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GETTING BACK UP: FLIGHT EXPERIENCES OF THE IM-1 AND IM-2 LUNAR LANDING MISSIONS & IMPROVEMENTS FOR IM-3

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In February 2024, Intuitive Machines became the first commercial company to land and operate on the Lunar surface with the IM-1 mission. The mission was challenged from pre-launch through landing and ended up on its side on the Lunar South Pole yet still operated for over 6 days. A year later, Intuitive Machines launched the IM-2 mission, also to the South Pole, applying lessons learned from IM-1 to address the issues on the first mission. All issues were addressed but a new anomaly with landing measurements in the final orbits again prevented a nominal landing. Nevertheless, IM-2 successfully operated for 13 hours on the surface to deliver critical science and technology data for NASA and commercial customers. This paper presents an overview of IM-1 and IM-2 missions and issues, corrective actions successfully implemented on IM-2, and a preview of improvements that the Company believes will make IM-3 a fully successful mission landing in the Reiner Gamma region of the Moon in late 2026.

This document was prepared without AI assistance.

INTRODUCTION

In 2024, Intuitive Machines (IM) became the first commercial company to successfully land on the Moon with the first US Moon landing since 1972. However, this attempt was not without anomalies in that the final landing attitude was off-nominal with the Nova-C lander on its side. This paper discusses the major anomalies on IM-1 and IM-2, corrective actions and improvements on IM-2, and a preview of significant improvements for the upcoming IM-3 mission. The paper is organized as follows: (1) an overview of the NASA Commercial Lunar Payload Services (CLPS) initiative and IM's role in it so far, (2) a description of IM's lunar flight, ground, and operational systems, (3) a discussion of IM-1 and the major issues encountered in that mission, (4) a discussion of corrective actions implemented for IM-2 and the resulting improved overall mission despite a second off-nominal landing, (5) improvements slated for IM-3, and (6) Conclusions.

NASA COMMERICAL LUNAR PAYLOAD SERVICES

NASA established the CLPS contract within the Science Mission Directorate (SMD) in 2018 as a method for competitively purchasing complete mission services spanning mission planning, payload integration, launch, transit, and surface operations. The CLPS contract mechanism is

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Indefinite Deliverable, Indefinite Quantity (IDIQ) with the intent to buy fixed-price services from the pool of eligible companies. NASA selected nine companies, including IM, for CLPS competition in November 2018 and added five more to the eligible bidder pool in 2019. The standard life cycle of a CLPS contract begins with NASA issuing a draft Request for Task Order Proposal (RFTP) followed by a final RFTP, responses generated from participating eligible bidders, NASA selection of an awardee from submitted RFTP responses, and mission execution. The firm-fixed price (FFP) contracts for each task order are "turnkey" and include payload integration, lander development, launch costs, operations, and communications during transit and surface operations. Considering that these services include launch costs, they are considerably less expensive than traditional NASA science missions (Table 1). NASA's stated desire for CLPS is to be one of many customers on commercial missions run by the selected vendor in a model more akin to terrestrial shipping than traditional space science missions with bespoke spacecraft for each mission. This paper discusses events on the IM-1 and IM-2 missions servicing CPLS task orders TO-2 and PRIME-1, respectively.

Table 1. IM-1, IM-2, IM-3, & IM-4 Schedules, Landing Sites, Payloads, and Price to NASA.

Mission	Award Date / Launch Date	Landing Site	Payloads	NASA Price
IM-1	May 2019 Feb 2024	Lunar South Pole Region (LSPR)	5 CLPS TO-2 payloads, 5 commercial payloads	$123M (includes modifications to move landing site to LSPR)
IM-2	October 2020 Feb 2025	LSPR	CLPS PRIME-1 drill, STMD Hopper, 10 commercial payloads	$97M (including NASA STMD payloads)
IM-3	August 2021 Expected Late 2026	Reiner Gamma	CLPS CP-11 payloads, 4 commercial payloads	$86M
IM-4	August 2024 Expected Late 2027	LSPR	CLPS CP-22 (L-CiRiS, MAG, LEIA, PROSPECT, SEAL), 4 commercial payloads	$116.9M

IM was established by Steve Altemus, Tim Crain, and Kam Ghaffarian in 2013 as a think-tank to apply engineering principles refined in human spaceflight to intractable problems across sectors including aerospace, energy, and medicine. At the time of applying to the CLPS contract bidder pool, IM was a company of approximately 40 employees with strengths in software development, mechatronics, and limited prototype development of systems such as medical devices and fixed-wing drones. In addition, over 1/3 of the IM team also had experience designing, building, and operating experimental systems including the NASA Morpheus terrestrial lander vehicle. IM established a Lunar Payload and Data Services (LPDS) program in 2019 to develop space flight systems, respond to CLPS RFTPs, and solicit non-NASA customers for commercial lunar missions.

IM LUNAR SYSTEMS OVERVIEW

The Nova-C Lunar Lander

The IM LPDS design team faced an initial challenge of sizing a lunar transit and landing spacecraft for an unknown future NASA demand and aspirational commercial market. Designing too much initial landing cargo capacity drives system complexity and launch system costs higher. On the other hand, designing too little capacity drives up the unit costs to customers as the booster and lander expenses have fewer kilograms to spread the costs of the booster, lander, and operations service. IM decided to target a 100kg landed cargo capacity lander and then traded propulsion options. Storable propulsion solutions offered the highest Technology Readiness Level (TRL) at the component level, but the team had extensive experience with cryogenic methalox systems from the Morpheus project. In the end, the LPDS team selected to vertically integrate propulsion with methalox (Figure 1) and became the only CLPS bidder with such a propulsion system.

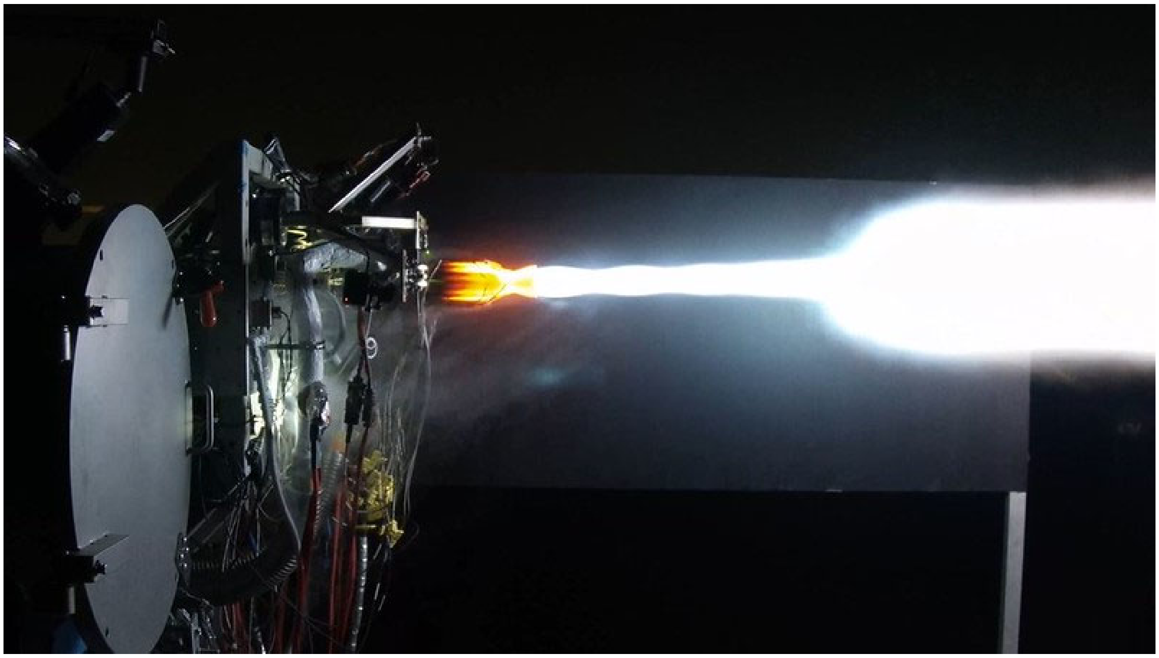

Figure 1. Nova-C Methalox Propulsion Testing at the Houston Spaceport

The initial lander architecture was built around this propulsion concept and became the basis for the Nova-C lander. The name was chosen considering “Nova” for a new start to lunar exploration and development and “C” the Roman numeral for 100 to reflect the targeted landed payload capacity of 100kg. IM manufactured and flew two Nova-C landers for IM-1 (Odysseus) and IM-2 (Athena) and is in the process of integrating the Trinity Nova-C for IM-3 and an as-yet unnamed Nova-C for IM-4 (Figure 2).

