Building an Economical and Sustainable Lunar Infrastructure To Enable Lunar Science and Space Commerce

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Background

• NASA’s Commercial Orbital Transportation Services (COTS) program was very successful in demonstrating ISS cargo delivery capabilities.
  - Resulted in development of 2 launch vehicles and spacecraft (SpaceX’s Falcon 9 and Orbital’s Antares with Cygnus)
  - Public-private partnerships approach resulted in significantly lower development costs, as much as 10-to-1 reduction in costs for Space-X’s Falcon 9 development.

• NASA’s Lunar CATALYST initiative sponsored by NASA’s HEOMD Advanced Exploration System division has competitively selected partners in 2014 to develop commercial lunar cargo transportation capabilities to the surface of the Moon.
  - Established no-funds-exchanged Space Act Agreements with 3 U.S. companies including Astrobotic, Masten Space Systems and Moon Express.
  - Commercial lunar transportation capabilities could support science and exploration objectives, such as sample returns, resource prospecting and technology demonstrations.

• NASA has recently released 2 RFI’s for lunar payloads and lunar cargo transportation services and is presently considering issuing solicitations for these capabilities and services.

• Lunar COTS is a concept study focusing on the technical and economical feasibility of building lunar infrastructure as well as the benefits and challenges of using a COTS-like model.
Lunar Commercial Operations & Transfer Services (LCOTS)
Concept Study

GOALS

- Develop affordable and commercial cis-lunar and surface capabilities in partnership with industry.
- Incentivize industry to establish economical lunar infrastructure services to support NASA missions and Lunar Commerce.
- Encourage creation of new space markets for economic growth and benefit.

Approach

1. Use 3-phase approach in partnership with industry to incrementally develop commercial capabilities and services.
2. Use COTS model approach to partner with industry to share cost and risk.
3. Begin with low-cost, commercial-enabled lunar missions to demonstrate small-scale lunar infrastructure capabilities.
Lunar COTS Phased Implementation

<table>
<thead>
<tr>
<th>Phase 1: Low-Cost, Commercial-Enabled Missions</th>
<th>Phase 2: Pilot Scale Demonstration</th>
<th>Phase 3: Long-Term Contracts</th>
</tr>
</thead>
</table>
| • Partner with industry to develop capabilities to enable an evolvable lunar infrastructure;  
  • Includes lunar cargo delivery, power stations, communication towers, etc.  
  • Assess potential lunar sites for accessibility to lunar resources and economic viability for resource extraction. | • Demonstrate infrastructure services on a pilot-scale to support future NASA missions and commercial activities, such as, lunar mining or resource extraction.  
  • Evaluate feasibility and economics of scaling up production to full scale. | • NASA awards long-term contracts for infrastructure services, such as, lunar cargo delivery and power/comm services.  
  • NASA may also award long-term contracts for full-scale resource extraction and/or delivery to cis-lunar destination. |
Lunar Infrastructure Elements

**Lunar Cargo Delivery**
- Performs precise, soft landings to deliver small payloads to multiple destinations on the lunar surface

**Power Stations**
- Enables power generation and storage capabilities using solar power battery system.
- Extends life of rovers to several years by providing re-charging and thermal control capabilities

**Lunar Communication Towers**
- Expands comm links to areas that are not in direct line-of-sight with Earth, such as, within craters or caves

**Multiple Power Towers**
- Provide continuous communications coverage with multiple towers
- Greater access to power recharging and hibernation stations
- Facilitates precise landings through triangularization of navigational data
NASA Lunar COTS Concept (LCOTS)

[Play Video]

Concept Objective:
Partnering with Industry to Build an Economical Infrastructure
Leading the way to the First Lunar Industrial City
Infrastructure System Reference Design

