

# MOON AGE AND REGOLITH EXPLORER (MARE) MISSION DESIGN AND PERFORMANCE

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On December 11, 1972, Apollo 17 marked the last controlled U.S. lunar landing and was followed by an absence of methodical in-situ investigation of the lunar surface. The Moon Age and Regolith Explorer (MARE) proposal provides scientific measurement of the age and composition of a relatively young portion of the lunar surface near Aristarchus Plateau and the first post-Apollo U.S. soft lunar landing. It includes the first demonstration of a crew survivability-enhancing autonomous hazard detection and avoidance system. This report focuses on the mission design and performance associated with the MARE robotic lunar landing subject to mission and trajectory constraints.

## INTRODUCTION

This report examines the mission design and associated performance requirement for a robotic spacecraft delivered to a post-trans-lunar injection (TLI) target and bound for a precision lunar landing at a selected location to support surface in-situ sample analysis. The trajectory design for the Moon Age and Regolith Experiment (MARE) includes a combination of a flight profile similar to that of Apollo<sup>1</sup> and, for similar reasons, combined with a unique powered descent flight profile design, constructed to provide the spacecraft with a high accuracy landing employing a relative navigation sensor suite, that also provides hazard detection and avoidance capability similar to that of the Project M<sup>§</sup> trajectory. The mission analysis in this report reflects an example launch readiness targeted for 2021. The mission design produces monthly mission opportunities with multiple daily launch opportunities for each monthly opportunity.

MARE begins with a due east launch of an Atlas V 411 (see Figure 1) which delivers the MARE spacecraft to a temporary low Earth orbit (LEO). The launch is timed such that the LEO parking orbit will be nearly coplanar with the lunar transfer orbit. The upper stage/MARE spacecraft stack then coasts to the preferred phase location for the trans-lunar injection (TLI) burn, which achieves a transfer target to a lunar intercept anywhere from 3 to 8 days after Earth departure, depending upon which of several daily launch opportunities, in a particular month, is accessed. After TLI, the MARE spacecraft and the Earth Departure Stage (EDS) separate. After achieving a safe separation distance, the upper stage performs a retargeting maneuver for a safe disposal. The MARE spacecraft, now on its trans-lunar coast toward lunar orbit insertion (LOI), performs all maneuvers from

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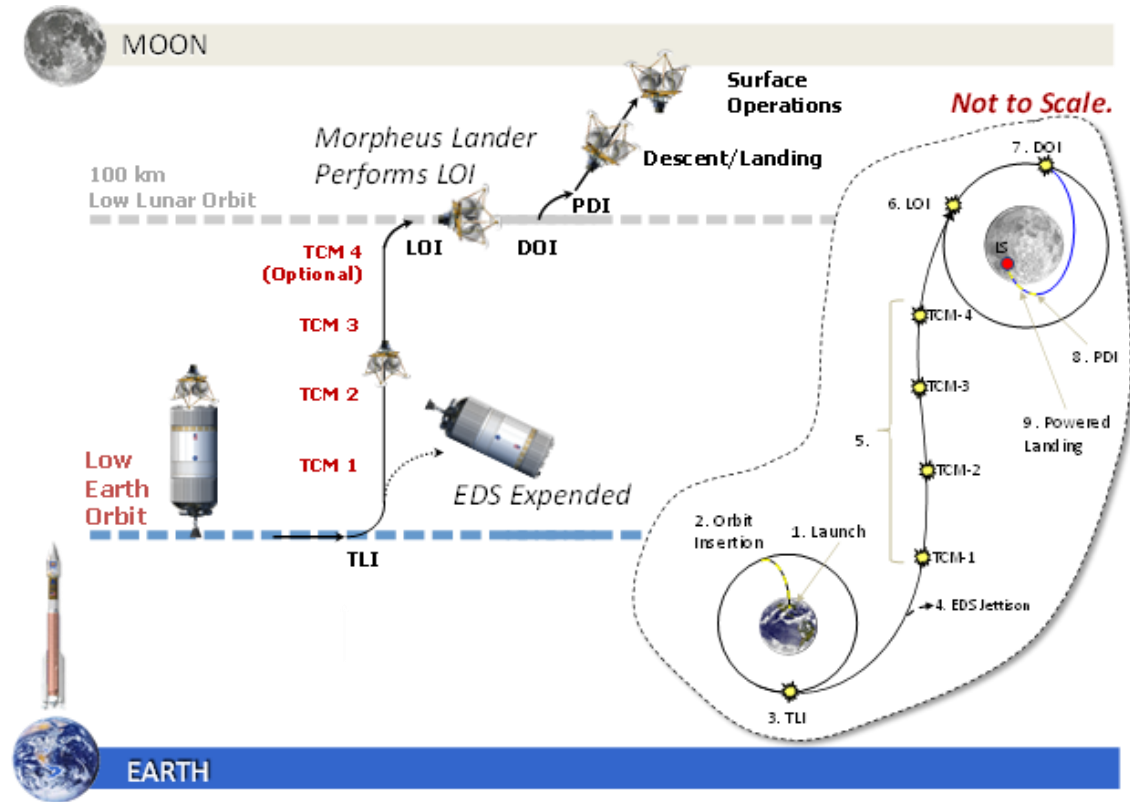
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§ [Project M Mission Design – https://robonaut.jsc.nasa.gov/media/Project-M-White-Paper.pdf](https://robonaut.jsc.nasa.gov/media/Project-M-White-Paper.pdf)

this point forward. Along the way, the outbound trajectory design accommodates up to four trajectory correction maneuvers (TCM). TCMs are only performed if the spacecraft trajectory is significantly dispersed from its planned trajectory.



**Figure 1. MARE mission overview: Bat chart (left) and Earth-moon rotating frame (right).**

At lunar arrival, the LOI maneuver places the MARE spacecraft into a retro-grade 100x100 km low lunar orbit (LLO). The retro-grade orbit provides that the subsequent landing phase will occur in sunlight with the sun generally behind the spacecraft at a low elevation, supporting terrain relative navigation sensors and a subsequent landing near the lunar dawn. Additionally, the selected LLO supports a minimum plane change requirement for the landing (see Figure 2). The spacecraft remains in LLO for approximately 3-4 revolutions (revs) during which time orbit determination (navigation) is conducted in support of the subsequent de-orbit and powered landing.

The descent orbit initiation (DOI) maneuver reduces the periapsis from 100 km to about 15 km altitude (relative to the surface). Variation in the post DOI periapsis altitude does not have a strong impact on the powered descent  $\Delta V$  cost, so a positive periapsis provides a once around capability in the event of a failed powered descent initiation (PDI) maneuver, thus enhancing the possibility of mission success with negligible performance impact.

