MOON AGE AND REGOLITH EXPLORER MISSION DESIGN AND PERFORMANCE

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Science Rationale

• Current inner-solar-system chronology models have billion-year uncertainties in period of 1-3 billion years ago
• Understanding the timing of geological events is keystone to understanding chronology
• Lunar crater counting and sample dating provide chronology basis
  – Used to extrapolate events on Mars, Mercury, Venus, Vesta, and others
  – Used in the dynamics modeling of the early solar system
• Problem: crater counted terrains may not have been source of dated samples, and Lunar Reconnaissance Orbiter (LRO) Camera images are revealing higher crater counts than previously observed.
• Solution: date samples with well understood origins from terrain with well understood crater counts.
Science Objectives

- Collection and dating of 2-3 cm rocks in a smooth, basaltic maria terrain region southwest of Aristarchus crater
- Thermophysical and mineralogical data from samples can be directly correlated with LRO data to revise lunar chronology
- Hundreds of candidate landing sites in the overall region

Technical Objectives (GN&C-centric)

- Science requirement: land within 100m of site. Science goal: land within 20m
- Land near lunar dawn (10° Sun elevation)
- Ensure safe landing: terrain consists of surface features (e.g., small sharp craters and rocks/boulders) that pose quantifiable landing risk to the NAVIS spacecraft
Morpheus Vehicle Provided an Early Prototype for MARE NAVIS and for Testing GN&C and Propulsion

Integrated LOx/LCH₄ Propulsion System
- Throttleable Main Engine
- Integrated Cryogenic RCS
- Helium Pressurization System
- Cryogenic Feedsystem
- Aluminum Propellant Tanks

Precision landing GN&C System
- Software/Algorithms/Hardware for autonomous precision landing
- Hazard Detection (HD) for safe site identification (prototype designed for human-lander, not NAVIS, requirements)
- Navigation Doppler LiDAR (NDL) for velocimetry (NAVIS will also use for range)
- No Terrain Relative Navigation (TRN)

Integrated GN&C and Propulsion System Demonstrated in Multiple Morpheus Flight Tests

2/8/2017 27th Annual Space Flight Mechanics Meeting
Mission Design Assumptions

• Lunar Landing Site, Lighting, and Epoch
  – Landing coordinates:
    • latitude = 23.7°, longitude = -47.4°, altitude = 0 m
    • Lunar mare terrain near Aristarchus crater
  – Landing opportunities in 2021
  – Landing epoch selected when sun elevation is 10° at landing site, at lunar dawn
    • Apollo landings required sun elevation angles between 7° and 20°. To maximize sun-lit time in the first lunar day, suggest selecting the lowest possible sun elevation that is still supportable with landing navigation (nav).

• Retrograde inclination arrival
  – LOI, DOI maneuvers conducted on lunar far side out of Earth view
  – Approach over lit surface with Sun behind spacecraft – good for visual nav

* For purposes of providing crew with good surface feature discernment and sun behind spacecraft during descent (to avoid sun glare at approach).
Mission Design Overview

1. Launch due East on an Atlas V 411 Launch Vehicle (LV)
2. LV inserts NAVIS into a temporary, circular Low Earth Orbit (LEO) for TLI phasing – nearly co-planar with transfer orbit
3. LV upper stage (Centaur) performs Trans-Lunar Injection (TLI) burn to achieve lunar intercept in 3-8 days (depending on launch date)
4. Upper stage jettison (all remaining maneuvers use NAVIS onboard propulsion)
5. Design for 3 Trajectory Correction Maneuver (TCM) burns – margin for optional 4th TCM
6. Lunar Orbit Insertion (LOI) burn into 100-km retrograde Low Lunar Orbit (LLO) with landing near lunar dawn and favorable approach lighting geometry for optical nav
7. Descent Orbit Initiation (DOI) burn to setup PDI
8. Powered Descent Initiation (PDI) at ~15 km altitude
9. Continuous main engine burn during Powered Descent to Landing at the science site near Aristarchus Crater
Lunar transfer (red, later switching to yellow) to LOI maneuver into LLO sets up spacecraft for coplanar landing.
## Lunar Landing – Sun Elevation, Azimuth, Mask Angle, Sunlit and Dark Durations vs Lunar Landing Epoch