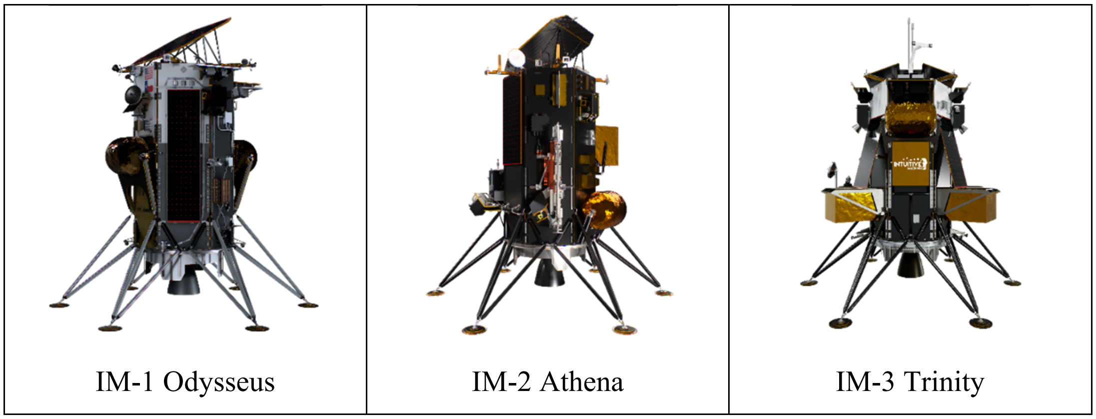
IM-1 Odysseus | IM-2 Athena | IM-3 Trinity

Figure 2. Nova-C Landers for IM-1 (Odysseus), IM-2 (Athena), and IM-3 (Trinity)

The Lunar Data Network

In 2019, concerned with availability due to overcapacity issues on the NASA Deep Space Network (DSN), IM began creating our own Lunar Data Network (LDN)[*]. By utilizing time on large (>18 meter) dishes around the world, we have been able to create a completely commercial alternative to the DSN for communications and orbital determination (OD) to Lunar distance and beyond. The LDN provides nearly 24/7 data coverage for cislunar missions. As detailed in the sections below, improvements in LDN OD measurement quality from lessons learned on IM-1 resulted in OD solutions validated to be statistically equivalent to DSN on IM-2. The LDN is therefore validated to be sufficient for both communications and OD for subsequent lunar lander missions and cislunar operations.

Nova Control and Flight Operations

One of NASA's CLPS goals is to stimulate lunar delivery and data services needed for a thriving commercial ecosystem. IM is the perfect example of how the government's goal has been fulfilled. IM has not only been awarded 4 CLPS task orders, but IM has grown to support other NASA missions, commercial satellite customers, and other government agency needs. In these early stages of lunar missions, we had significant cost constraints driven by the low-cost, high-risk approach of CLPS. Companies like IM could not afford to have a separate operations team from the engineering and production teams that design and build the landers and overall lunar program. This means that the people that designed, built, tested, and verified the vehicle are the operators in our Nova Control mission operations center (Figure 3).

This approach allowed IM to fly a brand-new spacecraft with numerous systems that had never been proven in space, at a pace that rivaled the Apollo mission timelines with two missions in a little over a year. The high-thrust, high-efficiency methalox propulsion system also enabled a fast transit of 4 days from Earth to the moon and only 5-6 days before landing on the surface (Figure 4) like the transits of Apollo. This meant that for IM-1, we were really all hands on-deck for the mission operations. As we have moved forward to IM-2 and beyond, the Company portfolio has grown to have multiple missions in various stages of development in parallel. IM meets the operational demands of these missions in part with additional staff and informed by the lessons learned on IM-1 and IM-2. These have allowed us to automate systems that originally required minute by minute manual support with a human operator in the loop. IM staff intentionally designed the

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[*] The LDN has been rebranded the Space Data Network (SDN) to reflect the fact that our ground network supports operations throughout the Earth-Moon sphere of operations and beyond. This paper retains the LDN nomenclature for consistency with some of the Figures generated before this change.

control room and operations approach to minimize the number of resources required to fly the spacecraft. From a front room that will only hold 10-12 controllers, to minimizing back-room support, the IM team intentionally tries to find ways to push automation forward and minimize/reduce total required resources at all operations positions. The look of our front room was inspired by the highly interactive control centers in submarines with outward focus on console stations and inward focus around a tactical meeting area for close coordination or troubleshooting.

Figure 3. Nova Control Operations Center at Intuitive Machines Offices in Houston

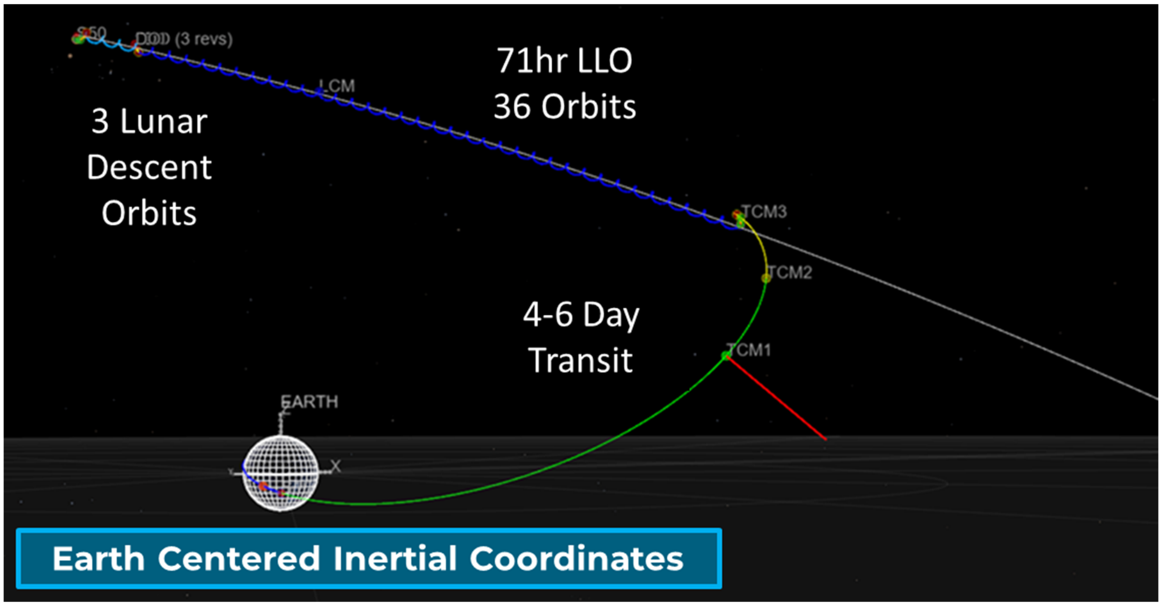


Figure 4. IM-2 Fast Transit to the Moon is enabled by Translunar Injection from the SpaceX booster and high thrust acceleration from the Nova-C propulsion system during Lunar Orbit Insertion.

Operations training and procedure development were informed by experience operating the Space Shuttle, International Space Station, the Morpheus lander, and a large body of propulsion test operations developing the IM methalox engine. IM operates lunar missions with three shifts per day (red, white, and blue) and a support Team 4 that is comprised of subject matter experts (SMEs) and led by a senior member of the project team. The majority of Team 4 is not called into service unless there is an anomaly that requires support outside of the control room. Our customers can either have support in our facilities or from their own facilities tied in through secure voice and data networks links.

IM-1 MISSION

The initial CLPS task order, TO-2, was unique in that NASA provided 12 payloads for the original nine bidders to select one, some, or all to fly to the Moon and operate. The bidders for TO-2 were also asked to propose their own launch date and landing location for TO-2. IM proposed to fly the Navigation Doppler Lidar (NDL) landing sensor, the Lunar Node 1 (LN-1) radiometric navigation demonstrator, the Stereo Cameras for Lunar Plume-Surface Studies (SCALPSS) system, and the Radiowave Observations at the Lunar Surface of the photo-Electron Sheath (ROLSES) and the Laser Retroreflective Array (LRA). The initial landing location selected by IM was a relatively "benign" mid-latitude location near Oceanus Procellarum, but IM was redirected to the Malapert area in the Lunar South Pole Region (LSPR) in response to NASA requests for an earlier LSPR capability. The primary impacts of this change to the Odysseus Nova-C lander for IM-1 were a modification of the top-deck solar array, antenna layout reconfiguration, and thermal management coatings on the vertical sides of the lander.

IM-1 Pre-launch Risk Assessment

Prior to launch of IM-1, the authors considered four key areas to be testable only in flight:

1. Thermal management of the cryogenic methane and oxygen commodities
2. Free-body flight control of the gimbaled methalox main engine
3. Lunar distance communications and tracking data generation with the commercial Lunar Data Network (LDN) and the Nova-C radios
4. Landing sensor (cameras and lasers) interaction with the lunar surface

As it turned out, thermal management exceeded performance expectations, flight control improvements were required by operators, tracking data was problematic, and a wiring issue prevented use of laser systems for landing. The issues and resolutions for the latter three pre-mission risks are discussed below.