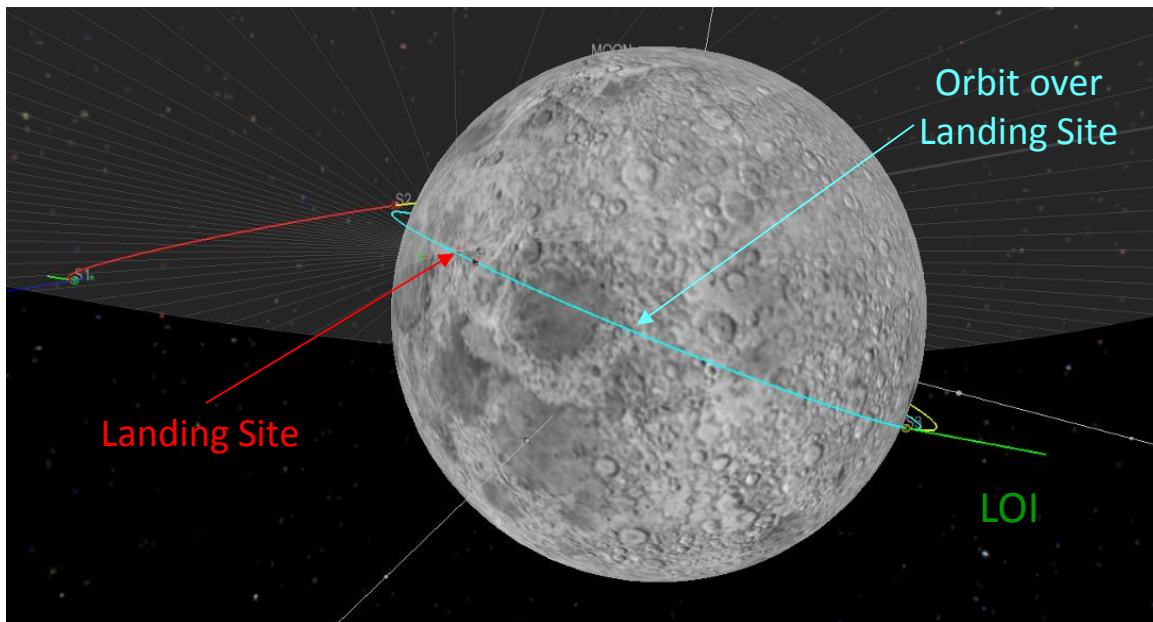
PDI marks the beginning of the powered descent arc: a continuous main engine burn which ends with touchdown on the surface of the Moon. PDI occurs near periapsis, about a half a rev after the DOI maneuver (about an hour). The powered descent arc, targeted to the Aristarchus plateau (latitude = 23.4°, longitude = -60°, altitude = 0 m), consists of the following segments: Braking, Pitch Up/Throttle Down, Approach, Pitch to Vertical, and Vertical Descent to Touchdown. Touchdown

on the surface begins the surface operations phase. PDI initiates the Braking Phase, a propellant-optimal maneuver, which uses a high throttle setting to efficiently reduce energy. Then, the Approach Phase pitches the vehicle up to  $80^\circ$ \* at reduced throttle and sets up a Hazard Detection (HD) light detection and ranging (LiDAR) scan at 160 m slant range and  $55^\circ$  elevation from the landing site. This is followed by a 50 m Vertical Descent Phase that ends with a touchdown at the lunar surface, with a 1 m/s downward velocity. The landing is targeted such that touchdown occurs shortly after lunar dawn (with a Sun elevation of  $10^\circ$ ), thus maximizing the amount of sunlight time for surface operations, given landing trajectory constraints.

## MISSION DESIGN ASSUMPTIONS

The mission and trajectory design assumptions reflect spacecraft capability and operations requirements. They are subdivided here into the following segments: Mission Assumptions, Launch and Lunar Transfer Assumptions, Lunar Arrival Assumptions, and Lunar Descent Assumptions. The assumptions allow our mission design team to produce, to the greatest extent possible, a realistic reference mission design and associated performance trades analyses.

The nominal trajectory design and performance trades provide a framework for spacecraft subsystem design and refinement and allow the MARE team to create a spacecraft design that is ideally suited to its mission. For example, the lunar landing epoch is based upon a compromise of mission opportunity associated with Earth-Moon geometry, minimizing sun elevation angle at landing (to maximize time in sunlight for immediate post-landing surface operations), and sun elevation angle limits imposed by terrain relative navigation (TRN) and possibly other landing sensor suites.



**Figure 2. Lunar transfer (red, later switching to yellow) to LOI maneuver into LLO that sets spacecraft up for coplanar landing.**

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\* In this body-fixed coordinate frame, a  $0^\circ$  pitch angle represents a horizontal orientation of the spacecraft/thrust pointing and a  $90^\circ$  angle represents a vertical orientation.

## Mission Assumptions

The mission assumptions cover the overall driving trajectory design assumptions and are listed here in bullet form.

- Lunar Landing Site
  - Landing coordinates: latitude =  $23.4^\circ$ , longitude =  $-60^\circ$ , altitude = 0 m  
This landing site represents a desirable region conducive to obtaining desired mission data. It is anticipated to be relatively flat with scattered rocks.
  - Landing epoch baseline: 2021  
The mission design and performance trade studies focus on an example year of mission execution, 2021.
  - Landing epoch selected when Sun elevation angle at lunar touchdown =  $10^\circ$ 
    - The  $10^\circ$  touchdown elevation angle represents a best compromise for the minimum elevation angle to maximize surface sunlit time after landing and a sufficiently large angle to provide good geometry for landing navigation sensors.
    - Apollo landings required sun elevation angles between  $7^\circ$  and  $20^\circ$ .
    - A  $5^\circ$  mask angle is applied to the landing site to account for terrain blockage of sun.
- Adjustable Retro-grade Inclination Arrival
  - The retro-grade landing provides an approach over the lit part of the lunar surface with Sun generally behind spacecraft in support of navigation sensors requiring visual surface access (e.g., TRN). Note: A necessary impact of the retro-grade landing will be that the LOI and DOI maneuvers are conducted on lunar far side, out of Earth view (and *communications*).
  - The adjustable arrival inclination provides for a coplanar LOI and Deorbit/Landing, which will generally produce a lower  $\Delta V$  requirement.

## Launch and Lunar Transfer Assumptions

- MARE Vehicle Masses and Engine Parameters (after TLI and separation from upper stage, not counting any launch support hardware)
  - Wet mass = 3,453 kg, Isp = 325 s
  - Main engine max thrust = 1,775 lbf, 5:1 throttle range
  - Engine Isp from quadratic provided by Propulsion, with percent thrust scaled to 1,775 lbf
  - Engine throttle response time treated as instantaneous in mission performance models
- Expendable Launch Vehicle (ELV) & Ascent
  - ELV has fixed launch azimuth for a given launch opportunity  
This is a constraint assumed to be imposed by the launch vehicle provider.
  - Due east launch assumed for most opportunities
- LEO parking orbit
  - Approximately 200 km,  $28.5^\circ$  inclination, circular (for most opportunities)  
This reflects a due east launch from the Kennedy Space Center (KSC).
  - Time in LEO parking orbit post insertion  $\geq 5$  minutes but  $\leq 105$  minutes  
This time span covers a single departure opportunity, assuming a successful TLI on the first rev.
  - No current provision for failed TLI  
Failure of a commercial ELV upper stage to restart is considered unlikely. Additionally, the ability to fix a failure from the ground before the stage batteries are depleted even more unlikely.

