Building an Economical and Sustainable Lunar Infrastructure To Enable Lunar Science and Space Commerce. A. F. Zuniga,[1] M. F. Turner[1] and D. J. Rasky[1], [1]NASA Ames Research Center, 555 McCord Ave., Moffett Field, CA (allison.f.zuniga@nasa.gov).

Introduction: A new concept study was initiated to examine the framework needed to gradually develop an economical and sustainable lunar infrastructure using a public/private partnerships approach. This approach would establish partnership agreements between NASA and industry teams to develop cis-lunar and surface capabilities for mutual benefit while sharing cost and risk in the development phase and then allowing for transfer of operation of these infrastructure services back to its industry owners in the execution phase. These infrastructure services may include but are not limited to the following: lunar cargo transportation, power stations, energy storage devices, communication relay satellites, local communication towers, and surface mobility operations.

The public/private partnerships approach for this plan leverages best practices from NASA's Commercial Orbital Transportation Services (COTS) [1] program which introduced a new affordable and economical approach to partnering with industry to develop commercial cargo services to the International Space Station. Similarly, this concept study, named Lunar COTS (Commercial Operations and Transport), aims to: 1) demonstrate commercial and affordable cis-lunar and surface capabilities and services; 2) encourage creation of new space markets to share cost and risk with industry; and 3) enable development of a sustainable and economical lunar infrastructure to support lunar science and new commercial ventures.

The primary goal of the lunar infrastructure development is to extend the life, functionality and distance traveled of surface mobility missions and to reduce cost, complexity, mass and volume of all surface missions. Presently, surface mobility or rover missions are heavily constrained by power demands, battery life, direct line-of-sight communications with Earth, extreme thermal conditions, traverse distances, landing conditions and 14 lunar day/night cycles. To date, there have not been any US surface mission that have survived a full 14 lunar day/night cycle primarily due to the extreme cold temperatures that exist during the lunar night (approx -250C). Therefore, the mission life of lunar surface missions is typically limited to less than 14 lunar days. The traverse distances are also severely limited primarily due to batteries not surviving the extreme cold temperatures in dark craters and throughout the 14-day lunar night.

A lunar infrastructure system with power, communication and navigation elements as well as a self-contained mobility system designed properly will have the capability to extend mission life to several years by providing power generation, storage, recharge and thermal control functions to the surface mobility system(s) and other payloads. In addition the communication tower will be able to increase communication links to the rover systems and not be limited to direct-line-of-sight to Earth communications. The local navigation aids located on the top of the communication tower will also aid the rover systems to navigate in dark areas, such as craters, where visibility is limited. A mobile infrastructure system will also have the added capability to extend the traverse distances of the mission to hundreds of kilometers. Therefore this new infrastructure system together with surface mobility systems have the potential to provide valuable and extensive scientific data over several years and cover numerous lunar sites over hundreds of kilometers. By partnering with industry to develop and own the infrastructure services using the COTS model, this plan will also result in significant cost savings and increased reliability and mission probability of success

A phased-development approach is also planned under this concept to allow for incremental development and demonstration of capabilities gradually over time. During the initial phase, a small-scale infrastructure is planned together with small mobility systems to collect ground truth data to identify valuable resources and assess its composition, distribution and accessibility. These data will be important not only to the science community but also the commercial space community for future planning of potential lunar industries.

This presentation will describe the Lunar COTS concept goals, objectives and approach for developing an economical and sustainable lunar infrastructure. It will also describe the technical challenges and advantages of each infrastructure element towards supporting future lunar science missions and lunar industrialization, such as lunar mining and space manufacturing. Finally, the presentation will also look forward to the potential of a robust lunar commercial economy supporting science missions and lunar industries and its potential effect on the next 50 years of space exploration

