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A HISTORY OF ORION MISSION DESIGN, COPERNICUS SOFTWARE DEVELOPMENT, AND THE ARTEMIS I TRAJECTORY

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This paper describes the history of the on-orbit trajectory design and optimization for the Orion spacecraft at NASA JSC, from the initial design through the execution of the Artemis I test flight. In parallel, the Copernicus spacecraft trajectory design and optimization system was also being developed and was the main software tool used for Orion trajectory design during this period. Finally, the paper gives an overview of the Artemis I in-space trajectory that was flown during the Artemis I mission from November 16 – December 11, 2022.

INTRODUCTION

Artemis I[1–3] was the first integrated test of the Orion spacecraft and the Space Launch System (SLS) rocket. The uncrewed flight was launched from Cape Canaveral on November 16, 2022, and splashed down in the Pacific Ocean on December 11, 2022. The Artemis I trajectory was the most complex trajectory ever flown by a human-rated spacecraft, and by JSC since the Apollo Program. As the first mission of the Artemis campaign, it is intended to be the start of a series of increasingly complex missions providing a foundation for human deep space exploration to the Moon and beyond. What follows is a history of the Orion in-space trajectory design from the perspective of the Flight Mechanics and Trajectory Design branch at the NASA Johnson Space Center (JSC), which includes the evolution of the trajectory that was ultimately flown on Artemis I. Many of the detailed assumptions changed over time, as vehicle development matured and mission requirements changed (e.g., Orion mass and propellant loading, upper stage performance capability, the existence of co-manifested payloads, orbit destinations, and various constraints on the vehicle or timeline). Over nearly twenty years, not only did the trajectories become more sophisticated and higher fidelity, but so did the tools they were designed with. The trajectories shown in this paper are examples of the kinds of missions that were designed and redesigned as vehicle inputs and mission objectives evolved. A timeline of these events is shown in Figure 1.

The Artemis I trajectory was designed using the Copernicus spacecraft trajectory design and optimization system (also developed at JSC). The final trajectory is the result of years of work, weathering many changing requirements and mission concepts, as well as driving the evolution of Copernicus. Cesar Ocampo conceived the idea of a comprehensive and generalized spacecraft trajectory design and optimization tool and began developing Copernicus at the University of Texas at Austin (UT) in 2001.[4,5] He built off of his previous experiences writing specific tools to solve specific problems, in order to create a general tool that could be used to solve a wide variety of

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complex problems. Novel features included: optimization as a first-class feature from the start, multi-body, multiple reference frames, selectable algorithms, a flexible segment architecture as the basic building block, both impulsive and finite burn maneuvers, and an interactive, user friendly GUI with interactive real-time high fidelity 3D visualization during the solution process.[6] The flexibility of the Copernicus architecture would be crucial to the developmental history of the Orion trajectory design, starting with the Constellation Program. At each stage, it was always taken for granted that any mission option being considered could be accurately designed and analyzed using Copernicus. As requirements and mission design considerations evolved, the tool was upgraded with new features as they became necessary. Copernicus is much more capable now than its initial conception, although the fundamental ideas from the original prototype still remain.

CONSTELLATION PROGRAM

Almost a year after the Space Shuttle Columbia accident, on January 14, 2004, the U.S. President announced a new vision for space exploration* that included the development of a new spacecraft called the Crew Exploration Vehicle (CEV), which was later named Orion in 2006. This spacecraft was envisioned to replace the space shuttles and be used to transport humans to the International Space Station (ISS), Moon, and Mars. The 2005 Exploration Systems Architecture Study (ESAS)[7] resulted in the Constellation Program to develop an architecture for a sustained human presence on the Moon. Constellation envisioned different types of lunar missions including global sortie and polar outpost missions. Key driving architecture requirements included global lunar surface access (i.e., to visit any point on the Moon) as well as anytime return from the lunar surface.[8] The Altair lunar lander, originally referred to as the Lunar Surface Access Module (LSAM), was intended to perform the Lunar Orbit Insertion (LOI) burns.[9] Orion (CEV) was responsible for lunar orbit maintenance during the surface stay, circularization and Ascent Plane Change (APC) burns, and finally the Trans-Earth Injection (TEI) burns for return to Earth.[10]

Characterization of the three-burn TEI sequence (an example is shown in Figure 4, with performance numbers in Table 1) was a major activity for the Orion trajectory design team during this period.[11–13] Starting in the Low Lunar Orbit (LLO), the first burn (TEI-1) raised the apoapsis to create an intermediate orbit, the second burn (TEI-2) performed a plane change to properly align the outgoing velocity vector, and finally the third burn (TEI-3) placed Orion on a hyperbolic trajectory departing the Moon and targeting Earth Entry Interface (EI). This sequence was necessary for global surface access, since the maximum cost of a single-burn plane change (i.e., 90°) in LLO would be prohibitively expensive (around 2,300 m/s). Figure 5 shows an example three-burn scan of the entire lunar nodal cycle for all lunar landing sites. Studies also included an option for a "fail-safe" TEI-2 burn, which meant that if the engine failed during the burn, then the periapsis of the resultant trajectory would not be sub-surface.[14] The Orion service module was designed with a

*The Vision for Space Exploration (February 2004) `https://www.nasa.gov/pdf/55583main_vision_space_exploration2.pdf`

Table 1: Three-Burn TEI Example Case (November 23, 2034)

Burn	Δv (m/s)
TEI-1	606.8
TEI-2	220.1
TEI-3	325.0

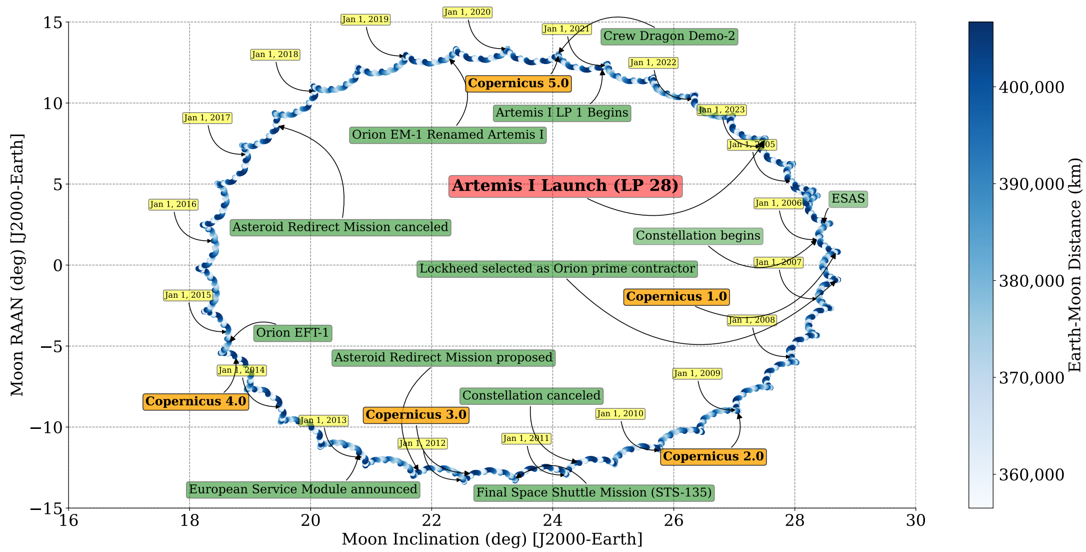
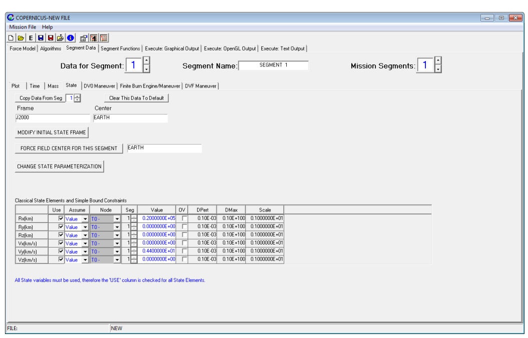
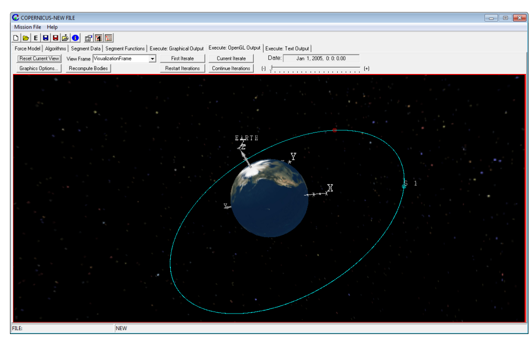


Figure 1: Visualization of the Lunar Nodal Cycle from 2005 – 2023 (DE431). From 2005 to 2022, during the period of Orion trajectory design, almost one full cycle has been completed. Key milestones for human spaceflight, Orion, and Copernicus are also shown.