IM-1 Transit and Lunar Orbit

The IM-1 Odysseus Nova-C was the first cryogenically fueled payload launched on a SpaceX Falcon-9 rocket. IM and SpaceX engineers worked on operational, data systems, and propulsion control system integration for months in advance of the IM-1 mission. A wet dress rehearsal resulted in a sufficient propellant load and verified systems were go for launch. However, the first launch attempt was ultimately scrubbed due to an insufficient prop load resulting from actual launch day timeline variations. Subsequently, with these adjustments accounted for, launch occurred on February 15, 2024, with an optimal propellant load in terms of both mass quantity and cryogenic temperatures. During transit, lunar orbit, and powered descent, Odysseus demonstrated the first use of cryogenic and methalox propulsion beyond Earth orbit with seven ignitions and no propellant loss (boiloff) because of the performance of the passive thermal control design of Nova-

C. However, several major anomalies and issues arose during transit and in lunar orbit that the operations team worked to overcome.

Initial Star Tracker Measurement Rejection. Star tracker quaternions were demonstrated to have a 0.002 acceptable threshold to unity in integrated live sky testing pre-launch. On separation, the actual quaternions generated by the star trackers had a norm of 0.003 from unit-value and failed a hard-coded acceptance test threshold for processing ST measurements. As a result, the Nova-C Automated Flight Manager (AFM) sequence remained in attitude rate control mode and did not have an attitude update required to advance to a fixed axis attitude control for power generation and stable communication.[1] The attitude of separation from the booster was such that the aft of Odysseus and the main engine were very nearly pointed to the sun (Figure 5) and the side solar arrays were generating a minimum of power as the vehicle slowly precessed around the x-axis from the imparted launch vehicle separation rates. The lander was in a net-negative power configuration with intermittent communications. The operations team used telemetry to identify the issue and developed a software patch, but applying a software patch in-flight was not something the team had practiced prior to launch. A series of virtual discussions with operators in Houston and the team traveling back from launch support in Florida determined that the software could be commanded to advance to power pointing assuming its current attitude was correct. Nova Control operators issued the command and Odysseus began firing helium Reaction Control System (RCS) jets to rotate to what it assumed was a power-first, comm-second attitude based on its initial onboard attitude propagated to the current time on Inertial Measurement Unit (IMU)-only measurements. During this rotation, the team observed the vehicle passing through nearly full power generation and recorded the onboard attitude at this time. Odysseus ended up in an improved but still power negative attitude and the team was able to upload a manual attitude target in the erroneous solution space that returned the vehicle to a healthy positive power generation attitude. The software patch was subsequently uploaded and the vehicle successfully processed star tracker measurements for the remainder of the mission.

RCS Pod Heater Failure. The RCS included redundant A and B strings, with nominal operations utilizing both strings. The RCS pods incorporated small heaters to manage the temperature of the thrusters within limits that ensured effective sealing. The helium RCS pod geometry and mounting location of the heaters proved to have too much curvature for adhesion and de-laminated early in the mission. This led to low temperature excursions resulting in a slow leak on RCS channel B. This was managed by manually isolating channel B for most of the mission. The thermal environment around the Moon proved to keep the RCS pods warm enough that the leak in channel B was resolved passively and it was returned to active utility.

Communications Challenges. IM performed significant pre-launch testing of LDN ground systems, Odysseus onboard systems, and operations room training utilization of the communications systems. IM engineers vetted LDN ground stations with NASA's assistance using the Lunar Reconnaissance Orbiter (LRO) and Geostationary Operational Environment Satellites (GOES) as tracking targets prior to launch. IM personnel also tested the Odysseus radios using a ground-test rig attenuating radio frequency signals at the antennae to emulate lunar distance communications. The first days after launch revealed that managing the LDN interfaces across different ground stations and organizations was susceptible to small errors in configuration. An unintended consequence of troubleshooting some of these communications configuration issues was that the onboard Fault Detection, Isolation, and Recovery (FDIR) logic for communications would cycle through alternate antennae and radio options if unanticipated loss of contact with Nova Control occurred (i.e. the FDIR logic is sophisticated enough to account for lunar occultation). A perfect storm occurred with a combination of the time constants of working through ground station settings, the FDIR logic timers, and the flight control phase plane period of attitude control dead-bands. None of this was catastrophic but did prove frustrating for the Nova Control operations team. Over the course of the trans-lunar coast, the operations team eliminated configuration issues and developed a method for selecting antennae/radio configurations that did not “fight” against the attitude control deadbands. Once the operations team achieved stable communications, they discovered that the methodology for downloading large files or large numbers of files was inefficient. Modifying this overall process included the creation of a new console position in-flight to expedite data transfers.

Figure 5. IM-1 Separation from the SpaceX Falcon-9 Upper Stage. The image illustrates the initial attitude being mostly engine-to-sun limiting solar array illumination.

Propulsion System Temperature Measurement Errors. Nova-C utilized thermocouples for most of its temperature measurements on IM-1. This design decision was made both to match what was used on test stands and to minimize hardware costs and new avionics development. Operators noticed a non-physical spread in temperature values for the propellant tank early in the mission. The fault tree initially included thermal gradients in an avionics board, a tank leak, evaporative cooling from moisture leaving the aerogel, and external heat sources creating temperature gradients on the extension wire. The root cause was isolated to temperature gradients that developed in the avionics board between the cold junction reference and cold junction temperature measurement. The offsets were observed to oscillate with heater cycling. The issue was exasperated specifically for propellant temperature measurements because of the extreme temperature difference between the sensed location and the cold junction. For the rest of the mission, operators only utilized these sensors to observe general trends and noted when the heaters were on (which drove larger delta-temperatures between the cold junction and cold junction temperature measurement). They also increased the deadband for heater operation to provide longer periods when the measurement was less impacted by this gradient. Ground thermal/vacuum testing of the Thermocouple Routing Board (TRB) did not catch this behavior because the test design did not create representative flight temperature gradients across the board while also measuring cryogenic conditions with thermocouples. For future missions, most thermocouple measurements were replaced with Resistance Temperature Detectors (RTDs).

Thrust Vector Control (TVC) Tuning. A significant yaw-channel error was observed during the initial Odysseus main-engine Commissioning Maneuver (CM) that was trending toward a main-stage abort from control limits before a nominal shutdown was achieved. This effect is exactly one of the pre-launch concerns for free-drift main-engine control. During Trajectory Correction Maneuver (TCM)-2, this trend repeated and led to an onboard control-limit abort. The operations team determined that the effect was similar to a moment arm error in the engine point-of-action relative to the center of gravity (CG). Operators updated a software parameter (I-load) to the control system for a successful TCM-3 execution with nominal control. IM engineers developed and installed a software update for flight control, but the Nova Control team used information from TCM-3 to determine that a sign-error on a torque parameter in the I-loads was the source of the yaw control issue. Corrected I-loads and reverting to the original flight control software were deemed a cleaner solution for the Lunar Orbit Insertion (LOI) maneuver and essential for the success of what would be the longest burn yet of the IM methalox propulsion system. This parameter set was used for the subsequent Lunar Correction Maneuver (LCM) and Powered Descent (PD) with excellent TVC performance.

A fortunate by-product of the LSPR landing site on IM-1 was that the orbital approach would have Odysseus in communications throughout the LOI maneuver. It was with some anticipation that the operations team uploaded the final maneuver targets to Odysseus and watched the telemetry pour in as the vehicle lit the main engine on time, flight control maintained a tight bullseye on the pitch and yaw phase plane, and the orbit slowly bent from flyby, to high-Lunar orbit, to Low Lunar Orbit (LLO), and then to engine shutdown. With a final maneuver duration of 06:50.991 minutes, the IM team had bested their own previous record for methalox maneuver time in deep space. [2]

Helium Loss Events. There were two occasions during transit where the Nova Control team reset the Odysseus flight computer to address an onboard data bus issue and to update the flight control software for TVC. In both cases, a significant loss of helium was observed as a result of the computer reset. In the second reset, a significant attitude rate was also observed after the computer had rebooted. Post-flight analysis determined that the phasing of flight control commands to the RCS controller could lead to unintended valve openings during a computer reset. This effect slipped through pre-flight testing because it only manifests from a reset when flight control is active.

LDN Radiometric Tracking Data Quality. An issue had been building in the background that the LDN range and Doppler observables were not cleanly tracking expectations. In the triage of updating the star tracker software, overcoming propulsion system initialization and commissioning, and two helium-vent computer restart events this had been deemed a lower priority to manage once Odysseus was stabilized. As we approached TCM-3 we began to realize we were short on data to form confident OD solutions.[3] Fortunately, the LN-1 payload was using DSN assets to perform its test during transit and NASA, the principal investigator for LN-1, and the DSN team were able to assist IM in getting enough DSN measurements to verify which passes from LDN were valid. A patchwork OD solution was achieved, but the measurements were limited, and the dynamic events of helium vents and a poorly executed TCM-2 had the OD team working miracles to get a solution good enough to execute an LOI targeting a 100km x 100km circular orbit. Following the IM-1 LOI, it initially appeared we were in a satisfactory orbit, but another OD pass confirmed otherwise.

