EVOLUTION OF ORION MISSION DESIGN FOR EXPLORATION MISSION 1 AND 2

Jeffrey P. Gutkowski,[*] Timothy F. Dawn,[†] and Richard M. Jedrey[‡]

The evolving mission design and concepts of NASA's next steps have shaped Orion into the spacecraft that it is today. Since the initial inception of Orion, through the Constellation Program, and now in the Exploration Mission framework with the Space Launch System (SLS), each mission design concept and program goal have left Orion with a set of capabilities that can be utilized in many different mission types. Exploration Missions 1 and 2 (EM-1 and EM-2) have now been at the forefront of the mission design focus for the last several years. During that time, different Design Reference Missions (DRMs) were built, analyzed, and modified to solve or mitigate enterprise level design trades to ensure a viable mission from launch to landing. The resulting DRMs for EM-1 and EM-2 were then expanded into multi-year trajectory scans to characterize vehicle performance as affected by variations in Earth-Moon geometry. This provides Orion's subsystems with stressing reference trajectories to help design their system. Now that Orion has progressed through the Preliminary and Critical Design Reviews (PDR and CDR), there is a general shift in the focus of mission design from aiding the vehicle design to providing mission specific products needed for pre-flight and real time operations. Some of the mission specific products needed include, large quantities of nominal trajectories for multiple monthly launch periods and abort options at any point in the mission for each valid trajectory in the launch window.

INTRODUCTION

The Orion spacecraft was conceived in 2004 as one of the many vehicle elements within the Constellation Program. The Constellation Program's goal was to land four astronauts anywhere on the surface of the Moon utilizing a two-rocket (Ares-I and Ares-V) launch concept, with a lunar lander (Altair), and Orion. See Figure 1 for a mission overview of the Low Lunar Orbit (LLO) Sortie Design Reference Mission (DRM) with a 7-day stay on the surface of the Moon. The other major DRM was for Orion to deliver crew to the International Space Station (ISS). Orion's propellant tank size, consumables, structure, and mass were all dictated by this exploration architecture. In 2009, the Constellation Program was canceled in favor of a scaled down, lower cost exploration architecture with only one rocket type and no lunar lander. The Orion Program continued in this new effort called the Exploration Missions. The Orion vehicle configuration was mostly kept the same but with some modifications, and a partnership was formed with the European Space Agency (ESA) to build the Orion Service Module (SM). The mindset for mission design shifted from sizing the Orion spacecraft for particular DRMs, for example the propellant tank capacity, to a capability mentality to determine what DRMs Orion can perform with its current design without requiring

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[*] Aerospace Engineer, EG/Aeroscience and Flight Mechanics, NASA Johnson Space Center, Houston, TX 77058.
[†] Aerospace Engineer, EG/Aeroscience and Flight Mechanics, NASA Johnson Space Center, Houston, TX 77058.
[‡‡] Aerospace Engineer, EG/Aeroscience and Flight Mechanics, NASA Johnson Space Center, Houston, TX 77058.

any major design block upgrades. By designing Orion to a capability instead of to a specific DRM, Orion is poised to fly many different, new, and exciting trajectories.
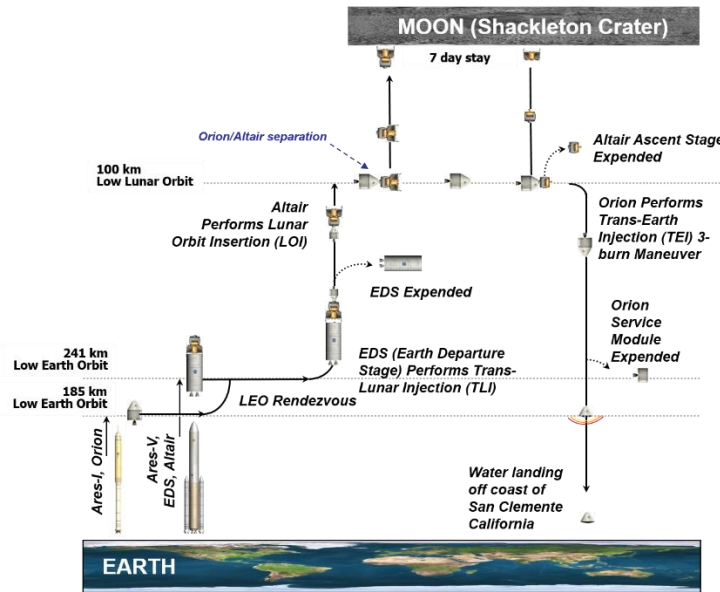

