Lunar COTS: Using the Moon’s Resources to Enable An Economical and Sustainable Pathway to Mars and Beyond

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• President Obama’s 2010 National Space Policy set the following goal for NASA:
  – By the mid-2030’s, send humans to orbit Mars and return them safely to Earth.

• As a result, NASA has established its Journey to Mars and Evolvable Mars Campaign (EMC) to:
  – Investigate architectures to further define capabilities needed for a sustainable human presence on the surface of Mars.
  – Proving Ground Objective: Understand the nature and distribution of volatiles and extraction techniques and decide on their potential use in future human exploration architecture.

• Under the EMC, NASA has also developed a Pioneering Space Strategy with the following principles:
  – Opportunities for U.S. commercial business to further enhance the experience and business base;
  – Near-term mission opportunities with a cadence of human and robotic missions providing for an incremental buildup of capabilities;
  – Substantial new international and commercial partnerships, leveraging the current ISS partnerships while building new cooperative ventures.
Moon as a “Stepping Stone” to Mars

- Prospect and extract lunar resources **to assess the value proposition** to NASA and our partners.
  - Lunar resources may prove beneficial for inclusion in future Mars architectures, e.g., lunar-derived propellant

- **Apply the proven COTS model** to develop low-cost commercial capabilities and services, such as:
  - Lunar Landers and Rovers
  - Resource Prospecting Techniques
  - Lunar Mining and ISRU capabilities
  - Lunar Relay Communication Satellites
  - Power Stations

- **Use campaigns of missions**, instead of single missions, in a 3-phase approach to incrementally develop capabilities and lower risks.

- **Establish Economic Development goals** by incentivizing industry to create cis-lunar markets.
  - NASA should not be sole customer; other customers and new markets should be targeted.

*The Moon can serve as a Gateway to Mars and the rest of the Solar System.*
 NASA Commercial Orbital Transportation Services (COTS)

- NASA’s COTS acquisition model proved to be very effective in reducing development and operations costs.
  - Studies showed a **10-to-1 reduction in development costs** for Space-X’s Falcon 9 rocket when compared to traditional FAR-based contracts.
  - Studies also showed that ISS cargo transportation services cost significantly less than previous Space Shuttle flights.

- **Best Practices from COTS** are summarized here:
  1. NASA and commercial partners **share cost, development and operational risk** to demonstrate new capabilities for mutual benefit.
  2. NASA makes **long-term commitments to procure commercial services** to help secure private investments.
  3. NASA encourages commercial partners to **target other markets outside Government** to make their business case close. NASA is anchor customer but not sole customer.
  4. NASA uses **SAA’s to enter into partnership** with commercial partners to offer maximum flexibility in design solutions without the full demands and requirements of typical FAR-based contracts.
  5. NASA includes **pay-on-performance milestones** in SAA’s to provide several off-ramps and reduce programmatic risk.
  6. Commercial partners **retain Intellectual Property (IP) rights** and operates and owns final product(s).
Lunar Commercial *Transfer* Services (LCOTS)

**GOALS**

- Establish affordable and economical cis-lunar capabilities and services.
- Enable development of a sustainable and economical exploration architecture for Mars and beyond.
- Encourage creation of new space markets to further reduce costs.

**Approach**

1. Use 3-phase approach in partnership with industry to incrementally develop commercial capabilities and services.
2. Begin with low-cost, commercial-enabled lunar missions to prospect for resources and identify hazards.
3. Determine technical and economic viability of extracting lunar resources.
## Apollo Pre-Cursor Campaigns – An Historic Context

<table>
<thead>
<tr>
<th>Ranger Campaign</th>
<th>Lunar Orbiter Campaign</th>
<th>Surveyor Campaign</th>
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</table>
| • Designed to take images of the lunar surface until impact.  
  • Acquired knowledge of potential landing sites for Apollo missions.  
  • Ranger missions 1-6 Failed, 1961-64  
  • Ranger mission 7-9 were successful, 1964-64. | • Designed to map the lunar surface to aid in the selection of landing sites for Apollo lunar program.  
  • All five missions were successful and 99% of the Moon was mapped, 1966-67. | • Designed to soft land on the lunar surface and help evaluate the suitability of landing sites for Apollo missions.  
  • Five of seven missions were successful, 1966-68. |

Each mission in a campaign benefited from learning from prior mistakes and took advantage of economies of scale to lower costs.
NASA’s post-Apollo Lunar Missions in Search for Water

