness checkouts were planned and conducted for both TDS and FDS. In addition to the KPLO bus system's final checkout, FD operational readiness checkout is another critical parts that need to be checked before the actual flight. The main goal of final operational readiness checkout is to validate how the FD-related systems and operators should respond under realistic nominal and anomalous operational scenarios. The FD final operational readiness checkout is a very important activity as the KPLO cannot be launched if the checkout result is not good enough as expected. Therefore, KPLO FD specialists carefully planned, organized, and conducted four simulations and two rehearsals before the KPLO launch. However, as the KPLO FD specialists did not have actual lunar exploration experiences yet, there was a limit to internally conducting those planned simulations and rehearsals. To ensure the efficiency and integrity of FD simulations and rehearsals, the KPLO FD specialists brought and worked together with the Space Exploration Engineering (SEE) team. The SEE is one of the well-experienced U.S companies with lots of experience in deep space missions, mainly focused on FD (Carrico et al. 1995; Policastri et al. 2009; Cooley et al. 2010; Carrico et al. 2011; Kam et al. 2015; Policastri et al. 2015a, b; Dichmann et al. 2016; Shyldkrot et al. 2019; SEE 2022). Based on the SEE teams' past actual flight experiences, blind test data sets, including simulated tracking measurements, were prepared and delivered to the KPLO FD specialists. Without knowing the detailed characteristics of test data sets, the KARI FD team conducted each step of simulation and rehearsals to follow the established FD operational procedure. The results obtained by the KARI team were investigated by the SEE team again for further supplement.

Despite the importance of FD simulation and rehearsal for deep space missions, there is a lack of relevant references. FD experts in related fields generally experience lots of difficulties in preparing for actual operations. Therefore, the current paper is motivated to share final operational checkout knowledge to relevant communities, especially in FD point of views. Even FD simulation and rehearsal is a very genuine and unique technical activity that is performed very differently in every other space mission, the results of this work will provide numerous insights to the FD experts willing to prepare deep space flight operations. Section 2 of this paper presents simulations and rehearsal setup details. Starting from the KPLO trajectory and mission overview, Section 2 treats details of the established FD operation procedure with tracking resources used for this simulation and rehearsals. In Section 2, the strategy used to generate blind test data sets, details of selected simulations and rehearsals cases are also discussed including types of simulated Deep Space Network (DSN) tracking measurements. In Section 3, the results for the total of six simulations and two rehearsals cases are summarized with lessons learned from each result. Finally, the conclusions are in Section 4. After completion of the final FD operational readiness checkout through those simulations and rehearsals, the KPLO FD specialists secured the ability to overcome challenges in a realistic KPLO FD operation scenario and were much more confident to fly Korea's first lunar mission.

2. SIMULATION & REHEARSAL SETUP

2.1 Trajectory & Mission Orbit Overview

KPLO trajectory was designed to use the WSB/BLT method to the Moon to minimize the spacecraft's fuel consumption. The launch period for the KPLO was firstly set to about 40 days and reduced to 7 days from Aug. 2 to Aug. 8 after regarding the launch conditions of Space-X Falcon-9 rocket. The KPLO will be launched toward the Earth-Sun L1 point and will reach its maximum distance of about 155 million km from the center of the Earth. The KPLO will then head back to Earth to gradually approach the Moon's orbit. After about 130 days of transfers, the KPLO is designed to fly close to the Moon Dec. 16, 2022 and will enter lunar orbit acquisition (LOA) phase. The final mission orbit around the Moon will have 90 deg inclination and be maintained within 100 ± 30 km dead-band through one year. During the cruise phase, a total of nine TCMs were planned from launch to lunar insertion, and a total of five lunar orbit insertion (LOI) maneuvers were scheduled to achieve the final mission orbit. Among the TCMs, TCM-3 is the only deterministic maneuver, and other statistical maneuvers are planned and will be executed if needed. Even TCM-1, -6 and -9 are statistical maneuvers, they are very likely to be executed as those burns are critical statistical maneuvers. The TCM-1 is planned to correct launch injection error immediately, and TCM-6 and -9 are aimed to target precise TCM-9 and LOI-1 states, respectively. The KPLO WSB/BLT trajectory is shown in Fig. 1. Fig. 1(a) depicts WSB/BLT trajectory for 4 Aug, 2022 launch case with 9 TCMs, and Fig. 1(b) shows the LOA phase, including a total of 5 LOIs. More details on KPLO mission trajectory analysis can be found in Bae et al. (2020a, b, c, 2021a, b, 2022b), Hong et al. (2020a, b, 2022b), Kim et al. (2020a, b, c, 2021), Lee et al. (2020a, b, c) and Song et al. (2020, 2021a, b), Bang et al. (2022a).

2.2 Roles of Trajectory Design System (TDS) and Flight Dynamics Subsystem (FDS)

TDS and FDS were the only systems used for the simulation and rehearsal out of the five major subsystems of KDGS. Roles of TDS and FDS are different as follows. Before launch, the main goal of TDS is to design the KPLO reference trajectory. During actual flight operations, TDS will monitor the exact flight trajectory (or orbital) status very closely with FDS. Also, when a contingency situation occurs, TDS will redesign or update the reference trajectory to recover the KPLO flight path. Along with TDS, FDS will play significant roles in maneuver planning (MP) with detailed engine characteristics, orbit determination (OD), executed maneuver estimation and recovery to define thruster efficiency, etc. TDS and FDS will be operated complementarily to maximize FD operational efficiency. For more details on the operational concept between TDS and FDS can be found in Song et al. (2021a).