Figure 1. Constellation Program LLO DRM

EXPLORATION MISSIONS

The Orion Program started out the post-Constellation Program era by redefining or slightly adjusting the requirements, vehicle specifications, DRMs and to ready itself for Orion's first in-space test flight, Exploration Flight Test 1 (EFT-1). EFT-1 was performed on December 5, 2014 and was a huge success for testing out Orion's heat shield and the entry, decent and landing portion of Orion's future missions. Exploration Mission 1 (EM-1) is planned for the 2018 timeframe. This will be an uncrewed mission to test Orion's capabilities in deep space. Exploration Mission 2 (EM-2) is the follow-on Orion mission in 2021. EM-2 will be Orion's first crewed mission. Exploration Missions 3 and beyond will follow at a flight rate of one per year. All EM missions will utilize the new heavy lift rocket, the Space Launch System (SLS), which is similar to the Constellation Program's Ares-V to deliver Orion with any other co-manifested payloads beyond Low Earth Orbit (LEO).

Lunar Orbit Comparison

The capability requirements for Orion center on its ability to perform cis-lunar missions with four crew for up to 21 days. This defines the consumable capability of Orion. Rather than changing the propellant capacity of Orion to perform a specific DRM, the mission design team needed to find what types of cis-lunar trajectories are within the current Orion propellant capacity. Without Altair, which performed approximately one half of the total propellant cost to perform a LLO DRM to a 100 km circular lunar orbit, the mission design team searched for a new, higher energy lunar orbit where Orion will have enough vehicle performance to execute both Lunar Orbit Insertion (LOI) and Trans-Earth Injection (TEI). Figure 2 shows a trade study that was performed to compare the total LOI and TEI delta velocity cost for different circular and elliptical lunar orbits. It was determined that an elliptical lunar orbit with an altitude of 100 x 10,000 km would provide sufficient propellant margin for Orion.
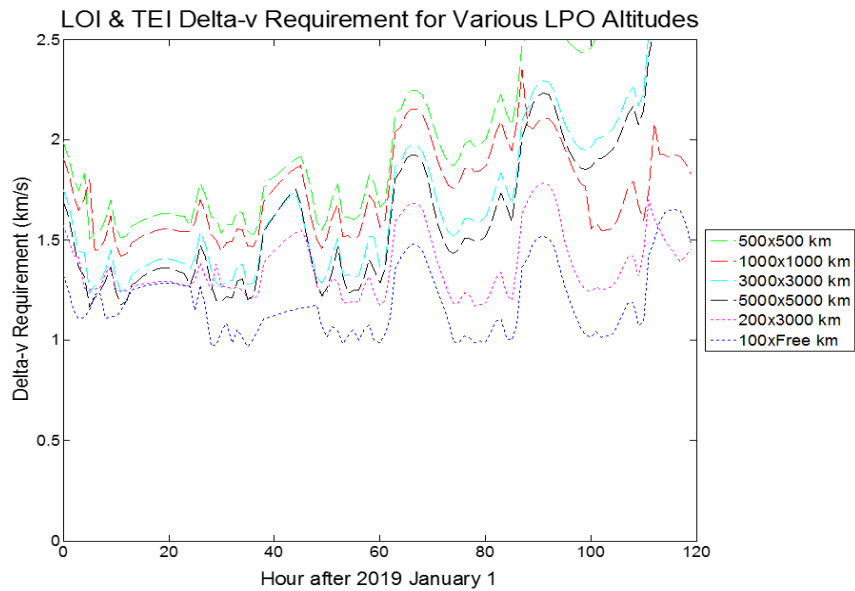
Figure 2. EM-2 Orbit Comparison

Exploration Mission 2 (EM-2) High Lunar Orbit (HLO) DRM

Orion will be launched into space on the SLS and sent to the Moon using the Interim Cryogenic Propulsion Stage (ICPS) as the upper stage. Refer to Figure 3 for a mission overview. The ICPS-Orion stack is placed into an elliptical Earth orbit of 41 x 1,805 km altitude. When the stack reaches apogee, the ICPS performs a Perigee Raise Maneuver (PRM) to increase the perigee altitude to 185 km. On the second orbit, the ICPS performs the Trans-Lunar Injection (TLI) that places Orion on a free return trajectory to a nominal Earth Entry Interface (EI) condition. The reason for the free return is that if Orion's main engine fails to ignite, then the crew can return to Earth without performing any major burns. The ICPS separates from Orion soon after TLI completion. At a minimum of three hours after TLI completion, the Orion SM performs the Outbound Trajectory Adjust (OTA) burn to lower the lunar flyby altitude to 100 km. When Orion reaches perilune, it performs a LOI into a 100 x 10,000 km altitude orbit called the High Lunar Orbit (HLO). The Orion crew loiters in lunar orbit for a minimum of three days, after which Orion performs a TEI for the Earth return.
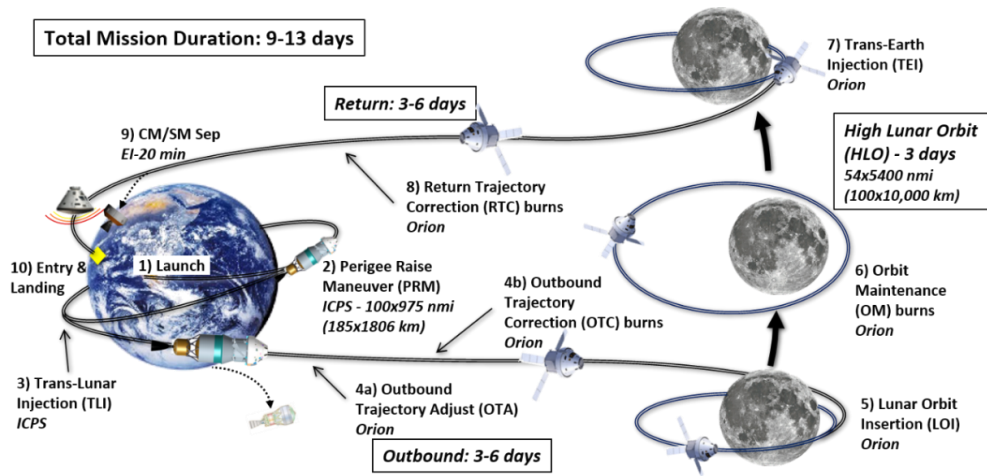