(a) In the first release, the entire GUI was contained in one window with many tabs. The variable grids were a key feature that continues to the current release.



(b) The integrated 3D graphics was another key feature of Copernicus from the beginning, allowing the user to see the iterations as they occur.

Figure 2: The initial Copernicus 1.0, released in March 2006, included a GUI and integrated 3D graphics visualization, and only ran on Windows. Mission designs were limited to only 10 trajectory segments, which was sufficient for many early Orion studies. The tool has evolved and become much more advanced, but all of the fundamental ideas from this original version remain in the very latest release.

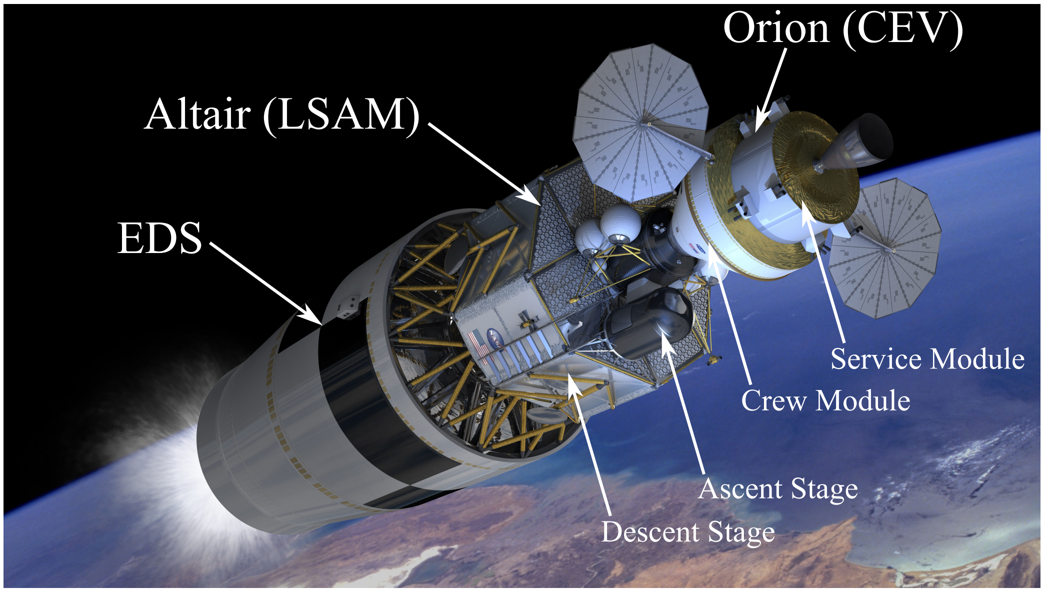


Figure 3: The Constellation Vehicles (Source: NASA, circa 2009). The on-orbit and lunar surface access hardware for Constellation consisted of Orion, Altair, and the Earth Departure Stage (EDS). The Altair lander performed the LOI burns, and Orion performed the subsequent on-orbit burns (e.g., the TEI burns). Orion and Altair/EDS were to be launched on different rockets (Ares I and Ares V, respectively) and rendezvous in LEO.

main engine (OME) and a set of eight backup (AUX) engines. Contingency options had either some or all of the three-burn sequence performed by the AUX engines, in case the main engine failed.

Early Orion concepts envisioned a land landing in the Western United States, but eventually the design converged to a Pacific Ocean splashdown. The end state of the Moon-to-Earth return trajectory for Orion was targeted for an EI geodetic altitude of 121.92 km and a geocentric flight path angle of -5.86°. An EI target line model[11,13] was added and built into Copernicus where longitude and geocentic azimuth could be constrained to polynomial functions of geodetic latitude (originally up to 4^{th} order, but eventually increased to 6^{th} order). Ultimately, a more complicated target line that was used for Artemis I was implemented as a Copernicus plugin.[15,16]

Starting with the initial UT-produced prototype version 1.0, released in March 2006 (see Figure 2), Copernicus matured significantly during the course of the Constellation Program.[17] Development was transferred to JSC in 2007 and many key capabilities in the tool seen today were developed during this time. The prototype was brought up to production level, with formal releases and documentation. Notable improvements and new features added to Copernicus over these years include:

- Allowing for unlimited number of segments, which are the fundamental building blocks of Copernicus. The original prototype only allowed up to 10 segments. The Artemis I trajectory required about 80 segments.
- Ability to insert/delete/move segments in the GUI and the automatic computation of the order in which interconnected segments should be propagated (i.e., the user does not have to specify that manually).
- Selectable gravity models, SPICE kernels, integrators and force models for each segment.

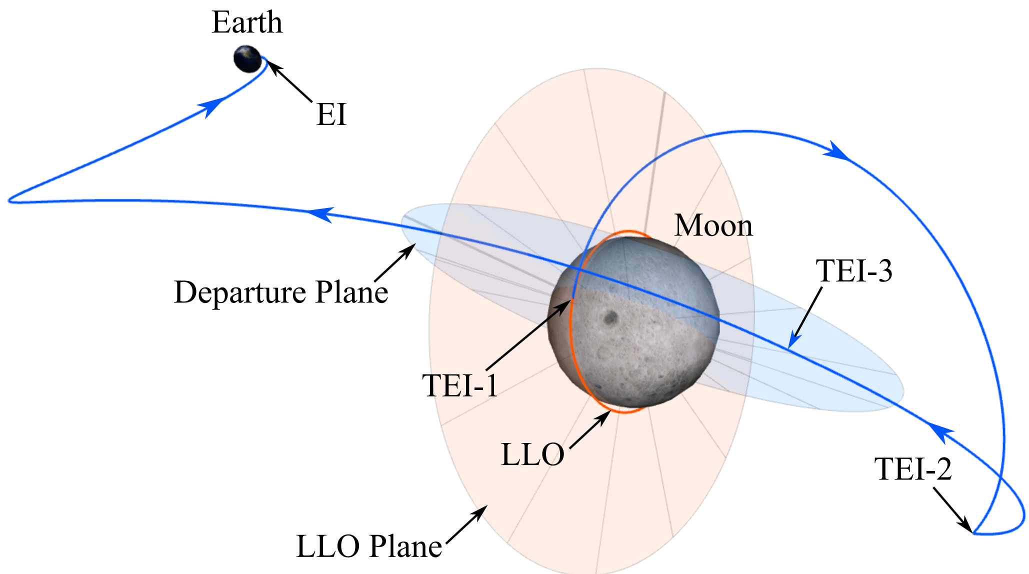


Figure 4: Example Three-Burn TEI Sequence (J2000-Moon Frame). Starting in a 100 km altitude LLO, the TEI-1 burn occurs on November 23, 2034, and the total TEI Δv is 1,152 m/s (see Table 1). The time from TEI-1 to TEI-3 is 2 days. During the Constellation Program, a major part of the Orion on-orbit mission design was understanding this problem. Early versions of Copernicus (which, at the time, was limited to only 10 trajectory segments) were used for these initial studies. This example only required 9 trajectory segments with impulsive Δv maneuvers.