- Earth-Moon Transfer Trajectory
  - Transfer durations will vary. Each landing opportunity may have multiple launch opportunities corresponding to different transfer durations.
  - Most likely, useful transfer durations will be between 3 and 7 days

### **Lunar Arrival Assumptions**

- LLO: Lunar Orbit Insertion (LOI)
  - Insertion into a retro-grade 100 km circular orbit, in the best orientation for descent  
The longitude of the ascending node (LAN) and the inclination of the post LOI LLO is selected to minimize the LOI  $\Delta V$  as well as the deorbit and landing  $\Delta V$ .
  - LLO will be in a retro-grade direction, so that approach to landing site is over lighted terrain to support visual based navigation (e.g., TRN).
  - Number of revs in LLO  $\geq 3$  but  $\leq 4$  (TBR)  
Three to four revs in LLO reflects the time required for orbit determination to provide a sufficiently accurate deorbit time of ignition (TIG) and maneuver.
  - LOI and DOI burns occur on the lunar far side, out of Earth view
  - No current  $\Delta V$  provision for plane change for missed DOI or PDI
- Lunar Landing Site, Lighting, and Epoch
  - Landing coordinates: latitude =  $23.4^\circ$ , longitude =  $-60.0^\circ$ , altitude = 0 m
  - Landing opportunities in 2021 are current baseline
  - Landing epoch selected when sun elevation is  $10^\circ$ , and rising, at landing site
    - Apollo landings required sun elevation angles between  $7^\circ$  and  $20^\circ$  and sun behind spacecraft
    - TRN sensor may require sun elevations  $\geq 10^\circ$  or  $20^\circ$
    - In order to maximize the useful time in the first lunar day, we should probably pick the lowest sun elevation we are comfortable with for Nav purposes and power generation.
  - Landing epochs were determined based on data from the JPL Horizons data system<sup>2\*</sup> for the analysis baseline landing site ( $23.4^\circ$  N,  $60.0^\circ$  W).

### **Lunar Descent Assumptions**

- Lunar Descent (Note: These assumptions are for the simplified descent model in Copernicus)
  - Deorbit burn (DOI) to reduce periapsis altitude to 15 km  
There is little impact to the powered descent performance if the deorbit periapsis is maintained as positive. The 15 km periapsis provides an opportunity for a possible retry given a failed PDI.
  - Powered descent phases: Braking, Pitch Up/Throttle Down, Approach, Pitch to Vertical, Vertical Descent
  - Braking Phase
    - The Braking Phase is throttled to 80% in nominal trajectory, for control authority. If navigation errors or vehicle anomalies cause the spacecraft to begin to overshoot its landing site, there is sufficient room to throttle up to compensate.
    - Gravity turn with linear angular ramp superimposed allowed for Braking phase
  - Pitch Up/Throttle Down, Approach, and Pitch to Vertical
    - Constant thrust level (adjusted as optimization variable)
    - Pitch rotation rates,  $5^\circ/\text{sec}$  for Pitch Up/Throttle Down and Pitch to Vertical

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\* Retrieved from <http://ssd.jpl.nasa.gov/?horizons>

- 10 seconds from Pitch Up/Throttle Down to start of the Automated Landing and Hazard Avoidance Technology (ALHAT) Hazard Detection and Avoidance (HDA) function
  - HDA function start at 300 m line-of-sight range from target landing site
  - Hazard avoidance divert point 150 m line-of-sight range from target landing site
  - At least 5 seconds from HDA function start to hazard avoidance divert point
  - Assume that the ALHAT Hazard Relative Navigation (HRN) function is not available because of the fixed flash LiDAR sensor (no position updates after HDA) – use IMU, altimetry, and velocimetry for accurate local navigation. We may revisit this assumption during a follow-up design cycle if we add a beam steering mirror to the flash LiDAR sensor
  - Approach Phase pitches up to 80° at reduced throttle, sets up HD LiDAR scan at 160 m slant range and 55° elevation from landing site
- Final vertical descent starts at 50 m above surface, 3 m/s descent rate at top decelerating to a 1 m/s descent rate at touchdown

### DELTA-V ( $\Delta V$ ) SIZING BUDGET

The spacecraft has the following delta-V ( $\Delta V$ ) budget (see Table 1). Currently, there are 3 planned TCMs (with an option for a 4<sup>th</sup>) with an overall  $\Delta V$  budget of 7 m/s. The Lunar Reconnaissance Orbiter (LRO) TCM budget of 30 m/s is significantly larger. The TCM budget for this mission could be increased to 30 m/s as needed, using  $\Delta V$  from the LOI budget, which is currently 100 m/s in excess of its planned nominal  $\Delta V$  budget. Ongoing analysis will confirm the TCM and LOI  $\Delta V$  budget and will also assess the  $\Delta V$  cost of delayed TLI and DOI.

**Table 1**  
 **$\Delta V$  Sizing Budget.**

| <u>Maneuver</u>                | <u>Vehicle <math>\Delta V</math></u> |
|--------------------------------|--------------------------------------|
| TCM1                           | 5 m/s                                |
| TCM2                           | 1 m/s                                |
| TCM3                           | 1 m/s                                |
| LOI                            | 1000 m/s                             |
| DOI                            | 20 m/s                               |
| PDI to Pitchover/Throttle-Down | 700 m/s                              |
| Pitchover/Throttle-Down        | 700 m/s                              |
| Vertical Landing               | 600 m/s                              |
| LOI Dispersion                 | 20 m/s                               |
| Landing Dispersion             | 20 m/s                               |
| RCS Control                    | 10 m/s                               |

## PERFORMANCE TRADES

A number of  $\Delta V$  performance trades were conducted to determine the spacecraft's ability to complete its part of the lunar transfer, insertion, deorbit, and landing burns. These trajectory trades were conducted using the Copernicus Trajectory Design and Optimization System, a trajectory optimization tool developed and maintained at the NASA/Johnson Space Center<sup>3, 4, 5</sup>

The ephemerides used in the development of these trajectories for the celestial bodies involved (Earth, Moon, and Sun), derived from the DE 421 ephemeris set produced by the Jet Propulsion Laboratory.<sup>6</sup> The coordinate frame specifications for celestial body orientations used were IAU body-fixed frames as specified in the "Report of the IAU Working Group on Cartographic Coordinates and Rotational Elements: 2009", suitable for initial trajectory studies.<sup>7</sup> The Copernicus tool uses the SPICE data system, and SPICE input data files (called "kernels") are available for both of these ephemeris inputs.\*

The focus of the trades, for this report, lay in the burns conducted in lunar vicinity. Once in a 100x100 km altitude lunar parking orbit (i.e., post-LOI), the deorbit and powered descent to landing  $\Delta V$  does not change significantly. For example the difference in powered descent  $\Delta V$  between a polar (90° inclination) and a retro-grade near equatorial (e.g., 180° inclination) landing (due to effects of slow lunar rotation) is only about 5 m/s (with the near equatorial retro-grade landing having the higher cost) out of approximately 2000 m/s for the entire deorbit and descent to landing performance requirement. The greater variation in  $\Delta V$  for the Orion spacecraft occurs with the LOI burn, which is dependent upon a number of orbit trajectory parameters such as launch epoch, Earth-Moon flight time, retro-grade vs posi-grade lunar parking orbit (inclination), lunar and landing site as well as operational requirements such as sun elevation angle at lunar landing and mask angle at the lunar landing site. Additionally, these parameters can also affect the trans-lunar injection (TLI)  $\Delta V$  requirement.

Since the mission target date lay in the year 2021, the mission design team conducted a trade study of TLI and LOI  $\Delta V$  costs across the entire year. Adherence to operational constraints such as specific lunar lighting conditions at landing (to maximize the sunlit operations duration) resulted in, essentially, monthly sets of launch opportunities. Both ascending and descending node Earth departure (TLI) opportunities were examined in an effort to produce the greatest available mission design variation, hence the lowest possible TLI C3 target and/or minimum LOI  $\Delta V$ .