Figure 3. EM-2 HLO DRM

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## CONSTELLATION AND EXPLORATION MISSIONS COMPARISON

With the EM-2 mission defined, a comparison can be made between the Constellation LLO sortie DRM and the HLO DRM.[1] A number of the differences highlighted in Table 1 show why Orion by itself cannot perform a LLO DRM. One key difference is the lack of a lunar lander in the EM-2 DRM. Without a lunar lander, the amount of Delta-V (DV) available for LOI and TEI is significantly limited.

Table 1. Constellation and EM-2 DRM Comparison

|	Constellation	EM-2
DRM	LLO sortie	HLO
Lunar Lander	Yes, Altair	No
Launches	Two launches, Ares I and Ares V	One SLS launch
Mission Duration	~23 days	9-12 days
Rendezvous	In LEO, ~315 ft/s (96 m/s)	N/A
Upper Stage Separation	From Ares I launch vehicle in LEO, Altair separated from upper stage post-TLI	From upper stage post-TLI
Outbound Trajectory Correction Burns	Performed by Altair	Performed by Orion
Free Return Trajectory	No	Yes
OTA	N/A	Takes Orion off of free return, ~33 ft/s (10 m/s)
LOI	Performed by Altair, ~2,786 ft/s (849 m/s)	Performed by Orion, ~1358 ft/s (414 m/s)
Time in Lunar Orbit	8 days	3 days
Orbit Maintenance	No, only a two-burn orbit cleanup to align orbit with lunar lander ascent, ~85 ft/s (26 m/s)	Yes, ~33 ft/s (10 m/s)
TEI	Three-burn sequence, ~3,500 ft/s (1,067 m/s)	One burn, ~2,133 ft/s (650 m/s)
Landing	Off the coast of California	Off the coast of California
Orion Solar Arrays	New development, can withstand higher acceleration loads at TLI	ESA Automated Transfer Vehicle (ATV) heritage, TLI acceleration load limits
Orion Main Engine	New development, Isp: 328 s	Shuttle heritage Orbital Maneuvering System Engine (OMS-E), Isp: 315 s, -50 m/s impact

EXPLORATION MISSION 1 (EM-1)

The initial concept for EM-1 is shown in Figure 4. The Earth trajectory portion of the mission is similar to EM-2 HLO. This was a simple, low risk mission for Orion to test out its systems on a free-return trajectory to ensure the vehicle could get back with minimal propellant required (only needs trajectory correction burns). This uncrewed mission was a dry rehearsal for Orion, demonstrating it could survive and achieve specific Flight Test Objectives (FTOs) while performing the free-return portion of the EM-2 trajectory.
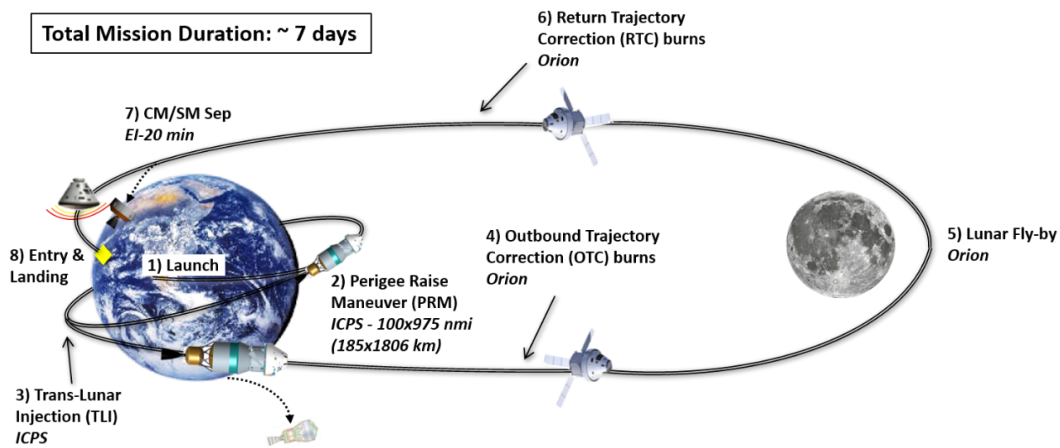
Figure 4. EM-1 Free-return Lunar Flyby DRM