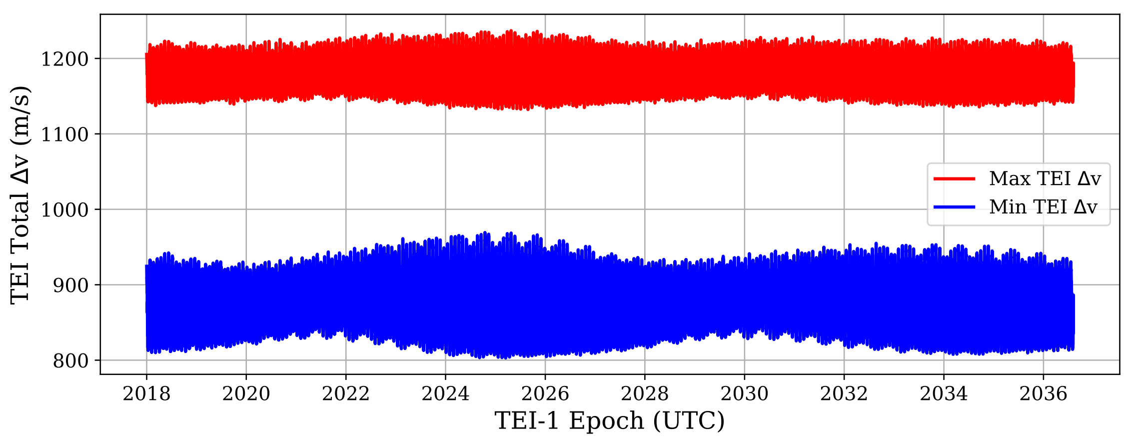


Figure 5: Bounding Costs of a Three-Burn TEI Sequence. This plot shows the maximum and minimum costs of all three-burn TEI sequences for a 48 hr TEI sequence (TEI-1 to TEI-3) with an 89 hr return to Earth (TEI-3 to EI), and an EI target line. This data represents a scan over an entire 18.6 year lunar nodal cycle and all possible landing sites on the Moon.

- Cross-platform and command-line operations. Originally, Copernicus ran only on Windows and could only be used from the GUI. A non-GUI, Linux version (released in 2009 with Copernicus 2.1) proved critical since Copernicus could now be run on computing clusters, a critical feature used for Artemis I.
- General speed and stability improvements, and code refactoring as modern Fortran features became available in newer compilers.[18]

The team also developed a tool called the Mission Assessment Post Processor (MAPP).[19] It was built using the Copernicus Toolkit (the core libraries of Copernicus) and used pre-generated databases of optimized trajectories for each mission phase (outbound, surface stay, return, etc.) to stitch together an approximation of a complete mission. MAPP had exceptional compute capability (i.e, billions of cases could be computed in a reasonable amount of time) and was instrumental in providing understanding of the design space of the Constellation architecture. MAPP was retired after Constellation was canceled, but some of the code was added either to Copernicus (e.g., HDF5 data exporting and splined SPICE ephemerides) or to Copernicus plugins that were ultimately used for Artemis I (e.g., the algorithm for computing sunrise and sunset, and some of the interpolation code).

POST-CONSTELLATION PERIOD

Table 2: Orion 3 Day Stay Missions to Lunar Orbits (TLI on January 1, 2024)

LOI Δv (m/s)	TEI Δv (m/s)	Δv Total (m/s)	h_a (km)	h_p (km)
805.04	818.76	1624	100	100
768.36	783.98	1552	300	100
735.66	752.81	1488	500	100
708.65	724.45	1433	1000	1000
617.74	638.55	1256	3000	3000

The Constellation Program was canceled in 2010. Near the end of the program, the JSC mission design team first began to consider what Orion could do without the Altair lander. See Table 2 for an early study from 2009 where Orion performs both LOI and TEI for a 3-day stay in various-sized lunar orbits. The total Δv was minimized, the destination orbit inclination and flight times were optimized, and the Earth EI constraints were unchanged. See also Figure 6 for an example trajectory.

Various activities occurred during this post-Constellation period[20,21] which included analysis of different mission types and destinations for the Orion vehicle. Missions were being reoriented to a "capability-driven framework"*, using cislunar space as a "proving ground"† or "gateway" for future missions, including to Mars. In 2011, Orion was rebranded as the Multi-Purpose Crew Vehicle (MPCV), and the SM was announced in 2013 to be the European Service Module (ESM) derived from the ESA Automated Transfer Vehicle (ATV), with a repurposed Space Shuttle Orbital Maneuvering System Engine (OMSe).[22,23] The SLS rocket also came into being, along with the Interim

*Human Space Exploration Framework Summary (Jan. 11, 2010) https://www.nasa.gov/exploration/new_space_enterprise/home/heft_summary.html

†Journey to Mars: Pioneering Next Steps in Space Exploration (Oct. 8, 2015) https://www.nasa.gov/press-release/nasa-releases-plan-outlining-next-steps-in-the-journey-to-mars

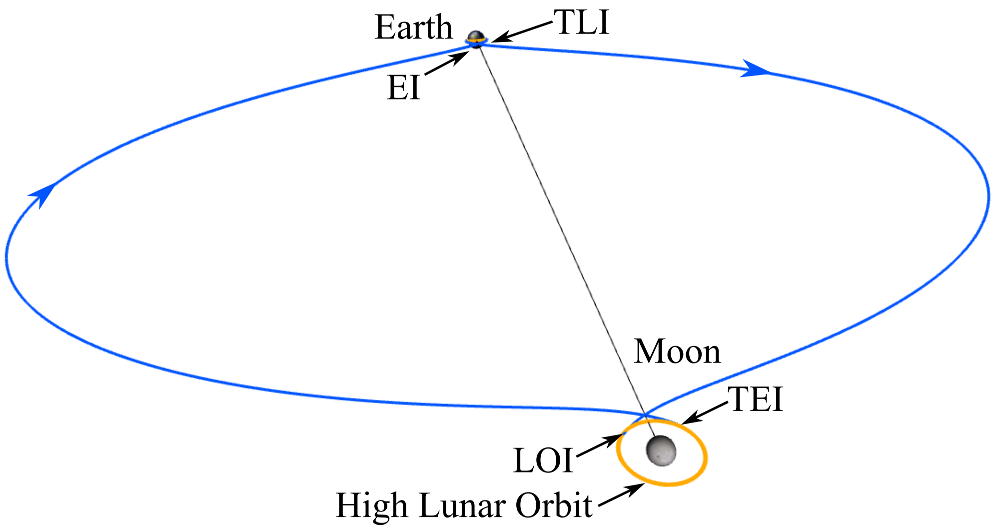


Figure 6: Example of Orion inserting into a 3000 km altitude circular lunar orbit, performing both the LOI and TEI burns, with a 3 day stay time and no lunar landing (Earth-Moon Rotating-Pulsating Frame). The TLI occurs on January 1, 2024. These early studies (see Table 2), started at the end of the Constellation Program.

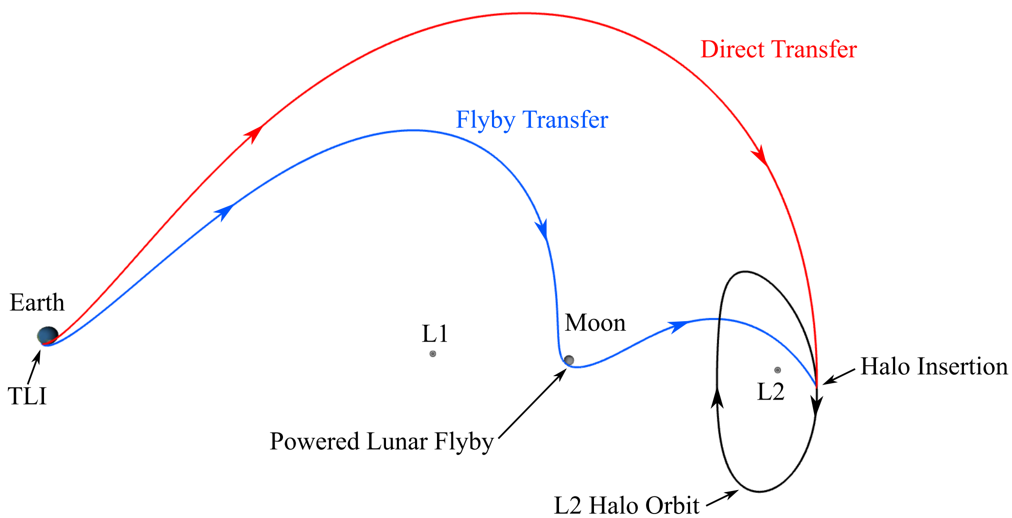


Figure 7: Examples of Orion inserting into an Earth-Moon L_2 halo orbit (Earth-Moon Rotating Pulsating Frame). Two cases are shown here, developed in early 2012, a direct transfer and a flyby transfer. The powered lunar flyby can be used to reduce the overall Δv cost for Orion. In this CR3BP case, the TLI is performed on January 1, 2011. The overall Orion Δv is 284 m/s for the flyby case and 957 m/s for the direct case.