Pictures from Odysseus navigation cameras evaluated by the IM science team members in Phoenix confirmed we were substantially off of our target orbit, and to make it worse, gravity field variations were pulling perilune even lower. We found out to our horror we were in a 150km x 1 km orbit. Odysseus was approaching the lowest point within a few orbits and then the variations would begin pumping perilune back up. Decision on whether to do an LCM before perilune near the surface or to delay the burn, was quickly made to wait it out. We passed below the reference spheroid and only within 1-2 km above a low point on the Moon (Figure 6). Operators then had Odysseus execute a commanded LCM to stabilize the orbit into a ~130 x 10 km orbit. This orbit was selected as a placeholder for LDO and indeed we opted to not do a Descent Orbit Insertion (DOI) maneuver and went straight into PD from this orbit.

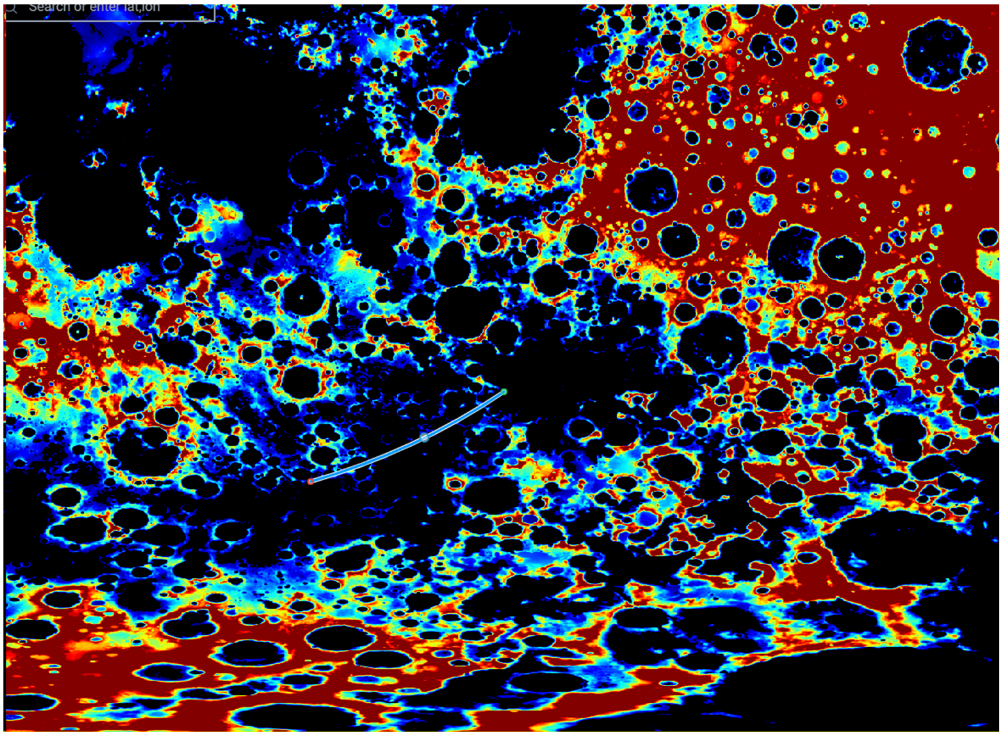


Figure 6. Closest Approach of IM-1 with topographical map showing low regions in black and blue and high plateau and ridges in red. Perilune occurred over an area with a low elevation.

IM-1 Deorbit, Descent, and Landing

Helium Loss Impacts. Because of the helium loss events during transit, Odysseus did not have sufficient Helium to pressurize oxygen and methane to planned values throughout PD. The Nova-C design team had experience with blow-down mode propulsion and guidance from Morpheus, and new propulsion and guidance schemes were developed and simulated after LCM to alter the descent profile and land in blow-down mode.[4] These were updated on the lander and enabled Odysseus' touching down with minimal helium but reserves of methane and oxygen in the propellant tanks.

Laser Range Finders (LRFs) Not Functional. The selected LRFs for Nova-C utilized a high-powered, Class 4 laser which was not "eye safe". As a safety measure, the sensor vendor included a firing circuit that must be closed within the connecting harness as a jumper to enable the laser firing circuit. Terrestrial testing with LRF units had engineering-unit harnessing which included this "jumper" to arm the units to fire the laser. However, the flight harness for the long and short range LRFs did not correctly close the firing circuit in the final pinout. This failure occurred within the harness itself and is not observable by visual inspection or the equivalent of a "remove before flight" tag. Because bench testing had confirmed the flight unit laser firing and vehicle testing confirmed the LRF power and data were functional, firing the vehicle lasers in the SpaceX payload processing facility was foregone for eye-safety measures. The Nova Control team first tried to fire the LRF systems during the low-perilune emergency to confirm low altitude but did not get a response. The LRFs had not been operated in-flight prior to this because the spacecraft was originally deemed to be out of the sensors' operational range to the Lunar surface. Ground team investigation into telemetry after LCM determined that both LRFs were not wired properly in the harnessing and would not fire during landing.

As a workaround, the Nova Control team developed and uploaded a patch to route the NASA CLPS payload Navigation Doppler LIDAR (NDL) range measurements to navigation software. The patch was successful and post-landing data indicated that the NDL performed above expectations, but the payload data packets from the NDL were formatted as "big endian" and the navigation measurement loaded expected "little endian", making the measurements invalid by the time they reached the Kalman filter for processing. Even though the navigation system had been updated and the NDL worked better than hoped, the sensor data was improperly formatted by the OBC and never used during landing.

Without direct surface measurements, Odysseus landed within 2.5 km of the Intended Landing Site (ILS) using only an initial OD solution, onboard IMU propagation, and the optical delta position (DPOS) visual odometry measurements (TRL-5 in house development). Odysseys had not quite finished horizontal flight and not achieved Vertical Descent flight mode 18 (Figure 7). As a result, Odysseus "stumbled" from landing with a lateral velocity beyond design limits.

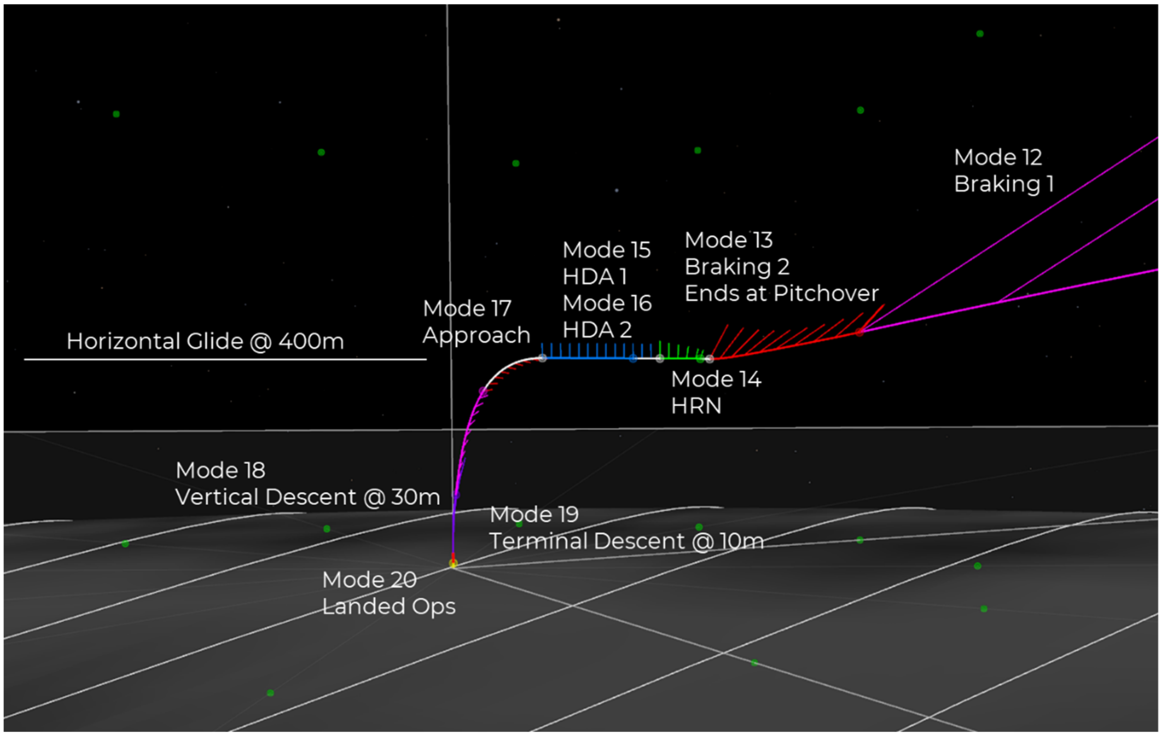


Figure 7. Nova-C Trajectory Plan from Pitchover to Touchdown with AFM Modes

IM-1 Surface Operations

Off nominal landing on the edge of a crater led to antennae not being pointed properly. Over the first 48 hours of operations on the Moon, Operators developed reverse polarization solution to bounce communications off the lunar surface with help of Goonhilly Earth Station, one of our LDN partners. In the process, we developed techniques to use LDN to monitor health, D32/Goldstone to transmit commands, and LDN-Parkes to downlink data from high-rate radio through hemi-antenna instead of high-gain antenna. In all, we operated for 154 hours on surface exceeding our requirement of 145 hours and learned several techniques for optimizing these challenging LSPR data transmissions. For example, we observed semi-periodic rise and fall of signal on lunar surface and learned to time large data downloads to the peaks and to move to smaller files on the descending power curve.