2.3 Flight Dynamics Operation Procedure

Using TDS and FDS described in Subsection 2.2, simulations and rehearsals were conducted to follow the established FD procedure. The top-level KPLO FD operation procedure is shown in Fig. 2, which can be applied to any maneuver burn sequences.

KARI FD specialists brainstormed FD operation procedures from scratch by imagining the actual operation scenario of the KPLO as much as possible. With established operation procedures, a detailed operation timeline for each activity is also prepared with an appropriate tracking pass schedule. As shown in Fig. 2, the FD operation procedure consists of a repetition of the basic activity set. One basic activity set is configured to have OD, trajectory update, MP, and trajectory review & confirmation. TDS will conduct the trajectory update, and the trajectory review & confirmation activities and others activities are conducted through FDS. Typically, two sets of basic activities, preliminary and final, will complete the nominal FD procedure before the maneuver execution. Unlike FD activities before maneuver execution, a slightly different procedure is adapted after the maneuver burn, which includes the maneuver recovery (MR) and the thruster efficiency determination. FD procedure was also prepared to initiate a separately prepared trajectory contingency procedure. The application of the trajectory contingency procedure is determined according to the analysis result of the trajectory update, which is performed immediately after the maneuver burn. More details on the functionalities of TDS and FDS can be found in Song et al. (2021a) and Bang et al. (2022b). Bang et al. (2022a) described more details of the TCM decision process which can lead to trajectory contingency for the KPLO mission. As

(a) (b)

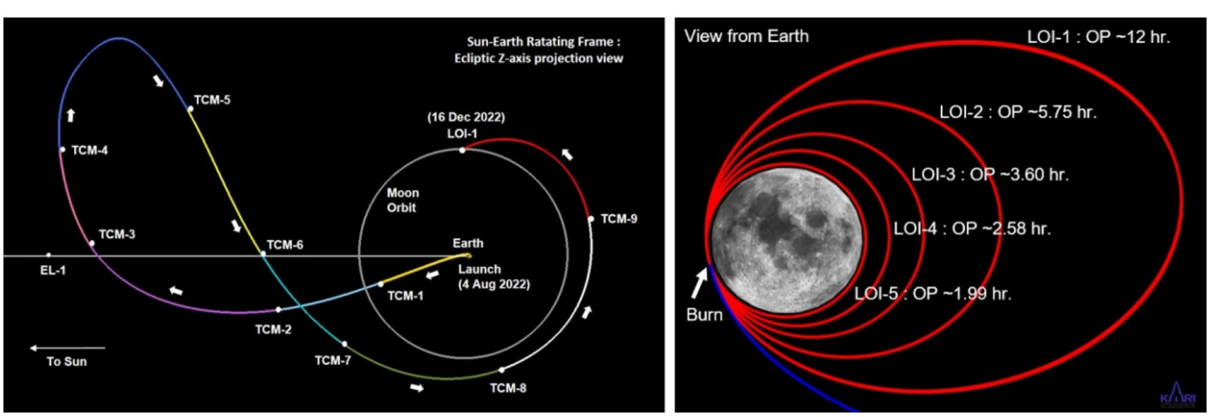

Fig. 1. Korea Pathfinder Lunar Orbiter trajectory view. Weak Stability Boundary/Ballistic Lunar Transfer trajectory for 4 Aug, 2022 launch case (a) and lunar orbit acquisition phase (b). TCM, trajectory correction maneuver; LOI, lunar orbit insertion.

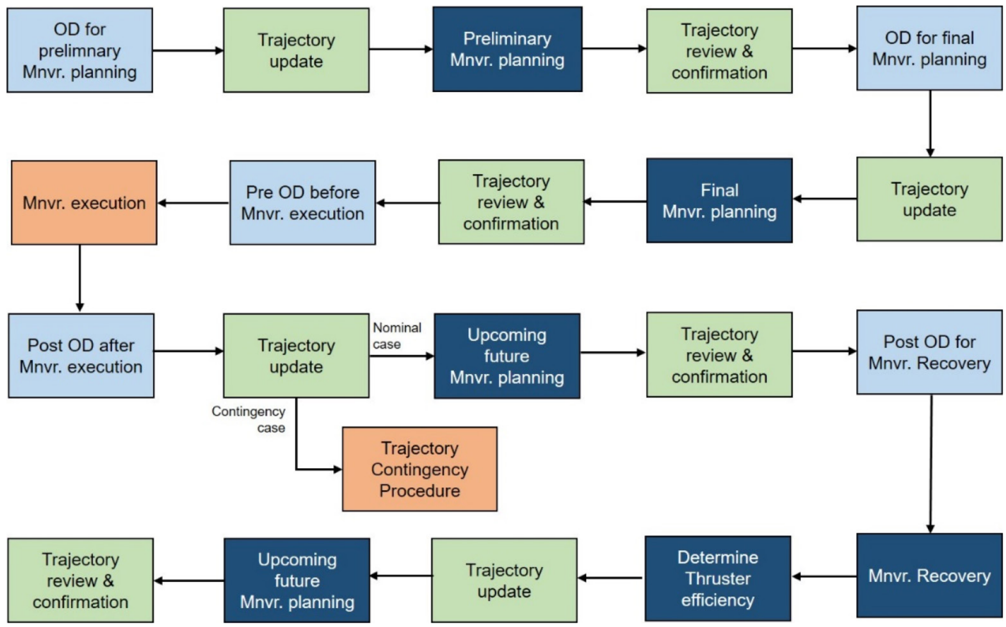

Fig. 2. Korea Pathfinder Lunar Orbiter flight dynamics operation procedure: top level workflow. OD, orbit determination.

with the progress of simulations and rehearsals, established FD operational procedures were modified and corrected to reflect a realistic operational timeline for each activity.