<table>
<thead>
<tr>
<th>Mission</th>
<th>Year</th>
<th>Significant Findings</th>
</tr>
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<tbody>
<tr>
<td>Clementine</td>
<td>1994</td>
<td>Its Bi-static Radar Experiment provided data suggesting the presence of water on the lunar surface near the poles.</td>
</tr>
<tr>
<td>Lunar Prospector</td>
<td>1998-99</td>
<td>On March 5, 1998, scientists announced that LP’s neutron spectrometer instrument had detected hydrogen at both lunar poles, which scientists theorized to be in the form of water ice.</td>
</tr>
<tr>
<td>LRO</td>
<td>2009-Present</td>
<td>Scientists using LRO’s Mini-RF radar have estimated the maximum amount of ice, as much as 5 to 10% of material, by weight, is likely to be found inside Shackleton crater located near the moon’s South Pole.</td>
</tr>
<tr>
<td>LCROSS</td>
<td>2009</td>
<td>Scientists found evidence that the lunar soil within shadowy craters is rich in useful materials, and also confirmed the presence of water in average concentration of 5.6% by mass.</td>
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These NASA missions have provided strong evidence for existence of millions of tons of water-ice on the Moon. We now need ground truth data to confirm.
# Lunar COTS Phased Implementation

<table>
<thead>
<tr>
<th>Phase 1: Low-Cost, Commercial-Enabled Prospecting</th>
<th>Phase 2: ISRU Pilot Plant</th>
<th>Phase 3: Full-Scale Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Prospect several sites for surface resources and hazards;</td>
<td>• Develop a pilot-scale ISRU plant to extract water and produce up to 1 metric ton of propellant.</td>
<td>• NASA awards long-term contracts for Lunar ISRU production on the order of several metric tons per year.</td>
</tr>
<tr>
<td>• Identify areas of high concentrations of water-ice and other volatiles</td>
<td>• Demonstrate capabilities for ISRU resource production.</td>
<td>• Awards are also made for delivery services to Cis-Lunar Depot.</td>
</tr>
<tr>
<td>• Assess potential sites for hazards and accessibility</td>
<td>• Demonstrate lunar transportation of large payloads from surface to cis-lunar propellant depot.</td>
<td>• Full-scale ISRU facility development of approx 200 mt of propellant per year.</td>
</tr>
<tr>
<td>• Develop and demonstrate key capabilities in partnership with industry.</td>
<td>• Evaluate feasibility and economics of scaling up production to full scale.</td>
<td>• ISRU development and production facility cost has been estimated at $40B ($4B/year over 10 years).</td>
</tr>
</tbody>
</table>
  - Lunar Landers and Rovers | | |
  - Resource Prospecting Techniques | | |
  - Lunar Mining and ISRU | | |
  - Lunar Communication Satellites | | |
  - Power Stations | | |
Potential Mission Objectives

Low-cost commercial missions may be able to meet several exploration, science and commercial objectives with small instruments and commercial products. Sample list of mission objectives are as follows:

- Prospect for, characterize and locate potential resources on the Moon (e.g. ice concentrations at the poles and precious metals at the equator);
- Measure distributions and depths of areas with high hydrogen concentrations;
- Measure amounts of radiation at various sites, within lunar caves and/or lava tubes;
- Demonstrate ISRU technologies and operations, such as drilling, for extracting lunar resources.
- Precise delivery and remote operation of commercial products from the lunar surface.
North Pole landing site options driven by following challenges:

- Hydrogen concentrations shown by map of LPNS Epithermal Neutrons
- Direct-To-Earth Communications
- Sun Illumination
- Slopes/rough terrain

*Note: Black areas have less than 5 days of Net Sun and DTE access*
1. **Employ the proven COTS model**
   - Enables economical and sustainable missions
   - Establish “cost and risk-sharing” partnerships

2. **Use available low-cost secondary payload opportunities**
   - On medium-class launch vehicles, e.g., SpaceX’s Falcon 9 or ULA’s Atlas V

3. **Partner with commercial and international organizations**
   - To leverage existing Lunar transportation and rover capabilities
   - E.g., Google Lunar X-Prize and CATALYST teams.