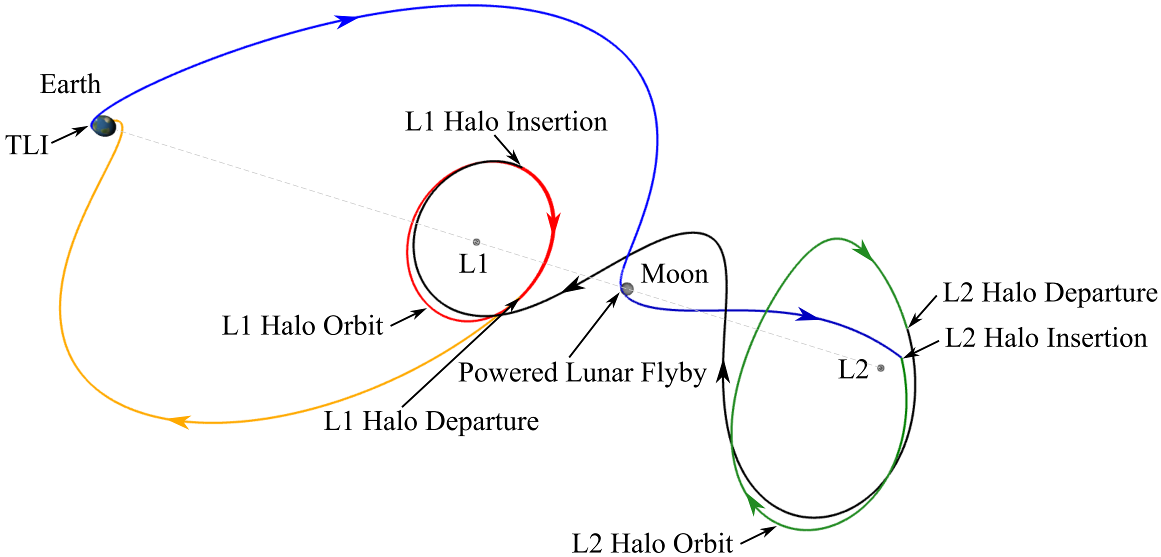


Figure 8: Example of an Orion Round-Trip Earth-Moon $L_2 \rightarrow L_1$ Halo Orbit Transfer (Earth-Moon Rotating Pulsating Frame). This trajectory has a 60 day total mission duration and departs from LEO on September 16, 2018. Orion performs three major burns (an outbound powered lunar flyby, L_2 insertion, and L_1 departure). The transfer from L_2 to L_1 halos use a manifold transfer with very small departure and arrival burns. Total Orion Δv is 894 m/s.

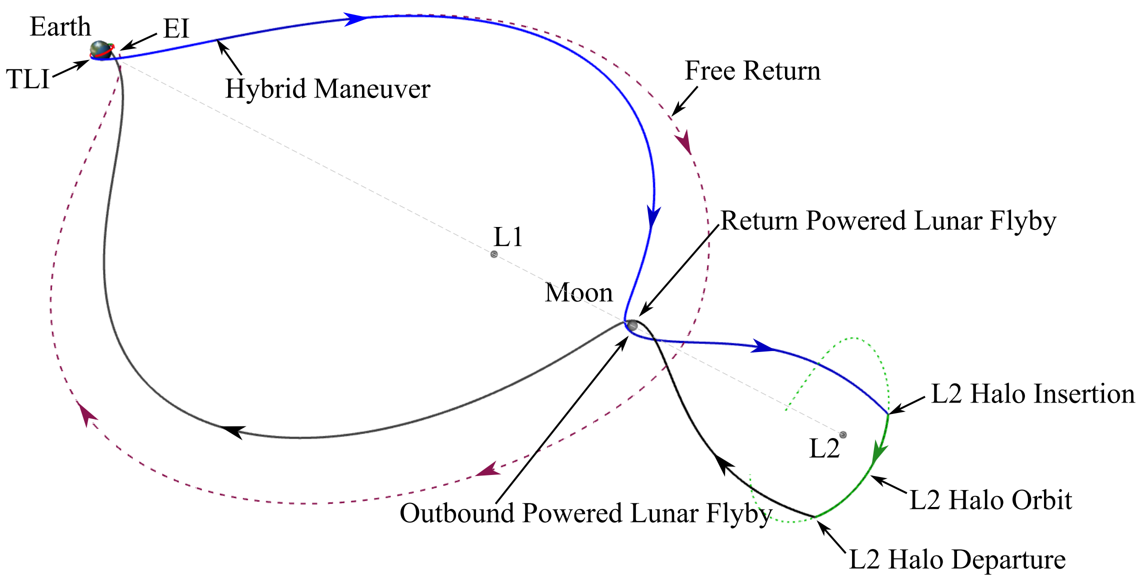


Figure 9: Example of an Orion L_2 Halo Orbit Destination for Exploration Mission I (Earth-Moon Rotating Pulsating Frame). In this mission for July 2021, the TLI puts Orion on a free-return trajectory, then 6 hours later, Orion performs a burn to setup the outbound powered lunar flyby that leads to an L_2 halo orbit insertion. After a 3 day stay in the halo orbit, Orion departs and performs another powered flyby for the return which targets EI. The free-return mission flight time is 8 days, while the halo mission is 15 days (with a total Δv cost of 883 m/s).

Cryogenic Propulsion Stage (ICPS) as the Earth departure upper stage. Orion ended up with less Δv capability than was assumed during the Constellation studies, with 1330 m/s total performance or 930 m/s after prop offload and knockdowns for Artemis I translational burns. For comparison, during Orion DAC-2, the reference vehicle configuration was required to have propellant tanks sized for a 1560 m/s translational burn and to have a minimum propellant loading for a 1492 m/s burn[24] (even earlier studies had assumed tanks sized for 1617 m/s).

Halo orbits became a destination orbit of interest for Orion during this period.[25,26] L_2 halos were of particular interest because it required a crewed mission to travel further from the Earth than ever before. Again, these were studies with Orion performing all burns after TLI. It became evident that, absent an additional propulsive element, Orion would need to conduct powered lunar flyby gravity assists in order to enable any kind of non-trivial mission in cislunar space. One and two lunar flybys were studied during this period for the early halo orbit studies, and would continue up to the present day including the Artemis I flight (which employed two flybys). It was also important to understand the contingency options for these flyby burns (e.g., a missed burn or a partial burn) since this would be critical information used for operational planning of crewed missions. Missions to lunar Distant Retrograde Orbits (DROs), which are a type of planar periodic orbit in the CR3BP system,[27,28] were also considered during this time. The term DRO itself was coined by Ocampo in 1993.[29]

Prior to 2014, most scripting and data analysis with Copernicus at JSC was done with Matlab. The Copernicus Python Interface (CopPy) was developed at this time, and would eventually become a critical piece of infrastructure. CopPy provided a means for manipulating the Copernicus input files in scripts (e.g., for running epoch scans). The DAMOCLES tool,[2] a critical component for Artemis I mission design, is a Copernicus wrapper written in Python and responsible for all the trajectory data generated for the Artemis I mission (both nominal and off-nominal).

ASTEROID REDIRECT MISSION

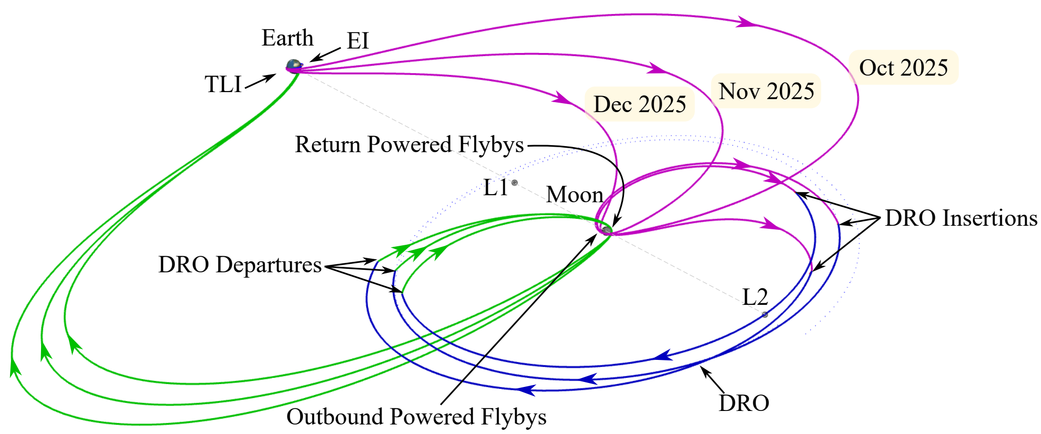


Figure 10: Multiple DRO Opportunities for ARCM (Earth-Moon Rotating Pulsating Frame). This case, designed in 2013, required 65 segments in Copernicus.