Figure 3 shows multiple TLI opportunities and associated LOI costs for monthly sets of opportunities. For all cases examined (both ascending and descending node TLI), the TLI C3 ranges from approximately -2.12 to -1.80 km<sup>2</sup>/s<sup>2</sup> and peaks near the end of 2021, in December. At this time the LOI  $\Delta V$  cost is lowest with a maximum around 833 m/s. The most demanding LOI  $\Delta V$  requirement occurs in the May through July 2021 timeframe. Coincidentally, the TLI C3 requirement is lowest in this same region. So the TLI C3 and the LOI  $\Delta V$  requirements generally run opposite to each other; when the TLI is cheaper, the LOI is more expensive, and vice-versa.

These best and worst ranges for both TLI C3 and LOI  $\Delta V$  are shown in Figure 4. In the May through July 2021 timeframe, the TLI C3 requirement is minimized (ranging from -2.12 to -1.9 km<sup>2</sup>/s<sup>2</sup>) while the LOI  $\Delta V$  is maximized (ranging from approximately 835 to 885 m/s) for 5 daily

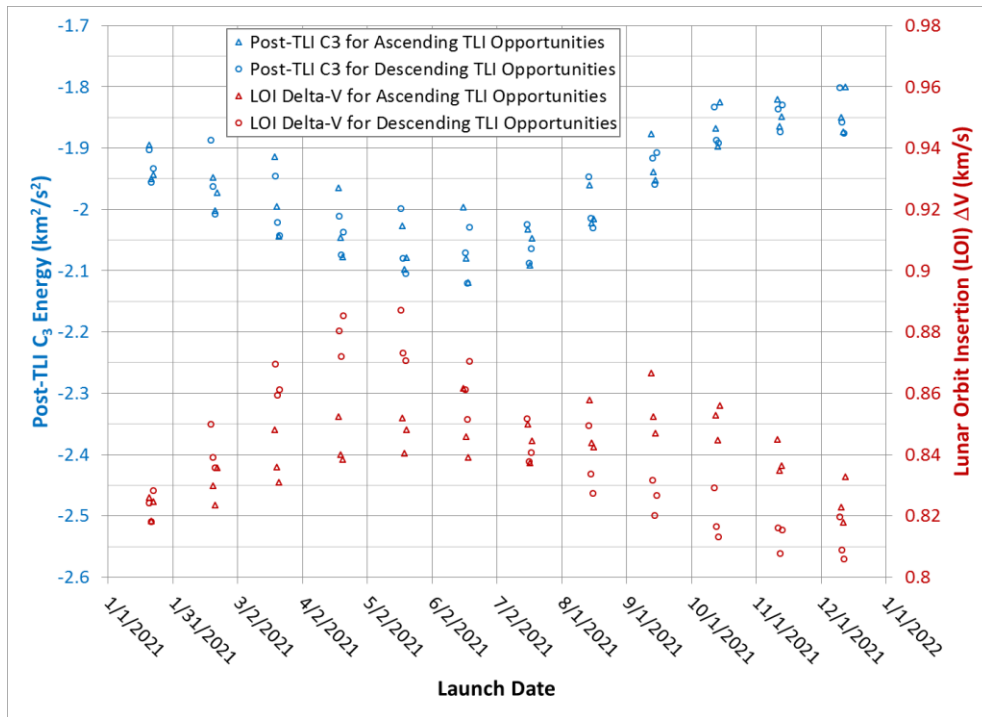
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\* Note that state data for the significant celestial bodies is provided for all time points in the trajectory history files.

Earth departure opportunities. Conversely, the November through December timeframe results in a maximum TLI C3 requirement (ranging from about -1.88 to -1.70  $\text{km}^2/\text{s}^2$ ) while the LOI  $\Delta V$  is minimized (ranging from around 805 to 843  $\text{m/s}$ ). A launch vehicle that can deliver this proposed lunar lander payload onto a maximum C3 of -1.7  $\text{km}^2/\text{s}^2$  could provide a TLI delivery capability for the spacecraft anytime throughout the 2021 year\*. The maximum 885  $\text{m/s}$  LOI  $\Delta V$  lies within the current 1000  $\text{m/s}$  planned LOI  $\Delta V$  budget.

In order to maintain flexibility in mission opportunities, the landing epoch design point reflects the most demanding LOI  $\Delta V$ . Assuming the launch vehicle can provide the TLI C3 requirement, then the current LOI  $\Delta V$  budget allows for 5 consecutive daily launch opportunities at every monthly opportunity throughout 2021 (see Figure 5). The daily opportunities show a range of LOI  $\Delta V$ s from 835 to 885  $\text{m/s}$ . Note that the landing epoch for this case remains fixed at the end of July 22, 2021. This reflects the need to provide a selected (in this case,  $10^\circ$ ) sun elevation at lunar landing, just after the lunar dawn.

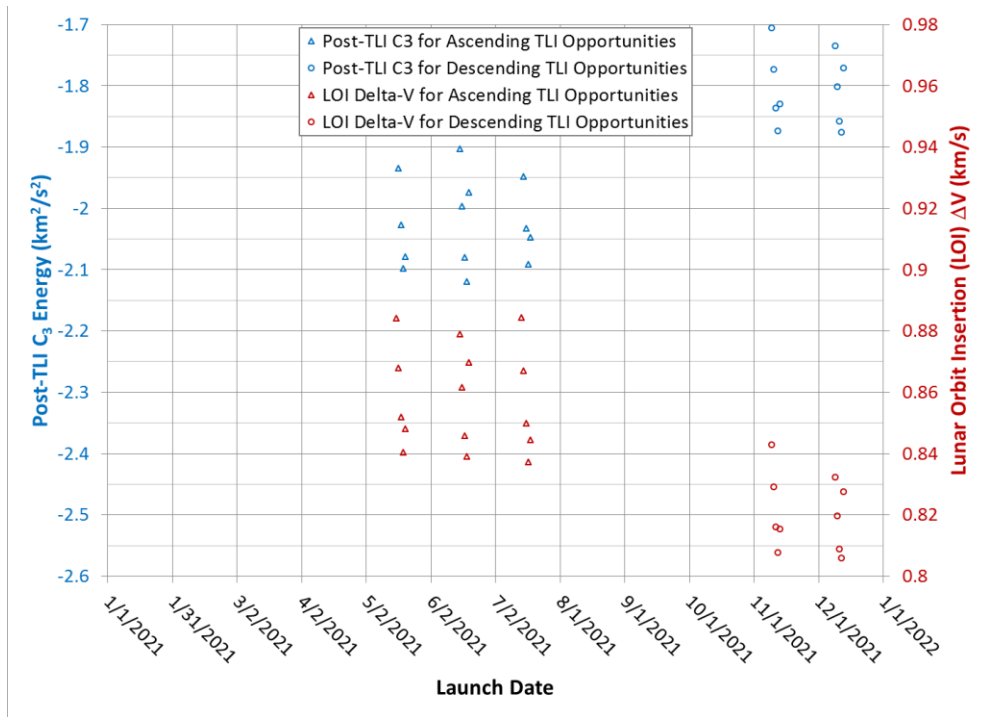
These performance trades show that the current spacecraft  $\Delta V$  budget possesses good flexibility to execute missions anytime throughout the 2021 year. Threats to this flexibility include drops in the  $\Delta V$  budget or increases in spacecraft mass. Another impact to the  $\Delta V$  budget would be including the capability of the spacecraft to accommodate a delay in TLI and/or a delay in deorbit/powering landing.