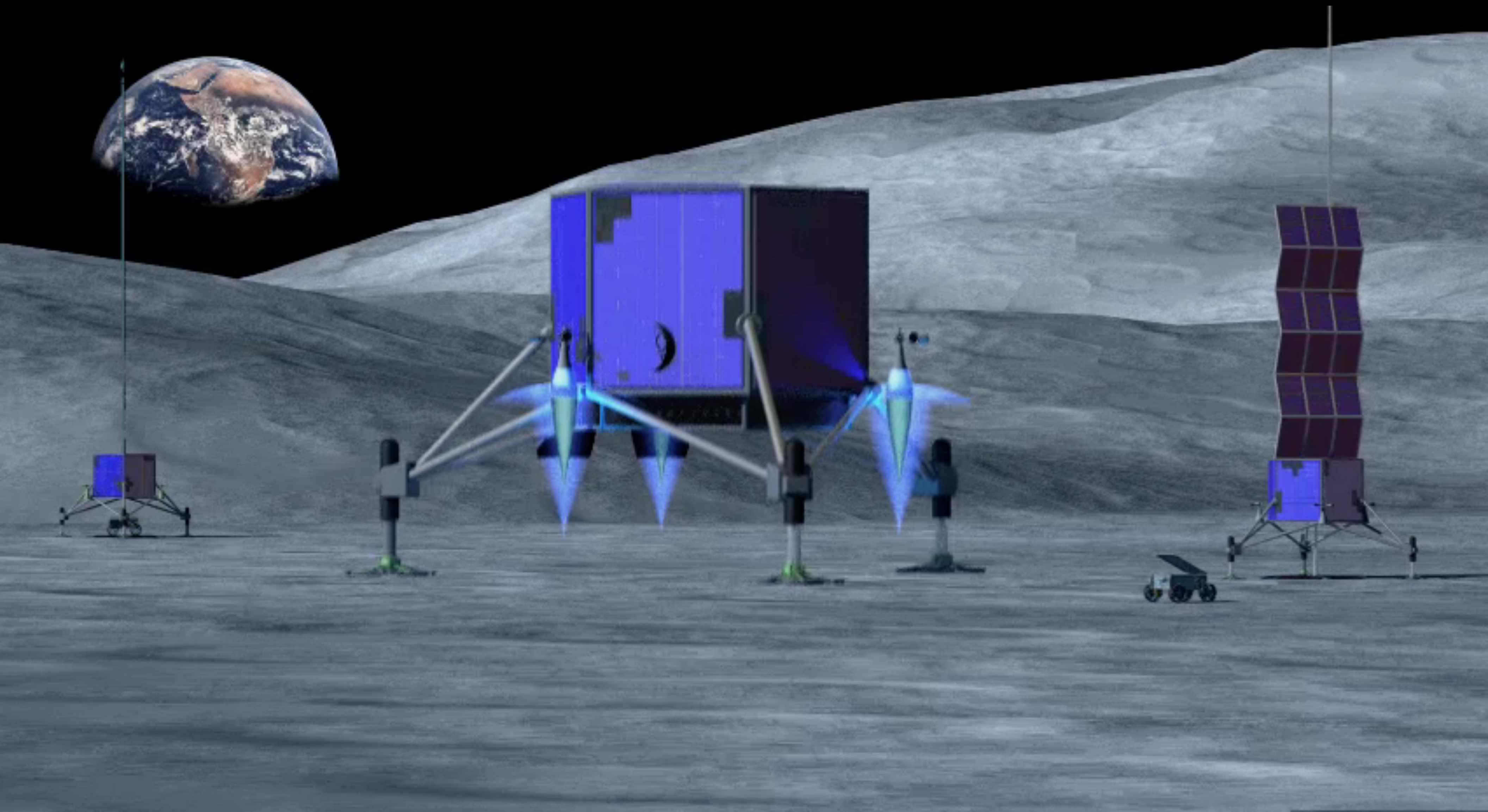
References:

[1] "A New Era in Spaceflight," NASA Commercial Operations and Transportation Services Program, U.S. Government Printing Office, Washington, DC, Feb 2014.

