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KARI and NASA JSC Collaborative Endeavors for Joint Korea Pathfinder Lunar Orbiter Flight Dynamics Operations: Architecture, Challenges, Successes, and Lessons Learned

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Abstract: This paper outlines the collaborative efforts between the Korea Aerospace Research Institute (KARI) and the National Aeronautics and Space Administration (NASA) Johnson Space Center (JSC) for the Flight Dynamics (FD) operation of the Korea Pathfinder Lunar Orbiter (KPLO). From the outset of the KPLO program, the joint KARI KPLO FD team and NASA JSC Flight Operations Directorate (FOD) have devoted significant time and effort towards ensuring the mission's success. This paper begins by introducing the aims and scope of the collaborative work, followed by a detailed description of the efforts made between the KPLO FD team and JSC FOD. This includes the top-level concept, interface architecture, test results, established operation procedures/timeline, and the summary of the joint rehearsal conducted. Finally, the paper discusses the challenges and lessons learned from this journey, particularly from the practical FD operational perspectives. Thanks to the joint team's collaborative efforts, KPLO has successfully entered lunar orbit and is performing its mission exceptionally well. The joint experience has fostered mutual trust between KARI and NASA JSC, serving as a foundation for further cooperation and collaboration. The efforts and outcomes described in this work will provide valuable insights to experts worldwide who are willing to foster similar international collaborations in the future.

Keywords: Korea, Pathfinder, Lunar Orbiter; Danuri; flight dynamics operation; KARI; NASA JSC

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1. Introduction

On 27 December 2022, the Korea Aerospace Research Institute (KARI) officially announced the successful insertion of the Korea Pathfinder Lunar Orbiter (KPLO) into lunar orbit. This achievement marks a significant milestone in the Republic of Korea's space history, as KPLO is the first Korean spacecraft to venture beyond Earth. The ultimate goal of KPLO is to establish fundamental deep space technology for future space exploration by Korea and to advance lunar science by conducting a one-year mission around the Moon. More specifically, the KPLO mission has established the following three main objectives. First, to secure critical technologies for lunar explorations that could potentially be extended to further planetary missions. Second, the mission involves investigating the lunar environment, which includes creating a lunar topographic map to facilitate future lunar landing site selection, conducting a survey of lunar resources, and studying the radiation and surface conditions on the Moon. Lastly, demonstrating and validating space internet technology are the final objectives of the mission. After a successful 4.5-month journey using a Ballistic Lunar Transfer (BLT) trajectory, KPLO is now operating in a circular orbit with an altitude of 100 $\pm$ 20 km and an inclination of 90 degrees, with all systems functioning normally [1–4]. To achieve mission objectives, the KPLO is equipped with six scientific instruments to facilitate its mission, including the Lunar Terrain Imager (LUTI) for capturing detailed images of the lunar surface [5], the KPLO Gamma Ray Spectrometer

(KGRS) for conducting elemental mapping by measuring gamma rays emitted from the lunar surface [6], the KPLO MAGnetometer (KMAG) for examining the magnetic environment of the Moon [7], the Wide Angle Polarimetric Camera (PolCam) for investigating the process of space weathering and the Moon's internal evolution [8], the Delay/Disruption Tolerant Networking experiment payload (DTNPL) for testing communication protocols in challenging conditions [9], and the ShadowCam for exploring the permanently shadowed regions of the Moon [10]. In Figure 1, the in-flight configuration of KPLO and the positions of the payloads onboard are depicted [4], and Figure 2 is an image taken by the LUTI payload on 28 December 2022 from 124 km above the lunar surface [11].

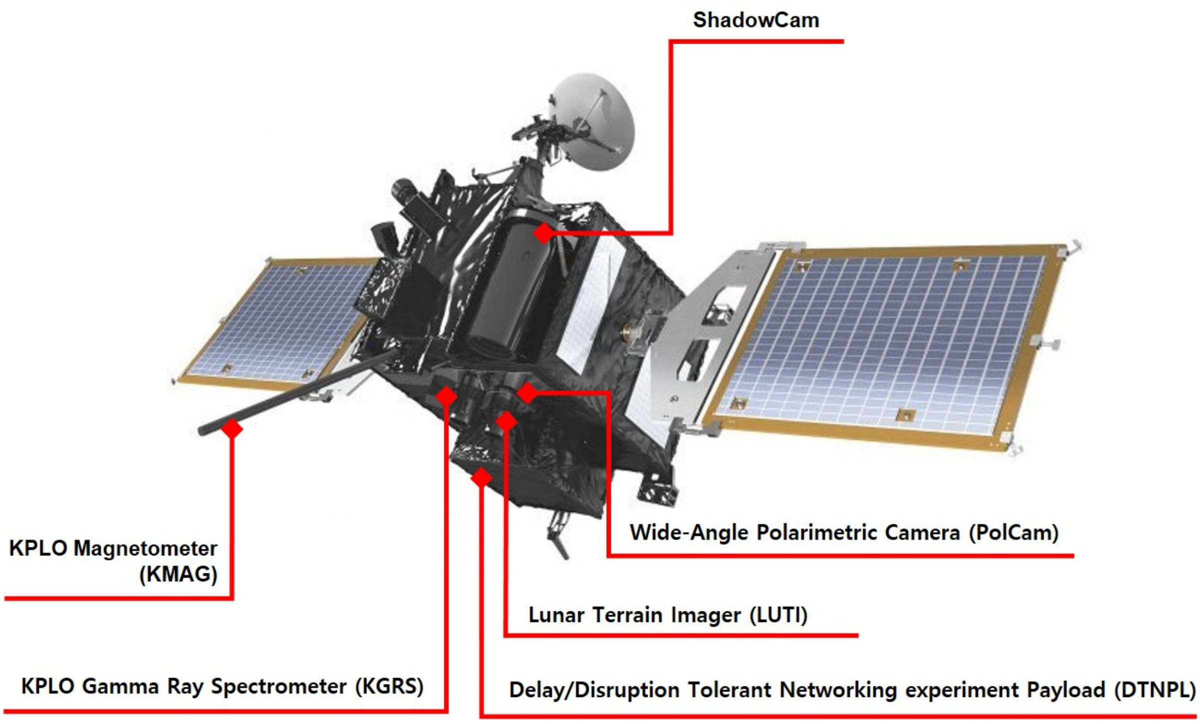

Figure 1. KPLO in-flight configuration with location of payloads.

