Human Lunar Exploration Architectures

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WELCOME ROCKET SCIENTISTS!
The Rocket Equation – It’s Not Just a Good Idea, It’s the LAW

\[ \frac{dv}{dt} = \frac{T}{m} - g, \text{ rocket equation where} \]
\[ m = m(t), \text{ mass of rocket and propellant a function of time} \]

\[ \Rightarrow dv = \frac{T}{m} \, dt - g \cdot dt \]
\[ = -u \frac{dm}{dt} \, dt - g \cdot dt, \text{ where} \]
\[ T = -u \frac{dm}{dt}, \]

since \( m = \frac{dm}{dt} \) is negative as the rocket

\[ \Rightarrow dv = -u \frac{dm}{m} - g \cdot dt \]

\[ \Rightarrow \int_{v_o}^{v_{bo}} dv = \int_{m_o}^{m_{bo}} -u \frac{dm}{m} - \int_{t_o}^{t_{bo}} g \cdot dt, \text{ integrating from initial} \]

\[ v \bigg|_{v_o}^{v_{bo}} = -u \int_{m_o}^{m_{bo}} \frac{1}{m} \, dm - g \int_{t_o}^{t_{bo}} dt, \text{ u and g are constants} \]

\[ (v_{bo} - v_o) = -u \cdot \ln(m) \bigg|_{m_o}^{m_{bo}} - g \cdot t \bigg|_{t_o}^{t_{bo}} \]
\[ = -u \left[ \ln(m_{bo}) - \ln(m_o) \right] - g \left[ t_{bo} - t_o \right] \]
\[ = -u \cdot \ln \left( \frac{m_{bo}}{m_o} \right) - g \left[ t_{bo} - 0 \right] \]

\[ \Rightarrow \boxed{ (v_{bo} - v_o) = u \cdot \ln \left( \frac{m_o}{m_{bo}} \right) - g \cdot t_{bo} } \], using ln power rule
Human Lunar Exploration is a function of two primary variables:

- The transportation architecture ("How You Get There")
- The Surface Mission Architecture ("What You Do There")

These two variables are utterly interrelated, but are often decided without regard to the other.

Further, “What you do there” is often a function of what you can get there!
How You Get There: Current Lunar Transportation Options

Lunar Transportation can be further defined by a series of architectural choices:

- **Launch vehicle capability**
  - Space Launch System (Block 1, 1A, II)
  - Falcon (9, 9 Heavy, X)
  - Delta IV (Medium, Medium+, Heavy)
  - International Launch Vehicles (HIIA, Ariane)

- **Staging locations**
  - None (direct)
  - Low Earth orbit (LEO, includes ISS)
  - High Earth Orbit (HEO)
  - Libration Points (L1, L2)
  - High Lunar Orbit (HLO)
  - Low lunar orbit (LLO)
Current Launch Vehicle Options
Earth return ΔVs assume aerocapture used for insertion into LEO or return to Earth’s surface

Each staging location offers different benefits to orbital and surface missions

Staging location will affect:
- Flight time to/from the surface
- Surface access
- Mass that can be landed
- “Split” of maneuvers among propulsive stages
“What You Do There” – Lunar Surface Mission Options

- Like transportation, the lunar surface mission is further defined by a series of mission content and operational choices.

- The combination of these choices will determine the overall scope of the mission.

Increasing complexity, mass, # of elements, return

Sortie (e.g., Apollo)

Campaign of missions (e.g., Global Exploration Roadmap)
Lunar Surface Mission Variables

Increasing complexity, mass, # of elements, return

Sortie → Campaign

- Science Content
- Surface Area Explored
- Landing site diversity/access
- Surface Mission Duration
- EVA hours
- Amount of self reliance
- SKG’s addressed
- Human Research addressed
- Technology infusion
- Contribution to Mars preparation
- International participation
- Commercial participation

- Sortie geology
- Local (EVA walking distance)
- Polar/equitorial
- Lunar daytime
- 2 crew minimum EVA
- None
- Few
- Few
- TRL now
- Minimal
- None