2.4 Blind Test Data Generation

For each simulation and rehearsal, blind test data sets were generated by SEE and delivered to KARI FD specialists including the simulated tracking data. The simulated tracking data were generated based on the contact schedule that originated from the contact period. The contact period was determined using the truth trajectory. The truth trajectories for each simulation and rehearsal were selected from a particular feasible trajectory from the Designed Reference Mission trajectory. A particular feasible trajectory was generated by the inclusion of perturbation due to dynamic model and maneuver errors. Using a particular feasible trajectory, simulated measurements were generated by incorporating white noise, biases, and transponder delay. Especially, white noise and biases were selected to be as realistic as possible. Generally, white noise and biases characteristics strongly depend on the tracking station, measurement types, and mission phases. Therefore, through the SEE team's practical experiences in past lunar or deep space missions, the characteristics of white noise and biases can be set to have as similar as possible to the actual characteristics. Without knowing the detailed characteristics of these various error sources, the KARI FD specialists performed OD, maneuver estimation, MR to judge thruster efficiency, and, finally, planned upcoming future maneuvers as the procedure shown in Subsection 2.3. Simulated measurement types, accuracy, and observation times were set to be as for the nominal mission cases, which considered the nominal operation procedure and the tracking system capabilities. For this simulation and rehearsal, the DSN Doppler and sequential range measurements were simulated to have 60 seconds interval. To generate blind test data sets, SEE team used System Tool Kit and Orbit Determination Took Kit by Ansys company (Ansys 2022). Details of tracking resources used to generate simulated tacking data can be found in Subsection 2.5.

2.5 Tracking Resources

The KPLO mission utilizes the NASA DSN as well as the KDSA for its tracking resources. During the critical mission phases, the three different DSN complexes, the Goldstone deep-space communication complex (DSCC), the Madrid DSCC, and the Canberra DSCC, will be the primary facilities during the critical mission phases. However, during the nominal mission phases, the Canberra DSCC will serve as the backup for KDSA anomalies. For this simulation and rehearsals, the following set of stations is used to generate simulated tracking data as shown in Table 1. In Table 1, station locations and measurement types used for this simulation and rehearsals are shown. Actually, the DSN location shown in Table 1 is an arbitrarily selected location to represent each of the DSN station complexes, and all

Table 1. Tracking station & simulated measurements types

Station ID	Location			Measurement type	Remark
	Lat (deg)	Long (deg)	Height (m)		
DSS1	35.339	–116.875	951.499	Sequential Range and DSN Doppler	Goldstone DSCC
DSS2	40.427	–4.251	833.854	Sequential Range and DSN Doppler	Madrid DSCC
DSS3	–35.398	148.982	692.020	Sequential Range and DSN Doppler	Canberra DSCC
KDSA	37.207	127.662	0.000	Doppler and Range	

DSS, deep space station; DSN, deep space network; DSCC, deep-space communication complex; KDSA, Korea Deep Space Antenna.

coordinates in Table 1 are geodetic positions with the WGS84 model. However, for the actual flight operation, readers may note that each single DSN antenna location is individually used with proper antenna ID and real locations as described in Slobin et al. (2022).

2.6 Case Selection

KPLO FD specialists carefully chose simulation and rehearsal cases after numerous internal discussions. The top priority considered while selecting the cases was the criticality of the selected event that might affect the success of the entire mission. Therefore, the selection was made to sufficiently train the FD specialists to deal with or overcome not only the nominal but also the trajectory contingency situation which might occur during the actual flight operation. The main objective of conducting simulations and rehearsals is slightly different. In the case of simulation, it is conducted in non-real time, and the main objective is to verify that there is no problem with the FD related system itself and also with the established FD operation procedure. However, the rehearsals are conducted in real-time with the main purpose of checking and verifying that the already established procedures can be completed within the planned time schedule. In Table 2, selected simulation and rehearsal cases (a total of six cases) are shown. A total of four simulations were planned for TCM-1, -3, and two LOIs. TCM-1 was selected to ensure FD specialists' reliable and immediate response after launch. TCM-3 was selected because it was one of the critical maneuvers during the trans-lunar phase. Two simulations were planned for just LOI-1 regarding its criticality, one with the nominal LOI-1 execution case and one with the assuming contingency with LOI-1 executions. For the rehearsal cases, TCM-1 was considered to be the first candidate as all FD functions should be fully prepared within a given time. Secondly, the LOI-1 was selected regarding its importance in the success of the overall mission.

3. RESULTS ANALYSIS

3.1 Simulation Results

3.1.1 LOI-1

The first simulation was conducted for the LOI-1 maneuver. The LOI-1 maneuver has been selected for the simulation and rehearsal cases several times as it was a very critical maneuver. For this simulation, the LOI-1 maneuver was assumed to be executed on 16 Dec, 2022, 17:15:59 (UTC). This simulation was planned to be started approximately 48 hours prior to the planned LOI-1 maneuver execution time. There were three tracking passes for the preliminary LOI-1 plan and these tracking passes covered about 26 hours prior to LOI-1. An additional pass prior was given to the final LOI-1 plan which covered about 13 hours prior to LOI-1. There are two tacking passes after the final LOI-1 plan and the execution of LOI-1. After the LOI-1 burn, there were three passes to perform post-MR activities. The simulation was intended to end about 24 hours after LOI-1. Due to the geolocation of deep space station 3 (DSS3) and KDSA,

Table 2. Selected simulation and rehearsal cases

Type	No.	Mission phase	Maneuver event	Remark
Simulation	1	Lunar orbit acquisition	LOI-1	
	2	Trans lunar	TCM-1	
	3	Trans lunar	TCM-3	
	4	Lunar orbit acquisition	LOI-1	LOI-1 contingency case
Rehearsal	5	Trans lunar	TCM-1	
	6	Lunar orbit acquisition	LOI-1	

TCM, trajectory correction maneuver; LOI, lunar orbit insertion.

simulated tracking data from these two stations overlapped. As DSN will provide continuous coverage during the LOI-1 maneuver phase, simulated tracking measurements for the KDSA were not used in this simulation.