In May 2013, EM-1 was seen as an opportunity to perform a riskier mission to a new type of orbit, a Distant Retrograde Orbit (DRO), which is a highly stable orbit that exists due to the interaction between the Earth and Moon's gravity. At the time, NASA was investigating this type of orbit as a prime candidate to redirect a small asteroid there for future Orion crewed missions to visit. This meant that Orion could perform science missions to this asteroid on a periodic basis as opposed to a long and intense mission to an asteroid farther out.[2] EM-1 was then changed to a DRO DRM taking advantage that the 21 day active lifetime capability requirement does not apply since it is uncrewed. See Figure 5 for the mission overview. Figure 6 shows the DRO in different coordinate frames. The Earth J2000 coordinate frame is viewing the X-Y plane, providing a good view of the Moon's orbital plane. The DRO's orbital plane has a minimal out-of-plane component with respect to the Moon's orbital plane.
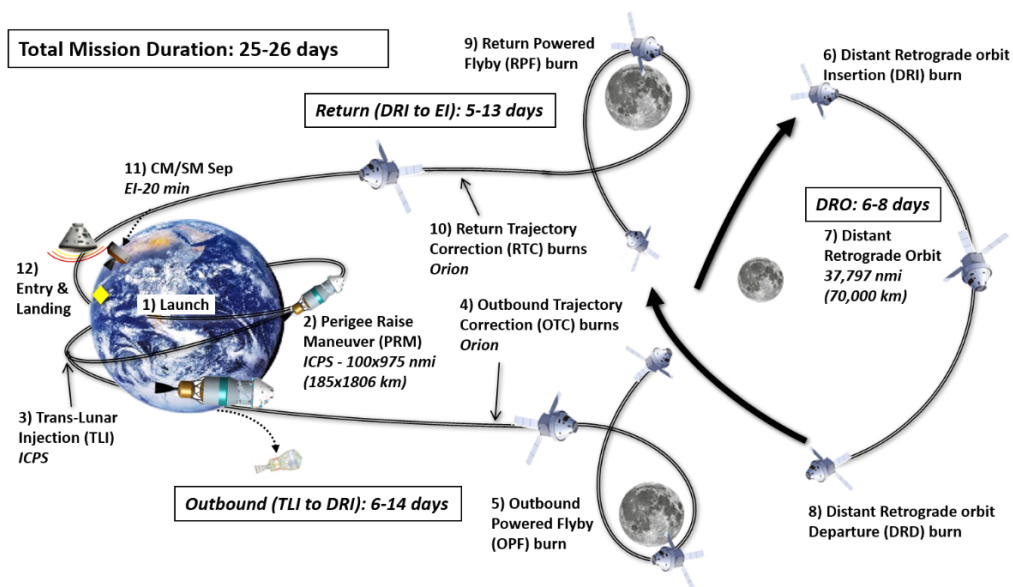
Figure 5. EM-1 DRO DRM
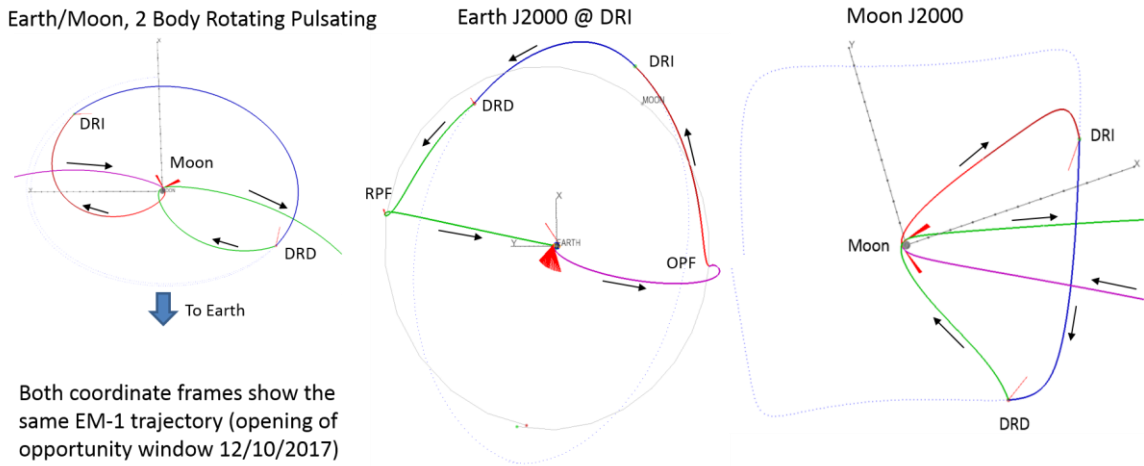
Figure 6. EM-1 DRO Various Frames for Visualization