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

Dr. Allison Zuniga, Mark Turner and Dr. Dan Rasky
NASA Ames Research Center – Space Portal Office

LEAG Meeting – Oct 11, 2017



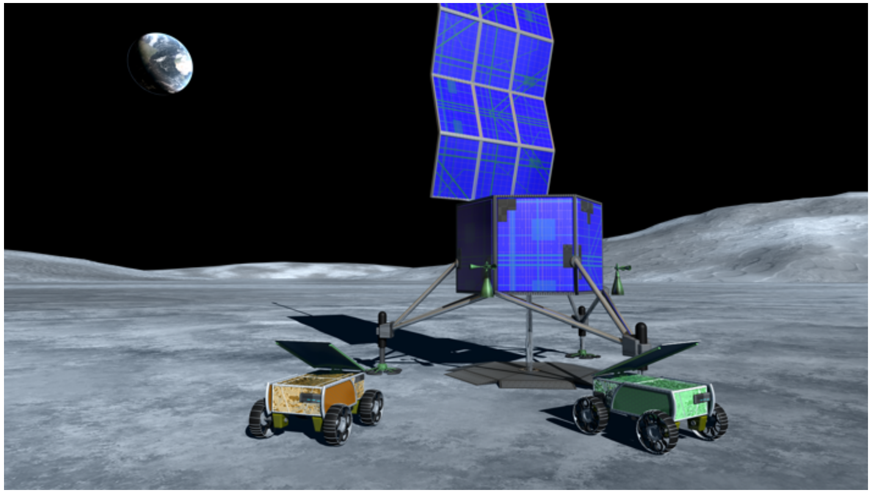
Background

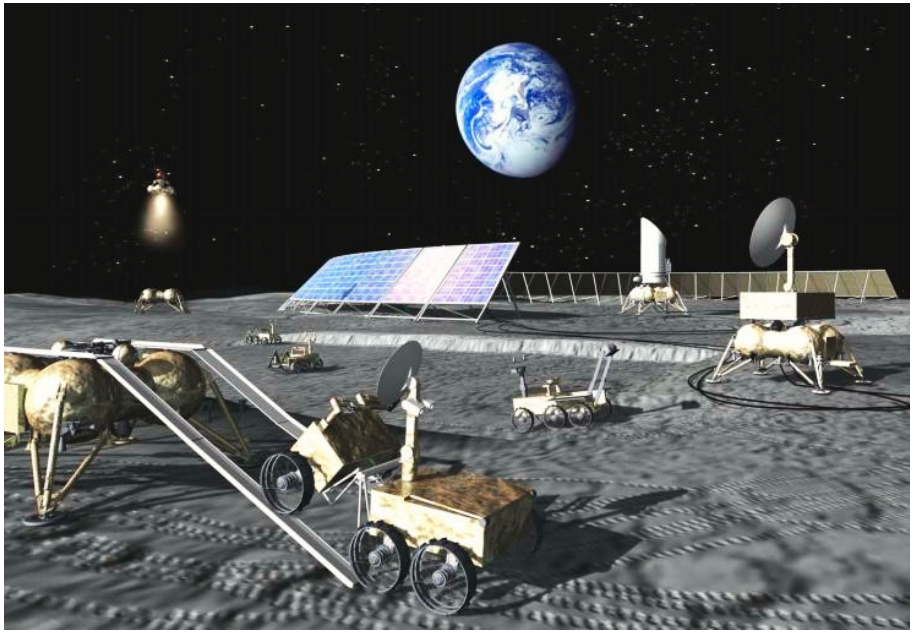
- NASA's Commercial Orbital Transportation Services (COTS) program was very successful in demonstrating ISS cargo delivery capabilities.
  - Resulted in development of 2 launch vehicles and spacecraft (SpaceX's Falcon 9 and Orbital's Antares with Cygnus)
  - Public-private partnerships approach resulted 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.
- NASA is coordinating with ISECG and LEAG to develop strategic lunar mission objectives and prioritize lunar sites.
- Lunar COTS is a concept study building on this work which continues to investigate 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.