After the launch of the Lunar Reconnaissance Orbiter (LRO) mission in 2009 [12], lunar exploration didn't receive much attention for some time, but now it's gaining significant interest worldwide. Multiple countries and private companies are engaging in lunar exploration, and there is a unique trend of using small satellites, especially CubeSats. Some major lunar exploration missions include the National Aeronautics and Space Administration (NASA)'s Artemis program [13], India's Chandrayaan program [14,15], and China's Chang'e program [16–18]. Additionally, Astrobotic's Peregrine Lander, scheduled for a launch in 2023, aims to make history as the first private company's lunar landing mission [19]. Regarding small satellites, NASA's Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) successfully tested new navigation technologies near the Moon with a mass of approximately 25 kg [20]. The Lunar Meteoroid Impact Observer (LUMIO) is also making progress as one of the two winning concepts from the European Space Agency (ESA) SysNova Lunar CubeSats for exploration challenge [21].

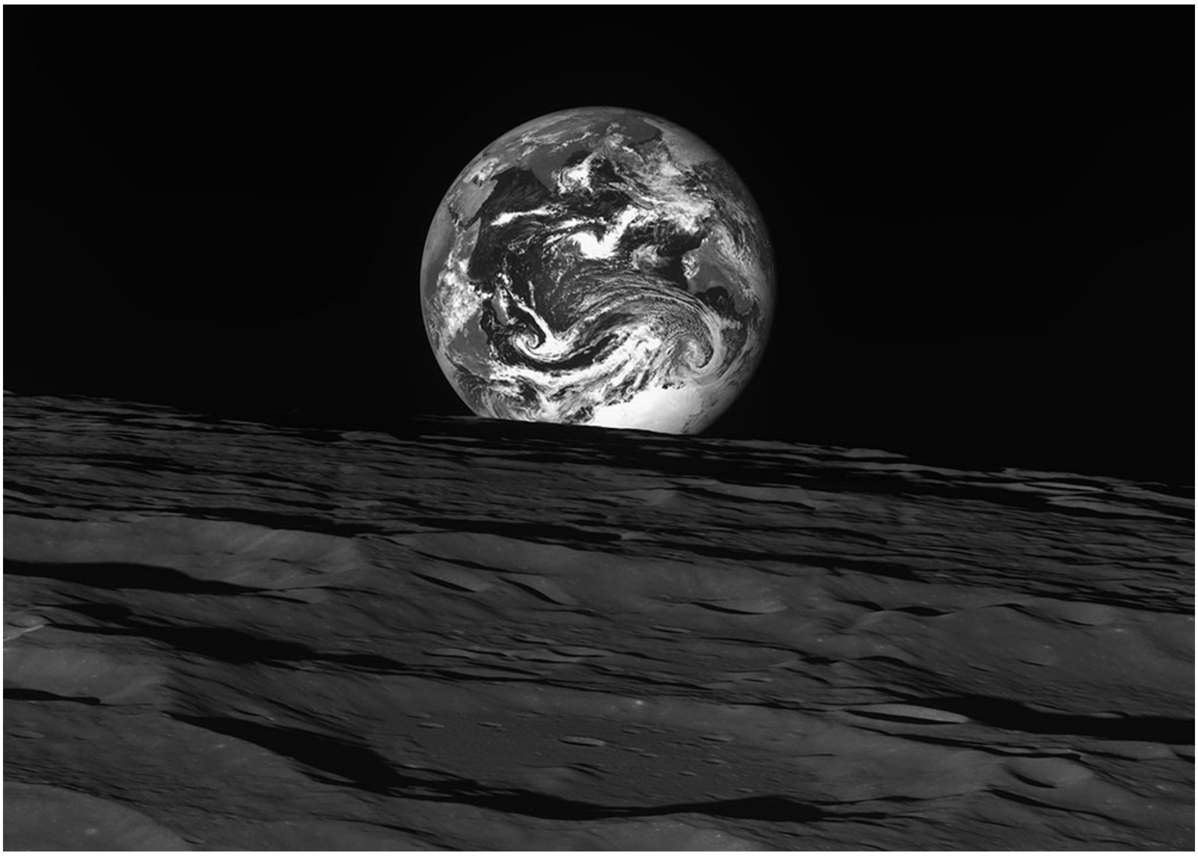

Figure 2. Image of Earth rising at the Moon taken by KPLO LUTI payload on 28 December 2022 [11].

In recent years, the significance of space exploration through international collaboration has been greatly emphasized. Numerous countries and private companies actively cooperate to undertake space exploration missions, not only in system development but also in-flight operation, for their shared objectives. In the past, international collaboration in space explorations was not very active, but there have been notable instances. For example, Japan Aerospace Exploration Agency (JAXA)'s Kaguya [22] and Indian Space Research Organization (ISRO)'s Chandrayaan mission [23] involved a joint effort with Jet Propulsion Laboratory (JPL) for the Orbit Determination (OD). Additionally, China's Chang'e missions collaborated with the European Space Operations Center (ESOC) for telemetry and tracking services [24].

Given that the KPLO mission was Korea's first lunar exploration, both the development process and operational preparation for the bus and the ground system were far from smooth. Despite KARI's extensive experience and know-how in developing and operating numerous Low Earth Orbit (LEO) and Geosynchronous (GEO) satellites, the development of a lunar exploration spacecraft presented completely different challenges. Throughout the development and operation of KPLO, numerous factors presented significant differences from those of traditional Earth-orbiting spacecraft. Specifically, the trajectory/orbit design, as well as Flight Dynamics (FD) operation, differed greatly from the experience and expertise previously held by KARI. However, KARI was able to overcome these challenges and successfully operated KPLO through collaborative efforts with NASA. In 2016, KARI and NASA reached an agreement for the KPLO program. As part of the agreement, NASA agreed to provide the Deep Space Network (DSN) service and navigation support to KPLO in exchange for onboarding the U.S. payload, the ShadowCam [25]. As a part of the collaborative agreement between KARI and NASA, the KPLO FD team and NASA Johnson Space Center (JSC) Flight Operations Directorate (FOD) worked together as partners to ensure the successful FD operations of KPLO. The collaboration between the KPLO FD team and

JSC FOD occurred within the KARI's KPLO Mission Operation Center (KMOC) and NASA JSC Mission Control Center (MCC). Therefore, readers should note that the terms KMOC and MCC will be used to refer to the KPLO FD team and JSC FOD, respectively, hereinafter, unless otherwise specified.

Although KMOC and MCC collaborated for the successful FD operation of KPLO, KARI holds the ultimate responsibility for KPLO operations, encompassing spacecraft operation, troubleshooting, and providing primary FD solutions to MCC. The real-time support from MCC is limited to periodic independent solutions, namely, Independent Verification and Validation (IV&V) activities. Due to the nature of IV&V, encountering numerous obstacles was inevitable during the collaborative work. Despite the importance of joint collaborative work, it is true that there is a lack of relevant references, particularly those based on practical experiences and know-how. Experts in related fields often encounter practical challenges while planning, preparing, and conducting international collaborations, especially when they are engaging in such collaborations for the first time.