ALTERNATIVE EXLORATION MISSION 2 (EM-2) DRMS

As mission design progressed and converged towards a DRO destination for the EM-1 mission, more attention has shifted to EM-2 planning. The EM-2 HLO DRM closely aligns with vehicle level requirements that ensure Orion will have the system capabilities for other types of cis-lunar missions. What EM-2 mission Orion actually flies is still being solidified, but there are two main categories: (1) a lower risk DRM than HLO, and (2) extended mission duration DRMs.

Lower Risk DRM

Since EM-2 is the first crewed mission for Orion and the first mission with the human life support systems, the Orion Program and NASA may choose to fly a mission that is less risky in some aspects. This involves finding a mission that requires less nominal propellant usage, while increasing contingency propellant available for aborts. Also, the mission may employ orbits that, in an abort situation, will allow the crew to return to Earth faster than with the HLO DRM. One such mission is called the Hybrid Triple DRM. "Hybrid" means that it is an alternate mission with a similar basic concept to portions of the HLO DRM. "Triple" refers to the three different Earth elliptical orbits that make up the mission. See Figure 7 for a mission overview. For this mission, the ICPS places Orion into an intermediate Earth orbit that is highly elliptical with a period of one day. In this orbit, Orion can check out all of the new systems before committing to a mission that takes humans farther than they have gone before, which is out to the Earth-Moon Libration point 2 (L2). The vehicle check out can be performed for as many revolutions as necessary. If anything goes wrong while in this orbit, Orion can return to Earth in less than 12 hours. Orion performs the TLI that results in a near-free return trajectory, where only a Return Trajectory Adjust (RTA) burn (average DV cost of 253 ft/s (77 m/s)) and other small correction burns are needed to keep Orion on track to a successful EI condition back at Earth. There is some added risk to this mission because Orion can pass through LEO and the Van Allen belts multiple times depending on how many revolutions Orion stays in the intermediate Earth orbit. The risk sources are radiation for the crew and Orion components and Micrometeoroid and Orbital Debris (MMOD). The radiation dosage to the crew for two revolutions in the intermediate orbit is roughly equivalent to a six-month stay on the ISS.
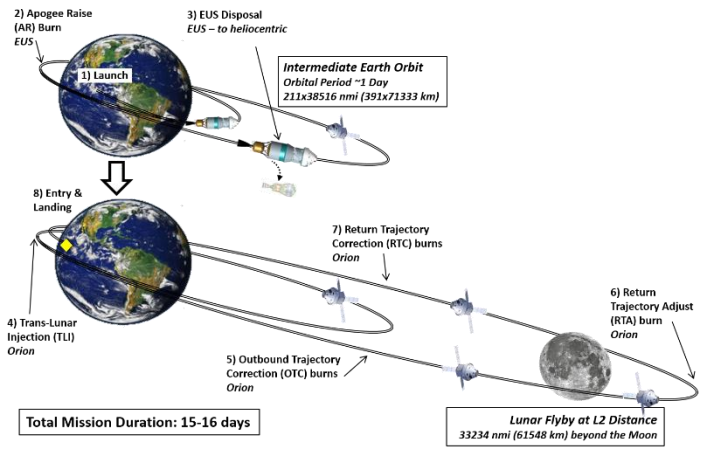
Figure 7. EM-2 Hybrid Triple DRM

Extended Mission Duration DRMs

A more capable upper stage is being planned, called the Exploration Upper Stage (EUS), for future EM missions. If the EUS is available for EM-2, then the DRM can be changed to an extended duration mission. The DRMs in this section are possible Orion missions for EM-3 and beyond. With the EUS, a Co-manifested Payload (CPL) can be delivered through TLI along with Orion. The CPL can be a logistics module that provides additional consumables to Orion beyond the current capability of four-crew for 21 days. The DRO DRM can be one of these missions as previously discussed.[2] Also, new destination orbits, such as the L2 Halo, the Near Rectilinear halo Orbit (NRO), and other high energy cis-lunar orbits are conducive for long duration habitat missions because they are relatively stable with very low orbit maintenance costs.[3] These cis-lunar orbits also provide appealing staging points to the lunar surface and space beyond the Earth-Moon system. The NRO is a type of Halo orbit that has a very close approach to the lunar surface. Figures 8 and 9 show a comparison of the size and location of the cis-lunar orbits that have been discussed.