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Landing epoch</th>
<th>Sun Azimuth</th>
<th>Loss of Power/Sundown Epoch</th>
<th>Sunlit/Dark Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Sun Elevation Angle (deg)</td>
<td>Mask Angle (Deg)</td>
<td>Mask Angle (Deg)</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>(deg) ... and rising</td>
<td>(deg)</td>
<td>(deg) ... and dropping</td>
</tr>
<tr>
<td>1</td>
<td>January 26, 2021 20:18:44</td>
<td>95.67</td>
<td>February 09, 2021 05:18:41</td>
<td>13.37</td>
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<tr>
<td>3</td>
<td>March 27, 2021 00:16:07</td>
<td>95.97</td>
<td>April 09, 2021 08:24:54</td>
<td>13.34</td>
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<tr>
<td>5</td>
<td>May 24, 2021 23:21:04</td>
<td>94.60</td>
<td>June 07, 2021 09:02:46</td>
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<tr>
<td>7</td>
<td>July 22, 2021 20:06:47</td>
<td>93.02</td>
<td>August 05, 2021 08:01:12</td>
<td>13.50</td>
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<tr>
<td>8</td>
<td>August 21, 2021 07:02:38</td>
<td>92.67</td>
<td>September 03, 2021 19:34:43</td>
<td>13.52</td>
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<tr>
<td>9</td>
<td>September 19, 2021 18:58:10</td>
<td>92.78</td>
<td>October 03, 2021 07:33:15</td>
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<tr>
<td>10</td>
<td>October 19, 2021 08:06:18</td>
<td>93.34</td>
<td>November 01, 2021 20:08:16</td>
<td>13.50</td>
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</table>
Performance Trades

1. Launch due East on an Atlas V 411 Launch Vehicle (LV)

2. LV inserts NAVIS into a temporary, circular Low Earth Orbit (LEO) for TLI phasing – nearly co-planar with transfer orbit

3. LV upper stage (Centaur) performs Trans-Lunar Injection (TLI) burn to achieve lunar intercept in 3-8 days (depending on launch date)

4. Upper stage jettison (all remaining maneuvers use NAVIS onboard propulsion)

5. Design for 3 Trajectory Correction Maneuver (TCM) burns – margin for optional 4th TCM

6. Lunar Orbit Insertion (LOI) burn into 100-km retrograde Low Lunar Orbit (LLO) with landing near lunar dawn and favorable approach lighting geometry for optical nav

7. Descent Orbit Initiation (DOI) burn to setup PDI

8. Powered Descent Initiation (PDI) at 15 km altitude

9. Continuous main engine burn during Powered Descent to Landing at the science site near Aristarchus Crater
TLI: Ascending vs Descending Node Departure

Earth

Ascending transfer trajectory

Descending transfer trajectory

Moon (at arrival)
TLI and LOI Performance Scan for 2021

- 3 Ascending TLI
- 3 Descending TLI Opportunities per Landing Opportunity
- 10° Sun Elevation for 23.4° N, 60.0° W
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
TLI and LOI Performance for Launch Opportunities in July 2021

Performance requirement for ascending node opportunities for Post TLI C3 and associated LOI ΔV for a landing epoch in July 2021

Landing at 10° Sun Elevation for 23.4° N, 60.0° W
Powered Descent/Landing Sequence

- DOI to PDI coast time - 1 hr
- PDI to touchdown: 11 min, 522 km surf dist, 17.2° arc
- Nominal braking phase throttle set to 80% for control authority