This paper aims to offer valuable insights into successful strategies for international collaboration by addressing challenges and discussing proactive efforts to overcome them, especially focusing on the joint FD operation preparation perspectives. Specifically, this paper outlines the overall concept of the joint FD operation between KMOC and MCC, highlights the extensive efforts undertaken to achieve a successful joint FD operation, and ultimately addresses the practical lessons learned throughout the six-year journey. As a result, members of KMOC and MCC experienced a strong sense of unity and teamwork during the real-time KPLO FD operation. The insights from this work can offer valuable guidance for future KARI–NASA collaborations and other international FD operations in space exploration missions. The outcomes can help minimize trial and error in such collaborative endeavors, promoting smoother and more efficient collaborations. The current paper is structured as follows: Section 2 provides an overview of joint FD operations and a summary of the Operational Interface Procedure (OIP) document, including the top-level concepts and interfaces of the ground systems used, as well as the roles of both entities in the collaboration. Section 3 details the collaborative efforts made by KMOC and MCC. Various tests and their associated results are presented. Additionally, the results of rehearsals conducted to prepare for actual operations are discussed, including the established operating procedures with their timelines. Section 4 covers the practical lessons learned during the joint KPLO FD operation. Finally, Section 5 presents the conclusion.

2. Joint FD Operation Overview

2.1. Korea Deep Space Ground System Architecture Summary

KARI designed, developed, and verified the Korea Deep Space Ground System (KDGS) to facilitate the highly efficient operation of the KPLO. The KDGS offers the necessary functionality and performance to support both the rehearsal and operation of the KPLO. The KDGS is composed of six distinct subsystems, each with its own unique functionalities, in addition to the 35-m aperture Korea Deep Space Antenna (KDSA). These subsystems include the Real-time Operation Subsystem (ROS), Flight Dynamics Subsystem (FDS), Trajectory Design System (TDS), Mission Planning Subsystem (MPS), Image Calibration and Analysis Subsystem (ICAS), and Science Data Management Subsystem (SDMS). The subsystems work collaboratively to produce diverse deliverables that are transmitted via External Ground Networks (EGNs) to external Science Operation Centers (SOCs) for supporting the payload operation. Compared to previous ground systems designed for Low Earth Orbit (LEO) and Geosynchronous Orbit (GEO), the KDGS is distinct in that it presents more complicated operational challenges owing to its intricate interfaces. The KDGS also interfaces with NASA through EGNs. Three major EGNs have been established between the KDGS and NASA. Connection with MCC has also been established through EGNs. The KMOC and MCC share flight dynamics operation-related products such as Maneuver Planning (MP) and OD products. This exchange is facilitated through the utilization of a data server known as the External Data Server (EDS) on the EGN platform.

Figure 3 shows the top-level architecture of the KDGS with each subsystem. A more detailed KDGS design and its functionalities can be found in Ref. [26].

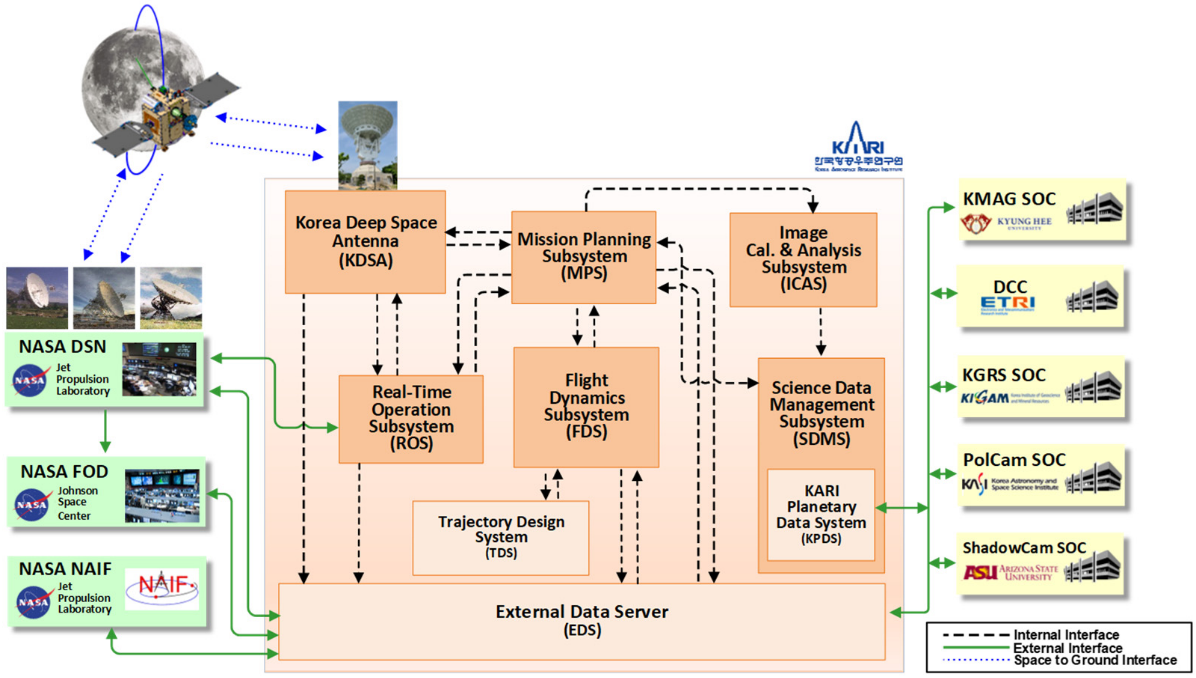

Figure 3. The top-level architecture of the KDGS [26].