In Table 3, OD results for each step of the FD operation process are shown. As seen from Table 3, uncertainty obtained during the LOI-1 burn showed to have several hundred m in position and several cm/s levels in velocity, respectively. Here, readers may note that all OD uncertainty discussed in the following sections are all 3-sigma values. Using OD results obtained, KARI FD specialists performed MP for LOI-1 burn and estimated, calibrated the LOI-1 burn after execution. With the post OD conducted for LOI-1 recovery, KARI estimated LOI-1 burn and it was found to be about 1.75% hot burn. KARI calibrated the LOI-1 burn and then solved that it was about 1.9% hot maneuver which is about 148.57 m/s.

KARI FD specialists delivered obtained LOI-1 simulation results to the SEE team and received a technical memo. The estimated LOI-1 burn was consistent with the simulation data generation runs which performed by SEE while generating the tracking data, which was about 1.75% hot maneuver. For LOI-1 burn calibration, it was turned out that SEE injected a 2% hot maneuver (about 148.79 m/s) into the simulated data (Nickel & Policastri 2022a). These results indicate that KARI FD specialists estimated and calibrated the LOI-1 maneuver within the cm/s level difference which is very precise. This was very encouraging results considering obtained results were solely from the blind tracking data processing.

3.1.2 TCM-1

The second simulation exercised the FD events leading up to and through the TCM-1. TCM-1 burn is a critical maneuver among the TCMs as it aims to correct errors from the launch vehicle. Another objective of performing TCM-1 is to test KPLO thrusters before their full-scale use. As the Delta-V savings can be maximized with the sooner TCM-1 execution, the KPLO scheduled TCM-1 about two days after being separated from the launch vehicle. This simulation assumed KPLO launch on 1 Aug, 2022, 00:21:22 (UTC) and TCM-1 execution on 3 Aug, 2022, 01:00:00 (UTC). The initial state for this simulation was set with the simulated orbit parameter message (OPM) file. The OPM file is generated from SEE with arbitrarily deviated initial states. In actual flight, the Space-X will deliver the OPM file, having separation information, to KDGS no later than 30 min after separation. For the TCM-1 simulation, three tracking passes were simulated about 24 hours prior to the preliminary TCM-1 plan and an additional pass about 12 hours prior to the final TCM-1 plan. Then two passes were additionally simulated after the final TCM-1 plan before the TCM-1 burn. After TCM-1 execution, there were three passes to perform post-MR activities, and the simulated tracking data ended about 24 hours after TCM-1.

KARI FD specialists used arbitrarily deviated OPM from the SEE team to set initial states for the first OD after separation. Then, used DSN Doppler data only, without ranging data, up to about 7 hours. This was intended as the KPLO is expected to receive its first ranging data after 7 hours (at maximum) due to spacecraft check-out activities after separation from the launch vehicle. Firstly, the KARI team tuned and updated initial states with the least square method using only DSN Doppler data. Then interactive tuning and updating parameters were continued until all of the residual measurement ratios were within 3-sigma boundaries including raging data received afterward. With TCM-1 prior 12-hour tracking data, the final OD for TCM-1 planning was conducted which showed 3D RMS uncertainties of about 306.952 m for position and about 0.447 cm/s for velocity.

With definitive ephemeris obtained, TCM-1 was planned to have about 20.417 m/s. KARI FD specialists continued the post TCM-1 OD and TCM-1 MR as well. Using 24 hours of tracking measurements, post TCM-1 OD was about to have 3D RMS uncertainties of about 701.006 m for position and about 10.633 cm/s for velocity. Even the current simulation used 24 hours of tracking data for post OD and MR, both the post OD and MR will be continuously updated and monitored as with the reception of newly updated measurements until showing reliable performances in real operations. Utilizing the post TCM-1 OD results, the MR

Table 3. OD results obtained during LOI-1 burn simulation

Event	Position (m, 3D RMS)	Velocity (cm/s, 3D RMS)	Remark
Preliminary LOI-1 planning OD	621.562	1.376	Used until LOI-1 – 26 hour tracking data
Final LOI-1 planning OD	520.849	0.951	Used until LOI-1 – 13 hour tracking data
Pre OD before LOI-1 burn	245.201	0.311	Used until LOI-1 – 1 hour tracking data
Post OD for LOI-1 recovery	264.382	1.197	Used until LOI-1 + 24 hour tracking data

OD, orbit determination; LOI, lunar orbit insertion.

process was done and the KARI team discovered about 40.819 m/s of TCM-1 burn. Therefore, having an efficiency factor of about two times than the planned maneuver. Numerous internal trials and debates were made to find the root cause of doubling the thruster efficiency. However, the KARI FD team finally delivered the results to the SEE after concluding that there were no critical errors in the processed FD operation procedure or functionality of the subsystem currently used. SEE confirmed these surprising results, and it turned out that deviated efficiency was originally 200% which concurred not only with the KARI FD operation procedure but also with the system performances (Nickel & Policastri 2022b). Fig. 3 shows the measurement residual ratio plot for the final OD that was used to finally recover the TCM-1 burn. As shown in Fig. 3, all of the measurement residual ratios are nicely within the 3-sigma boundaries before, during, and after TCM-1.