- Targeted landed dry mass not to exceed 900-1000 kg
- Payload mass ranges from 350-450 kg incl. power station, comm tower and rovers
- 2 meter Diameter modular hex Bus
- Lander legs are < 4 meter dia fixed
- 10 meter tall communication tower
  - Mast is telescopic and deploys after landing
  - Allows for over 1 km line of sight
  - Expands comm coverage to areas that are not in direct line-of-sight of Earth
- Solar panels
  - Polar lander: body mounted with additional deployable solar panels as shown
  - Equatorial Lander – horizontal deployable solar panels
- Power Station
  - Consists of 24-36 modules of lithium ion batteries
  - Provides 800–1600 W of power in during lunar day and 40-70 W continuous power during lunar night
  - Re-charges rovers during daylight and provides keep alive power and thermal control of rovers to survive 14-day lunar night

- Extends mission life to several years (6 to 8 years depending on battery life)
- Adding mobility system will extend traverse distances to hundreds of kilometers
## Launch Vehicle Payload Capabilities

<table>
<thead>
<tr>
<th>Launch Vehicles*</th>
<th>LEO (mt)</th>
<th>GTO (mt)</th>
<th>Payload to Lunar Surface (non-lander) (mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlas V</td>
<td>18.8</td>
<td>8.9</td>
<td>0.5 – 1.4</td>
</tr>
<tr>
<td>Falcon 9 FT (Full Thrust)</td>
<td>22.8</td>
<td>8.3</td>
<td>0.4 - 1.1</td>
</tr>
<tr>
<td>Falcon Heavy</td>
<td>63.8</td>
<td>26.7</td>
<td>1.5 - 3.9</td>
</tr>
<tr>
<td>Vulcan Centaur</td>
<td>22</td>
<td>11</td>
<td>0.7 – 1.8</td>
</tr>
<tr>
<td>Vulcan ACES</td>
<td>35</td>
<td>17</td>
<td>1.0-2.7</td>
</tr>
<tr>
<td>New Glenn 2-stage vehicle</td>
<td>45</td>
<td>13</td>
<td>0.8– 2.0</td>
</tr>
</tbody>
</table>

**Notes**
- Isp ranges from 285 to 336 seconds for Lander system
- *Launch vehicle data obtained from publicly available websites.*
Lunar Trajectory Analysis

- STK was used to analyze lunar trajectories to several equatorial and polar destinations.
  - A direct lunar trajectory was selected for best performance.
  - Sensitivity analysis was also performed.
- Key Parameter that drives lunar landing mass is Lander specific impulse, Isp:
  - MMH/NTO Biprop Isp ranges from 274-333 sec
  - Mass landed on the Moon doubles over this range
  - Off-the-shelf engines in this range:
    » Moog Biprop ~274-310 sec
    » Aerojet Biprop 300-333 sec
- Sensitivity analysis showed that Delta V difference between polar and equatorial sites are negligible (within ~15 m/sec)

Finding
Future development should focus on high thrust/high ISP lander system which has greatest impact to landing mass performance.
Draft Design Reference Mission

**Low Lunar Orbit (polar)**

- **TLI burn by Upper Stage** ($\Delta V = 3105 \text{ m/s}$)

- **LOI by Lander** ($\Delta V = 835 \text{ m/s}$)

- **Upper Stage**

- **Lunar Descent** ($\Delta V = 1822 \text{ m/s}$)

**Launch Vehicle Capabilities**

- Medium-class launch vehicles, such as Falcon 9 or Atlas V, may deliver 1 or 2 lunar landers to lunar surface.
- Heavy-class launch vehicles, such as Falcon Heavy or New Glenn, may deliver up to 4 lunar landers to multiple lunar destinations.

**Draft Mission Objectives**

- Demonstrate lunar cargo delivery capabilities.
- Demonstrate power generation and storage capabilities using solar power battery system.
- Demonstrate comm link capabilities from rovers to ground stations via high tower comm system.
- Demonstrate autonomous operation of rovers with commands from ground.
- Demonstrate capability to re-charge rovers during lunar day and capability to hibernate with thermal control during the 14-day lunar night.
# Draft Mission Timeline