Figure 8. Cis-lunar Orbit Comparison X-Z Plane View
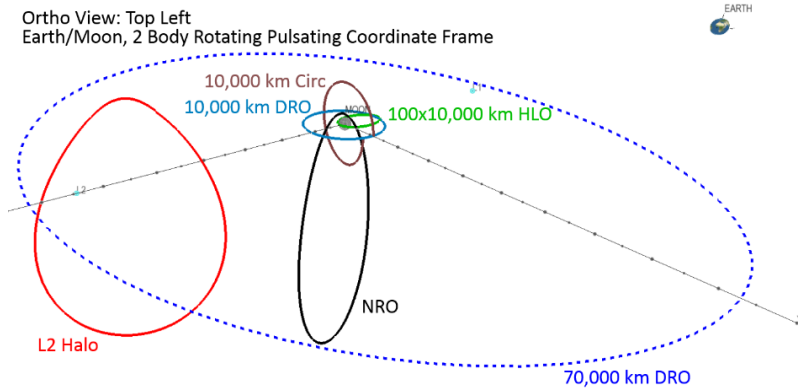
**Figure 9. Cis-lunar Orbit Comparison Orthogonal View**

DRM DEVELOPMENT

Once a DRM is selected for a particular mission, a number of analyses are conducted and products are produced in order for the DRM to be used and baselined throughout the Program. These include reference missions, multi-year trajectory scans, and abort analyses. All of these products rely heavily on NASA's Copernicus trajectory optimization tool.

Conceptual Flight Profile (CFP)

A mission specific DRM is called a Conceptual Flight Profile (CFP). It is an end-to-end continuous trajectory from launch through splashdown starting at a specific launch epoch. It is not meant to be a stressing trajectory for performance or for a particular subsystem; rather, it is a reference trajectory that is baselined by the Program to be a representative EM mission. This product is used by Orion subsystems, such as power, thermal, and communications, to see how each phase of flight fits together.

Trajectory Scans

Multi-year trajectory scans are conducted using multiple instances of the Copernicus tool spread across a large computer cluster. This scan data provides insight into how many mission opportunities there are in a given year, how long the launch period is, and if there are any trends due to Earth-Moon geometry cycles. The scans can be used to determine stressing trajectories for each subsystem and characterize the design environment. For example, a specific trajectory can be delivered to the power subsystem that represents the mission with the longest duration eclipse. Figure 10 shows an example of a trajectory scan product, the total delta velocity required by Orion to complete the EM-2 HLO DRM for every mission opportunity between the years of 2015 and 2036. Reference 4 has more details on the EM-2 HLO trajectory scan results.
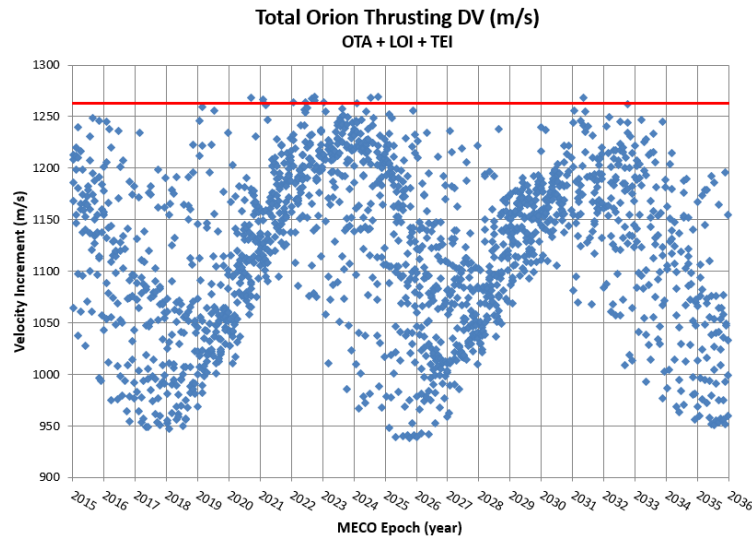
Figure 10. EM-2 HLO Total Delta Velocity Required between 2015 and 2036
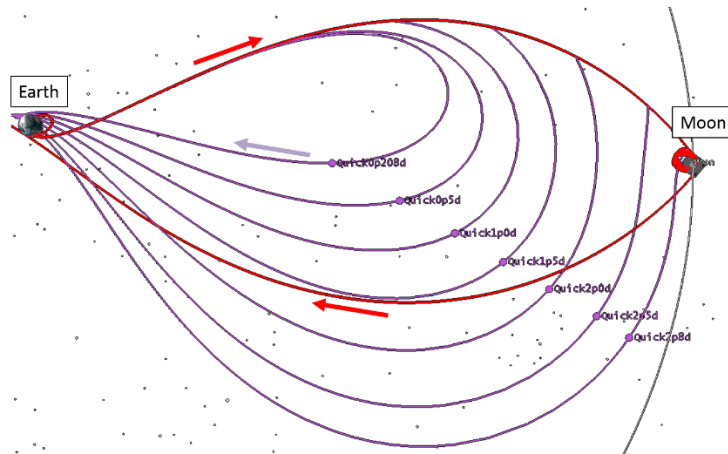
Aborts