4. **Explore additional partnerships to develop other key capabilities, such as:**
   - Lunar Mining, Drilling and Excavation Techniques
   - Lunar Relay Communication Satellites
   - Lunar ISRU Operations
   - Solar or Nuclear Power Stations

5. **Partner with companies interested in being the first to develop commercial products for the Moon.**
### Potential Lunar Lander Options

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<tr>
<th>Lunar Lander Teams</th>
<th>Targeted First Mission and Capabilities</th>
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<tbody>
<tr>
<td>Astrobotic’s GLXP Team</td>
<td>Planned for launch in late 2017 to Lacus Mortis. Peregrine capability ranges from 35 kg to 265 kg to lunar surface.</td>
</tr>
<tr>
<td>Moon Express GLXP Team</td>
<td>Signed launch agreement with RocketLab’s Electron Launch Vehicle for 3 lunar missions from 2017 to 2020.</td>
</tr>
<tr>
<td>Masten Space Systems</td>
<td>Launch is TBD. Landers in development include Xaero, Xoie, Xombie and XEUS.</td>
</tr>
<tr>
<td>Israel’s SpaceIL GLXP Team</td>
<td>Signed launch agreement via SpaceFlight with SpaceX’s Falcon 9 for a late 2017 launch.</td>
</tr>
<tr>
<td>Germany’s Part-Time Scientists GLXP Team</td>
<td>Planned for launch in 2017 to Apollo 17 landing site (Taurus-Littrow Valley).</td>
</tr>
<tr>
<td>ULA’s XEUS, ACES derived Lander</td>
<td>Planned for launch early next decade on ULA’s Vulcan launch vehicle. Lander capability is approx 3.8 mt to lunar surface for single launch and much greater using distributed launch.</td>
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## Potential Rover Options

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<tr>
<td>Astrobotic/Carnegie Mellon University GLXP Team</td>
<td>Multiple rover options including Andy rover for first mission and Polar rover with excavation and planetary cave exploration capabilities.</td>
</tr>
<tr>
<td>iSpace Technologies operates Japan’s Hakuto GLXP Team</td>
<td>Multiple rover options for resource prospecting and tethered rovers to explore polar craters and caves.</td>
</tr>
<tr>
<td>Chile’s AngelicVM GLXP Team</td>
<td>The Unity Rover plans to deliver small payloads on first and follow-on missions.</td>
</tr>
<tr>
<td>Germany’s Part-Time Scientists GLXP team partnered with Audi</td>
<td>The Audi Lunar Quattro is equipped with a 4-wheeled electrical drive chain, tiltable solar panels, rechargeable batteries and science grade HD cameras.</td>
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# Resource Prospecting Instruments

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<th>Instrumentation Options</th>
<th>Key Measurements</th>
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<tr>
<td>Neutron Spectrometer System (NSS)</td>
<td>Senses hydrogen-bearing materials (eg. 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>Camera and LEDs only</td>
<td>Measures soil and regolith composition at 100 micron scale.</td>
</tr>
<tr>
<td>Drills</td>
<td>Captures samples from up to 1 m; provides more accurate strength measurement of subsurface.</td>
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Lunar Infrastructure

**Lunar Communication Relay Satellites**
- Enables communication that are not in direct line of sight with Earth, such as, North and South Poles and Lunar Farside.
- Provides telemetry links and payload data relay from lunar orbit and lunar surface.

**Power Stations**
- Several options including solar, nuclear and power beaming from solar satellites.
- Several challenges to overcome including 14-day night time periods and PSRs at poles.

**Landing Zones**
- To enable safe, reliable and successful landings, landing zones should include landing pads and local navigation aids.

*Government can be a catalyst to lunar industrialization by setting in place the infrastructure needed for new lunar industries to flourish.*
Next Steps

- Continue to investigate and **develop 3-Phase approach** for Lunar ISRU development.
  - Develop mission objectives, budgets and schedule options for each phase.
  - Define requirements, DRMs and mission reference architecture.
- Conduct 1-day **Deep Space Industrialization Workshop** at NASA Ames to determine readiness level from industry.
  - Explore areas of interest for public-private partnerships.
  - Follow-up with industry interviews.
  - In parallel with another NASA ARC workshop entitled, “Developing International Markets for Deep Space”
- Continue to develop life cycle cost and economic assessment for:
  - Pilot-scale and full-scale ISRU facility for extracting water and creating LOX/LH2 propellant;
  - Delivery to a propellant depot at a cis-lunar destination.

**Lunar COTS 3-phase approach has great potential of yielding an economical and sustainable approach for reaching Mars and beyond.**
Questions?