In 2010, the JSC mission design team performed preliminary studies for crewed Orion missions to Near Earth Objects (NEOs)[30] Following these studies, the Asteroid Redirect Mission (ARM)

Table 3: Orion 6 Day DRO Stay Missions for ARCM

Departure Epoch	Orion Δv (m/s)	Mission Duration (days)	Post-ICPS TLI C_3 $(\mathrm{km}^3/\mathrm{s}^2)$
Oct 2025	841	26	-2.31
Nov 2025	996	23	-1.90
Dec 2025	957	21	-1.82

(first proposed in 2012[31]) would end up being the main source of the basic trajectory flown by Artemis I.[32–34] The concept was to capture and bring a small NEO into cislunar space so that Orion could visit multiple times. Eventually, the NEO destination was established as a lunar DRO. The Asteroid Redirect Crewed Mission (ARCM) was a rendezvous mission, where Orion was to dock with a spacecraft attached to the asteroid in order to study its properties and return samples. This meant that Orion could not enter at any point in the DRO, but rather had to account for phasing and the location of the asteroid once it had been placed there. A 70,000 km DRO (as measured from the Moon to the first x-axis crossing along the Earth-Moon line) had an approximate 2 to 1 resonance with the Moon's orbit which allowed for consecutive monthly mission opportunities. Figure 10 shows the results of a study to minimize the sum of the Orion Δv maneuvers for three consecutive monthly opportunities. The performance results are shown in Table 3.

Like the halo missions, the DRO mission required powered lunar flybys. The four major burns performed by Orion are the Outbound Powered Flyby (OPF) and DRO Insertion (DRI) on the outbound leg, and the DRO Departure (DRD) and Return Powered Flyby (RPF) on the return leg. A more expensive single-burn departure option could also be possible in some cases, depending on the assumed vehicle performance and the desired stay time. For example, a 6 day stay time in the DRO allowed for mostly optimal departures and arrivals for the 14 day (70,000 km) DRO, whereas a shorter DRO stay time would be necessary if either departure or arrival was performed in one burn. The Asteroid Redirect Mission was canceled in 2017.

EXPLORATION MISSION 1 TO PROJECT ARTEMIS

Concurrently with the ARCM design, EM-1 was conceived as the first uncrewed Orion test flight.[1] EM-1 was to be a lunar free return mission (see Figure 11) to minimize risk, as this was the first launch of the SLS and Orion vehicles. This mission was to be a building block of a crewed EM-2 to a lunar orbit, where TLI puts Orion on a free return (to reduce risk for the crew if the first OME burn failed), after 3 hours Orion performs a hybrid burn that targets the lunar orbit destination, followed by an LOI, lunar orbit stay, and a TEI. Eventually, EM-1 was changed to a DRO mission, to serve as an ARCM precursor, while EM-2, the first crewed Orion flight, was changed to a free return trajectory, originally through L_2, but finally a basic flyby at a lower lunar altitude.[35]

Table 4: EM-1 DRO Case (December 17, 2017 with 6-day DRO Stay)

Burn	Orion Δv (m/s)
Trans-Lunar Injection (TLI)	139
Outbound Powered Flyby (OPF)	148
DRO Insertion (DRI)	144
DRO Departure (DRD)	110
Return Powered Flyby (RPF)	211

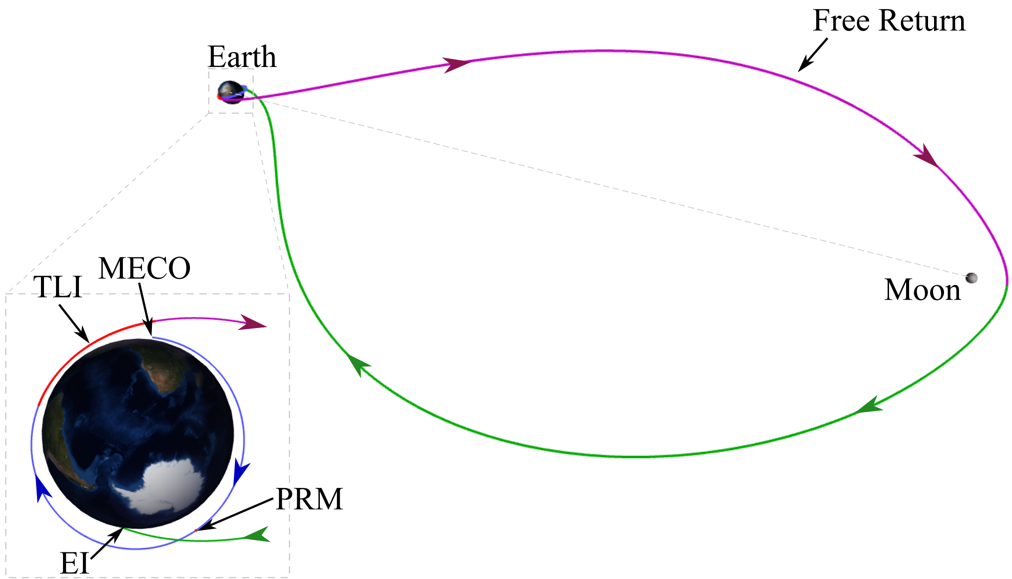


Figure 11: EM-1 Free Return Trajectory. Before it was changed to a DRO mission, the original EM-1 was to be a free-return trajectory. This is essentially the halo orbit mission shown in Figure 9 without the hybrid burn and subsequent halo orbit visit. This version would have no major burns performed by Orion. The launch epoch of this trajectory is December 1, 2021, with a total flight time of 7.16 days. The lunar flyby altitude is 8,118 km.

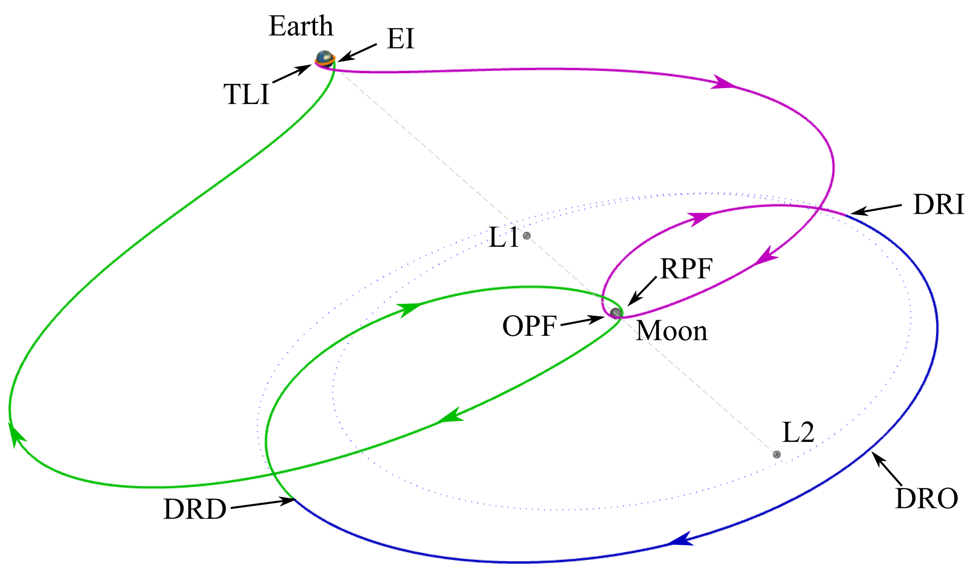


Figure 12: Original DRO Mission Case for Exploration Mission 1 (Earth-Moon Rotating Pulsating Frame). This trajectory was based on the ARCM trajectories with the crucial difference that, since there was no asteroid rendezvous, Orion could always enter the DRO orbit at the optimal location for a given launch date.