- Multidisciplinary science
- 1000’s of km
- Global access
- Multiple months
- Full crew maximize EVA hours
- Autonomy + full ISRU
- Most
- Most
- Maximize new technology
- Fully Mars focused
- Fully integrated
- Fully integrated
Lunar Surface Mission Study History

- 1985 Lunar Bases book (Mendell)
- 1988 Eagle Engineering LBSS Study
- 1989 90-day study
  - 4 options
- 1990 LMEPO Architectures
  - 4 options
- 1991 Synthesis Group
- 1992 First Lunar Outpost
- 1993 LUNOX
- 1999 Decadal Planning Team (DPT)
- 2001 NEXT
- 2003 Space Architect Studies
- 2004 Concept Exploration and Refinement (CE&R) Studies
- 2004 LaRC/JSC Transportation Studies
- 2005 ESAS
- 2006 LAT 1
- 2007 LAT2
- 2008 Cx/LSS Surface Architecture Reference (SARD)
- 200x LSS Scenarios
- CxAT-Lunar
- 2010 GPOD
- 2011 HAT

Option 1 – Mini-habitat elements with Crew Lander (LAT-1)
Option 2 – Mini-habitat elements with Crew/Cargo Lander
Option 3 – Single Delivery, Monolithic Habitat
Option 4 – Mobile Lander Habitat System
Option 5 – Early Delivery of Pressurized Rover
Option 6 – Nuclear Surface Fission Power

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Rebuild of LCGR scenarios increasing crew flights to at least 2 per year</td>
</tr>
<tr>
<td>5</td>
<td>Nuclear power based scenarios – Use a fission reactor as the primary power source</td>
</tr>
<tr>
<td>6</td>
<td>Power beaming scenarios – Consider ways to beam power from orbit or surface to systems</td>
</tr>
<tr>
<td>7</td>
<td>Recyclable lander – Scenarios that make massive reuse of lander components to build up the Outpost and surface infrastructure</td>
</tr>
<tr>
<td>8</td>
<td>Extreme mobility – Scenarios that deploy Small Pressurized Rovers early and use them as primary habitation</td>
</tr>
<tr>
<td>9</td>
<td>Side-mount or underslung Lander – Scenarios that support a lander configured to make unloading much easier than 8m deck</td>
</tr>
<tr>
<td>10</td>
<td>Refuelable lander – Scenarios that support a lander designed for multiple flights to and from LLO</td>
</tr>
<tr>
<td>11</td>
<td>Mars Centric – Scenarios that optimize Mars exploration needs earlier</td>
</tr>
<tr>
<td>12</td>
<td>Pre-Global Point-of-Departure Architecture</td>
</tr>
<tr>
<td>13</td>
<td>Cargo Capability Limited Architecture Study</td>
</tr>
</tbody>
</table>
LUNAR SURFACE - SORTIE
Lunar Surface
- Mission Duration – up to 7 days
- Block 1 CPSs (no LBO)
- Lunar Lander requires Low Boil-off

Notes:
- spacecraft icons are not to scale
- ΔV’s include 5% FPR
- RCS burns not displayed in chart
- Not all discrete burns displayed
• Landing site near the central peak of Tsiolkovsky Crater
• 4 Crew performs EVA each landed day (28 EVA days total)
• Crew lives out of lander’s hab module
• 2 unpressurized rovers
• Geology emphasis – sampling of 4 different geological units within roving distance of landing site
• 1 long EVA of ~32 km round-trip (EVA “6/7”)
• All other EVAs < 20 km round trip
• LRV traverse geological sampling
  – Stop every kilometer and sample regolith
  – Selected rake samples
• Ground penetrating radar
  – Map subsurface structure and determine mare thickness
• Deploy network of instrument station sites
  – Geophones
  – Seismic sources
  – Surface magnetometers
Four crew spend one week exploring the Tsiolkovsky Crater in daily EVAs. Geology focus with significant sample return. Unpressurized rovers, maximum 32 km traverse. Ground penetrating radar to map subsurface structure and determine mare thickness. Geologic instrument deployment.