IM-2 MISSION

IM-2 launched from NASA's KSC at 00:19 UTC, February 27, 2025, on a SpaceX Falcon 9 rocket. The Athena Nova-C lander was successfully deployed onto a nominal trajectory, followed closely by the deployment of three rideshare satellites. The transit phase proceeded nominally, with successful payload checkouts sprinkled amongst three trajectory correction maneuvers (TCMs). Athena conducted a lunar orbit insertion maneuver at 06:19 UTC on March 3, 2025, and entered a 103 x 99 km LLO. After successfully managing spacecraft health over three days in LLO, Athena performed a DOI maneuver on the far side of the Moon and entered a 90x20 km LDO. While in LDO, Nova Control operators determined that the landing system LRFs were not providing usable measurements for landing navigation. After troubleshooting for three revs in LDO, it was determined that the highest probability of success was with targeting our nominal landing time because of limitations within the onboard terrain database. Athena exhibited nominal propulsion system, guidance, and control during PD, pitching over to execute the Horizontal Glide phases of flight (AFM modes 14-16, Figure 7). Unfortunately, LRF measurements did not improve with proximity to the Lunar surface as desired and Athena executed Horizontal Glide 10-20m above the surface (Figure 8). As with Odysseus on IM-1, the resulting altitude error from lack of LRF measurements led to Athena contacting the Lunar surface before transitioning to Vertical Descent and with sufficient lateral velocity to cause the lander to come to rest in an off-nominal, but operational, orientation on its side.

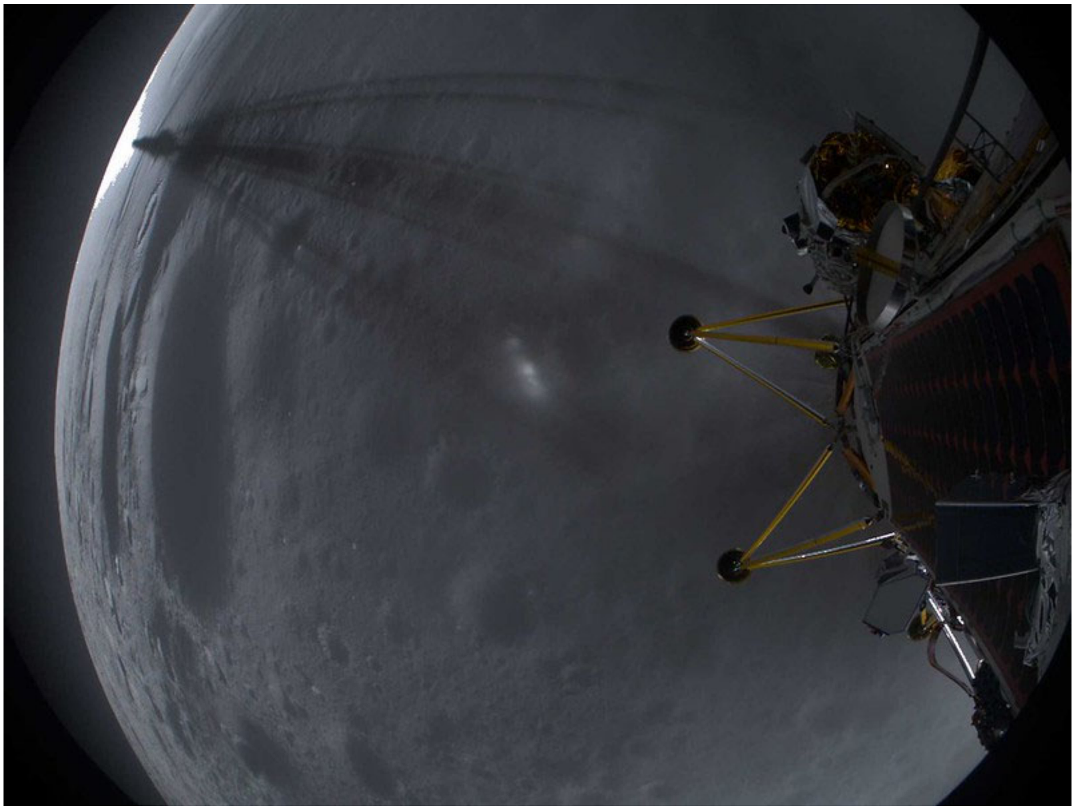


Figure 8. IM-2 Immediately Prior to Contact. Athena demonstrated excellent control stability and system health but had a significant altitude error resulting from a lack of LRF measurements.

IM-2 System Improvements

The IM team made numerous improvements to the design and operations of Nova-C for IM-2, including addressing the key issues encountered on IM-1 as described in Table 2. Effectively, all issues from IM-1 were addressed, but the LRF firing circuit issue potentially masked discovery of sensor performance in the Lunar environment as described below.

Table 2. Improvements from IM-1 to IM-2 on Key Issues. Red=major impact to mission/potential loss of mission, yellow=significant impact to operations but recoverable, green=nominal performance.

IM-1 Issue	IM-2 Action/Improvement	Result
Star Tracker Measurement Rejection	Opened unity quaternion quality check tolerances and made the tolerance value an I-load parameter	No rejection of ST measurements, automatic progression to Mode 5 (as planned): Transit pointing for power-positive primary, comms-secondary ops.
RCS Heater Pod Failure / Ghe leakage	Improved heater design, location on RCS pod surfaces, and testing	No RCS pod thermal issues
Communications Challenges	Comprehensive end-to-end configuration management upgrade and testing. Improved process and training for large file transfers	Excellent operational performance for communications. Large file transfers frequently executed with low gain antenna.
Erratic Propulsion System Temperature Measurements	Improved TC and RTD design and additional testing for IM-2	Quality thermal measurements throughout mission

TVC Tuning	Improved quality control of TVC and CG measurements. Improved onboard CG tracking estimation algorithms.	Onboard tuning executed all maneuvers other than TCM-2 (onboard solution was, in fact, superior to uploaded values).
Helium Loss Events	Hardened software response to flight computer or application resets. Increased testing of reset response in software and FlatSat environments.	No Helium loss events during IM-2. Ample Helium reserves for Powered Descent with a smaller Helium tank used than on IM-1. No impact to OD.
LDN Radiometric Tracking Data Quality	Comprehensive LDN qualification program. Ground station test kits for OD measurements developed and used at all LDN sites. Nominal use of DSN during mission to augment/verify LDN. Improved OD software. Improved coordination between propulsion and OD teams for small forces and venting modeling and timing.	DSN/LDN and LDN-only OD solutions shown to be statistically equivalent. LDN validated as capable of executing IM-2 and subsequent missions.
Laser Range Finder Safety Circuit Failed Open	Confirmed schematic / pin-out review prior to harness fabrication. Lander post-integration system level functional testing. LLO testing of power draw above 30 km. LDO testing of laser response below 30 km.	LRFs fired but measurements effectively produced noise in the lunar environment and were unusable. Details below.

IM-2 Transit and Lunar Orbit

All transit and lunar orbit anomalies and issues observed during IM-1 were addressed and did not occur during IM-2. There were a few minor anomalies observed during transit on IM-2 unrelated to IM-1. First, the initial pointing file used by LDN stations for initial acquisition of the Athena Nova-C lander was one minor increment out of configuration. Pointing file version 5.1.0 was distributed to LDN teams rather than the desired 5.1.1. This resulted in a slight delay of acquisition of signal (AOS) after launch vehicle separation and was quickly resolved by Nova Control operations. Second, because of the mission's increased performance requirements (75kg more P/L than IM-1), the initial attempts to fire the engine utilized a finessed methodology to chill-in the propulsion feed lines. This resulted in two attempted firing aborts, where the prop system temperatures did not achieve adequate start box temperatures. A refined approach on the third attempt and all subsequent burns was nominal with no issues. Third, being sensitive to TVC tuning from IM-1, the ground team used results from TCM-1 (1.3% pointing error, <1% DV magnitude error) and provided a new set of TVC I-loads to fine-tune main engine control for TCM-2. These improvements were vetted in a high-fidelity off-line simulation; however, the simulation defined mass parameter inputs were slightly different from flight software inputs and the uploaded update did not take this into account. As a result, TCM-2 pointing was degraded (3.3% pointing error, < 1% DV magnitude error) but the onboard CG estimator was correcting for the initialization error during the maneuver. The onboard CG estimate was then used to initialize TCM-3 and nominal performance was restored with less than 1% pointing error on a 4.5 m/s maneuver target. Fourth, the mass distribution of payloads on Athena was such that slosh effects during almost 8.5 minutes of LOI were more significant than on Odysseus on IM-1 despite no changes to the slosh baffle design. Slosh modes at the expected 0.4 Hz frequency manifested approximately 6 minutes into LOI (Figure 9) but were effectively managed by flight control with main engine gimbal actuation remaining within nominal bounds (<0.5 degrees, Figure 10) and only a 2.5% duty cycle on the roll control RCS jets. Propellant levels during LOI passed through NASA MSFC predicted max slosh excitation level leaving the operations team confident in execution of PD without slosh impacts. Final performance on IM-2 LOI as determined by post-mission analysis of OD measurements was 836.67 m/s against a target of 834.86 m/s and less than 1.5% pointing error.