One of the earliest DRO cases for Exploration Mission 1 (EM-1) (developed circa 2012-2013) is shown in Figure 12. Main Engine Cutoff (MECO) is on December 17, 2017, and the Orion performance numbers are shown in Table 4. For this case, the ICPS Δv was limited to 2,900 m/s and Orion performed part of the TLI burn (a concept that will ultimately be employed for Artemis II), with a total mission duration of 25.7 days. This trajectory is the ancestor of the Artemis I mission that was ultimately flown, since this very Copernicus mission file was updated and evolved over the next few years into the one used to generate the final flight trajectory. This initial reference case was constructed from an ARCM case, except the asteroid rendezvous was removed and the location of the DRO insertion was optimized. The DRO size was kept unchanged (exactly 70,000 km) as was the basic outbound and return lunar flyby structure. Direct (single burn) DRO returns were also considered for abort and early-return options, if the propellant was available, although with the final Artemis I mission assumptions, these were not feasible options.[36]

As the initial reference DRO case was transitioned to EM-1, many changes were made such as increased fidelity (using realistic mass and engine parameters), addition of an OMSe checkout burn (OTC-1), and addition of an ICPS-Orion spring separation model. As the Orion and SLS programs matured, it also became necessary to consider end-to-end mission trajectory design.[37,38] Copernicus was primarily an on-orbit design tool, and originally had no way to incorporate user-provided algorithms. In the version 4.1 release of Copernicus (2015), a new plugin architecture was introduced, which allowed user-defined code to be included in the optimization problem and allowed Copernicus to communicate with other tools. A key use of this feature was a plugin to compute the mission's initial on-orbit state at core separation after the SLS MECO by interpolating a database of pregenerated SLS ascent trajectories. Eventually, numerous other plugins were necessary for the final Artemis I mission design.

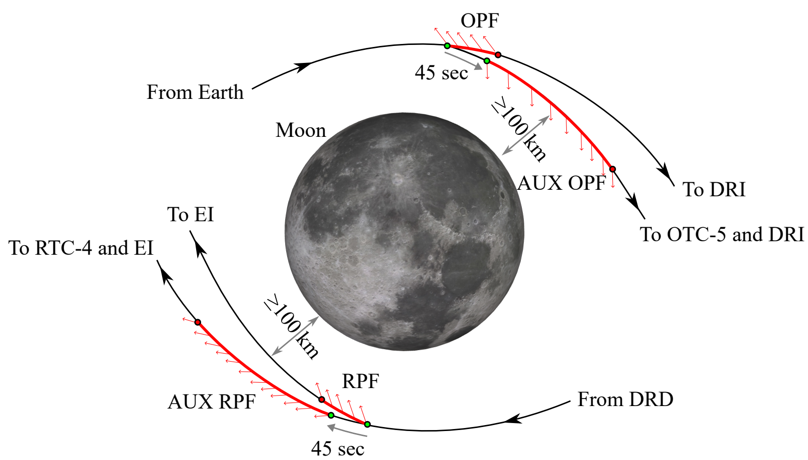


Figure 13: Artemis I OPF and RPF Downmode Geometry. The trajectory is optimized to include the two flyby "downmode" burns, which protect for the ability to perform them using the Orion AUX engines if the main engine fails. After a subsequent correction burn (OTC-5 for the outbound and RTC-4 for the return), the XDM trajectory rejoins the nominal trajectory at the next major event.

Another key change from the original DRO mission design to the EM-1 trajectory was an operational design choice that protected for an engine failure. The AUX Downmode (XDM) (see Figure

Table 5: Performance Cost of XDM (Flight Reference Trajectory for November 16, 2022 06:48:00 UTC)

Burn	Δv (m/s) (with XDM)	Δv (m/s) (without XDM)
OPF	178.68	166.73
DRI	110.48	110.51
DRD	145.29	145.01
RPF	293.00	269.51

13) was a mission contingency that assumed if the OMSe failed during a burn, then Orion would switch to an AUX burn configuration. Based on a strategy from the Space Shuttle Program, the Orion XDM model minimized the penalty which would result from switching from one engine to the other. For EM-1, this strategy was applied to both OPF and RPF. Due to the different thrust and Isp as well as the optimal TIG, a switch from one to the other could have resulted in a propellant cost greater than what was available. Thus, an optimization strategy, where both OMSe and AUX were considered, solved for a balanced TIG, which resulted in a higher cost to the OMSe-optimal TIG, while protecting for a backup engine contingency. For the November 16, 2022 reference mission, the XDM added about 12 m/s to the OPF cost, and about 23.5 m/s to the RPF cost (see Table 5).

Major activities during this period were studying ways to mitigate missions that had one or more requirement violations. An eclipse duration violation was usually mitigated with trajectory shaping techniques (e.g., adding an out-of-plane component to the DRO).[39] A landing lighting violation for the default 26 day short class mission was usually mitigated by changing the RPF epoch (e.g., extend the DRO stay to at least a full rev and create a 40 day long class mission). The addition of varying mission classes expanded the number of available daily mission opportunities that met all the various mission constraints.[2] However, for the actual Artemis I launch date, no extra mitigations were necessary, and a nominal reference trajectory was flown. After cancellation of the ARCM and the development of the Lunar Gateway concept, changing the mission from a DRO to an NRHO[40] was also considered, although this was ultimately not done. Additionally, a crewed EM-1 option was investigated in early 2017 in order to achieve the goal of landing humans on the Moon by 2024 instead of 2028, but this concept was also discarded.

ARTEMIS I

In May 2019, NASA renamed EM-1 to Artemis I, and the "home stretch" began for the mission design for the first flight test of the integrated SLS and Orion spacecraft. This period finalized the details of mission data product generation, which included pre-flight packages as well as real-time products and operational concepts to support what would be the flown trajectory.[41] The Artemis I Launch Periods (LPs) were from 14–16 days long each lunar month with a launch opportunity almost every day. For each LP, the mission design team at JSC produced a full set of reference and abort trajectory products that were delivered to relevant stakeholders 2.5 months before the open of the launch period to prepare for flight. LP–1 began on November 6, 2020, and Artemis I launched during LP–28 on November 16, 2022.

Figure 14 shows the major burn Δv's for a nominal (approximately 26 day) mission scan over a 1 year period (starting with LP–22 and including the actual launch epoch). For each launch day, a launch window was generated for the selected mission class (e.g., short class, long class, or a mission with mitigations such as eclipse avoidance maneuvers). Launch windows of up to 4 hrs were generated, as well as millions of abort and contingency options.[3,36] Operationally, only 2 hr launch windows were supported, so for days with launch windows greater than 2 hrs, a down-selection process was implemented to select only up to 2 hrs (note that some launch days had windows shorter than this naturally). The specific 2 hr period was selected based on a set of cross-program "desirements", or aspects of the trajectory that were favorable outside of the basic convergence requirements. For example, SLS is required to have the ability to launch in darkness, but a daylight liftoff was highly desired. More examples include key events occurring in illumination from the Sun, or maximizing the likelihood of favorable weather. These priorities were ranked in order from most to least desired, which was used to determine the final window selection. An example of this is shown in Figure 15.

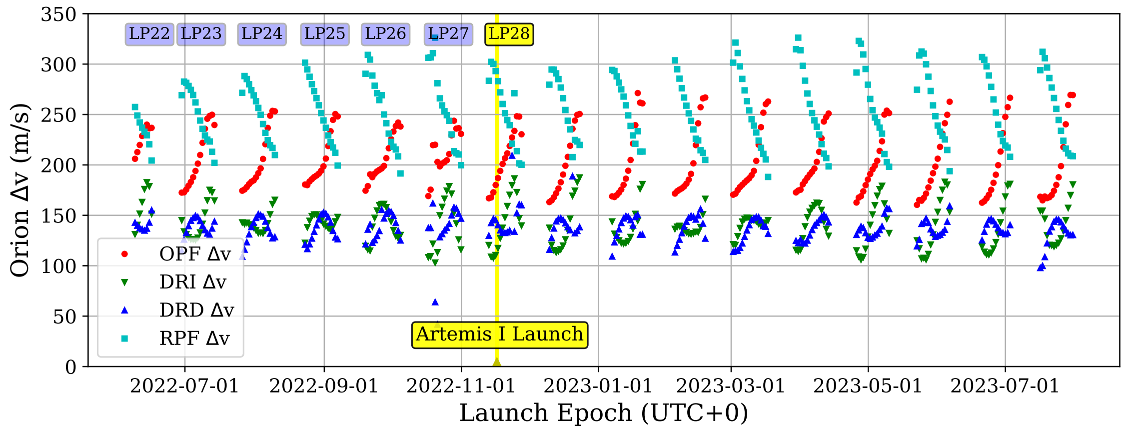


Figure 14: Reference Trajectory Scan. This plot shows the Copernicus-optimized burns from a reference trajectory scan of the nominal 26 day mission class. The JSC mission design team processed trajectories for each Launch Period (LP), starting with LP–1 on November 6, 2020. The Artemis I launch occurred in LP–28 on November 16, 2022. Each grouping represents subsequent launch periods labeled from LP–22 to LP–28.