- Geophones
- Seismic sources
- Surface magnetometers
• Unpressurized rovers (2)
• Ground penetrating radar
  – Map subsurface structure and determine mare thickness
• Instrument stations
  – Geophones
  – Seismic sources
  – Surface magnetometers
• Geological sampling tools
  – Core drills
  – Sample rakes
  – Bulk sample tool
  – Sample bags
  – Cameras

<table>
<thead>
<tr>
<th>Element</th>
<th>SAIF ID</th>
<th>Mass (t)</th>
<th>FSE (t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unpressurized Rovers (2)</td>
<td></td>
<td>400.00</td>
<td></td>
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<tr>
<td>Ground Penetrating Radar (2)</td>
<td></td>
<td>40.00</td>
<td></td>
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<tr>
<td>Instrument Stations (4):</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Geophones</td>
<td></td>
<td>44.80</td>
<td></td>
</tr>
<tr>
<td>Seismic sources</td>
<td></td>
<td>incl. above</td>
<td></td>
</tr>
<tr>
<td>Surface magnetometers</td>
<td></td>
<td>34.40</td>
<td></td>
</tr>
<tr>
<td>Geologic Sampling Tools:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Core drills (2)</td>
<td></td>
<td>33.80</td>
<td></td>
</tr>
<tr>
<td>Sample rakes (2)</td>
<td></td>
<td>3.00</td>
<td></td>
</tr>
<tr>
<td>Bulk sample tools (4)</td>
<td></td>
<td>16.80</td>
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</tr>
<tr>
<td>Sample bags</td>
<td></td>
<td>8.00</td>
<td></td>
</tr>
<tr>
<td>Cameras (4)</td>
<td></td>
<td>25.00</td>
<td></td>
</tr>
<tr>
<td>Sample Return Container (6)</td>
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<td>24.00</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>635.70</td>
<td></td>
</tr>
<tr>
<td><strong>Capability</strong></td>
<td></td>
<td>500.00</td>
<td></td>
</tr>
<tr>
<td><strong>Difference</strong></td>
<td></td>
<td>-135.70</td>
<td></td>
</tr>
</tbody>
</table>
GER-DERIVED LUNAR DESTINATION

DRM
This lunar destination DRM is derived from the GER Lunar mission:

- Multiple (5) extended stay (up to 28 day) missions, beginning with robotic precursors and initial cargo landers
- Lunar surface emphasis is to test the capabilities and learn self-sufficiency in preparation for human Mars missions
- 4 crew
- Polar site
- Small cargo landers (1 mt)
- Larger cargo landers (8 mt)
- Automated predeployment
- Rover chassis
- Resources
- Pressurized Rover: Mobile Habitation
- Long-distance mobility (100’s km)
- Technologies:
  - Mobility
  - Dust control
  - Habitation
  - Autonomous landing and hazard avoidance
  - Advanced surface power (if available)
GER – Lunar Surface Mission
7-28 day Extended Stay Mission with HLLV

- **28 day Mission Duration**
- **7 days initial HLR Mission**
- **Block 1 CPS (no ZBO)**
- **Cargo Capacity ~8 t**
Five years prior to Human Lunar Return, cargo missions begin to deliver robotics and science equipment. The crew arrives with two large cargo landers and two small logistics landers, and spends 7 days on the surface. Over the next five years, a total of five crewed missions with surface stays of up to 28 days are completed.
The GER DRM accumulates surface elements prior to the crew’s arrival via a combination of small (~1 mt) and large (~8 mt) cargo landers.