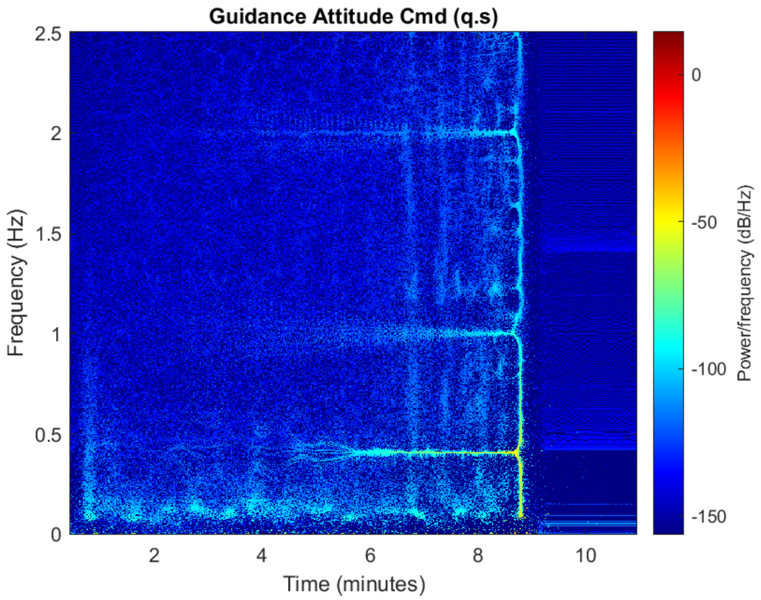


Figure 9. IM-2 Spectra of Guidance Commands vs. Time in LOI. The expected 0.4 Hz slosh mode begins manifesting impacting the guidance response slightly before 6 minutes into the burn.

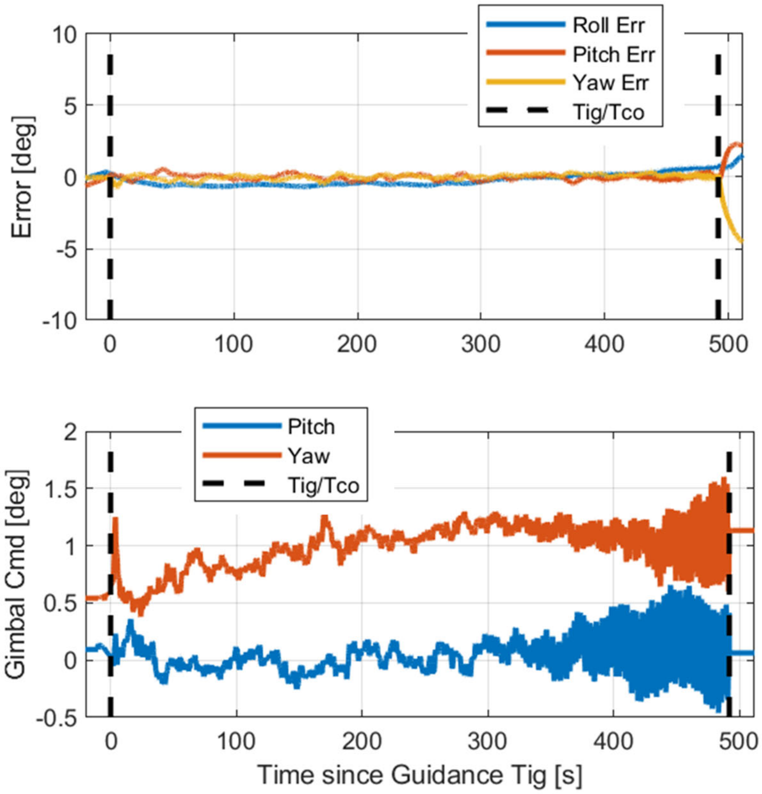


Figure 10. IM-2 LOI Pointing Error and Main Engine Gimbal Commands During LOI. The vertical dashed lines represent engine ignition and shutdown. The region of highest slosh sensitivity was encountered during this maneuver and no significant slosh modes manifested in subsequent PD.

LDN Radiometric Tracking Data Quality

The LDN team put 2024 to good use and improved OD measurements were in-family with DSN tracking passes, if not as exquisite as DSN measurements, as illustrated in Figure 11. LDN radiometric observables were unbiased and within an order of magnitude of DSN returns and had a slightly higher usable percentage once in LLO. Dynamic considerations from Nova-C RCS uncoupled small forces, gravitational perturbation, and main-engine tail-off small forces dominated OD solutions compared to noise from the LDN measurements. OD solutions using LDN-only observables were shown to be statistically in-family with LDN+DSN solutions (see TCM-3 example in Figure 12), validating the use of LDN for future cislunar operations.