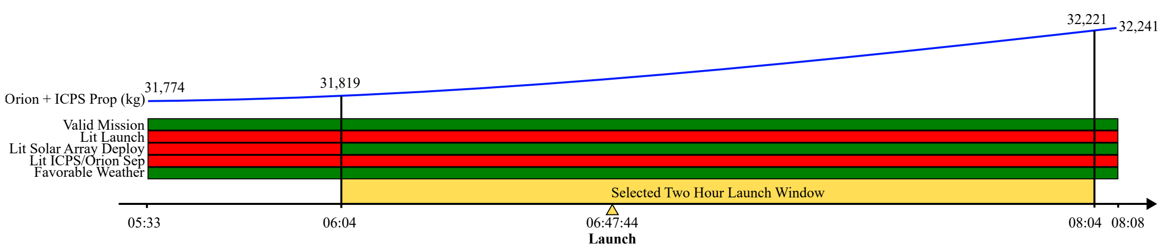


Figure 15: Launch Window Selection for November 16, 2022. A two-hour launch window was selected from the full 155 minute data set by ranking various "desirements". In this figure, green indicates the desirement is satisfied, red indicates it is not, and yellow depicts the resulting 120 minute window selection. Although there are valid missions starting from 5:33 UTC, opening the window at 6:04 UTC allowed the solar array deploy lighting desirement to be satisfied.

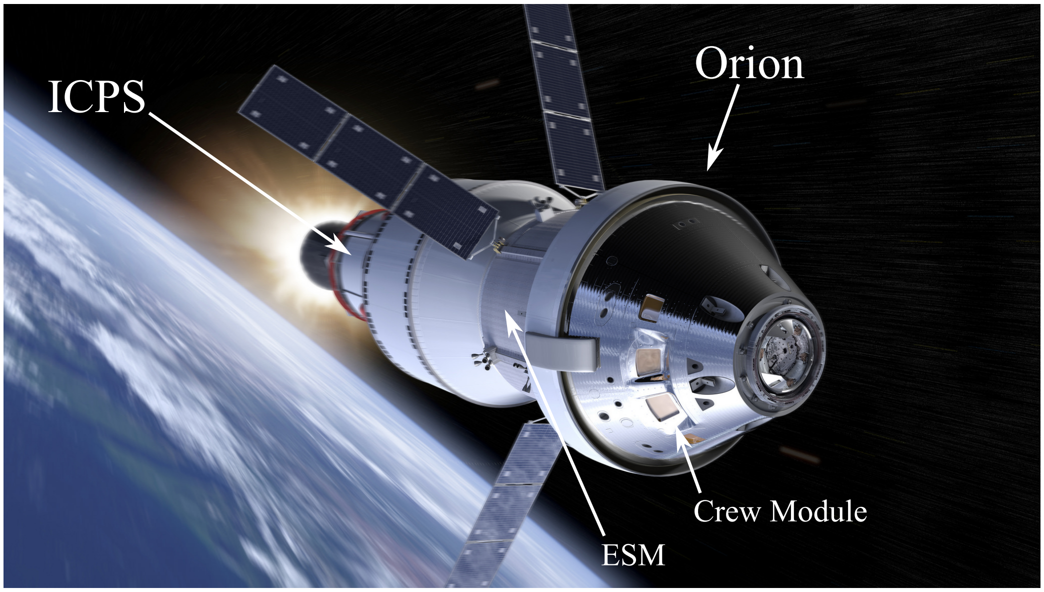
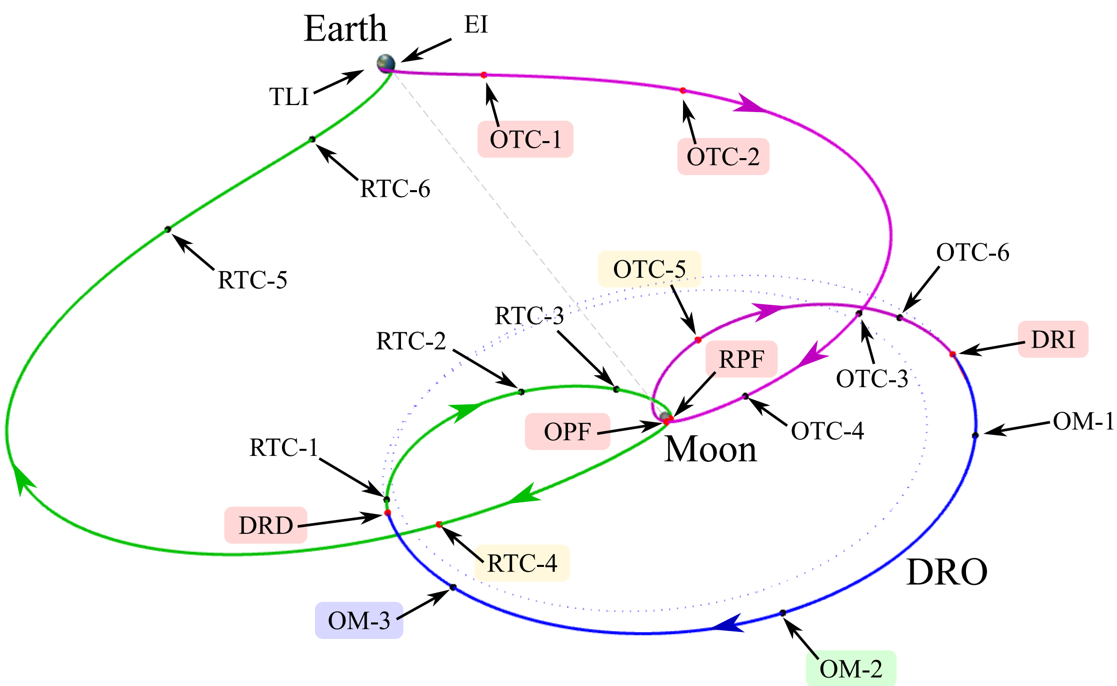


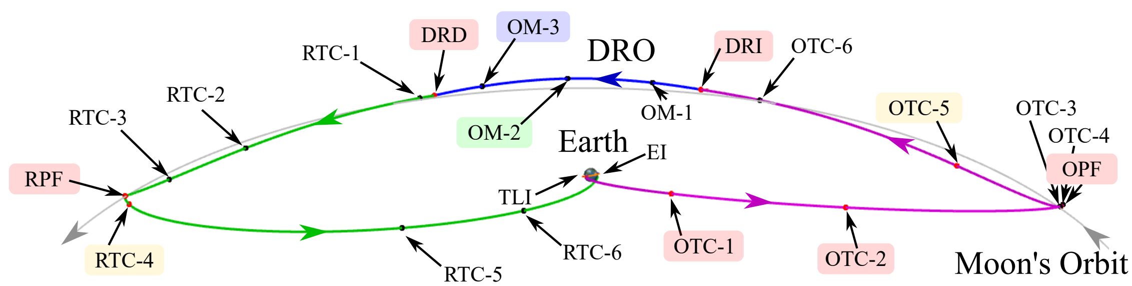
Figure 16: Artemis I Earth Departure Configuration (ICPS and Orion). The Crew Module (CM) is the only component of the in-space architecture that has survived from the start of the Constellation Program (compare to Figure 3).

Table 6: Summary of Orion Burns for Artemis I.