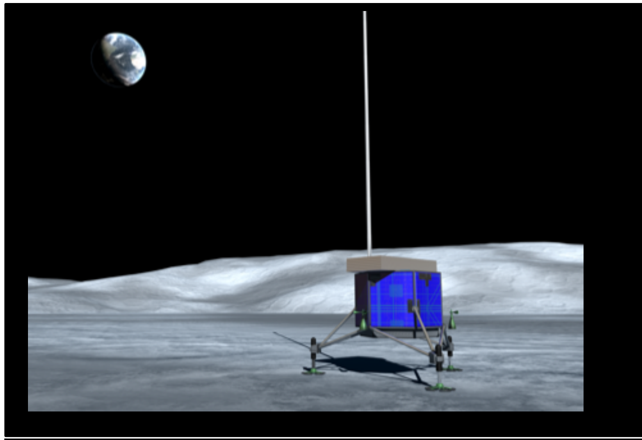


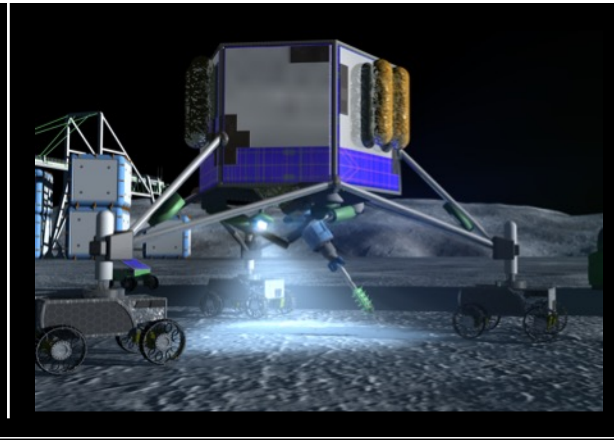


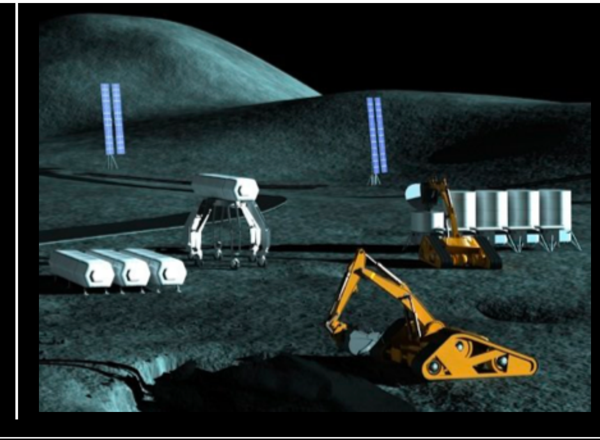
Approach

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

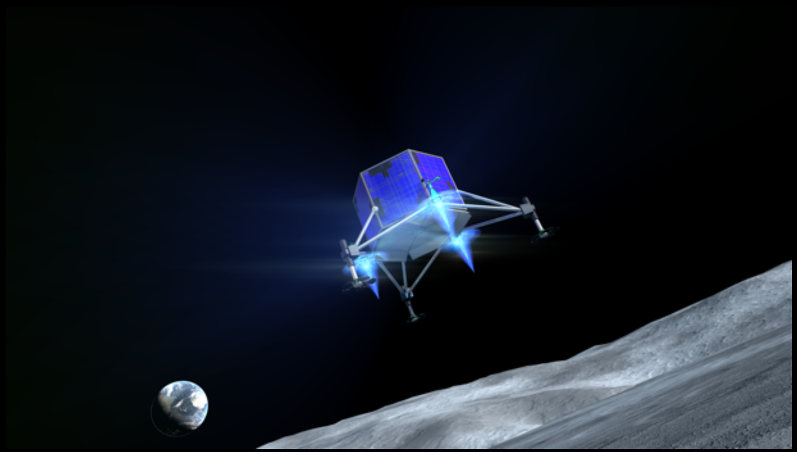


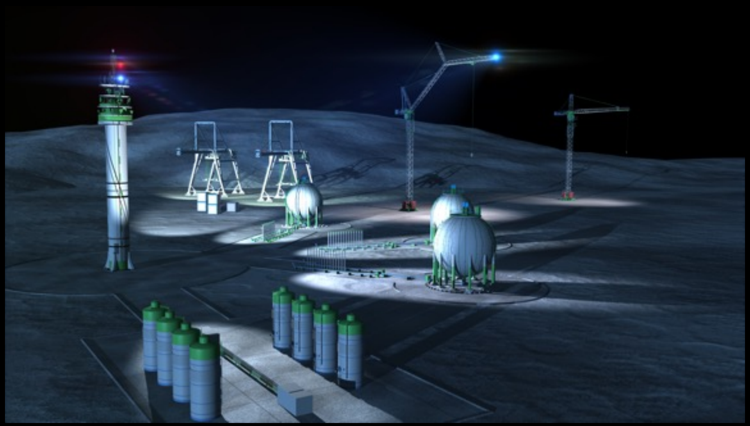




Phase 1: Low-Cost, Commercial-Enabled Missions	Phase 2: Pilot Scale Demonstration	Phase 3: Long-Term Contracts
• Partner with industry to develop capabilities to enable an evolvable lunar infrastructure; • Includes lunar cargo delivery, power stations, communication towers, etc. • Assess potential lunar 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.