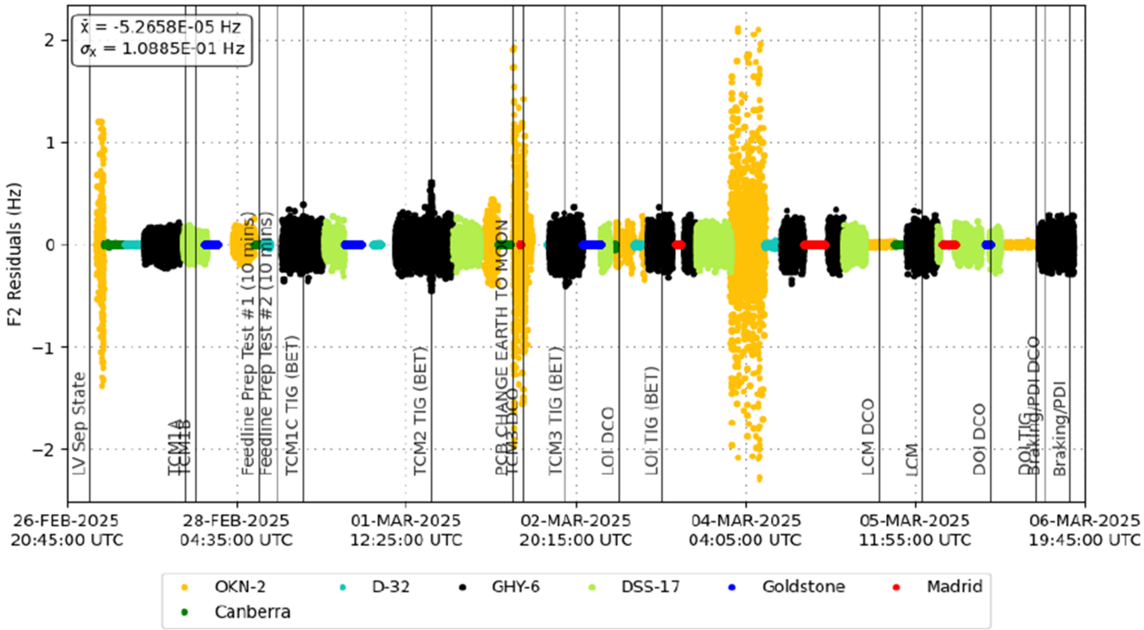


Figure 11. IM-2 LDN and DSN OD Doppler Residuals

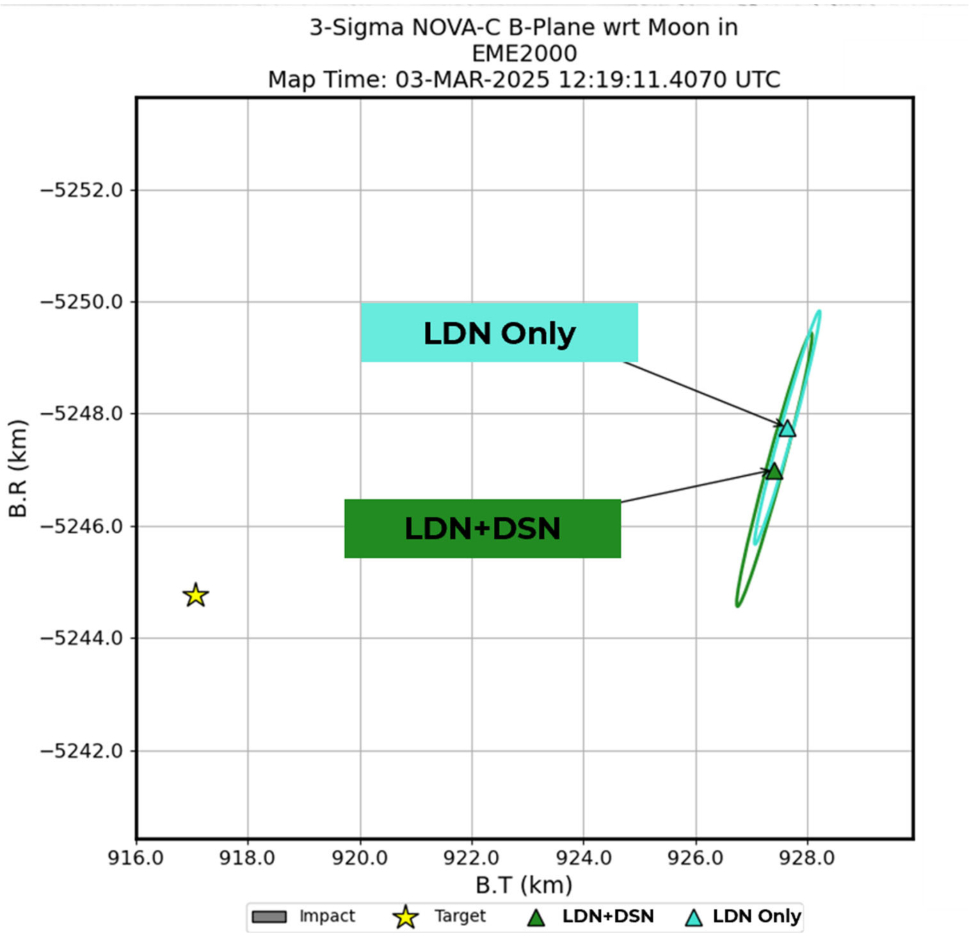


Figure 12. Comparison of pre-TCM-3 OD Solutions Using LDN-Only and LDN+DSN Observables.

IM-2 Deorbit, Descent, and Landing

Based on the IM-1 experience, the mission design team believed it prudent to expand the planned duration in LDO from 1 orbit to 3 orbits to provide time for confirming landing systems' readiness and troubleshooting. Helium pressure reserves were higher than expectations and the methalox main engine performed as designed for the ~14 minutes of PD. DPOS visual odometry performed as expected on IM-2 from LLO to pitchover. New Line of Sight to Surface (LOSS) optical crater tracking, first included on this mission, was advanced to TRL 9 with measurements correctly processing from lunar orbit to an altitude of less than 10 km. However, two issues occurred which again prevented a Nova-C lander from properly entering vertical descent and landing nominally.

Limited LOSS Database for Contingencies. The IM-2 mission design and operations teams considered and planned for alternative landing opportunities should the nominal PDI not be performed at the planned time. However, the overall team did not include additional crater maps in the Athena onboard database for subsequent orbits. This resulted in LOSS crater tracking measurements not being an option for orbits after LDO-3 and impacted decision making for executing the landing attempt at the planned epoch with uncertain functionality of the LRFs.

Laser Range Finder Measurement Noise. Cabling for the LRFs was confirmed to correctly close the laser firing circuit at the component level, on the Athena lander prior to shipping, and on the lander prior to encapsulation at the SpaceX facility in Florida. Nova Control operators powered the short and long range LRFs in LLO and confirmed the firing circuits were intact and power draw was consistent with laser firing via telemetry. However, this test occurred at an altitude beyond the maximum range of the LRFs and measurement accuracy could not be evaluated. Athena performed a DOI on the far side of the Moon and operators began testing the long range LRF near perilune on the first orbit after DOI (LDO-1). Initial returns in telemetry were puzzling showing either no measurements or measurements less than a kilometer (at estimated ranges of 20-30 km). The Nova Control team regrouped during loss of signal (LOS) for LDO-1 when Athena was on the far side of the Moon and discussed repeating test-firing procedures and manually adjusting sensor parameters on LDO-2 and LDO-3 as required. Strict adherence to test procedures returned the same results and the operations team began to get a picture of highly noisy measurements from the LRFs. A decision point came after LDO-3 to continue to troubleshoot and potentially restore LRF operations or to attempt landing while LOSS measurements were still available. Without LOSS measurements, there was a high probability of landing beyond the safe zone of the ILS in shadow in the rugged terrain of the LSPR. The operations team decided to attempt landing while LOSS measurements were still available and adjust LRF sensor threshold and gain settings during PD to see if increased signal strength as the lander neared the surface would cut through the noise and provide usable measurements for landing. This proved not to be the case, and Athena entered the horizontal phase of flight after pitchover with approximately 400m of altitude error and just above the lunar surface. Athena faithfully executed the horizontal phase of flight and began descending and reducing horizontal velocity in AFM Mode 17: Approach (Figure 7) when the leading landing gear contacted a crater rim on the Lunar surface.

After landing, the Nova Control team retrieved critical flight data from Athena for completing root-cause analysis of the LRF performance issues. It was determined that the Lunar environment induced a noise signature in the LRF detectors that identified measurements from ambient signals even when the laser emitter of the device was not active. The noise response of the LRF measurements (Figure 13) indicated no structured response to the lunar surface indicative of values usable by the onboard Kalman filter.

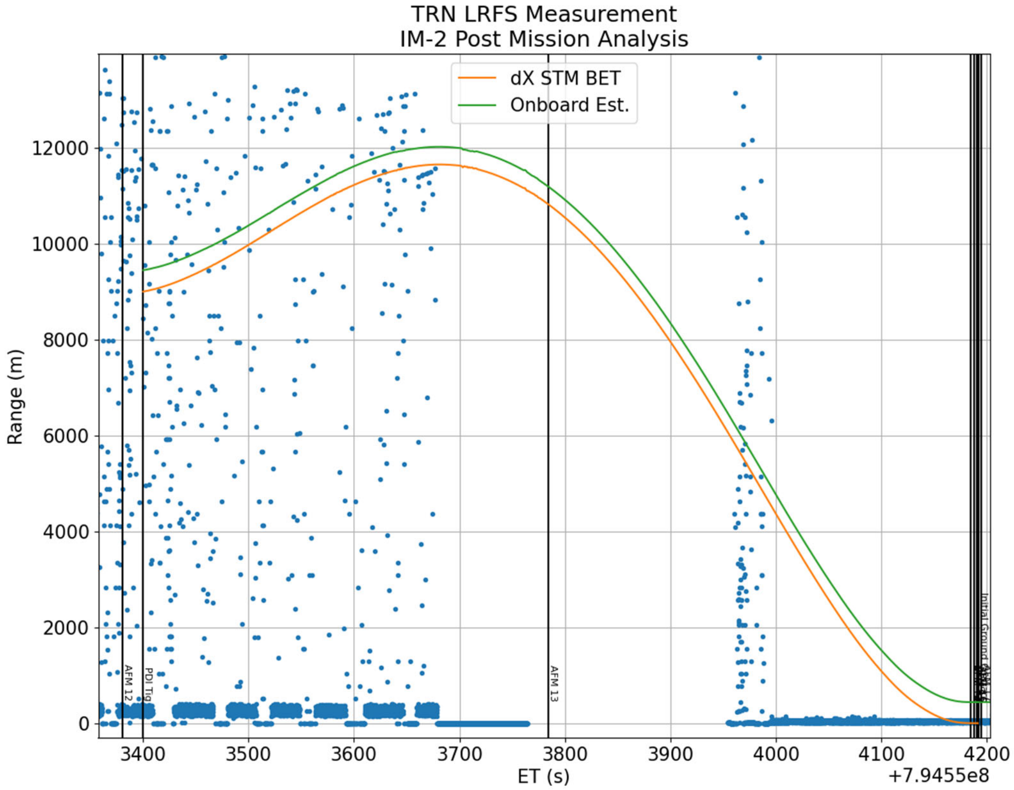


Figure 13. IM-2 LRF Measurement Returns (blue dots) vs. Time with Onboard (green) and Preliminary (orange) Post-mission Altitude References.

IM-2 Surface Operations

Athena survived contact with the Lunar surface prior to entering AFM Mode 18: Vertical Descent and continuously communicated with the LDN during a dynamic landing sequence. Final attitude of Athena was on its side and in a small crater on the Lunar South Pole (Figure 14). Unlike Odysseus on IM-1, the surface orientation of Athena was such that the solar arrays were receiving diminishing sunlight after landing and the lander was immediately in a power-negative state. Nova Control operators immediately began load shedding by powering down all non-critical systems and worked closely with NASA CLPS, NASA STMD, and commercial payload customers to prioritize testing of systems while battery power was available. These coordinated efforts, including a reconfiguration of onboard antenna pairs, resulted in 13 hours of surface testing. Despite the chilling cold of the crater Athena was laying in, the high-power radio was pushing data at top speed through our hemispherical antennas (due to off-nominal orientation) and getting too hot, which would effectively kill the mission. The ops team was able to work with the National Radio Astronomy Observatory (NRAO) and creatively use their 27 dishes with interferometry to form an aperture synthesis interferometer with an effective aperture of over 2,000 miles. Given this huge synthetic dish, the ops team was able to dramatically lower the power level of the radio, solving our heating issues and saving precious power. This configuration allowed the ops team to effectively downlink all of Athena's onboard data, and work with NASA and customers to test a majority of the payloads during surface operations.