Aborts are another key aspect to determining when a DRM has a valid mission opportunity. Not only does the nominal mission have to meet requirements and performance constraints, aborts do as well. An abort may be declared for various reasons, for example, the main engine fails during a

burn, a propellant leak, a consumable leak such as cabin air, crew sickness, etc. Some of these aborts might dictate a different course of action. For a cabin air depressurization situation, the abort needs to get the crew back to Earth within five days. For a loss of main engine, return time might not be as critical, so it may require minimizing the abort burn propellant needed. The abort burn would be performed by Orion's backup auxiliary thrusters (Aux), which are less efficient and use more propellant for the same delta velocity burn due to their lower specific impulse and thrust.[5]

For EM-1, the abort options are: (1) continue on with the mission using Aux instead of the Orbital Maneuvering System (OMS) for the remaining burns; (2) Direct or Flyby aborts (with 1 or more burns); or (3) during a burn, immediately switch or downmode from OMS to Aux. During some phases of the mission, Orion is capable of returning to Earth faster than five days. However, for more difficult phases of the mission to abort (e.g., transfers between the Moon and DRO), the return to Earth will take longer.

For EM-2, the abort options are very similar: (1) 1-burn Direct or Flyby aborts, or (2) downmode from OMS to Aux. Orion has sufficient performance to return the crew within the five day requirement at any point during the mission. Figure 11 shows what 1-burn direct aborts look like if initiated at different points along the outbound trajectory. When considering other cis-lunar destinations and missions beyond EM-2, Orion will keep pushing the boundaries of where humans have explored. As these destinations become farther away from Earth or more complicated, the abort strategy and mentality will need to change. Eventually, it will be impossible to return the crew to Earth in less than 5 days. In this case, the crew will have to become more self-sufficient and resourceful along with an increase in vehicle robustness.

Figure 11. EM-2 Outbound Direct Aborts

Risk Mitigation

While a DRM is being discussed, sometimes major modifications are made to a mission to mitigate risk. This was demonstrated when the EM-2 Hybrid Triple DRM was formulated. In addition, the EM-2 HLO DRM originally did not target a free return trajectory at TLI. This caused an added expense of propellant (the propellant required for the OTA burn) in order to reduce risk for the first crewed mission. As opposed to always deriving the most optimal trajectory for minimizing propellant usage, trajectories may be shaped to be nominally more expensive, in order to ensure aborts in a certain flight phase have either a lower propellant cost or faster return trip time. Another example applies to the first major burn for Orion in the EM-1 DRO DRM, which is the Outbound Powered Flyby (OPF) burn. The OPF burn occurs behind the Moon with no communication (direct line of sight) with Earth. An OMS Check-Out (OCO) burn has been added three hours after TLI, which is

at the same time as the first Outbound Trajectory Correction burn (OTC-1), to ensure it is functioning properly prior to the critical OPF burn. This OCO burn also increases propellant costs.

MISSION DESIGN CONSIDERATIONS: THE ROAD TO FLIGHT

As the launch date for EM-1 approaches, the mission design team will be required to adapt from investigating stressing trajectories for vehicle design to providing large quantities of pre-flight operational products and specific burn targets for the actual flight. In order to prepare for this, the mission design tools need to have increased fidelity, take into account integrated mission constraints and desirements, and set up the ground work for automating the mission specific design process. Desirements are mission aspects that the Program desires to have incorporated into the mission, but are not as critical as requirements, for example, specific lighting conditions at landing.

Higher Fidelity

The SLS Program is responsible for the launch of SLS and the upper stage through TLI and stage disposal. This creates a joint design and operations effort during the Earth orbit portion of every DRM. Originally, this was handled through the data exchange of discrete states: (1) at Main Engine Cut-off (MECO), which is when the upper stage and Orion separate from the ascent vehicle; and (2) at TLI. The End-To-End trajectory simulation (ETE) tool was developed to connect the distinctly separate ascent trajectory optimizer (Program to Optimize Simulated Trajectories aka POST) and the in-space trajectory optimizer (Copernicus).[6] This tool allows for the automatic exchange of state and target data and the smooth transition between flight phases of different vehicles. The ETE tool also allows each DRM to be further optimized, taking full advantage of all the mission design variables available from each vehicle.