3.1.3 TCM-3

The TCM-3 was selected for the third simulation case, as it was not only the deterministic maneuver but also the most critical maneuver during the lunar transfer. The TCM-3 simulation also assumed continuous tracking before and after maneuvers. Simulated tracking measurements started about two days prior to the TCM-3 and continued until about two days later of the TCM-3 execution time. The TCM-3 was assumed to be on 26 Aug, 2022, 05:00:00 (UTC). During the TCM-3 simulation, different timeline sets of tracking data were used to establish KPLO's own operational timeline regarding the KARI shift schedule in KST. Simulations were continued for about four days to complete the TCM-3 simulation and conducted tasks for each day are summarized in Table 4.

In Table 5, major results obtained until day two from TDS and FDS are listed including: OD uncertainties, delta-V magnitude for both upcoming first burn (TCM-3) and future burns, and MP results with quality check (QC).

On day 3, the first post OD after TCM-3 burn was attempted. Using about 19 hours of tracking data after TCM-3, 3D RMS OD uncertainties were found to be about 1,853.002 m for position and 4.485 cm/s for velocity. Also, TCM-3 burn magnitude was estimated to be about 16.339 m/s during the OD run, which indicates about 31.3% more cold burn than we have planned and expected for TCM-3. Using the associated results, KARI FD specialists decided to correct the TCM-3 burn error using statistical TCM-4 burn and updated the KPLO trajectory. This was because the magnitude of TCM-9 burn was found to be increased up to about 7.489 m/s without TCM-4 burn. The discovered magnitude exceeds the allowable maximum TCM-9 burn magnitude originally designed. The KARI FD team decided to hold the final decision until to get more solid analysis results on simulation day 4. With more tracking data, the second post TCM-3 OD was conducted and 3D RMS OD uncertainties were greatly reduced to about 772.655 m for position and 0.740 cm/s for velocity. However, TCM-3 burn magnitude was still estimated to be about 16.335 m/s. Therefore, the trajectory was updated to use about 3.135 m/s of TCM-4 to reduce TCM-9 to about 0.002 m/s. Using the second post TCM-3 OD

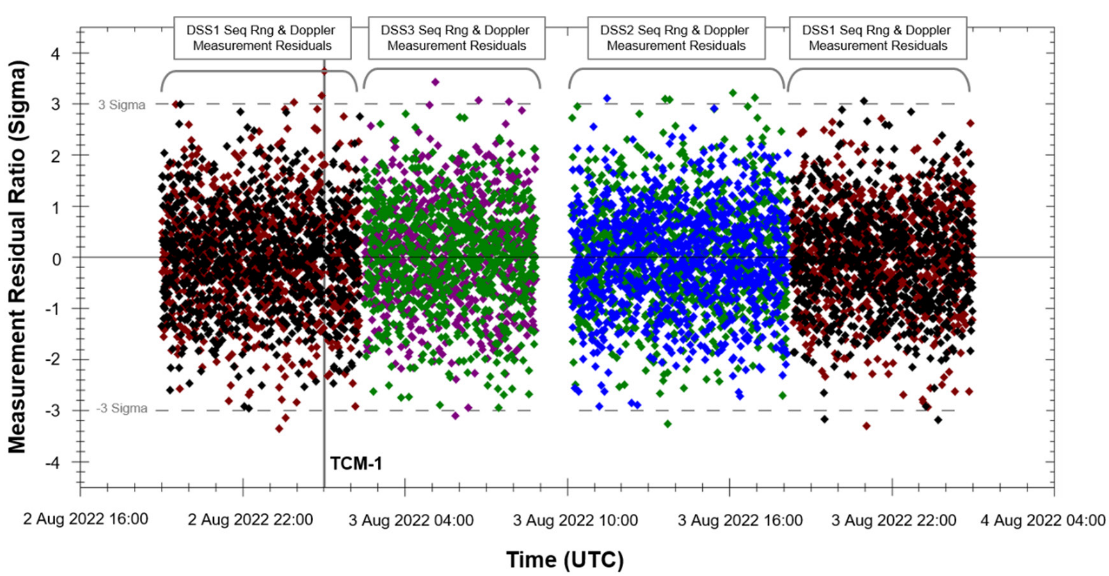

Fig. 3. Measurement residual ratio plot from final orbit determination to recover final TCM-1 burn. DSS, deep space station; TCM, trajectory correction maneuver.

Table 4. Summary of TCM-3 simulation tasks conducted for each simulation days

Days	Tasks	Remarks
Day 1	TCM-3 preliminary planning OD	Used tracking data - from 23 Aug, 2022, 00:00:00 (UTC) - to 24 Aug, 2022, 00:00:00 (UTC)
	Definitive products generation	
	Trajectory update for TCM-3 preliminary planning	
	MP for TCM-3 preliminary planning	Including maneuver QC
	Trajectory review	
	Trajectory & maneuver confirmation	
Day 2	TCM-3 final planning OD	Used tracking data - from 23 Aug, 2022, 00:00:00 (UTC) - to 25 Aug, 2022, 12:00:00 (UTC)
	Definitive products generation	
	Trajectory update for TCM-3 final planning	
	MP for TCM-3 final planning	Including maneuver QC
	Trajectory review	
	Trajectory & maneuver confirmation	
	Predictive products generation	
Day 3	TCM-3 post OD #1	Used tracking data - from 23 Aug, 2022, 00:00:00 (UTC) - to 27 Aug, 2022, 00:00:00 (UTC)
	Definitive products generation	
	Trajectory update for TCM-3 post OD #1	
	MP for TCM-3 post OD #1	Including maneuver QC
	Trajectory review	
	Trajectory & maneuver confirmation	
	Predictive products generation	
Day 4	TCM-3 post OD #2	Used tracking data - from 23 Aug, 2022, 00:00:00 (UTC) - to 28 Aug, 2022, 05:00:00 (UTC)
	Definitive products generation	
	Trajectory update for TCM-3 post OD #2	
	MP for TCM-3 post OD #2	Including maneuver QC
	TCM-3 MR	
	Trajectory review	
	Trajectory & maneuver confirmation	
	Predictive products generation	

TCM, trajectory correction maneuver; OD, orbit determination; QC, quality check; MP, maneuver planning; MR, maneuver recovery.