<table>
<thead>
<tr>
<th>Event</th>
<th>Min</th>
<th>Max</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch</td>
<td>-15</td>
<td>-115</td>
<td>Minutes</td>
</tr>
<tr>
<td>TLI</td>
<td>0</td>
<td>0</td>
<td>Minutes</td>
</tr>
<tr>
<td>LOI Begins</td>
<td>4.5</td>
<td>5.5</td>
<td>Days</td>
</tr>
<tr>
<td>LOI Ends</td>
<td>6.5</td>
<td>7.5</td>
<td>Days</td>
</tr>
<tr>
<td>DOI</td>
<td>7.5</td>
<td>14.5</td>
<td>Days</td>
</tr>
<tr>
<td>Landing</td>
<td>7.55</td>
<td>14.55</td>
<td>Days</td>
</tr>
</tbody>
</table>

**Note:** Mission Timeline Ranges. TLI = 0
### Sample Instrumentation Options

<table>
<thead>
<tr>
<th>Sample Instrumentation Options</th>
<th>Key Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron Spectrometer System (NSS)</td>
<td>Senses hydrogen-bearing materials (e.g. Ice) in the top meter of regolith.</td>
</tr>
<tr>
<td>Near-Infrared Volatile Spectrometer System (NIRVSS)</td>
<td>Identify volatiles, including water form (e.g. ice bound) in top 20-30 cm of regolith. Also provides surface temperatures at scales of &lt;10 m</td>
</tr>
<tr>
<td>Camera, LEDs plus NIR spectrometer</td>
<td>Provides high fidelity spectral composition at range.</td>
</tr>
<tr>
<td>Radiation sensors</td>
<td>Measure radiation shielding by lunar regolith in lava tubes.</td>
</tr>
<tr>
<td>Drills</td>
<td>Captures samples from up to 1 m; provides more accurate strength measurement of subsurface.</td>
</tr>
<tr>
<td>Magnetometer</td>
<td>Measures variations in the strength of the Moon’s magnetic field.</td>
</tr>
<tr>
<td>Seismometer</td>
<td>Measures propagation of seismic waves through the Moon to help understand the Moon’s internal structure.</td>
</tr>
<tr>
<td>Laser Retro-Reflectors</td>
<td>Improved knowledge of Moon’s orbit, variations in the rotation of the Moon and rate at which Moon is receding from Earth.</td>
</tr>
</tbody>
</table>
Benefits to Lunar Industrialization

**Industry**
- Opportunity to be first to corner a space-based market which may be very lucrative (e.g. lunar cargo delivery, lunar mining, lunar tourism, etc)
- Estimated projections state potential for multi-trillion dollar economy.

**Public**
- Exciting new adventures for explorers of all races, genders and background!
- Benefits humanity in offering expanded opportunities and resources.

**Govt’s Role**
- No one company can industrialize the Moon alone. Investments to enter market are too huge and risky to enter alone.
- Govt can play key role by establishing Public-private partnerships to help accelerate infrastructure development.
- Other govt incentives should be explored to lower barriers of entry and enable new lunar industries and markets.

*The Moon can serve as a Gateway to the rest of the Solar System and beyond.*
Next Steps

1. Further develop mission concept options for 3-Phase approach to Lunar COTS.
   - Continue maturing design options for power generation and thermal control to extend mission life to several years.
   - Add mobility and suspension system to power station to extend traverse distances to hundreds of kilometers.
   - Use of impactors and/or penetrators that can be deployed on descent trajectory.
   - Develop design options for Lunar Drones to gather data over rough and steep terrain.
   - Investigate low-cost science instrument options
   - Develop design options for Sample Return Missions (include options for ascent stage).
   - Use Deep Learning and AI technologies to rapidly optimize solutions for landing site selection, resource identification, traverse and mission planning, etc.

2. Conduct 2-day Lunar Industrialization Workshop at Ames to:
   - Provide forum between commercial space companies and NASA technical experts to exchange ideas and develop plans.

3. Explore partnership opportunities with other NASA Centers and commercial industry to help advance Lunar COTS concept.
   - Conduct industry interviews to determine areas of interest for partnership; evaluate technical and business readiness levels.