Flight Dynamics Operations for the First ispace Lunar Lander Mission M1

Javier Hernando-Ayuso(1), Fernando Gonzalez Meruelo(1), Alejandro Sanchez Duran(1),
Tiago Monteiro Padovan(1), Dylan Harrison(2), Amanda Marx(2), Jonathon Smith(3)
(1)ispace
Tokyo, Japan
Email:j-hernando@ispace-inc.com

(2)ispace technologies U.S.
Denver, U.S

(3)Navi, Inc
Pasadena, U.S

***Abstract* – ispace, a global lunar resource development company with the vision, "Expand our Planet. Expand our Future.", specializes in designing and building lunar landers and rovers. ispace aims to extend the sphere of human life into space and create a sustainable world by providing high-frequency, low-cost transportation services to the Moon. As part of that vision, Mission 1 was launched on December 11th, 2022 on board a Falcon 9 en route to the Moon where it arrived on March 21st, 2023 after approximately three months following a Low-Energy Transfer (LET) trajectory. After one month orbiting the Moon in a Low-Lunar Orbit (LLO), it attempted to land on April 25th, 2023. Throughout the mission, the Flight Dynamics (FD) team routinely performed orbit determination, maneuver planning and product generation and distribution. Specifically, eight orbital maneuvers were planned and executed, including one with collision avoidance considerations in LLO. In addition, the overall nominal performance of the guidance system enabled all of the planned maneuver execution error corrections to be skipped. These FD operations were performed using an in-house suite of software tools supported by a commercial astrodynamics library. These tools can be divided into three categories. The first one is a set of libraries and scripts for preliminary and detailed trajectory design. Next, an automated covariance analysis command-line interface (CLI) tool called Luna (Lunar Uncertainty Navigation Analysis) was developed. Finally, the FDS (Flight Dynamics Software) was the CLI application used in real-time FD operations. A common characteristic of Luna and the FDS is that they use an external library as a backend for all astrodynamics-related calculations, but are used for tracking and coordination of required computations. To minimize human error during operations, they provide a framework that defines how the information can flow both internally and externally. Internally, they feature several databases and define the allowed operations to transform the data from previous calculations and downlinked telemetry for navigation and guidance to closely follow a reference flight path, and simplify the transition from design to operations. Externally, they constrain the operator to products that can ingest from other entities or teams and ensure that only the correct products can be delivered to each interface. Finally, the in-house software suite and the operations team were brought together by an additional piece of software: a training tool that automatically maps design inputs to simulated scenarios. It was employed to support the validation of the software and certifications of the operations team.**

I. INTRODUCTION

ispace, a global lunar resource development company with the vision, "Expand our Planet. Expand our Future.", specializes in designing and building lunar landers and rovers. ispace aims to extend the sphere of human life into space and create a sustainable world by providing high-frequency, low-cost transportation services to the Moon. As part of that vision, Mission 1 was launched on December 11th, 2022 on board a Falcon 9 en route to the Moon. Figure 1 shows ispace M1 lander.

Fig. *1. ispace M1 lander*

In order to maximize the payload capacity, the lander followed a Low-Energy Transfer (LET) to the Moon. In a LET, the spacecraft reaches apogee distances on the order of 1.5 million km and requires a transfer duration of several months, but exploits the gravitational force of the Sun to lower the delta-v needs for the lunar transfer. After a series of Deep Space Maneuvers (DSM), the lander arrived at the Moon's orbit on March 21st, 2023. Figure 2 shows an schematic of the trajectory followed by the M1 lander.