2.2. Joint Operation Top-Level Concept

Among the subsystems comprising the KDGS, the FDS, and TDS played the primary role in facilitating collaboration at the KMOC. Additionally, the MCC Trajectory Subsystem (MTS), JSC's flight dynamics software, served as the primary tool in the MCC. For a more detailed understanding of the specific functionalities, operational concepts, and interoperability of the FDS and TDS, readers may refer to Song et al. [27]. The collaboration between the KMOC and MCC began with the gathering of KPLO tracking data. Both teams retrieved tracking measurements from Deep Space Network (DSN) and KDSA, if available, through a DSN Tracking data server. After securing the tracking measurements, both teams ran independent OD simultaneously using their own software. After completing the OD, the KMOC sent the generated OD products to the MCC. The MCC then compared the OD results and provided an OD solution comparison report. Once the OD results were confirmed, both entities proceeded with the MP process. Similar to the OD procedure, a trajectory comparison report, which included MP comparison characteristics, was generated by MCC and transmitted to the KMOC. In addition, MCC supported conjunction analysis with other space objects during the Trans-Lunar-Cruise (TLC), Lunar Orbit Acquisition (LOA), and nominal mission phases of the KPLO. In Figure 4, the top-level joint FD operation procedure is depicted. In general, the procedure depicted in Figure 4 is iterated through preliminary and final MP until the burn execution of the very next maneuver. Here, readers may note the "maneuver command generation" activity depicted in Figure 4 is usually valid after the completion of the final MP. However, KMOC occasionally generated burn execution commands and uploaded them to the spacecraft using preliminary products, and this decision was strongly influenced by the importance of the very next maneuver. This was done to address emergency cases when the command uploading, generated with the final MP, was unavailable due to unexpected operational situations.

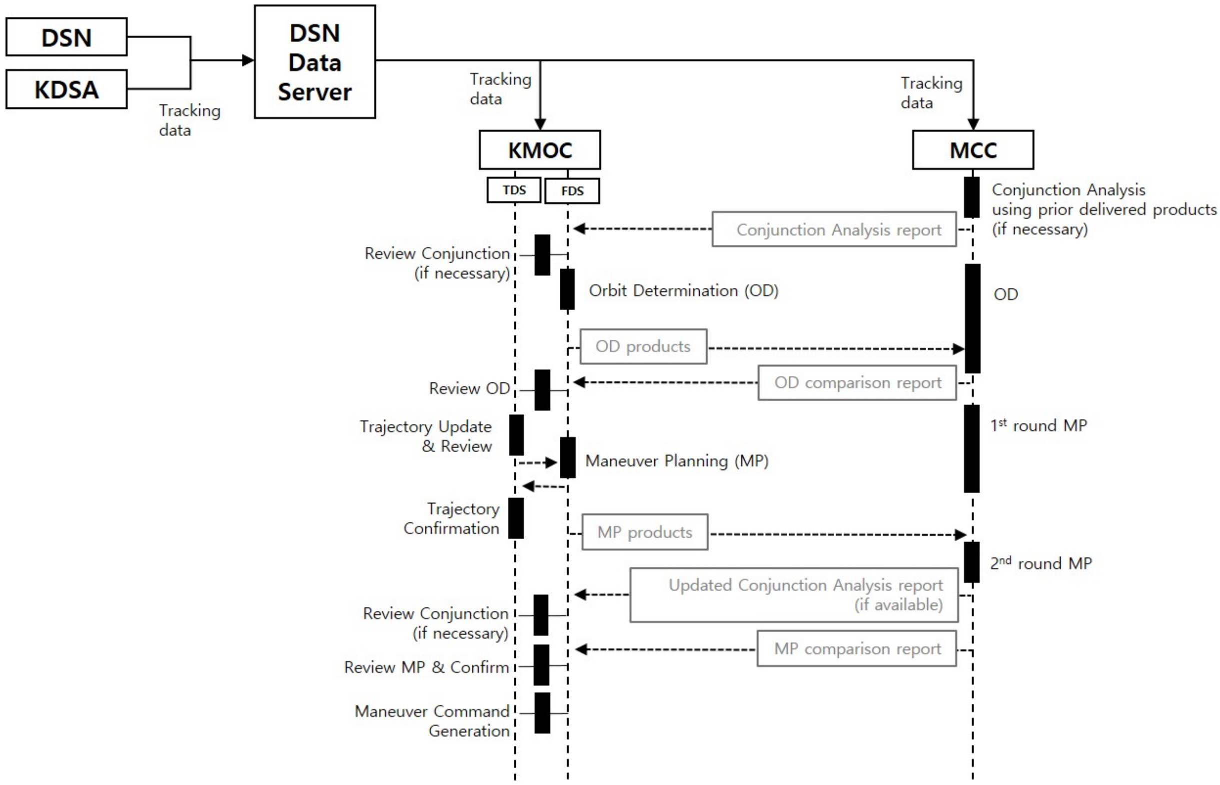

Figure 4. Top-level FD joint operation flow between KMOC and MCC.

2.3. Operational Interface Procedure (OIP) Document

The objective of the Operational Interface Procedures (OIP) is to comprehensively document real-time FD operational interfaces and standardized procedures governing the exchange of information between KMOC and MCC. This documentation encompasses the entire mission duration, from launch vehicle separation to lunar disposal, for the KPLO. The collaboration on the OIP between KMOC and MCC began with the creation of the OIP and continued until the very last moment of the KPLO launch. For smooth collaboration, a Technical Interface Meeting (TIM) was regularly conducted by KMOC and MCC via video teleconference every two weeks, and if necessary, it was conducted once a week throughout the entire joint development of the OIP.

As its name suggests, the OIP document provides a detailed overview of the types of deliverables that the two entities will exchange and the corresponding timeline for FD operational procedures. It encompasses all the necessary information for effective operational collaboration between the KMOC and MCC. The completion of the OIP document and its utilization as a basis for actual FD operations necessitated extensive discussions, negotiations, and a trial-and-error that demanded a significant investment of time and effort from both the KMOC and MCC. The following is a summary of the contents included in the OIP document [28].

- Console descriptions and roles, including each console's call sign and shift schedule guidelines dependent on KPLO mission phases.
- Network and connection guidelines for product exchange and voice communication, including designated folder names, email addresses, and international teleconference numbers.
- Detailed product exchange information, including descriptions of file name formats, line-by-line data field information, and example screenshots of each product.
- Joint operation interface procedures for maneuver execution, OD solution evaluation, conjunction analysis, burn target and trajectory assessment, emergency situations,

and contingency trajectory redesign. These procedures specify what product each organization should deliver and when.

The OIP document has been prepared in a detailed manner to facilitate easy comprehension for the relevant personnel who are participating in the joint FD operation. Additionally, the OIP continues to be updated as necessary, even after the launch of KPLO, as it functions as a living document with formal signatures required from both organizations prior to the update.