Table 5. Summary of major results obtained during TCM-3 burn simulation

Category	Preliminary planning	Final planning
OD position uncertainty (m, 3D RMS, 3σ)	2,982.633	749.112
OD velocity uncertainty (cm/s, 3D RMS, 3σ)	0.441	0.391
TCM-3 burn magnitude (m/s)	23.791	23.790
TCM-6 burn magnitude (m/s)	8.659	8.659
TCM-9 burn magnitude (m/s)	0.001	0.001
LOI-1 burn magnitude (m/s)	145.550	145.550
TCM-3 burn magnitude after QC (m/s)	23.778	23.778

TCM, trajectory correction maneuver; OD, orbit determination; LOI, lunar orbit insertion; QC, quality check.

results, MR was conducted and a thrust efficiency of about 0.7 was confirmed. Efficiency of about 0.7 corresponds to about 16.64 m/s of TCM-3 delta-V. Finally, the actual maneuver for this simulation was confirmed to be about 16.34 m/s from SEE (Nickel & Policastri 2022c). Through this simulation, KARI FD specialists were able to train on Go/No-Go decision-making trees for statistical maneuver execution. Also, the most encouraging results were that the functions of the KARI-developed TDS and FDS are ready for actual operations under various operational circumstances.

3.1.4 LOI-1 contingency

The final simulation was chosen to be the LOI-1 contingency case. Unlike the previous LOI-1 simulation, the SEE team provided the blind test data to result in incomplete lunar capture. Namely, the LOI-1 burn assumed to be executed on 16 Dec, 2022, 17:16:02 (UTC) will either be a hot or cold burn which needs to trigger the trajectory contingency recovery plan. Similar to previous simulations, the KARI team conducted both sets of OD, trajectory update, and MP for preliminary and final LOI-1 burn planning. Using about four days of tracking data, from 11 Dec, 2022, 17:36:19 (UTC) to 15 Dec, 2022, 19:10:11 (UTC), LOI-1 final planning OD uncertainties were about 319.664 m for position and 0.267 cm/s for velocity in 3D RMS. Using the final OD results, the planned LOI-1 burn magnitude with QC was found to be about 145.777 m/s.

The first post LOI-1 OD was conducted using additional LOI-1 + 2 hours of tracking data. The reason for such an immediate OD run is to quickly estimate and predict the state of KPLO after the LOI-1 burn. This will eventually enable the appropriate design of follow-up maneuvers. The estimated LOI-1 burn performance from the first post LOI-1 OD was about 78.642 m/s which indicated about 50% of underperformed LOI-1 burn. Recognizing the seriousness of the situation, the FD team was prepared to trigger the trajectory contingency recovery plan. Firstly, the FD team propagated the trajectory to characterize the orbital states. Fortunately, the KPLO was found to be captured around the Moon, having 41.05 hours of the orbital period, but will impact the Moon about two weeks after. After several hours of inspecting the current orbital states, the decision to add two more recovery maneuvers (rTCM and rLOI) to recover the KPLO mission orbit was made. Series of post LOI-1 burn OD, recovery maneuver plan and LOI-1 burn MR was continued using additional tracking data of LOI-1 + 6, + 12, + 24, and + 36 hours. With more tracking data, OD uncertainties were gradually decreased and the estimated value of LOI-1 burn magnitude also stabilized. After gathering all of the LOI-1 + 36 tracking data, the thrust efficiency for executed LOI-1 burn was found to be about 0.302. This indicates that induced delta-V for LOI-1 burn is only about 44.05 m/s. In Table 6, contingency maneuver plans to recover the KPLO mission orbit, including rTCM and rLOI are presented.

As shown in Table 6, a total of about 727.71 m/s of Delta-V was required to recover the KPLO orbit that meets the requirements including 44.05 m/s of already executed LOI-1 burn. This is about 86.93 m/s more Delta-V than the originally required total Delta-V to insert the KPLO into nominal mission orbit which was about 640.78 m/s. The rTCM burn was planned to recover the target perilune altitude and lunar inclination conditions about 62 hours after incomplete LOI-1 burn. The timing of the first recovery burn was decided regarding numerous conditions, such as securing enough tracking measurement after an incomplete LOI-1 burn, time to verify not only OD performance but also the recovery burn plan, the time to analyze the exact health status of the spacecraft, etc. About 60 hours after rTCM burn, another rLOI burn was planned to reduce the orbit period to about 12.28 hours. Then a reminder of LOIs burns was designed as with the original targeting strategy to finally recover the KPLO mission orbit. Fig. 4 shows the established capture orbit in the Moon inertial frame after recovery maneuvers.