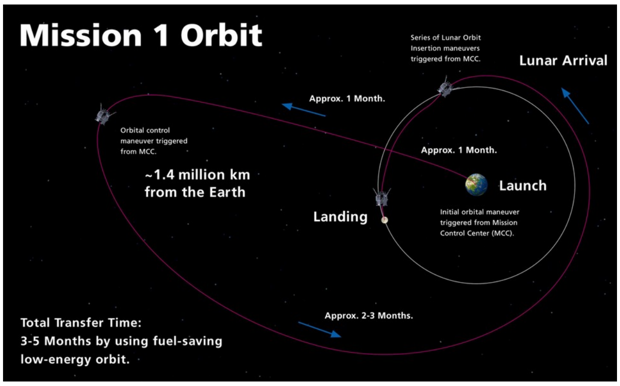

Fig. *2. Trajectory of M1 lander*

A series of Lunar Orbit Insertion maneuvers (LOI) delivered the spacecraft into a Low-Lunar Orbit (LLO). After one month orbiting the Moon, the spacecraft initiated its automated landing sequence on April 25, 2023. Unfortunately, the landing failed due to a navigation anomaly which caused it to over-estimate its altitude over the lunar surface. After hovering for about three minutes, the lander expended its remaining propellant, and reached the surface with a catastrophic speed [1].

The operations of M1 were performed from the Mission Control Center (MCC, see Fig. 3), situated in central Tokyo, Japan. From this facility, the operations team planned and executed all activities to safely deliver the lander from separation from the launch vehicle until the beginning of the landing phase. The operations team was supported on console by the subsystems engineers who designed the lander. As part of the operations team, the Flight Dynamics (FD) team was in charge of all orbit-related calculations to ensure that the trajectory of the lander was accurate and precise.

Fig. *3. ispace MCC after completion of the initial critical operations.*

In this manuscript, the FD operations of ispace M1 lander are described. First, the software tools used during pre-flight and flight phases are explained. Then, the organization of the flight dynamics operations are described. Finally, the results of the flight dynamics are presented.

II. FLIGHT DYNAMICS SOFTWARE SUITE

To support the Mission Design and Flight Dynamics operations, an extensive in-house software suite was developed. The team exploited the flight-heritage of a proprietary Commercial Off-The-Shelf (COTS) Flight Dynamics library which features a C++ back-end and a Python front-end, to build multiple software applications that were used in all the project phases from preliminary mission design until the post-mission analyses.

A. *Trajectory Design and Analysis Tools*

A set of libraries and scripts was developed to support the design and analysis of ispace lunar trajectories. This enabled quick iterations of the trajectory from preliminary phase studies to a more detailed design in later phases, and allowed the use of heritage software components that had already been tested and validated. A backwards-propagated method from the state of lunar arrival provided an initial guess for the LET, as described in detail in [2]. Then, the trajectory was numerically optimized using a multiple-shooting algorithm to minimize the required delta-v, while satisfying all mission requirements.

In addition, *Luna*, a command line interface (CLI) utility for covariance analysis, was developed. This tool can process the trajectories generated by the design tools and assess their navigability and determine the DV99 needed to fly the mission.

B. *Operational Flight Dynamics Software (FDS)*

The operational Flight Dynamics Software (FDS) was designed following the principle of operational robustness. To this end, the operators are restricted to which actions they are allowed to perform depending on the context. For instance, any particular product cannot be sent to the wrong interface, only the corresponding one. Another way in which this robustness is achieved is by limiting some activities like orbit determination or maneuver planning to local contexts which are isolated from the global system. This prevents operational mistakes and allows multiple operators to work in parallel in the same task without interfering with each other.