Colored lines represent thrust direction. Each color represents a different descent flight phase.
Powered Descent Landing Phases
Pitch-up/Throttle-down, Approach, Pitch to Vertical, and Vertical Descent

End of Braking Phase

Pitch Up & Throttle Down

Approach

HD Scan Start
160 m Slant Range, 55° Elevation from Landing Site

Pitch to Vertical

Vertical Descent

Colored lines represent thrust direction.
Each color represents a different flight phase.
Powered Descent
Including Active Sensors

PDI  Powered Descent Initiation
TRN  Terrain Relative Navigation
HD   Hazard Detection
NDL  Navigation Doppler Lidar
IMU  Inertial Measurement Unit
TVD  Terminal Vertical Descent

Notional
<table>
<thead>
<tr>
<th>Mission Event</th>
<th>Epoch (UTC)</th>
<th>MET</th>
<th>Event Duration</th>
<th>Nominal ΔV</th>
<th>Active Vehicle</th>
<th>Comments</th>
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<tbody>
<tr>
<td>Start Timed Events</td>
<td></td>
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<tr>
<td>Launch</td>
<td>7/16/2021 18:15:07</td>
<td>0:00:00</td>
<td>0:09:00.0</td>
<td>TBD: Provided by Atlas V &amp; Centaur</td>
<td>Atlas V</td>
<td>Due East launch.</td>
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<tr>
<td>Orbit Insertion / Stage 2 MECO</td>
<td>7/16/2021 18:24:07</td>
<td>0:09:00</td>
<td>1:17:54.6</td>
<td>TBD</td>
<td>Centaur Upperstage</td>
<td>Insertion into 200 km circular LEO at 28.5 deg inclination.</td>
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<tr>
<td>LEO Coast</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>TLI (Impulsive)</td>
<td>7/16/2021 19:42:02</td>
<td>1:26:55</td>
<td>TBD</td>
<td>TBD: Centaur</td>
<td>Centaur Upperstage</td>
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<tr>
<td>Begin Trans-Lunar Coast</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Jettison TLI Stage</td>
<td>TBD</td>
<td>TBD</td>
<td>135:36:03.9</td>
<td>TBD</td>
<td>Centaur Upperstage</td>
<td>Transfer times from 3 to 8 days.</td>
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<tr>
<td>TCM 1</td>
<td>TBD</td>
<td>TBD</td>
<td></td>
<td>TBD</td>
<td>MARE Lander</td>
<td></td>
</tr>
<tr>
<td>TCM 2</td>
<td>TBD</td>
<td>TBD</td>
<td></td>
<td>TBD</td>
<td>MARE Lander</td>
<td></td>
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<tr>
<td>TCM 3</td>
<td>TBD</td>
<td>TBD</td>
<td></td>
<td>TBD</td>
<td>MARE Lander</td>
<td></td>
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<tr>
<td>LOI Start</td>
<td>7/22/2021 11:18:05</td>
<td>137:02:58</td>
<td>0:05:28.2</td>
<td>849.9</td>
<td>MARE Lander</td>
<td>Insertion into 100 km circ retrograde LLO.</td>
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<tr>
<td>LOI End</td>
<td>7/22/2021 11:23:34</td>
<td>137:08:27</td>
<td></td>
<td></td>
<td>MARE Lander</td>
<td></td>
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<tr>
<td>LLO Coast</td>
<td></td>
<td></td>
<td>7:30:44.6</td>
<td>16.0</td>
<td>MARE Lander</td>
<td>DOI reduces periapse to 15 km.</td>
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<td>DOI Start</td>
<td>7/22/2021 18:54:18</td>
<td>144:39:11</td>
<td>0:00:05.4</td>
<td>16.0</td>
<td>MARE Lander</td>
<td>Assumes MARE main engine.</td>
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<tr>
<td>DOI End</td>
<td>7/22/2021 18:54:24</td>
<td>144:39:17</td>
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<td>MARE Lander</td>
<td></td>
</tr>
<tr>
<td>Descent Orbit</td>
<td></td>
<td></td>
<td>1:01:20.0</td>
<td></td>
<td>MARE Lander</td>
<td>About half a rev.</td>
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<tr>
<td>PDI / Braking Start</td>
<td>7/22/2021 19:55:44</td>
<td>145:40:37</td>
<td>0:09:47.4</td>
<td>1811.9</td>
<td>MARE Lander</td>
<td>80% throttle setting.</td>
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<tr>
<td>Approach Start</td>
<td>7/22/2021 20:05:39</td>
<td>145:50:32</td>
<td>0:00:44.6</td>
<td>72.0</td>
<td>MARE Lander</td>
<td>Approach pitch 80°. HD Lidar scan.</td>
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<tr>
<td>Pitch to Vertical</td>
<td>7/22/2021 20:06:14</td>
<td>145:51:07</td>
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<td>MARE Lander</td>
<td></td>
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<tr>
<td>10 m Altitude</td>
<td>7/22/2021 20:06:34</td>
<td>145:51:27</td>
<td>0:00:18.2</td>
<td>31.9</td>
<td>MARE Lander</td>
<td>Brake to 1 m/s at 10 m altitude.</td>
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<tr>
<td>Touchdown</td>
<td>7/22/2021 20:06:47</td>
<td>145:51:40</td>
<td>0:00:13.1</td>
<td>21.8</td>
<td>MARE Lander</td>
<td>Touchdown at 1 m/s</td>
</tr>
</tbody>
</table>
Summary