The KARI team received a review memo from the SEE team regarding the LOI-1 contingency simulation and found that the actual was 39.65 m/s. Overall, given such

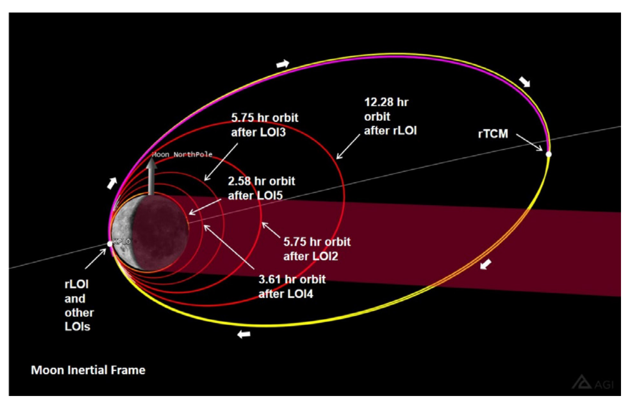

Fig. 4. Lunar capture orbit after contingency recovery maneuvers shown in the Moon inertial frame. rTCM, recovery trajectory correction maneuver; rLOI, recovery lunar orbit insertion.

Table 6. Contingency maneuver plans to recover the Korea Pathfinder Lunar Orbiter mission orbit

Maneuver Name	Burn start time (UTC)	Delta-V (m/s)
rTCM	19 Dec, 2022, 07:21:45	15.93
rLOI	21 Dec, 2022, 19:59:48	110.21
LOI-2	23 Dec, 2022, 08:46:33	143.85
LOI-3	24 Dec, 2022, 19:20:17	139.02
LOI-4	26 Dec, 2022, 07:26:16	137.82
LOI-5	28 Dec, 2022, 05:54:26	136.83
Total		683.66

rTCM, recovery trajectory correction maneuver; rLOI, recovery lunar orbit insertion.

a large off-nominal maneuver, the MR solved reasonably well as KARI team calculated a 0.302 efficiency versus the actual 0.272 efficiency. The incomplete LOI-1 burn was correctly identified and the combination of rTCM and rLOI successfully returned the KPLO to the nominal science orbit after the LOI-1 anomaly (Nickel et al. 2022a). Through this simulation, KARI FD specialists secured the ability to deal with the trajectory contingency situation which might occur during the actual operation.

3.2 Rehearsal Results

This section describes the rehearsal results for LOI-1 and TCM-1 burn cases. As already mentioned, the purposes of the rehearsals are to exercise the FD operation procedure using developed FD-related operation systems and operators to complete all the tasks within the given operational timeline. Therefore, the rehearsals were performed in real-time as much as feasibly possible. Unlike previous simulations, every result obtained from each step during the rehearsals was delivered, presented by KARI, and reviewed by SEE in real-time through online telecom.

3.2.1 LOI-1

In order to align more with the actual operational timeline established, measurement tracking data for the LOI-1 rehearsal are simulated differently than the previous simulations. For this LOI-1 rehearsal, the measurement data starts approximately 66 hours prior to the planned LOI-1 execution time on 16 Dec, 2022, 17:15:21 (UTC). There are six tracking passes prior to the preliminary LOI-1 plan (~21 hours prior to LOI-1) and an additional pass prior to the final LOI-1 plan (~14 hours prior to LOI-1). There was one pass after the final LOI-1 plan. During and after LOI-1 execution, there were three passes to perform MR activities. The LOI-1 rehearsal was scheduled to end about 16 hours after the LOI-1 burn.

KARI FD specialists, step by step, conducted LOI-1 rehearsal based on the established real-time operation schedule. The real-time operation schedule is a spreadsheet that has a list of tasks identified with a timeline of 30-minute intervals. It includes detailed tasks that have to be performed with TDS and FDS, specific modules to be used to perform the task, a list of important products to be generated with their destination, any briefings or review meetings schedules, etc. Of course, the real-time operation schedule was drafted first, then updated several times through the previous simulation experiences. LOI-1 rehearsal went smoothly as scheduled, from preliminary to final LOI-1 planning. OD results for the final LOI-1 planning showed 3D RMS uncertainties of about 306.462 m for position and 0.454 cm/s for velocity, respectively. The delta-V of about 145.588 m/s was planned for LOI-1 burn with QC, and a reminder of LOI burns was found to be nominal by inspecting the analysis results from TDS. After the LOI-1 burn, a series of post-burn OD was conducted to estimate the executed LOI-1 burn characteristics. Finally, the LOI-1 burn was found to be a hot burn having about 145.945 m/s delta-V that resulted in the efficiency of about 1.022.

To wrap up the LOI-1 rehearsal, KARI and SEE teams jointly reviewed the results and revisited the lessons learned from this rehearsal. Every result was consistent and in good agreement. However, the actual LOI-1 burn magnitude given for this rehearsal was about 148 m/s which is about 1.4% more than what the KARI team has recovered (Nickel et al. 2022b). In-depth discussions were made to address the cause, and both teams agreed that more accurate recovery would be possible considering the real operation workflows. Unlike the current rehearsals, real-time thrust-on-time and attitude telemetries will be provided during real operations. Therefore, more additional information can be used while recovering the executed maneuver. In addition, the magnitude and pointing uncertainty on the maneuver model, including mass usage during the burn, can be also updated more appropriately to enhance maneuver estimation and recovery performance during the actual operation.