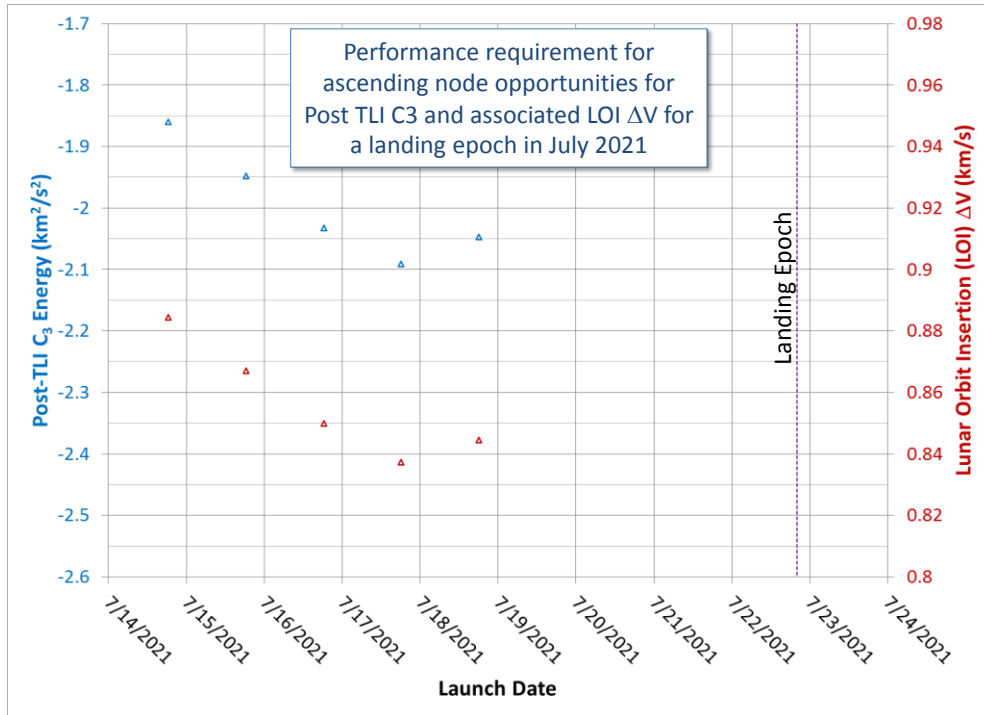
**Figure 3. TLI and LOI Performance Scan for 2021 – 3 Ascending and 3 Descending TLI Opportunities per Landing Opportunity at  $10^\circ$  Sun Elevation for  $23.4^\circ$  N,  $60.0^\circ$  W.**

\* Current estimates show that a target launch vehicle (i.e., an Atlas 411) would be able to deliver the current spacecraft design mass to a C3 of -1.7  $\text{km}^2/\text{s}^2$ . Reference: NASA Launch Services Program. (2014, February 1). *Launch Vehicle Performance Website*. Retrieved from <http://elvperf.ksc.nasa.gov/Pages/Default.aspx>





**Figure 4. Worst TLI and LOI Performance Cases for 2021: 5 Launch Opportunities per Landing Opportunity at 10° Sun Elevation for 23.4° N, 60.0° W**



**Figure 5. TLI and LOI Performance for Launch Opportunities in July 2021 (Landing at 10° Sun Elevation for 23.4° N, 60.0° W).**

## Launch and Landing Opportunities

The launch and landing opportunities are driven by a number of sometimes interdependent parameters including, but not limited to vehicle capability (e.g.,  $\Delta V$  budget), operational constraints or requirements (e.g., landing at or near the lunar dawn to maximize sunlit operations time, retro-grade landing approach to accommodate visual based sensors [TRN], accommodating multiple TLI revs in Earth orbit and multiple deorbit to PDI revs in lunar orbit), and planetary geometry (e.g., lunar inclination and the moon's distance from the Earth at lunar arrival). These parameters affect the  $\Delta V$  requirement on the spacecraft and determine if and when a launch/landing opportunity is available.

In this mission design, the spacecraft is launched first to a temporary Earth orbit in order to propagate to a phase location that provides the minimum possible TLI C3 requirement. This recommended approach is contrasted with a direct launch to TLI sequence, which is not recommended as any potential slight reduction in TLI C3 or LOI  $\Delta V$  requirement would be accompanied by a restrictive performance-based launch time. Favorable geometry for the direct to TLI launch is much more infrequent than that of a launch to TLI via an intermediate Earth phasing orbit. The added requirement for a specified landing epoch (to accommodate landing lighting conditions) only serves to make direct to TLI opportunities more infrequent. The phasing Earth orbit right ascension of the ascending node (RAAN) can also be selected to minimize the TLI C3 and/or LOI  $\Delta V$ , by proper selection of the launch time.

A scan of possible landing epochs was conducted using a range of sun elevation angles (at landing) and landing mask angles. For a number of reasons, the Apollo program targeted a sun elevation angle during the landing of the lunar module (LM) to be between  $7^\circ$  and  $20^\circ$ . This, combined with a retro-grade orbit approach insured that the sun would be behind the LM during approach and landing, thus minimizing or eliminating sun glare on the crew. For the MARE mission, a similar approach is used, though for slightly different reasons. A  $10^\circ$  sun elevation angle was selected to provide sufficiently short surface feature shadows so that the TRN system would properly recognize that feature, while keeping the elevation angle low enough to move the landing as close to the lunar dawn as possible, thus maximizing the duration of daylight operations.

The region around the candidate landing sites is considered to be relatively flat, so a  $5^\circ$  mask angle was included in the landing opportunity calculations. This is considered to be a relatively conservative estimate and will result in a reduction in the duration of daylight operations. Note that a  $10^\circ$  sun elevation angle already exceeds the  $5^\circ$  mask angle (by  $5^\circ$ ), so the mask angle will not restrict the lighted operations time until the end of the first lunar day.

The data shown in Table 2 represent the available lunar landing epochs, during the year 2021, which adhere to constraints of a  $10^\circ$  sun elevation angle and a  $5^\circ$  mask angle. These epochs occur approximately a month apart (due primarily to the  $10^\circ$  sun elevation angle requirement at landing).

For the 12 available landing opportunities (cycles) in 2021, the sun azimuth relative to the landing site ranges from  $92.67^\circ$  to  $96.07^\circ$  (slightly south of east). The actual relative azimuth angle during landing will be determined by the approach azimuth for a given mission. For example, a LLO inclination of  $23.4^\circ$  would result in a spacecraft final approach azimuth coming out of the east. So, in this case, the sun would be within a couple degrees of being directly behind the spacecraft. A polar orbit landing (inclination =  $90^\circ$ ) would have the sun nearly perpendicular to the spacecraft approach trajectory. In general, however, there is little variation in the sun azimuth over all opportunities in 2021.

There is also little variation in the 1<sup>st</sup> day sunlit durations for the 12 landing epochs in 2021. They range from 13.34 to 13.52 days. The subsequent dark times range from 15.51 to 15.78 days. A robust power and thermal design should accommodate any of these landing epochs.