3. Joint Collaborative Efforts

KMOC and MCC made significant efforts to complete the OIP document and conduct extensive testing and rehearsals to operate KPLO FD as a joint team. Notably, the verification activities conducted to enhance the comprehensiveness of the OIP document were divided into two parts: Part 1 and Part 2. The main objective of Part 1 was to verify the product interface requirements between KMOC and MCC, while Part 2 aimed to execute synchronous operations as a joint team to achieve all the objectives within the time constraints necessitated by real-time operations. During the six years of collaboration, Part 1, the test, began approximately 27 months before the actual joint operation, which was the launch of KPLO. Part 2, the joint rehearsal, commenced around 20 months before the KPLO launch. The operator's training activities were also planned and started to be prepared with the initiation of Part 2 activities. Both Part 1 and Part 2 activities persisted until the final moments before the KPLO launch, ensuring the resolution of all underlying issues. The ultimate joint rehearsal was conducted about 1 month before the launch to guarantee the joint teams' full preparedness for the mission. This section presents the details of the collaborative efforts made between KMOC and MCC, including a summary of the tests and rehearsals conducted.

3.1. Part 1: Product Interface Requirements Verification

3.1.1. Interface Design

MCC does not receive any real-time telemetry from KPLO. This key decision drove many joint KPLO operational practices and procedures since MCC must receive all needed information from KMOC in the form of ASCII and simple file transfers. To establish efficient and seamless interoperability, KMOC and MCC engineers brainstormed on the deliverables generated by both entities. The types of files that need to be exchanged were identified, and a file naming convention was established, along with determining the detailed content for each file. Simultaneously, a network was designed and implemented to safely connect KMOC and MCC, ensuring secure communication for the file transfers. Further development has taken place regarding the exchange methods of deliverables. In parallel, both entities carried out updates to the FD software to meet the designed interface requirements. Based on the interface design results, it is specified that a maximum of 17 files need to be exchanged between KMOC and MCC per one joint operation cycle. Figure 5 illustrates the top-level interface architecture between KMOC and MCC for actual flight operation.

To validate the designed interface, Part 1 verification activities, previously described, were further categorized into two sub-tests: the practice test and the final test. For each test, test data and test environments were prepared and established, along with detailed joint test procedures. Additionally, Test Readiness Review (TRR) and Post Test Review (PTR) were jointly held for each test.

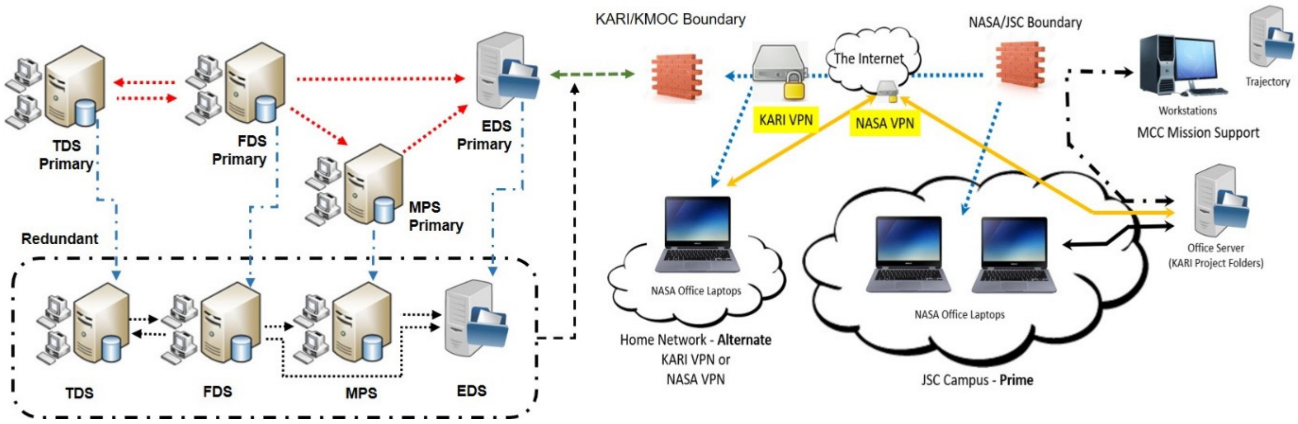

Figure 5. Top-level interface architecture between KMOC and MCC.

3.1.2. Practice Test

The primary objective of the practice test was to verify the product interface requirements and ensure compatibility between the FD software solutions from each entity. For the practice test, a total of 24 test cases were prepared, each with unique input/output products, resulting in approximately 79 files in total. These 24 cases were used to verify network connection, product delivery/reception, product format, LEO conjunction assessment, lunar orbit conjunction assessment, MP performance, and OD performance. To compare the MP solutions, three test cases were selected based on their impact on the overall success of the KPLO mission: the third Trajectory Correction Maneuver (TCM-3), the first Lunar Orbit Insertion (LOI-1), and an Orbit Maintenance Maneuver (OMM). For the comparison of OD solutions, three different major tracking arcs representing the TLC, LOA, and nominal mission orbit phases of the Gravity Recovery and Interior Laboratory (GRAIL) mission were selected. Real tracking data sets from the Deep Space Network (DSN) were provided by the JPL. The practice test results revealed that twenty test cases were successful, while four test cases failed, indicating the need for further investigation. Among the failures, one was from an MP comparison, two were from an OD comparison, and one was related to product delivery/reception. KMOC and MCC agreed to address these issues prior to the final test. Despite the failures in four test cases, both KMOC and MCC were able to extract valuable insights from these tests. For example, during the test, specific updates were identified for the OIP document and the ongoing trajectory constraint document, which were also prepared in collaboration. Moreover, the importance of sharing a detailed engine model of KPLO for more precise MP solution comparisons was acknowledged. Furthermore, the need to enhance the mutual understanding of the OD software utilized by both entities was emphasized in order to facilitate a more accurate OD solution comparison.

3.1.3. Final Test

The final test was conducted as a follow-up evaluation to verify and address any issues identified during the practice test. For the final test, KMOC and MCC carefully selected a total of 19 test cases and prepared the necessary test data and environments. Similar to the practice test, various aspects, including network connection, product delivery/reception, product format, LEO conjunction assessment, lunar orbit conjunction assessment, MP performance, and OD performance, were verified again using updated test data. Criteria for determining a successful comparison of MP and OD solutions during the real-time KPLO FD operation between KMOC and MCC were also established in accordance with the mutual agreement between the two entities regarding KPLO mission requirements.