LCOTS Concept of Operations





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

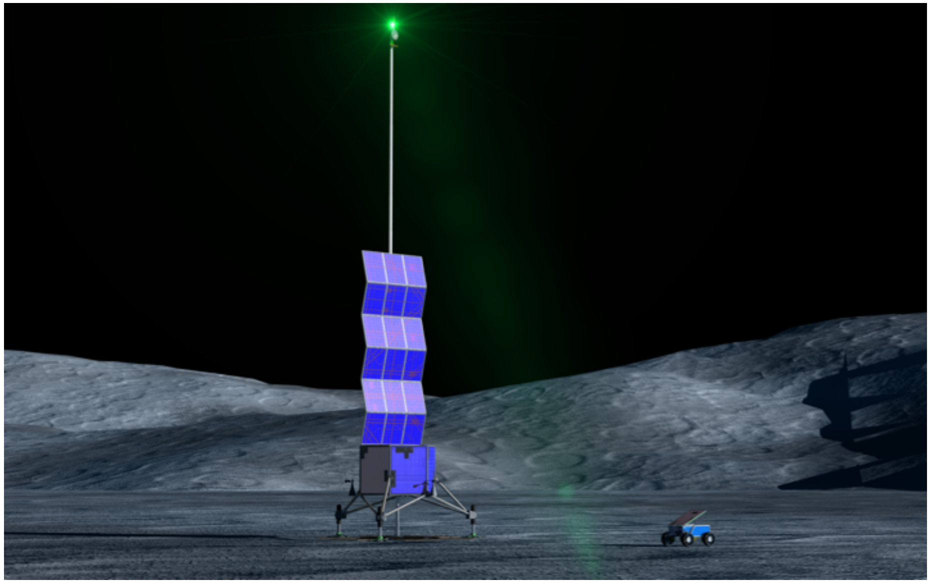
Lunar Infrastructure Elements

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

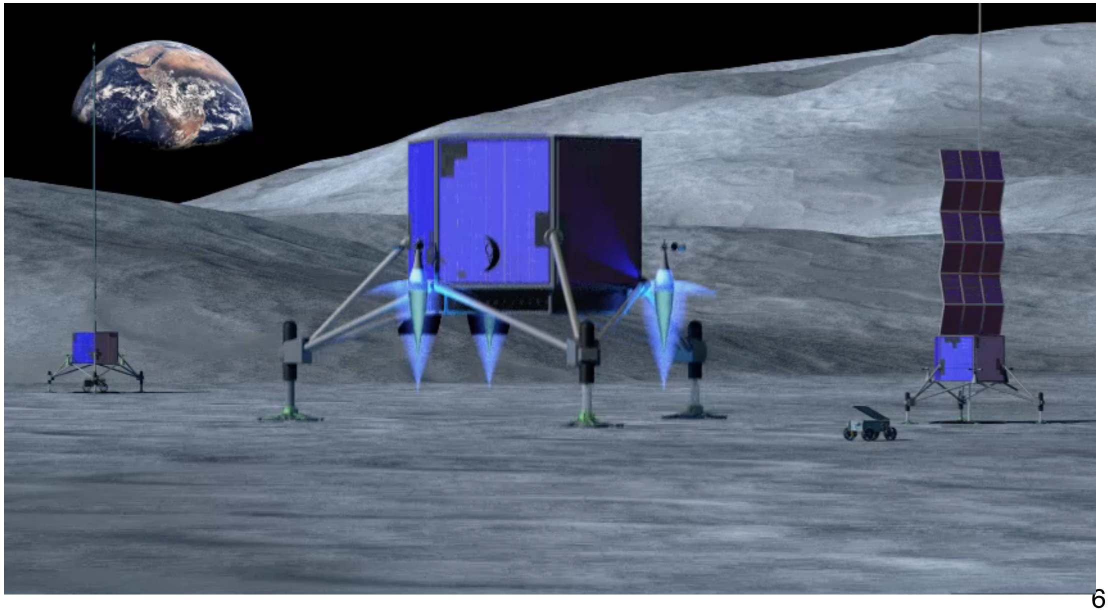


Lunar Communication Towers

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