**Table 2.**  
**Lunar Landing - sun elevation and azimuth, mask angle, and sunlit and dark durations**  
**as a function of landing epoch for a lunar landing site at 23.4° N, 60.0° W**

| Cycle | Landing epoch               | Sun Azimuth | Loss of Power/Sundown Epoch | Sunlit/Dark Duration |               |
|-------|-----------------------------|-------------|-----------------------------|----------------------|---------------|
|       | Sun Elevation Angle (deg)   |             | Mask Angle (Deg)            | Mask Angle (Deg)     |               |
|       | 10                          |             | 5                           | 5                    |               |
|       | (deg) ... and rising        | (deg)       | (deg) ... and dropping      | (Days - Sunlit)      | (Days - Dark) |
| 1     | January 26, 2021 20:18:44   | 95.67       | February 09, 2021 05:18:41  | 13.37                | 15.78         |
| 2     | February 25, 2021 10:52:29  | 96.07       | March 10, 2021 19:07:16     | 13.34                | 15.76         |
| 3     | March 27, 2021 00:16:07     | 95.97       | April 09, 2021 08:24:54     | 13.34                | 15.72         |
| 4     | April 25, 2021 12:21:14     | 95.42       | May 08, 2021 21:02:43       | 13.36                | 15.65         |
| 5     | May 24, 2021 23:21:04       | 94.60       | June 07, 2021 09:02:46      | 13.40                | 15.58         |
| 6     | June 23, 2021 09:44:22      | 93.72       | July 06, 2021 20:36:36      | 13.45                | 15.53         |
| 7     | July 22, 2021 20:06:47      | 93.02       | August 05, 2021 08:01:12    | 13.50                | 15.51         |
| 8     | August 21, 2021 07:02:38    | 92.67       | September 03, 2021 19:34:43 | 13.52                | 15.53         |
| 9     | September 19, 2021 18:58:10 | 92.78       | October 03, 2021 07:33:15   | 13.52                | 15.57         |
| 10    | October 19, 2021 08:06:18   | 93.34       | November 01, 2021 20:08:16  | 13.50                | 15.64         |
| 11    | November 17, 2021 22:22:45  | 94.20       | December 01, 2021 09:24:15  | 13.46                | 15.72         |
| 12    | December 17, 2021 13:25:03  | 95.13       | December 30, 2021 23:16:17  | 13.41                |               |

**EXAMPLE NOMINAL MISSION TIMELINE WITH GN&C CONSIDERATIONS**

The nominal mission provides a good common platform to compare the individual performance of the various spacecraft subsystems. Additionally, it provides a template for doing system integration. Note that the nominal mission is not intended for vehicle sizing or to provide a ΔV budget. That said, for this proposal, the example nominal mission design is based upon a landing epoch of July 22, 2021 20:06:47. There are 3 daily launch opportunities that support this landing epoch, that are within the spacecraft ΔV budget. The July 2021 epoch is one of the more stressing cases on the spacecraft, with respect to ΔV requirement.

*Launch to Orbit.* The nominal mission begins with an Atlas V 411 due east launch to a low earth orbit (LEO) target in a 28.5° inclined orbit. In LEO the MARE spacecraft, on top of a Centaur upper stage, coasts for up to a full revolution (rev) to a TLI time of ignition (TIG).

*Lunar Transfer.* The launch vehicle upper stage provides the spacecraft with the entire TLI maneuver, which is targeted to a 100 km altitude circular LLO. The intermediate lunar parking orbit is selected over a direct landing mission to provide a degree of freedom for setting up the proper phase location in the orbit at which to execute the TIG for initiating the landing sequence.

The longitude of the ascending node (LAN) and inclination are designed to provide a minimum ΔV LOI, deorbit insertion (DOI), and powered descent. The DOI and powered descent ΔV is minimized by the proper selection of LAN and inclination to minimize any plane change associated with these maneuvers. The ΔV budget for the LOI, DOI, and powered descent phases is 1000 m/s, 20 m/s, and 2000 m/s, respectively.

The overall flight time from TLI to LOI (5.65 days) is adjusted to minimize the LOI  $\Delta V$ . The upper stage separates from the spacecraft after TLI and will be directed to either impact the lunar surface or fly a posi-grade lunar passage to a hyperbolic target that takes it outside the Earth-Moon system into helio-centric space.

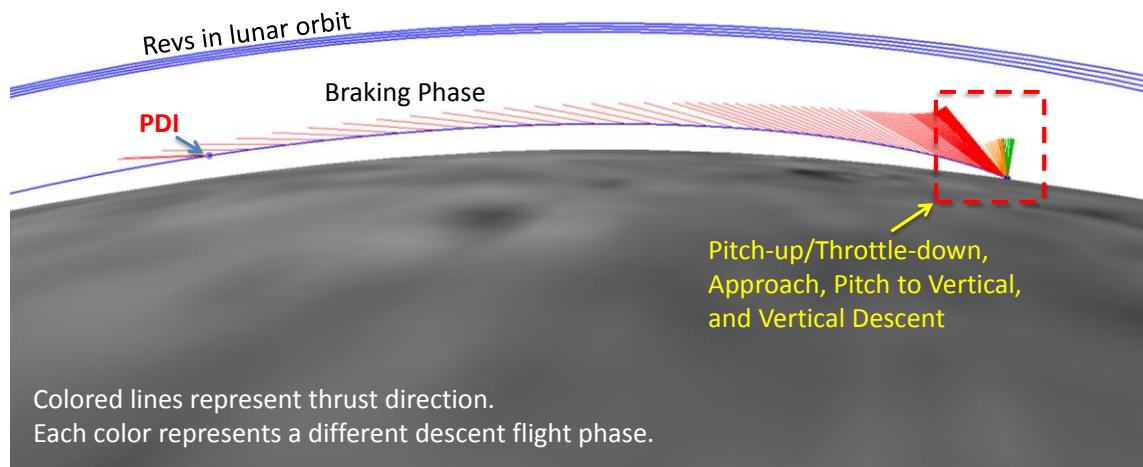
Up to 3 planned and 1 optional TCMs are provided for the transit from Earth to the moon. They are executed as needed, in the event of a sufficiently large navigation error. The overall budget for the TCMs is 30 m/s. During the transit, the spacecraft flies in a specified attitude for thermal management and to provide sufficient power to the spacecraft.

*LOI.* 5.65 days after TLI, the spacecraft executes a 5.5 minute LOI burn, placing it in a 100x100 km altitude LLO. It remains in LLO for 3-4 revs while orbit determination is conducted to provide a sufficiently accurate state vector for the PDI.

*DOI.* Following LLO coast, the spacecraft conducts a 5.4 second deorbit burn to create a 100x15 km transfer orbit. The spacecraft coasts from apoapsis to the 15 km periapsis region for PDI. The positive 15 km periapsis provides a possible second PDI attempt should the nominal attempt fail. There is not a significant difference in powered descent  $\Delta V$  cost with variations in PDI altitude, so the minimal cost to maintain a positive periapsis for PDI is offset by the mission flexibility provided in the event of a failed PDI maneuver.