<table>
<thead>
<tr>
<th>Element</th>
<th>QT(Y)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crew</td>
<td>4</td>
<td>International Astronaut Crew</td>
</tr>
<tr>
<td>PUP (Portable Utility Pallet)</td>
<td>3</td>
<td>• 100 kW-hr battery storage each</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• 2 kW solar array each</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Transported by SEVs</td>
</tr>
<tr>
<td>PCT (Portable Communications Terminal)</td>
<td>1</td>
<td>Provides high bandwidth communications</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Transported by PUP</td>
</tr>
<tr>
<td></td>
<td></td>
<td>It is assumed that at least 1 LRS is on orbit</td>
</tr>
<tr>
<td>Robotic Precursor 1 (R1)</td>
<td>1</td>
<td>Small International Science Rover</td>
</tr>
<tr>
<td>Robotic Precursor 3 (R3)</td>
<td>1</td>
<td>Small International Science Rover</td>
</tr>
<tr>
<td>UPR (Unpressurized Rover)</td>
<td>1</td>
<td>Provides Excursion Capability before second SEV arrives</td>
</tr>
<tr>
<td>Off-loader (LSMS or Cradle)</td>
<td>1</td>
<td>Can tele-robotically offload cargo landers or be used off the back of</td>
</tr>
<tr>
<td></td>
<td></td>
<td>an SEV.</td>
</tr>
<tr>
<td>Science Package</td>
<td>1</td>
<td>Pre-deployed in second mission</td>
</tr>
<tr>
<td>Logistics</td>
<td>9</td>
<td>Multiple logistics payloads required for 28 day capability</td>
</tr>
<tr>
<td>STM (Suitport Transfer Module)</td>
<td>1</td>
<td>Allows transfer of material through a Suitport</td>
</tr>
<tr>
<td>SEV (Space Exploration Vehicle)</td>
<td>2</td>
<td>200 kW-hr battery storage each</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average speed toward destination = 5 km/hr</td>
</tr>
</tbody>
</table>

**Diagram:**

- 1 Ton Lander
- 8 Ton Lander
- 8 Ton Lander w/ Ascent Stage
- STM
- Crew
- SEV
- Off-loader
- PUP
- PCT
- Science Package
- ALC
- UPR
- R1
- R3
- Logistics

**Table:**

- **Element**
- **QT(Y)**
- **Notes**
  - Robotic Precursor 2 (R2) 1 Small NASA Robotic Assistant & Science Rover
  - ALC (Airlock Logistics Carrier) 7 Pressurized Logistics
• In a perfect world, all space missions would be “Mission Driven” – the desired science (or other end goals) would dictate the size and scope of the mission.
  – Apollo example: “land a man on the moon and return him safely to the Earth” drove technology development and the design of all the mission elements.
  – Space Shuttle: reusability and large payload carrying requirements

• Most ALL current space missions are “Capability Driven” – the capabilities of existing launch vehicles and spacecraft technology limit what missions CAN be done, and missions are proposed within these capabilities

• Incremental capability increases (due mainly to new or incremental technology insertion) provides some relief to capability limitations
  – Mars Science Laboratory: 6 wheel rocker-bogey rover, Viking entry system, RTG power system (demonstrated capabilities); “sky crane” landing system, aeromaneuvering precision guidance (increased capabilities)
“Flexible Path” Exploration Architecture

- Ground and Flight Capability Demonstrations, Including Terrestrial and In-Space Analogs
- “Gaining the High Ground” Human Access to Cis-Lunar Space
- New LEO Missions
- GEO/HEO Missions
- Lunar Flyby & Orbit
- Lunar Surface Missions
- “Minimal” NEA Mission
- “Exploring Other Worlds” Access to Low-Gravity Bodies
- “Full Capability” NEA
- “Planetary Exploration” Access to Planetary Surfaces
- Phobos/Deimos
- Mars

Key
- Capability Gates
- Candidate Destination

Increments in technology, systems, flight elements development and operational experience
Concluding Observations

• Human lunar missions are shaped by 2 distinct, but related variables:
  – Transportation architecture
  – Surface mission architecture

• A wide range of lunar surface mission content is possible from most any cis-lunar staging location

• The physics of spaceflight has not changed since Apollo

• Technology has changed only incrementally since Apollo

• Therefore, the options available for the conduct of space missions have changed only incrementally since Apollo

• What HAS changed is NASA’s shift to a capability-driven “Flexible Path Architecture”
  – Near-term human exploration capabilities include the Space Launch System (SLS), the Orion crew vehicle, commercial LEO capabilities, and the international partnership begun with the ISS
Thank you and congratulations, Rocket Scientists!

\[ \Delta v = v_e \ln \left( \frac{m_i}{m_f} \right) \]