Unlike the practice test, KMOC provided MCC with detailed KPLO engine modeling and operational concepts, and MCC updated their MTS to incorporate the accurate KPLO engine model. For the final test, TCM-1 and TCM-9, as well as LOI-5 cases, were selected for comparing MP solutions. Table 1 presents a comparison of MP solutions between KMOC and MCC in terms of delta-V magnitude. As shown in Table 1, notable enhancements were made in MP solution differences after incorporating the detailed KPLO engine model with associated operational concepts. To compare MP solutions shown in Table 1, reference center frames to compute delta-Vs were Earth-centered for TCMs and Moon-centered for LOIs and OMM, respectively. Although not depicted in Table 1, the comparisons of each burn's delta-V vector components yielded similar trends to the delta-V magnitude comparison results already shown in Table 1. During the final test, all the evaluated delta-V vector components showed a remarkably precise alignment, surpassing the comparison conducted in the practice test. The time-varying history of delta-V vectors for each entity provided crucial clues to resolve discrepancies observed during the practice test. Specifically, KMOC and MCC engineers noticed that larger burns exceeding 10 m/s (TCM-3 and LOI-1 burns in Table 1) exhibited more discrepancies compared to the smaller burn, OMM. Based on these observations, the accurate modeling and alignment of the Liquid Setting Burn (LSB)'s time-varying characteristics were recognized as of utmost importance. The LSB is a small burn designed to occur 100 s before the main burn starts, aiming to minimize the fuel sloshing effect during burns that exceed 10 m/s in magnitude. As a result of this root cause analysis, not only the components of delta-V but also their magnitudes, as demonstrated in Table 1, were precisely matched during the final test. For TCM-3, even though it was not originally intended as a test case for the final test, the decision was made to include it for the final test to evaluate the improved performance after applying the updated KPLO engine model following the practice test.

Table 1. Comparison results of MP solutions between KMOC and MCC for both the practice and final tests.

Test	Cases	KMOC Delta-V (m/s)	MCC Delta-V(m/s)	Delta-V Diff. (m/s)	Delta-V Diff. (%)
Practice	TCM-3	17.531	17.537	−0.006	−0.034
	LOI-1	145.777	145.816	−0.039	−0.027
	OMM	6.624	6.625	−0.001	−0.015
Final	TCM-1	4.248	4.248	0.000	0.000
	TCM-9	5.759	5.759	0.000	0.000
	LOI-5	125.185	125.184	0.001	0.001
	TCM-3	18.288	18.288	0.000	0.000

In contrast to the comparison of MP solutions, the comparison of OD solutions between the two entities encountered numerous challenges and demanded a considerably greater amount of time and effort, even after KMOC and MCC thought that the issues from the practice test were cleared. For the final test, OD solution comparison was to be conducted using KMOC-generated simulated tracking measurement, and therefore, test data sets for TCM-3, TCM-9, and LOI-1 were prepared. However, the comparison results of OD solutions for these three test cases did not show consistent results, even when the final test was conducted with different test settings and test data than those used in the practice test. Upon recognizing this discrepancy, KMOC and MCC temporarily suspended the final test and directed joint efforts toward identifying underlying causes. Furthermore, given the limited collaboration timeline leading up to the launch of KPLO, it was decided to concurrently investigate the cause while establishing the FD operational procedure, timeline, and conducting joint rehearsals. The details of efforts made to identify the underlying cause are discussed in the lessons learned in Section 4.

The root cause of the OD solution difference remained unidentified, but it was presumed to be caused by the difference in each entity's OD processing software algorithm with KMOC simulated tracking data. Instead of using KMOC-simulated tracking data, both entities agreed to use tracking data from various sources to compare OD solutions in the final test. Since KMOC, MCC, and JPL had already reached a consensus on OD solutions using actual tracking data from GRAIL and LRO, a decision was made to include an additional set of real-mission tracking data from the Double Asteroid Redirection Test (DART) mission, provided by JPL. Additionally, simulated tracking data for the ORION vehicle, also sourced from JPL, was used to proceed with the final test. Consequently, OD processing by all entities was performed to a good agreement; the differences fell within the range of 100~250 m for 3D position and within the order of several cm/s for 3D velocity, respectively. These results gave the joint team confidence that KMOC and MCC were ready to proceed with the KPLO flight. After obtaining reliable OD solutions, engineers from both KMOC and MCC worked together to finalize the OD solution comparison criteria for each mission phase of KPLO. Numerous debates were held to reach a consensus on the comparison criteria based on joint practice, final test results, and the analysis results of each entity. Consequently, comparison criteria for each mission phase of KPLO were finalized, including the TLC, LOA, and nominal mission phases. In addition, both teams agreed to continuously optimize and update criteria during the joint real-flight operation of KPLO through OD calibration. The key point to note here is that establishing general comparison criteria is highly challenging, especially in international collaborations in the IV&V environment. This is because these criteria are driven solely by mission-oriented specific requirements; namely, they are highly mission-dependent. Additionally, the criteria can vary significantly for each different mission phase. The most reliable way to finalize such comparison criteria is to continuously calibrate them through sufficient testing and simulation to ensure mission success. In addition to MP and OD solution comparisons, all other verifications related to network connection, product delivery/reception, product format, LEO conjunction assessment, and lunar orbit conjunction assessment were successfully completed through the final test.

3.2. Part 2: Synchronous Operations as a Joint Team

3.2.1. Detailed Operational Procedure/Timeline Establishment

KMOC had no prior experience with lunar orbiter FD operations nor with joint FD operations through international collaboration with NASA. To ensure efficient and seamless operational collaboration between the two entities, KMOC first brainstormed realistic FD operation procedures and timelines as much as possible. MCC then reviewed and updated them to reflect MCC's specific protocols. The final version of the established FD operational procedures provided a comprehensive breakdown of tasks for each entity at 30 min intervals from 25 h prior to Time of Ignition (TIG) until 3 h prior to TIG. Furthermore, it included a clear description of the software utilized at each step, the designated time for joint telecon, and specified the deliverables to be exchanged throughout the procedure. By incorporating this information, operators from each entity were able to communicate more smoothly during the actual joint FD operations.

The top-level procedure for maneuver preparations shown in Figure 4 is nominally initiated 72 h prior to TIG for known nominal burns in order to have both KMOC and MCC resources scheduled and allocated. KMOC and MCC started joint operation for the preliminary MP at 48 h prior to TIG and 24 h prior to the final MP. For the final MP, the KMOC and MCC established continuous real-time voice communication for 24 h using an international teleconference number routed into the voice systems of the respective control centers. Table 2 provides a highly simplified example of the joint operation procedure for the final MP, which solely focuses on the TIG minus 25 h timeline. In addition, it is important to note that the example in Table 2 is structured according to task significance rather than following a 30 min interval format utilized in real operations.

Table 2. A highly simplified version of joint FD operation procedure/timeline.