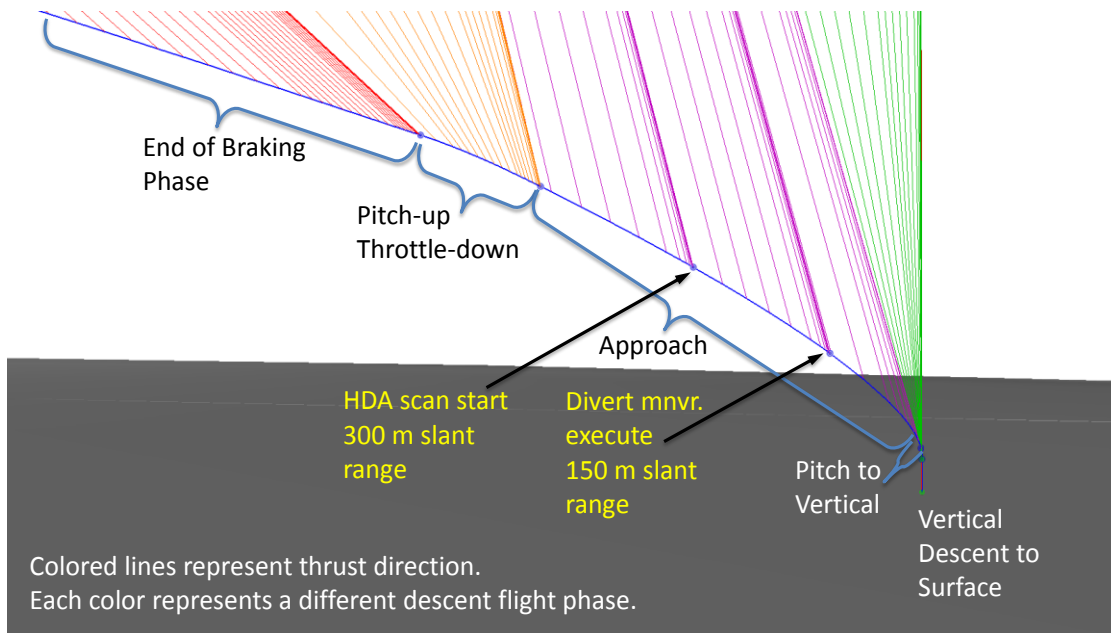
The onboard landing Navigation is initialized approximately 90 minutes before the DOI burn, based on the final ground-based spacecraft state update from a Deep Space Network (DSN) observation. After initialization, the landing Navigation filter processes state measurements from the vehicle IMU, along with two star trackers (until the PDI burn).

*Powered Descent to Landing.* After coasting for approximately 1 hour in the post-DOI transfer orbit, PDI occurs near periapsis and initiates the overall powered descent sequence (see Figure 6), which lasts 11 minutes and carries the spacecraft from 15 to 0 km altitude over approximately 522 km of surface range distance.



**Figure 6. PDI begins the powered descent and landing sequence.**

The powered descent phase consists of 5 distinct sequences: the Braking Phase, the Pitch-Up/Throttle-Down Phase, the Approach Phase, the Pitch to Vertical Phase, and the Vertical Descent Phase (Figure 7).



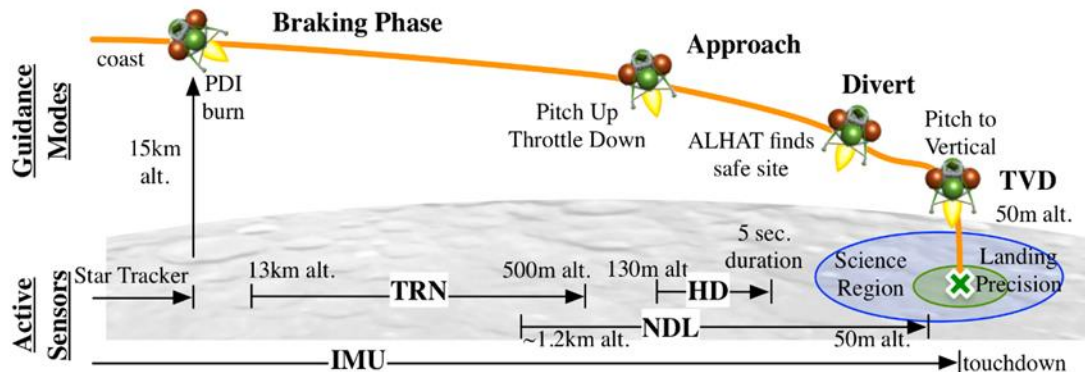
**Figure 7. Powered descent landing phases.**

The Guidance, Navigation, and Control (GN&C) aspect of the powered descent to lunar landing is illustrated in Figure 8 and includes the nominal plan for Guidance Modes and active GN&C sensors. The Guidance Modes include Braking (starting at the PDI burn), Pitch Up/Throttle Down, Approach, Divert, Pitch to Vertical, and Terminal Vertical Descent (TVD) to touchdown. The GN&C sensors include an Inertial Measurement Unit (IMU), a star tracker (prior to the initiation of powered descent burns), a passive-optical camera-based Terrain Relative Navigation (TRN) sensor, a Navigation Doppler Lidar (NDL) velocimetry/ranging sensor, and a HD sensor. The TRN, NDL and HD sensors are part of the ALHAT suite of sensor systems that provide global and local navigation knowledge to enable safe precision landing of the vehicle within the targeted science region.<sup>8</sup> The triggering of the Guidance Modes and phasing of the GN&C sensors is accomplished with the use of an onboard Autonomous Flight Manager (AFM) that monitors the descent timeline and navigation state. Additional insight into the MARE GN&C subsystem can be found in a companion paper<sup>9</sup>.

*Braking Phase.* The Braking Phase is an optimal performance phase that focuses on removal of the bulk of the horizontal velocity with an associated altitude reduction. This phase lasts approximately 9.75 minutes and reduces the relative velocity from 1693.3 to 16.4 m/s. This phase uses a throttle setting of 80% or 1440 lbs (6405 N) and holds this setting through this entire phase. The throttle setting below 100% allows for response to off nominal situations (e.g., thrust increases in the event of navigation errors or engine performance issues that result in potential overshooting of the landing site). The thrust pointing policy is a linear turn rate, expressed in a local vertical, local horizontal (LVLH) coordinate frame. During this phase, the TRN is active and feeding back, to the spacecraft, navigation state information based upon interpretation of ground track terrain observation. Late in this phase (about 10 seconds before the Pitch-Up/Throttle Down Phase, the ALHAT HDA function is initiated. It starts approximately 300 m line-of-sight range from the target landing site. The conclusion of this phase initiates a Pitch-Up/Throttle Down phase.

In addition to the TRN, additional navigation measurements (NDL, HD) come online at the altitudes indicated in Figure 8. The camera-based TRN sensor provides position estimates between

approximately 13 km altitude down to approximately 500 m altitude. The NDL sensor provides velocity and line-of-site range measurements from approximately 1.2 km altitude down to approximately 50 m altitude, and the HD sensor operates at an approximate altitude of 130 m (and slant range of 160 m to the targeted landing site).



**Figure 8. Powered Descent Concept of Operations Showing Guidance Modes and Active Sensors (Reference 9).**

*Pitch-Up/Throttle-Down Phase.* This 45 second phase transitions both vehicle attitude and thrust magnitude and initiates the final portion of descent flight profile. The throttle is reduced from 80% to 31% and from a pitch angle to  $39.3^\circ$  to  $80^\circ$  degrees over the entire phase. Once lowered, the optimized throttle level is maintained throughout this phase. The steeper pitch angle provides better spacecraft orientation with regards to the surface for hazard detection (HD) and landing sensors. The pitch rotation rate is limited to  $5^\circ/\text{sec}$  (as well as for the Pitch to Vertical Phase). The hazard avoidance divert point occurs at a 150 m line-of-sight range from the target landing site. At least 5 seconds is required from HAD function start to the hazard avoidance divert point.