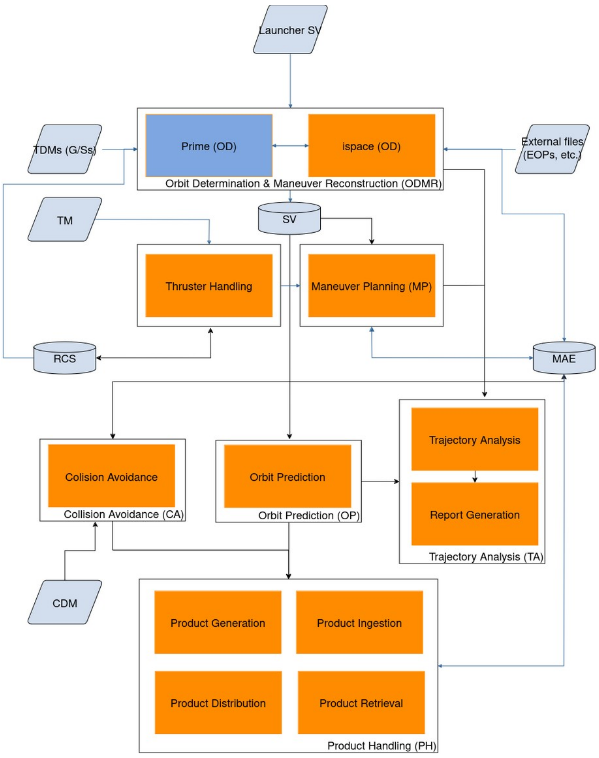

Fig. 4. Architecture of the FDS.

The architecture of the FDS is shown in Fig. 4. The main components are:

- Orbit Determination and Maneuver Reconstruction component (OD), which is in charge of estimating the position and velocity of the lander and assessing the execution of maneuvers.
- Maneuver Planning (MP), which oversees the update of all incoming maneuvers so the lander follows its reference flight path.
- Orbit Propagation, which provides a prediction of the lander trajectory.
- Collision Avoidance, which analyzes and mitigates any conjunction with other orbiting bodies. This component relied on space-track for the near-Earth operations [3], and on NASA's MADCAP for cislunar space [4, 5].
- Product Handling (PH), which is in charge of interfacing with other entities, both in the incoming and outgoing direction
- Trajectory Analysis component, which outputs figures and tables that can be used by the Report Generation module.
- Report Generation, which automatically generates LaTeX reports to share the FD results with other teams.

The architecture of Fig. 4 shows a few other minor components. Some of them are internal databases: State Vector (SV), Telemetry (TM), Reaction Control System (RCS), Main and Assist Engine (MAE). The remaining elements correspond to external interfaces handled by PH: Launcher SV, Tracking Data Messages (TDMs) from Ground Stations (G/S), Earth Orientation Parameter (EOP) files, and Conjunction Data Messages (CDM).

C. Training tool

Finally, a training tool was developed to generate data cases that automatically populate the databases of the FDS from a *Luna* case. These training cases helped to develop and test the FDS, as well as to train and certify the team and validate the operational procedures.

III. FLIGHT DYNAMICS OPERATIONS

The Flight Dynamics team was in charge of designing the trajectory from separation from the launch vehicle until the automated landing sequence start. During operations, the team must assess the position of the lander, fine-tune incoming maneuvers, and disseminate this information to the rest of the operations team. Note that ispace FD was not in charge of any attitude-related operations, which was handled by a separate team.

The core team consisted of four FD engineers in the Japan office, which were supported by two engineers from the US office and an external contractor during the most critical phases of the mission. These up to seven members would be rotated in shifts to staff the two FD consoles which were available in the MCC.

An external entity with several years of experience was hired to provide Orbit Determination results, which were used by the ispace FD team to validate their own results. Regular meetings between the external entity and ispace FD were held to compare results and plan future activities.

Prior to launch, an extensive simulation campaign was held to validate all tools and processes, and to train the team for the incoming operations.

After launch, two types of activities were held following the operational procedures: Routine operations and special operations. Contingency procedures, not described in this work, were also prepared and validated.

A. Routine Operations

Routine operations were recurring weekly activities when no special operations were scheduled. During a week of routine operations, one ispace FD engineer was assigned as prime operator, and another teammate was assigned as backup operator. The backup operator would assist the prime operator on-demand and attend all relevant meetings, including those with the external OD provider. The operator assigned as backup during one week would become the prime operator the following week to facilitate the handover.

Nominally, the operations team scheduled a daily contact with the spacecraft and Doppler measurements were available for every pass. Additionally, Ranging operations were performed twice a week using different ground stations, typically on Tuesday and Friday.

The FD team planned a series of activities for every day of the week. The week started with a routine team meeting.

During Monday, all telemetry (TM) and tracking data from the previous week was downlinked and ingested into the FD system.