TIG (Hours)	FDS KMOC	TDS KMOC	MTS MCC	Remarks
−25.00	• Mass and propulsion parameter check			
−24.00			• Initiate conjunction assessment and deliver products to KMOC, if necessary	
−22.00			• Deliver preliminary MP comparison report to KMOC if available	• Joint telecon for conjunction analysis (if necessary)
−21.00	• Pull tracking data and OD run • Push OD products to MCC once completed		• Pull tracking data and OD run • Push OD comparison report MCC once completed	
−17.00				• Joint telecon for OD results confirmation
−16.50		• Trajectory update and analysis	• Final MP (1st round)	
−14.50	• Final MP • Push MP products to TDS once completed			
−13.00		• Trajectory review and confirmation		
−12.00	• Push MP products to MCC		• Final MP (2nd round)	
−11.00			• Conjunction assessment and deliver products to KMOC, if available	
−10.00				• Joint telecon for conjunction analysis (if necessary)
−8.50			• Deliver final MP comparison report to KMOC	
−7.50				• Joint telecon for MP results confirmation
−7.00	• KMOC internal maneuver briefing and confirmation			
−3.00	• Command upload completion			

For the conjunction assessment shown in Table 2, MCC agreed to support KMOC not only during the lunar transfer phase but also in lunar orbit. Therefore, during the joint FD operation, MCC provided conjunction assessment integration and calculation of the probability of collision (Pc) to KMOC for entire mission phases. As a result of the conjunction analysis procedure, a conjunction analysis report was generated and delivered by MCC to KMOC if a conjunction of concern between KPLO and another spacecraft was identified by JPL's (Joint Propulsion Laboratory's) Multi-mission Automated Deep-Space Conjunction Assessment Process (MADCAP). This conjunction report also included a probability of collision as calculated by MCC. During the actual flight operation, depending on the Pc calculation result, KMOC assesses whether the Pc is acceptable or if a collision avoidance maneuver is necessary.

The joint FD operation procedure/timeline shown in Table 2 was shaped and matured through extensive and iterative technical discussions between KMOC and MCC. It was further refined and solidified as a more confident version through the rehearsal, which is discussed in the next section. After developing a detailed procedure and timeline, the joint team was able to operate smoothly and complement each other without any confusion in any given situation.

3.2.2. Joint Rehearsal

Based on the interface test results, Part 1, and the prepared joint operational procedure/timeline, KMOC, and MCC were confident in proceeding to conduct a joint rehearsal, namely Part 2 verification. Two rehearsals were planned and conducted: a practice rehearsal and a final rehearsal. Unlike the tests conducted in Part 1, the rehearsals were conducted in real time. Voice communication between KMOC and MCC remained operational throughout the 24 h duration of the rehearsals, and both entities facilitated smooth communication by utilizing the designated call signs for each control center's console as defined in the OIP document.

As previously mentioned, the objective of Part 2 verification was to carry out synchronized operations as a collaborative team in order to accomplish all the tasks outlined in the OIP documents. For the practice rehearsal, KMOC and MCC targeted the TCM-3 burn and aimed to complete all joint work before TIG-6 h of the TCM-3 burn. Consequently, KMOC and MCC initiated a countdown to the planned TCM-3 burn time, scheduled for ignition on 29 August 2022 at 00:19:33, which was 25 h after the start of the rehearsal. This TCM-3 burn time was determined based on the designed reference trajectory. The first joint rehearsal, practice rehearsal, was successfully conducted, and the established operational procedure and timeline were verified. Despite the successful completion of the practice rehearsal, both entities captured forward works and agreed to resolve those forward works before the final rehearsal.

The final rehearsal took place one month before the actual launch of KPLO. Even after the practice rehearsal, there were ongoing minor updates to the detailed joint operational scenarios and the various documents between KARI and NASA JSC. Based on these updated final versions, the final rehearsal was conducted. For the final rehearsal, the focus was on the Orbit Trim Maneuver-2 (OTM-2) of KPLO and targeted both OTM-2a and OTM-2b burns simultaneously. During the final rehearsal, operational procedures between the two entities were verified to address a virtually simulated conjunction situation. In accordance with these conjunction scenarios, team members from both entities underwent training during the final rehearsal and conducted joint review activities on the MADCAP and PC Calculation reports. Furthermore, all procedures and functionalities, primary and backup communication lines, and network for deliverables shadings were thoroughly validated. Figure 6 depicts the KMOC and MCC team members during the 24 h joint rehearsal. Through the two rehearsals, KMOC and MCC were very confident in the success of joint FD operations and made the "Go for launch" decision.

(a) (b)

Figure 6. KMOC and MCC team members during the 24 h joint rehearsal. JSC FOD team on left (**a**) and KARI KPLO FD team on right (**b**).

4. Challenges and Lessons Learned

Synchronizing the settings of different software solutions and collaborating as one team in actual FD operations was far from easy. Through numerous trials and errors, several crucial lessons were learned.

4.1. Terminology and Common Knowledge

Mutual understanding of definitions and sharing detailed operational concepts were of utmost importance in the collaboration. Despite its obviousness, there were instances where this aspect was overlooked, leading to additional time spent resolving related issues. Sharing common knowledge becomes even more critical in joint international efforts, as terms that may seem straightforward can have different interpretations and uses by each entity. For instance, during the comparison of FD software solutions between KMOC and MCC, both parties had to verify and review the types, definitions, and availability of coordinate systems used by each other, even encountering coordinate systems that were not actually utilized by either institution's FD software. Additionally, minor terms used during joint testing and rehearsals, such as "test" or "rehearsal", had slightly different meanings and approaches for each entity, resulting in further confusion.

Initially, the extent and level of detail required to exchange common knowledge between KMOC and MCC were not thoroughly considered, as both teams were already experts in the FD field. However, after the Part 1 practical test, KMOC provided a comprehensive document to MCC detailing the engine characteristics of KPLO. This document covered thruster installation configuration, operational modes, types of thruster usage, thrust, specific impulse (Isp) time-varying characteristics, and the associated algorithm implemented by KMOC. The delivery of this document and subsequent updates to MCC's MTS yielded satisfactory and accurate outcomes.

The authors strongly recommend verifying term definitions and common knowledge before investing further effort, regardless of how trivial it may seem, in case of any doubts. Utilizing interface control documents can enhance mutual understanding, containing all necessary information for knowledge sharing. Detailed and clear explanations should be provided to the fullest extent possible. Although writing OIP and trajectory requirement documents between KMOC and MCC was laborious, their detailed content proved highly beneficial for successful and reliable joint FD operations. Regular updates and sharing of these documents are essential for effective communication and collaboration.