*Approach Phase.* The Approach Phase pitches the spacecraft up to  $80^\circ$  at a 31% throttle level. This sets up the HDA LiDAR scan at 160 m direct line-of-sight distance and  $55^\circ$  elevation angle from the landing site.

*Pitch to Vertical Phase.* This phase transitions the spacecraft from an  $80^\circ$  pitch angle to  $90^\circ$  (vertical) and a 50 m altitude target over 2 seconds. The NDL is shut down below approximately 50 m below which subsequent Navigation with IMU dead reckoning commences (as dust kicked up on TVD can obscure the NDL measurements).

The initial overlap of NDL and TRN measurements provide a blended Navigation solution that minimizes position error growth following TRN shutdown. The direct NDL velocity measurement provides a precise enough knowledge state to ensure landing within the 20 m radius (3-sigma) landing ellipse following NDL shutdown and IMU dead reckoning during TVD. The HD sensor obtains a 3D point cloud of surface terrain data (surrounding the planned landing location) and processes an onboard solution for a safe landing location, which is targeted by AFM with a small, 10-meter divert (away from the planned, compromised nominal landing location). Landing safety analyses, including spacecraft geometry, terrain type and knowledge uncertainty indicates that the GN&C subsystem with HD can execute a safe landing to greater than a 99% probability, within a 20 m radius (3-sigma) landing ellipse (Reference 9).

*Vertical Descent Phase.* This phase completes the entire landing phase by taking the spacecraft from a 3 m/s vertical descent rate to 1 m/s over 21 seconds, covering 50 m of vertical descent to the lunar surface.

Soft touchdown occurs at 1 m/s downward velocity, with contact determined through logic developed and tested during the JSC Morpheus project. The spacecraft is oriented during TVD within +/- 5 degrees for pointing radiators to local North and solar array centerline along local East-West.

The nominal mission at a glance is shown in Table 3. The timeline represents daily mission opportunities, beginning on July 16, 2021. All missions are possible within the current proposed vehicle  $\Delta V$  budget. The mission timeline covers the Epoch (expressed in Coordinated Universal Time [UTC]), mission elapsed time (MET), and Event Duration of each of the primary trajectory events. For active propulsive maneuvers, the nominal  $\Delta V$  is matched with the “Active Vehicle” contributing to the maneuver. Where appropriate, comments are made about each Mission Event.

**Table 3. Notional Nominal Mission Timeline**  
**(Opening of window of daily launch opportunities). Mission Events: July 22, 2021 Landing Opportunity, 5.65 Day Transfer Duration, Landing Site 23.4° N, 60.0° W.**

| Mission Event                  | Epoch (UTC)         | MET       | Event Duration | Nominal $\Delta V$   | Active Vehicle        | Comments  |
|--------------------------------|---------------------|-----------|----------------|----------------------|-----------------------|---|
|                                | (m/d/yyyy hh:mm:ss) | (h:mm:ss) | (h:mm:ss.s)    | (m/s)                |                       |   |
| Launch                         | 7/16/2021 18:15:07  | 0:00:00   |                | TBD: Provided        | Atlas V               | Due East launch.  |
| Orbit Insertion / Stage 2 MECO | 7/16/2021 18:24:07  | 0:09:00   | 0:09:00.0      | by Atlas V & Centaur | Centaur Upperstage    | Insertion into 200 km circular LEO at 28.5 deg inclination. |
| LEO Coast                      |                     |           | 1:17:54.6      |                      | Centaur Upperstage    | LEO Duration between 10-120 min.                            |
| TLI (Impulsive)                | 7/16/2021 19:42:02  | 1:26:55   | TBD            | TBD: Centaur         | Centaur Upperstage    |   |
| Begin Trans-Lunar Coast        |                     |           |                |                      | Centaur Upperstage    | Transfer times from 3 to 8 days.                            |
| Jettison TLI Stage             | TBD                 | TBD       | 135:36:03.9    | TBD                  | Centaur & MARE Lander | Target Centaur US to impact moon.                           |
| TCM 1                          | TBD                 | TBD       |                | TBD                  | MARE Lander           |   |
| TCM 2                          | TBD                 | TBD       |                | TBD                  | MARE Lander           |   |
| TCM 3                          | TBD                 | TBD       |                | TBD                  | MARE Lander           |   |
| LOI Start                      | 7/22/2021 11:18:05  | 137:02:58 |                |                      | MARE Lander           | Insertion into 100 km circ retrograde                       |
| LOI End                        | 7/22/2021 11:23:34  | 137:08:27 | 0:05:28.2      | 849.9                | MARE Lander           | LLO.  |
| LLO Coast                      |                     |           | 7:30:44.6      |                      | MARE Lander           | 3-4 revs in LLO for Nav.                                    |
| DOI Start                      | 7/22/2021 18:54:18  | 144:39:11 |                |                      | MARE Lander           | DOI reduces periapse to 15 km.                              |
| DOI End                        | 7/22/2021 18:54:24  | 144:39:17 | 0:00:05.4      | 16.0                 | MARE Lander           | Assumes MARE main engine.                                   |
| Descent Orbit                  |                     |           | 1:01:20.0      |                      | MARE Lander           | About half a rev.   |
| PDI / Braking Start            | 7/22/2021 19:55:44  | 145:40:37 | 0:09:47.4      | 1811.9               | MARE Lander           | 80% throttle setting.                                       |
| Pitch Up and Throttle Down     | 7/22/2021 20:05:31  | 145:50:24 |                |                      | MARE Lander           | Reduced throttle.   |
| Approach Start                 | 7/22/2021 20:05:39  | 145:50:32 | 0:00:44.6      | 72.0                 | MARE Lander           | Approach pitch 80°. HD Lidar scan.                          |
| Pitch to Vertical              | 7/22/2021 20:06:14  | 145:51:07 |                |                      | MARE Lander           |   |
| Vertical Descent               | 7/22/2021 20:06:16  | 145:51:09 |                |                      | MARE Lander           | Vertical descent from 50 m alt.                             |
| 10 m Altitude                  | 7/22/2021 20:06:34  | 145:51:27 | 0:00:18.2      | 31.9                 | MARE Lander           | Brake to 1 m/s at 10 m altitude.                            |
| Touchdown                      | 7/22/2021 20:06:47  | 145:51:40 | 0:00:13.1      | 21.8                 | MARE Lander           | Touchdown at 1 m/s  |

## SUMMARY AND EXPECTED FUTURE RESULTS

The authors have created a viable mission design profile for the MARE mission. The trajectory design has a performance budget well founded on both analysis and historical data. This report provides a working concept for structuring a launch campaign for individual (monthly) landing opportunities. It appears that the current  $\Delta V$  budget provides more than adequate performance and may be reduced to provide mass relief to the overall spacecraft (or additional payload to the lunar surface).

Ongoing work would provide a more detailed examination of possible launch opportunities and the impact of their mission events and timeline to key mission parameter (such as lunar transfer time). Additionally, an expansion of the overall launch window will be conducted, including up to 5 daily launch opportunities to support extended pad delays (due to weather, equipment malfunction, etc.), thus reducing the possibility of an undesirable launch scrub.

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