#	Burn	Description	Reference Δv (m/s)	Flight Δv (m/s)
1	USS-1	Upper Stage Separation (Δv = 5.5 ft/s)	1.67	1.55
2	OTC-1	OMSe checkout burn ($\Delta t = 30$ sec)	34.51	34.95
3	OTC-2	Small burn used during launch window optimization for convergence ($\Delta t < 10$ sec)	0.13	0.22
4	OTC-3	Outbound Trajectory Correction (not included in reference)	0	0.87
5	OTC-4	Outbound Trajectory Correction (not included in reference)	0	0.21
6	OPF	Outbound Powered Flyby	178.68	178.64
7	OTC-5	Outbound XDM recovery burn in reference. Not used for that during flight since downmode was not performed.	0.62	0.97
8	OTC-6	Outbound Trajectory Correction (not included in reference)	0	2.67
9	DRI	DRO Insertion	110.48	110.63
10	OM-1	Orbit Maintenance (not included in reference).	0	0.015
11	OM-2	Potential DPC eclipse mitigation burn. Not used for that for the selected launch date. Not performed.	0	0
12	OM-3	Orbit Maintenance (not included in reference). During flight, this was repurposed as a 100 sec 6+X AUX burn.	0	13.21
13	DRD	DRO Departure	145.29	138.48
14	RTC-1	Return Trajectory Correction (not included in reference)	0	0.14
15	RTC-2	Return Trajectory Correction (not included in reference)	0	0.52
16	RTC-3	Return Trajectory Correction (not included in reference)	0	0.62
17	RPF	Return Powered Flyby	293.00	292.90
18	RTC-4	Return XDM recovery burn in reference. Not used for that during flight since downmode was not performed.	2.41	0.15
19	RTC-5	Return Trajectory Correction (not included in reference)	0	1.52
20	RTC-6	Return Trajectory Correction (not included in reference)	0	0.29



(a) (Earth-Moon Rotating-Pulsating Frame)



(b) (J2000-Earth Frame)

Figure 17: Optimized Copernicus Flight Reference Trajectory for November 16, 2022 06:48:00 UTC. See also Table 6 for more information about each burn and how the flight values compared with the reference. The major optimized burns are highlighted red. OTC-5 and RTC-4 were also optimized in the reference as part of the AUX downmode solution but were not used for that purpose since downmodes were not required. During the flight, OM-3 was repurposed as an unplanned 100 sec AUX burn optimized during flight as a new Development Flight Test Objective (DFTO).

Artemis I (see Figures 16–17) launched from KSC on November 16, 2022 at 06:47:44 UTC. Table 6 shows a summary of the Orion burns in the pre-flight reference trajectory and the best estimated flight values.[41] The final Artemis I Copernicus reference mission file included 80 segments and 16 plugins. Running all the cases necessary for the mission planning required parallelized runs on a computing cluster. The framework developed for this task is planned to be included in the next release of Copernicus so it will be available to all users, many of whom also have a need to parallelize large trajectory scans.[42] Figure 17 shows the pre-flight reference trajectory (on the whole minute) closest to the actual launch time of the Artemis I mission, including the locations of the major burns and the various Outbound Trajectory Correction (OTC), Orbit Maintenance (OM), and Return Trajectory Correction (RTC) burns.[43] During the mission (after DRI), the Orion Program decided to repurpose OM-3 as an unplanned DFTO, to perform a 100 sec AUX 6+X burn as a test of that engine configuration. This required reoptimizing the trajectory to include this burn, which also slightly modified the subsequent burns. This was done with Copernicus, which was used throughout the flight to provide mission support. This new burn was about 13 m/s and caused the nominal DRD to be reduced from 145 m/s to 138 m/s (overall about a 6 m/s additional cost to the mission). Otherwise, the flight followed very closely to the designed reference mission, providing a good validation of Copernicus and the entire mission design and operations process.

Artemis I provided the first opportunity to use Copernicus in an operational environment at JSC, providing real time support for the mission during flight.[41] Lessons learned from this process will be incorporated into future releases of the tool. In 2020, with the release of version 5.0 (see Figure 18) the Copernicus architecture was changed from a single executable to a shared library with a Python API.[44] This API allows a user to build even more sophisticated plugins, as well as to use Copernicus as a platform to build other applications and analysis tools. Going forward, this will become an even more important and useful feature for development and operations of future Artemis missions. In 2021, 20 years after development began, Copernicus was awarded the NASA Software of the Year Award.

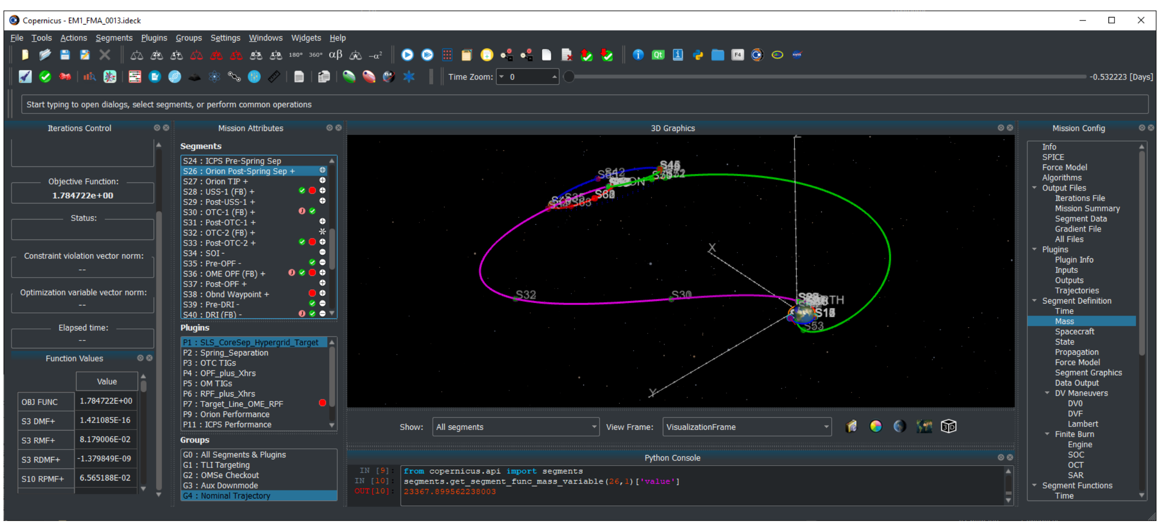


Figure 18: Artemis I Mission in the Copernicus GUI. Starting with version 5.0 (2020), the new Python GUI and API have greatly expanded the flexibility and customizability of Copernicus, laying the groundwork for more development to come.

CONCLUSIONS AND FUTURE WORK

Orion's trajectory design has seen many changes from its inception in 2005 to its first flight in 2022, but its main mission is still cislunar space and beyond. Orion trajectory design continues at JSC (and other NASA centers and industry partners), and future Artemis missions will build upon the many lessons learned from Artemis I. Copernicus development also progresses, including the addition of new API and parallelization components, and it will continue to be a key tool for trajectory design for NASA missions, including Artemis, HLS, and Gateway. The trajectory designers will continue to apply technical rigor and evolve key software as space exploration endures.

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TERMINOLOGY

APC	Ascent Plane Change
API	Application Programming Interface
ARCM	Asteroid Redirect Crewed Mission
ARM	Asteroid Redirect Mission
ATV	Automated Transfer Vehicle
AUX	Orion ESM Auxiliary (+X) Engine
CEV	Crew Exploration Vehicle
CM	Crew Module
CR3BP	Circular Restricted Three-Body Problem
DAC	Design Analysis Cycle
DFTO	Development Flight Test Objective
DRD	DRO Departure
DRI	DRO Insertion
DRO	Distant Retrograde Orbit
DPC	DRO Plane Change
EDS	Earth Departure Stage
EI	Entry Interface
EM-1	Exploration Mission 1
EM-2	Exploration Mission 2
ESA	European Space Agency
ESAS	Exploration Systems Architecture Study
ESM	European Service Module
GUI	Graphical User Interface
HDF5	Hierarchical Data Format
HLS	Human Landing System
ICPS	Interim Cryogenic Propulsion Stage
Isp	Specific Impulse
ISS	International Space Station
JSC	Johnson Space Center
KSC	Kennedy Space Center
LEO	Low Earth Orbit
LLO	Low Lunar Orbit
LOI	Lunar Orbit Insertion
LP	Launch Period
LSAM	Lunar Surface Access Module
MAPP	Mission Assessment Post Processor
MECO	Main Engine Cutoff
MPCV	Multi-Purpose Crew Vehicle
NASA	National Aeronautics and Space Administration
NEO	Near Earth Object
NRHO	Near Rectilinear Halo Orbit
OM	Orbit Maintenance
OME	Orion Main Engine
OMSe	Orbital Maneuvering System Engine
OPF	Outbound Powered Flyby
OTC	Outbound Trajectory Correction
RPF	Return Powered Flyby
RTC	Return Trajectory Correction
SLS	Space Launch System
SM	Service Module
TEI	Trans-Earth Injection
TIG	Time of Ignition
TLI	Trans-Lunar Injection
USS	Upper Stage Separation
UT	University of Texas at Austin
XDM	AUX Downmode

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