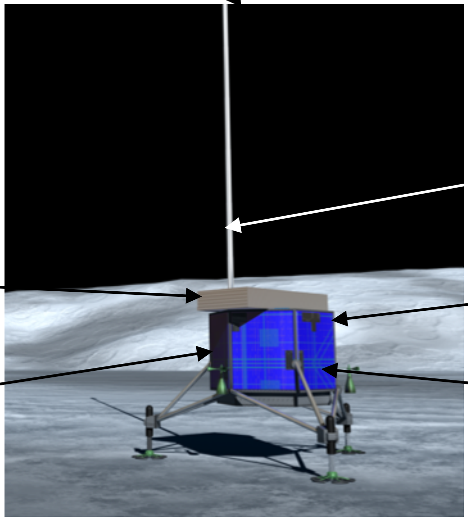
Multiple Power Towers

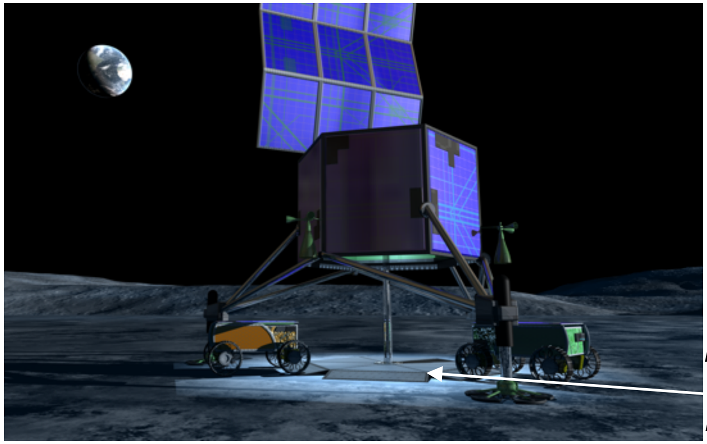
- Provide continuous communications coverage with multiple towers
- Greater access to power recharging and hibernation stations
- Facilitates precise landings through triangularization of navigational data