4.2. Parameters and Configuration

Comparing software solutions from different entities was a highly challenging task because each software was developed using different programming languages and algorithms. In the context of IV&V, it became even more difficult as KMOC and MCC had to proceed without a clear understanding of the internal details, such as the algorithms and parameter definitions used by the software. Despite using validated FD software, FD specialists had to fine-tune input values and verify parameter definitions to ensure close alignment between the solutions derived by the two entities.

For example, to improve the results of MP solution comparisons, in addition to their efforts on matching the KPLO engine modeling, KMOC and MCC engineers revisited every detail of algorithms and parameter definitions from the beginning. Every perturbing force applied with associated algorithms was revisited while solving the issues raised from the practice test. An applied numerical integrator to compare MP solutions was also double-checked with a step-size control method. After consistency was ensured, every definition of target parameters with associated tolerance applied for each entity was checked again to ensure that both KMOC and MCC's FD software were on the same page.

In terms of OD solution comparisons, engineers had to invest a more significant amount of effort and time compared to MP solution comparisons. The details of dynamic settings for OD were double-checked. This included verifying various parameters like OD noise setting, DSN and KDSA geodetic location, speed of light, transponder delay, relativistic correction, luminosity, Earth Orientation Parameter (EOP), space weather model, nutation/precession model, and other more detailed spacecraft-related parameters. Any discrepancies identified during the double-checking process were further analyzed to evaluate their potential impact on the overall solution comparisons. It was found that there were minimal differences in the parameters and models used by KMOC and MCC. Fortunately, these differences were determined to have no significant effect on the solutions derived by each entity.

A valuable lesson learned from this collaboration was the importance of implementing a systematic verification process for dynamic settings, such as parameters and configurations, in advance. Despite the impressive problem-solving skills displayed by FD specialists from both KMOC and MCC, it was unfortunate that prior confirmation of these elements was overlooked. Even for highly specialized entities involved in such collaborations, the authors strongly recommend confirming the parameters and configurations for the software used by each entity beforehand. This simple and essential approach would undoubtedly enhance the effectiveness and productivity of the collaboration.

4.3. Staffing and Joint Team Building

Through this collaboration, KMOC has gained a profound understanding of the criticality of staffing in FD operations, particularly in planetary exploration missions. This is because the KPLO mission marked a significant milestone in the Republic of Korea's space development history as its first-ever mission beyond Earth's orbit while simultaneously being the first case of conducting joint FD operations in international collaboration. The FD operations for lunar exploration missions exhibit notable distinctions, not only in terms of design, development, and verification of related subsystems but also in their operations when compared to the conventional FD operations for LEO or GEO satellites. It is indeed true that KMOC, namely KARI, overlooked this crucial staffing and team-building aspect.

The KPLO FD operations were conducted by a small team of KMOC personnel, who had a limited number of members. They had the responsibility for all aspects of FD-related tasks for KPLO, including the design, development, and verification of the TDS and FDS, as well as operations. However, contrary to KARI's expectations, the KPLO FD team faced a substantial increase in workload as the mission progressed due to the nature of planetary exploration missions. Specifically, KPLO selected the BLT trajectory for TLC, which took approximately 4.5 months, and during the 2-week LOA phase, the workload became even more demanding. Furthermore, contrary to KMOC's expectations, there were frequent occurrences of conjunction-related tasks after entering the lunar mission orbit. The limited staffing at KMOC also had an impact on team building with MCC. During the procedures and timelines establishment for joint FD operations, KMOC faced difficulties in finalizing its own shift schedule. Consequently, the team had to work continuously without a designated shift schedule to ensure seamless collaboration with MCC. All of these factors were due to a lack of comprehensive understanding and preparation for planetary exploration mission operations as well as international collaboration.

When planning international collaborations in space exploration missions, particularly similar to the KMOC and MCC partnership, ensuring sufficient staffing for joint team building is crucial. It is important to consider personnel availability from the initial design phase of joint operation procedures and timelines, considering the specialized characteristics of both planetary exploration missions and the demanding nature of international collaboration. Additionally, allocating operational staff at the appropriate time is highly recommended to facilitate smooth joint operations. The most suitable timing for allocation would be when both entities have nearly completed their preparations, such as finishing tests and finalizing joint documents. The assigned operational staff will then undergo training using the prepared procedures and documents, actively addressing and resolving any emerging issues. By implementing these strategies, collaboration-based joint operations will be strengthened and solidified. These aspects hold great importance as they directly contribute to the overall success of the mission.

5. Conclusions

In this work, the efforts and lessons learned from the collaborative work between the Korea Aerospace Research Institute (KARI) and the National Aeronautics and Space Administration (NASA) Johnson Space Center (JSC) Flight Operations Directorate (FOD) are summarized, with the goal of achieving effective joint Fight Dynamics (FD) operations as a unified team. The dedicated efforts of Korea Pathfinder Lunar Orbiter Mission Operation Center (KMOC) and NASA JSC Mission Control Center (MCC) over the past six years have resulted in the successful insertion of Korea Pathfinder Lunar Orbiter (KPLO) into lunar orbit. Currently, KPLO is orbiting the Moon at an altitude of 100 km with a 90-degree inclination, and all payloads, including the bus system, are operating normally, achieving maximum science return.

To ensure smooth and efficient collaboration between KMOC and MCC, the interfaces between the two entities were optimized for joint operations. Extensive testing and trial-and-error processes were undertaken in order to establish systematic operational procedures with clear timelines. Moreover, two comprehensive joint rehearsals were successfully conducted. These collective efforts ultimately led to the completion of the Operational Interface Procedure (OIP) document as well as other documents which served as a valuable reference during the actual flight operations.

The course of this joint work was far from smooth. In particular, the collaboration between KMOC and MCC, with its Independent Verification and Validation (IV&V) characteristics, presented numerous challenges. Through two rounds of testing, the establishment of procedures and timelines, and the execution of rehearsals, valuable insights were gained. Careful examination of numerous parameters and internal algorithms was required to ensure consistent outcomes from the FD software used by both entities. Moreover, significant efforts were made to ensure consistency in the terms used and to maximize common understandings of operational concepts. Additionally, staffing and team building posed significant obstacles, especially to KMOC, to functioning as a unified joint team. In summary, the main lesson learned from these experiences is that every aspect should be carefully considered, and dedication to the fundamentals should be maintained. While this lesson may appear self-evident and trivial, it is still an important factor that must never be disregarded in real-world collaborative endeavors.

The joint experience between KARI and NASA JSC has built mutual trust and serves as a foundation for future cooperation. Furthermore, the efforts and lessons shared in this work offer valuable insights to experts worldwide who aim to foster similar international collaborations, facilitating smoother partnerships and minimizing potential challenges.

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