On Tuesdays, both the external OD provider and the ispace FD team estimated the orbit of the lander and compared their results until reaching an agreement. In parallel, and during the routine contact with the spacecraft, a Ranging operation was performed.

The MP was routinely performed on Wednesday mornings using the OD solution of the previous day. Then, on the afternoon of the same day, a standard set of products was generated and distributed to all relevant parties to inform of of the progress after the OD and MP processes.

While no activity was scheduled on Thursdays, on Fridays a meeting with the Planning Team of ispace was held to discuss the activities in the following week, including the details of the planned tracking passes. A second Ranging operation was performed during the Friday routine contact.

All Routine operations activities are summarized in Table 1.

Table 1. Routine operations summary

Day	**FD activity**
Mon	FD Routine meeting TM downlink Tracking data ingestion
Tue	OD process Meeting w/ external OD Ranging
Wed	MP process Product generation Product distribution
Thu	N/A
Fri	Planning meeting Ranging
Sat	N/A
Sun	N/A

B. Special Operations

Special operations included launch preparation, Launch and Early Operations Phase (LEOP), maneuvers and the landing preparation.

Launch preparation started with the training, certification and rehearsal of the team. As part of the preparation, the FD system had to be set up and prepared for flight, which included generation and distribution of products to support other teams.

The LEOP was one of the most critical phases of the mission due to M1 being the first mission for ispace, its lander and the operations team. The most important milestone for the FD team was to assess the need for a launch correction maneuver right after launch, since delaying this burn would require more delta-v in the case of a bad injection. To this end, two engineers were staffing the FD positions to provide updates on the Orbit Determination and Maneuver Planning of the lander as new tracking data was coming in, and three 9-hour shifts were scheduled with a handover between two consecutive teams, enabling continuous FD activities. Frequent updates were released to the rest of the operations team as new telemetry and tracking data were received.

For each maneuver, a final OD and MP solution were produced and distributed to the operations team six hours before the execution. Backup plans for each maneuver were also delivered. Moreover, the execution of the maneuver was monitored in real-time, and refined with tracking data in the hours following the burn to assess the need of using the backup slot assigned to each maneuver. The maneuvers during the LET, which were less critical and could be delayed a few days if necessary, were handled only by the core Japan team. In contrast, all maneuvers in lunar orbit were supported by the full extended team, and the same shift pattern as LEOP was employed.

Finally, the landing preparation was staffed similarly to any other maneuver in lunar orbit. Contingency plans to divert to a backup landing site if needed were also prepared.

IV. FD OPERATIONS RESULTS

During M1 operations from launch until the beginning of the landing sequence, the FD team successfully performed all OD operations and validated the results with the external OD provider for a total of 31 meetings, proving the newly developed system. In total, the OD process was performed 145 times during the mission, including variations of some scenarios.

A total of 7 orbital maneuvers were performed during the mission (two DSMs, three LOIs and two correction maneuvers). ispace FD demonstrated its capability to guide the spacecraft along the planned trajectory. The MP process was run a total of 161 times, including variations of some scenarios.

The spacecraft was safely delivered to the interface point with the automated landing sequence. Unfortunately, the local topography during the descent caused the navigation filter to converge to a wrong altitude value, rejecting measurements with large residuals from the altitude sensors [1], finally causing the demise of the lander after it ran out of fuel and crashed onto the lunar surface. The causes for this anomaly were investigated, and mitigation measures were put in place for the next ispace mission M2, planned to launch in Q4 2024.

V. CONCLUSIONS

In this manuscript, the flight dynamics operations of the first ispace lunar lander M1 were described.

An extensive software suite was developed using commercial libraries as back-end, and it was used from preliminary trajectory design through all the mission.

All FD operations from launch until the beginning of the automated landing sequence were successful, and the lander was navigated and guided accurately all the way to the final interface point.

The anomaly during the automated landing sequence was identified and mitigated for the next ispace mission M2 launching in Q4 2024.

VI. REFERENCES

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