Integrated Mission Constraints

The first determination of a mission opportunity is if the rocket (SLS), upper stage (ICPS or EUS), and Orion can all perform the mission within their own vehicle's propellant usage capabilities. The mission then needs to satisfy other vehicle requirements such as aborts and consumable limits (i.e. 21 days active lifetime for Orion). However, as mission specific trajectories start to be defined in the lead up to flight, other constraints might be levied on the trajectories to produce a final valid mission opportunity check. NASA and the Programs will ultimately decide if an integrated mission constraint is violated and if the mission will be flown on that specific launch date and time.

One of these mission constraints is lighting for launch, landing and separation events (between ICPS/Orion for example). Lighting is important for recovery and imaging since EM-1 and EM-2 are Orion's first two flights. However, SLS and Orion have a requirement to be able to do all these events in darkness. During the mission, the length of time Orion is in eclipse may be a mission constraint for power and thermal concerns. Relative to power, Orion may not have battery capacity to survive a multi-hour eclipse of the sun since Orion's main power source is its solar arrays. Relative to thermal, the solar arrays might become too brittle since the temperatures in shadowed deep space are extremely cold.

One way to avoid violating a mission constraint is to find specific trajectories that satisfy them nominally. Other mission constraints are seasonal and might require cutouts in mission opportunities for multiple months in a given year. Trajectory reshaping and varying mission duration are also options. If there is propellant margin above what the nominal mission requires, a trajectory can be designed to avoid violating certain constraints.

Mission Design Automation

In order to meet the increasing demands for mission specific pre-flight products to aid mission operations and real-time data needs, the mission design team is developing an automated trajectory design tool. This tool helps automate the process of modifying existing trajectories and re-running them in Copernicus for new launch dates and times, initiating trajectory scans, post processing the scan data, and delivering products to be used by Orion subsystems and the flight operations team. Flight operations uses the products to schedule ground station tracking assets, install and upload burn trajectory targets throughout the mission, and use pre-converged optimal trajectories to handle time critical abort situations. Figure 12 shows the process for how trajectories from a scan are filtered through the process to eventually result in a set of selected missions that conform to all the desired requirements and integrated mission constraints. For efficiency, this process needs to be automated and to be nimble enough to respond to last minute changes to the trajectory inputs as the day of launch approaches, for example, updated vehicle mass properties and propellant loading changes. Figure 13 shows a zoomed in look at what types of trajectories need to be created and analyzed for each launch date.
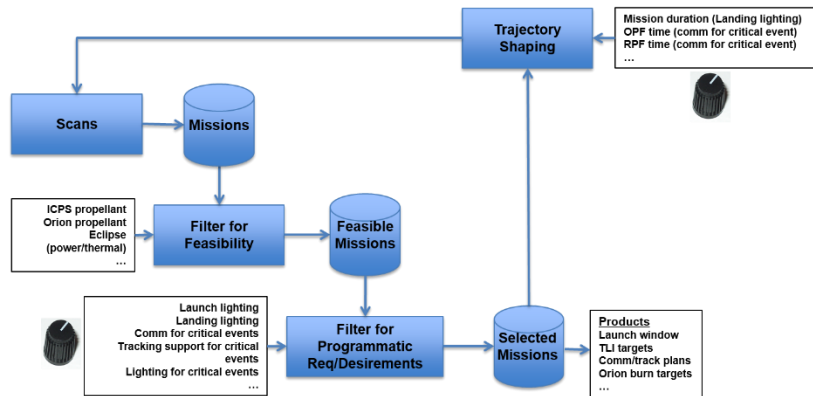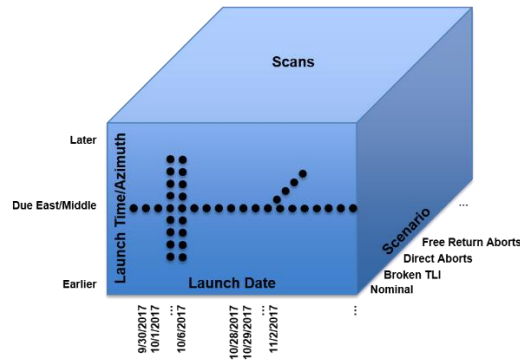

Figure 12. Automated Mission Design Flow Diagram

Figure 13. Trajectory Scan

CONCLUSION

Orion's mission has changed multiple times since its inception due to large programmatic changes and smaller vehicle component level changes. With EFT-1 successfully flown and EM-1 workflow transitioning from design to testing, verification, and pre-flight operations, some parts of the Orion mission design are starting to solidify. However, what Orion will be specifically required to fly for EM-2 and beyond is still being determined. This demonstrates the flexibility in the Orion design to be able to fly not just one type of DRM, but also a large array of cis-lunar trajectories in

the coming future. The Exploration Mission mindset of designing Orion to a specific capability rather than a specific mission has allowed this flexibility.

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