• There exist feasible mission opportunities given the assumed launch vehicle capabilities and lander assumptions for the MARE mission

• There are multiple launch opportunities corresponding to each monthly landing opportunity

• The trajectory design supports navigation sensor suite pointing requirements within available propellant ($\Delta V$) limits
MARE was not selected as a 2015 NASA Discovery Mission

The MARE studies developed analysis tools, design concepts, and capabilities that can be leveraged for future proposals or projects

The flow down of MARE mission requirements into NAVIS GN&C is driving follow-on ALHAT project efforts
  - 3rd-generation NDL prototype to achieve performance needed for both NAVIS and other Mars-landers. Will be flight tested in 2016 through ALHAT COBALT project.
  - The HD design concept for NAVIS is being further developed through other ALHAT development efforts within the NASA/AES CATALYST program
References

Proposed Delta-V Sizing Budget*

<table>
<thead>
<tr>
<th>Maneuver</th>
<th>Vehicle ΔV</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCM1</td>
<td>5 m/s</td>
</tr>
<tr>
<td>TCM2</td>
<td>1 m/s</td>
</tr>
<tr>
<td>TCM3</td>
<td>1 m/s</td>
</tr>
<tr>
<td>LOI</td>
<td>1000 m/s</td>
</tr>
<tr>
<td>DOI</td>
<td>20 m/s</td>
</tr>
<tr>
<td>PDI to Pitchover/Throttle-Down</td>
<td>700 m/s</td>
</tr>
<tr>
<td>Pitchover/Throttle-Down</td>
<td>700 m/s</td>
</tr>
<tr>
<td>Vertical Landing</td>
<td>600 m/s</td>
</tr>
<tr>
<td>LOI Dispersion</td>
<td>20 m/s</td>
</tr>
<tr>
<td>Landing Dispersion</td>
<td>20 m/s</td>
</tr>
<tr>
<td>RCS Control</td>
<td>10 m/s</td>
</tr>
</tbody>
</table>

Total ΔV = 2,977 m/s

* Pre-analysis
Lander Mission

- Two weeks of science during lunar daylight
- Robotic arm on lander acquires samples for science instruments
- Surface power: fixed solar arrays and rechargeable batteries
- Landing oriented for power generation and thermal dissipation

Arc of Sun Vector
North-Facing Radiator
Solar Arrays within 5 deg of East-West line
Arm Ops Envelope

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