3.2.2 TCM-1

Finally, the TCM-1 burn was selected as the final rehearsal case. This decision was made as the KPLO's scheduled launch date was very ahead, so FD specialists should be familiar enough to deal with every TCM-1 related task. Also, it was intended to check the readiness of the established TCM-1 operational timeline with trajectory contingency plans. Another reason was that the TCM-1 burn was very critical to the success of remainder maneuvers during the trans-lunar phase. For the TCM-1 rehearsal, the KPLO was assumed for an Aug 8, 2022 launch. Also, an off-nominal launch injection state was used to require execution of the TCM-1 maneuver. The target interface point (TIP) was assumed on 8 Aug, 2022, 23:19:46 (UTC) with TCM-1 execution time of 11 Aug, 2022, 01:00:00 (UTC) which is about 48 hours after lift-off. As just like the previous LOI-1 rehearsal, blind simulated tracking data sets were provided by SEE. However, blind simulated tracking data sets were prepared slightly differently than the previous rehearsals which were intended to fit with KARI's established operational timeline. There were three tracking passes prior to the preliminary TCM-1 plan (~24 hours after TIP), with an additional pass prior to the final TCM-1 plan which covered about 32 hours after TIP. During and after TCM-1, there were five passes to perform post-MR activities. Finally, the simulated measurement for this rehearsal ended about 28 hours after the TCM-1 burn.

During the TCM-1 rehearsal, there were three real-time telecoms between KARI and the SEE team to review the KARI results. The first joint review was held to confirm the preliminary OD and TCM-1 burn planning solutions which used about 24 hours of tracking data after TIP. Preliminary KARI OD results looked very good. Tracking measurements were all accepted and processed as expected with reasonable position and velocity uncertainty. All quality check outputs were also consistent with a good OD solution. Based on preliminary OD solutions, KARI FD specialists correctly identified a 1σ "cold" launch case, with a shortfall of 0.05 km^2/s^2 from the original target C3 value. For preliminary TCM-1 burn planning, it was consistent with expectations for a 1σ cold launch which required about 20.707 m/s of statistical TCM-1 to compensate for the cold launch case. The second joint telecom was held to review the final OD and TCM-1 burn planning with TIP + 32 hours tracking data, and also to review the first post TCM-1 burn data. KARI team's OD results continued to be good, along with the final TCM-1 burn plan, which again showed about 20.707 m/s for TCM-1. For the first post TCM-1 burn analysis, post TCM-1 OD resulted in a very reliable trend as tracking measurements were accepted over the finite burn duration and the filter continued accepting measurements after the maneuver epoch. However, KARI team recovered TCM-1 to be about 50% greater than planned using measurement of TCM-1 burn + 3-hour tracking data. Additional OD and MR were conducted with more post TCM-1 tracking data (about 28 hours after TCM-1 burn) and held the third joint telecom to wrap up the rehearsal. At this final joint telecom, the second post TCM-1 burn analysis results were jointly reviewed. For the OD performance review, the position uncertainty continued to reduce after the TCM-1 burn as expected and all OD outputs were consistent with a good OD solution. For the TCM-1 recovery review, SEE confirmed that about 30.41 m/s of TCM-1 was originally placed for this rehearsal which was very close to KARI's MR result which identified about 50% hot burn (West et al. 2022). Reminders of KARI planned future burns, TCM-2 and 3, were also reviewed. As a result, the preliminary TCM-2 magnitude was consistent with a "hot" TCM-1 burn and the resulting large TCM-3 magnitude was also consistent with a large TCM-1 burn error (West et al. 2022).

4. CONCLUSIONS

In this work, FD simulation and rehearsal results for the KPLO operational readiness checkout are presented. The FD operational readiness check was one of the very critical parts that needed to be verified before the actual flight. Therefore, KARI FD specialists conducted four simulations and two rehearsals to check the KPLO final FD operational readiness. The FD simulations and rehearsals were focused on overall FD processes and responding to realistic anomalous situations such as launch vehicle (LV) injection errors and maneuver execution errors, etc. The critical FD portions of the KPLO mission were set to be exercised by these simulations and rehearsals, for example, how the operators and system should respond. Both the nominal and trajectory contingency cases were carefully chosen as to be simulation and rehearsal cases regarding the criticality of the event to the overall success of the entire mission. The well experienced the SEE team, in the lunar and/or deep space mission, prepared different sets of blind test data for each different simulation and rehearsal case. Inside blind test data sets, DSN sequential ranging and Doppler measurements were simulated to include various errors that might be induced during the actual flight operation. After conducting each simulation and rehearsal, obtained results were reviewed and verified by the SEE team through the KARI and SEE joint meeting.

Without knowing the detailed characteristics of blind test data sets, KARI FD specialists exercised each simulation and rehearsal using FD operation systems, TDS and FDS. As a result of the four different simulations, detailed functionalities of TDS and FDS and each system's readiness for actual flight operations under various operational circumstances were verified. Also, FD operational procedures prepared by the KARI team were modified and corrected as a result of the simulation to reflect a realistic operational timeline for each FD activity, such as OD, trajectory review, MP with QC, post maneuver OD, MR, trajectory update, etc. Based on lessons learned from the simulations, the FD operation procedure gradually matured to fit the realistic FD operation as with the reliability of TDS and FDS itself. After completing simulations, the KARI team conducted two additional real-time rehearsals. The main purpose of real-time rehearsal was to exercise FD operation processes, FD operation systems, and the operator's ability to complete all the tasks within the given operational timeline. The KARI team completed all tasks in time following FD operational procedure. Also, every obtained result during rehearsals was consistent with the expected results. Through the simulations and rehearsals, KARI FD specialists firmly secured the ability to deal with not only the nominal FD but also trajectory contingency operation scenarios which can occasionally occur during the actual flight. The most encouraging results obtained from simulations and rehearsals were that the KPLO FD team was much more confident of overcoming the challenges in a realistic flight and was sure to be ready to fly the KPLO. Moreover, lessons learned from these activities can be expanded and applied to various space exploration missions in Korea in the future.

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