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

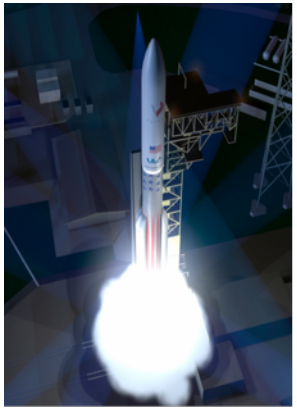




- ***Extends mission life to several years (6 to 8 years depending on battery life)***
- *Adding mobility system will* ***extend traverse distances to hundreds of kilometers***

Launch Vehicle Payload Capabilities

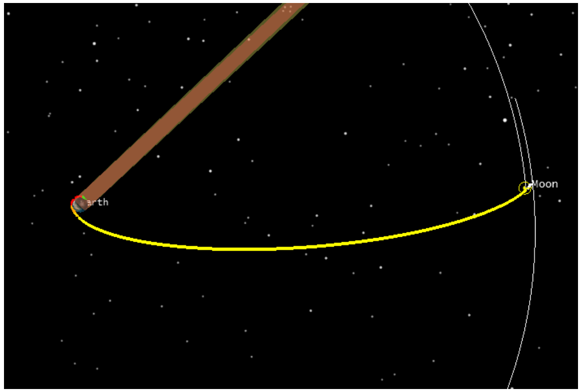
Launch Vehicles*	LEO (mt)	GTO (mt)	Payload to Lunar Surface (non-lander) (mt)
Atlas V	18.8	8.9	*0.5 – 1.4*
Falcon 9 FT (Full Thrust)	22.8	8.3	*0.4 - 1.1*
Falcon Heavy	63.8	26.7	*1.5 - 3.9*
Vulcan Centaur	22	11	*0.7 – 1.8*
Vulcan ACES	35	17	*1.0-2.7*
New Glenn 2-stage vehicle	45	13	*0.8– 2.0*

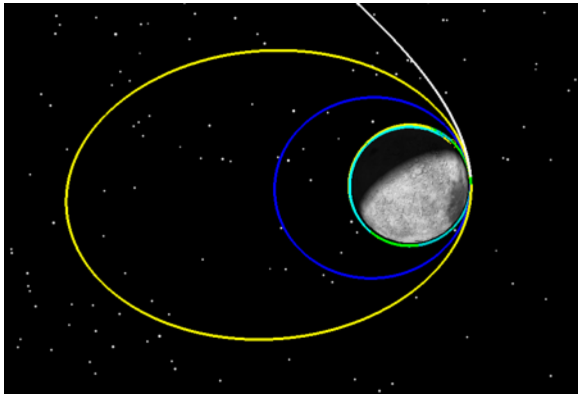


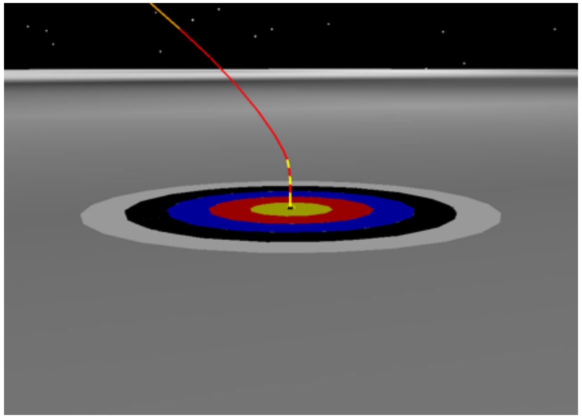
Notes
Isp ranges from 285 to 336 seconds for Lander system
*Launch vehicle data obtained from publicly available websites.