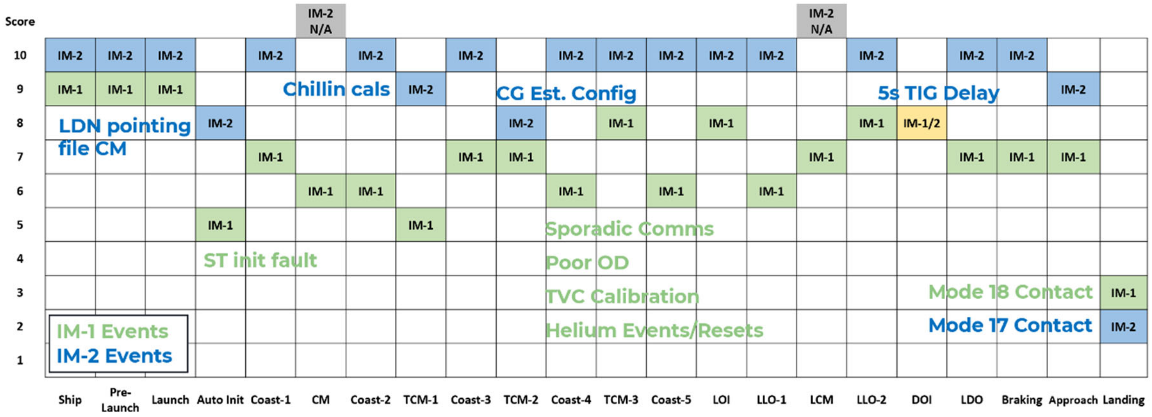
Figure 14. Image from Athena after Landing on Lunar South Pole.

Comparison of IM-1 and IM-2 Mission Execution

Following IM-2, the mission operations team performed a qualitative assessment of each mission by phase scoring execution on a scale of 1 (loss of mission failure) to 10 (performance exceeding nominal expectations) as summarized in

Table 3. The green cells of the table labeled IM-1 indicate the performance of the first mission while the blue cells with IM-2 indicate the assessment of performance on the second mission. For all phases from shipping to the launch complex to approach, IM-2 significantly improved on performance compared to IM-1. The operations experience on IM-1 was one of crisis management, moving from one crisis to the next as the Nova-C, LDN, and operations systems were put to the test during a fast-transit to the Moon. This experience of staying just one step ahead of the fatal error, was exhilarating, exhausting and extremely valuable operational experience. By contrast, IM-2 generally met or exceeded expectations in all systems except for the initial LDN pointing file and the upload of suboptimal TVC information for CG estimation. The environment in Nova Control was calm, well-ordered, and by-the-books until the noise issue on the LRFs became apparent in the final phase of the mission in LDO. The late turn toward not having a perfect landing after a smooth transit and commissioning was a blow to the team and serves as a motivating force for improving the last kilometer of performance for IM-3.

Table 3. Qualitative Comparison of IM-1 and IM-2 Mission Performance



Score	Ship	Pre-Launch	Launch	Auto Init	Coast-1	CM	Coast-2	TCM-1	Coast-3	TCM-2	Coast-4	TCM-3	Coast-5	LOI	LLO-1	LCM	LLO-2	DOI	LDO	Braking	Approach	Landing
						IM-2 N/A										IM-2 N/A						
10	IM-2	IM-2	IM-2		IM-2		IM-2		IM-2		IM-2	IM-2	IM-2	IM-2	IM-2		IM-2		IM-2	IM-2		
9	IM-1	IM-1	IM-1					IM-2													IM-2	
8				IM-2						IM-2		IM-1		IM-1			IM-1	IM-1/2				
7					IM-1				IM-1	IM-1						IM-1			IM-1	IM-1	IM-1	
6						IM-1	IM-1				IM-1		IM-1		IM-1							
5				IM-1				IM-1														
4																						
3																						IM-1
2																						IM-2
1																						

IM-3 MISSION

IM-3 will transport payloads to the Reiner Gamma, mid-latitude landing site using the Trinity Nova-C lander. This mission will also deliver the first IM communications and navigation satellite, Altus-1, into a high-inclination elliptical frozen orbit. Other than an east-to-west orientation to the trajectory, IM-3 is essentially the same in mission design as the previous lander missions. However, several improvements have been made to the Nova-C lander to help ensure a nominal landing.

IM-3 System Improvements

The IM team is focused on building upon the improvements exhibited between IM-2 and IM-1 and extending the exceptional performance of the Nova-C lander through the terminal phases of powered descent to a nominal touchdown.

Landing Navigation System Improvements. Following IM-2, the IM team performed a comprehensive mission review including a dedicated team looking comprehensively at the final phases of the mission in LDO through touchdown. This team included external planetary landing experts from NASA and the Jet Propulsion Laboratory (JPL) as well as internal technical experts with experience on ICESat and LRO laser systems, and with lunar surface imagery. Root cause for the LRF anomaly on IM-2 was determined to be treatment of the sensor as a commercial “black-box”. The team followed a similar approach with other navigation sensors such as IMUs and star trackers with no ill effects. In this case, a more thorough test and integration plan is needed for the LRFs which are the most critical sensors for landing.

IM has established a Descent Phase Working Group (DPWG) that has developed a thorough lab, field, and flight test campaign for an updated compliment of redundant LRF sensors. Trinity possesses a primary LRF for high altitude operations with a dissimilar hot-backup and a cold spare. For low altitude LRF measurements, a three-beam primary sensor is complimented by two redundant, dissimilar hot-backups. In the spirit of not overlooking latent issues in other systems, IM is improving the pre-flight test rigor on other sensors that have performed nominally on the previous missions (i.e. the IMU, star tracker, and navigation camera pre-flight testing). The DPWG includes support from NASA NESC and JPL SMEs and the addition of an in-house laser system expert with over 25 years of experience with laser systems deployed by NASA. The navigation system now has an Integrated Product Team (IPT) lead to overseeing all aspects of navigation system software and hardware testing prior to flight. Significant improvements in optical image synthetic imagery[5] for testing and improved optical navigation algorithms[6],[7] are underway to relieve the criticality of LRF measurements in the overall navigation approach for safe landing. An improved vision processing computer for Trinity enables comprehensive terrain databases for contingency landing opportunities and an order of magnitude improvement in optical navigation throughput. The DRM for IM-3 includes 12 revolutions in the LDO to provide multiple opportunities to test the LRFs at perilune prior to committing to landing. IM conducts a monthly briefing to CLPS and other NASA stakeholders of the DPWG team progress and continues the spirit of collaboration to improve all aspects of landing.

Testing Process Improvements. IM is improving testing in all aspects of the IM-3 mission, not just in landing navigation. A touchdown trigger detection stand will confirm that the engine-shutdown triggers developed originally for Morpheus will perform as expected in 1/6th gravity on the Trinity lander. A detailed terramechanic model is under development with the assistance of the University of Wisconsin's CHRONO team[8,9,10] to conduct high-fidelity contact dynamic analysis to confirm lander stability when the navigation system delivers the lander within expected vertical and lateral tolerances. In addition, the production team has consistently evolved every part of the Assembly, Integration and Testing (AI&T) flow to improve efficiency and consistency between builds. Improved facility layout, tools control, tank testing process and infrastructure, significant "Flame Range" propulsion test facility improvements, improved LDN test equipment and process, ground support equipment improvements, integrated testing process controls, comprehensive Enterprise Resource Process (ERP) software integration, expansion of testing and certification infrastructure, and improved full life-cycle data simulation capabilities for integrated testing and operational crew training.

Operations Improvements. During IM-1, the Nova Control operations team had a handful of staff with previous space operations console experience. Our team now includes dozens of skilled operators, in many cases Lunar veterans with two missions on their resume. Important improvements to include integration of payload customers (improved customer experience), acquisition of KinetX for continued OD and trajectory excellence, new operations facilities and back rooms, new LDN sites, a robotics operations control center and, backup facilities with IM's newly acquired Lanteris team in Palo Alto, CA round out a steady march toward operational excellence which is tough and competent.

CONCLUSION

Like the Man in the Arena in Theodore Roosevelt's "Citizenship in a Republic" speech, Intuitive Machines dared greatly to prove that a small commercial company, without the resources of a full nation state space program, could develop, integrate, and operate a mission to land on the Moon. And while both IM-1 and IM-2 were marred by imperfect landings, "there is no effort without error and shortcoming" and dearly bought lessons for both missions have yielded significant achievements for Lunar development including: a validated alternative to the DSN for lunar communications and OD, demonstrated high-performance cryogenic methalox propulsion, optical Lunar surface navigation, and the development of an effective lunar operations team. These capabilities were achieved at a fraction of the price of similar technology developments pursued individually.

While Odysseus on IM-1 and Athena on IM-2 may have indeed been knocked down, the IM team is focused on sticking the landing with Trinity on IM-3 with the tenacity to continue learning, growing, and improving toward ultimate success.

ACKNOWLEDGMENTS

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