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)



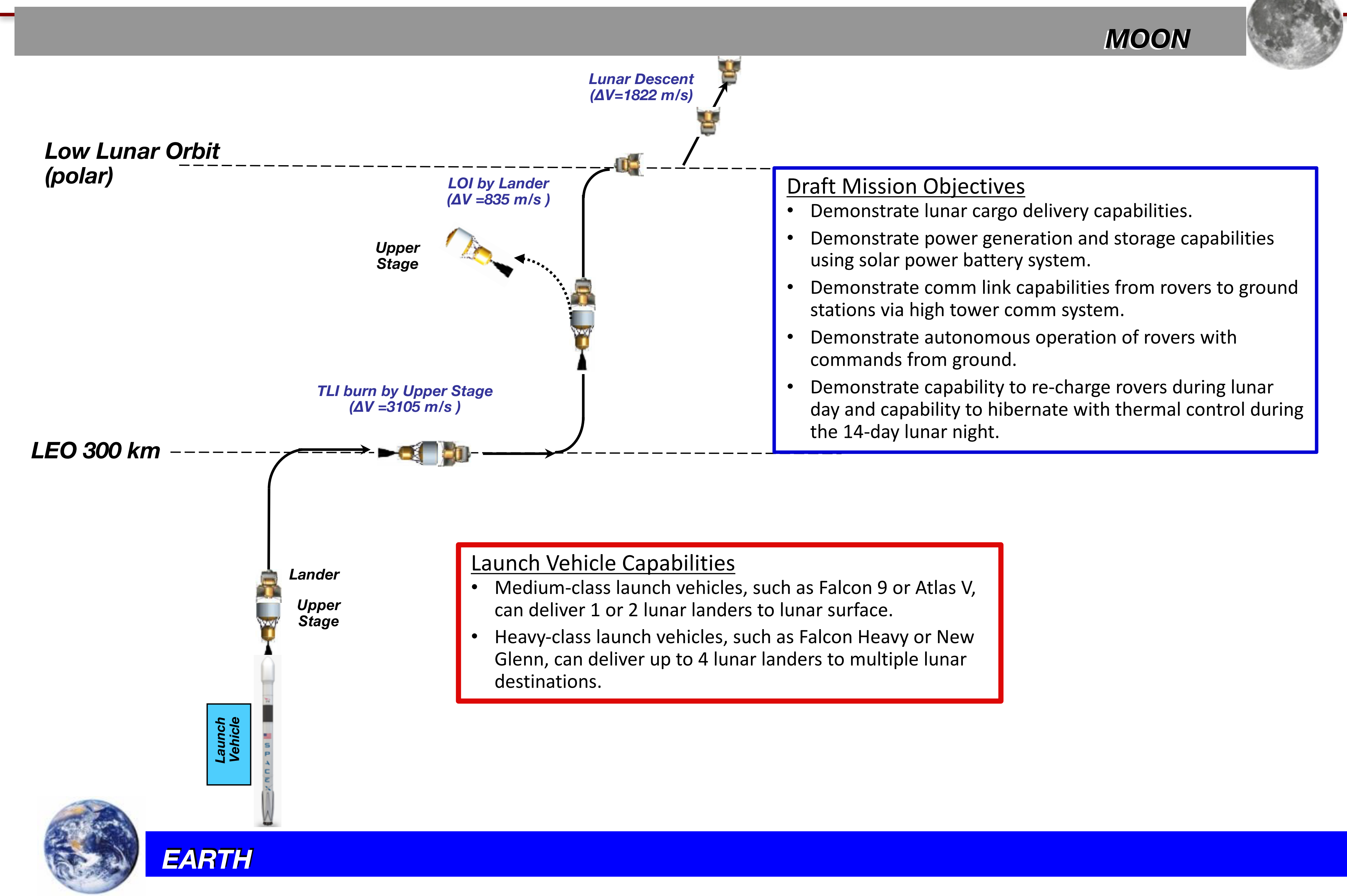




<u>Finding</u>
Future development should focus on high thrust/high ISP lander system which has greatest impact to landing mass performance.

SPACE PORTAL
for enterprise and commerce

Draft Design Reference Mission



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.

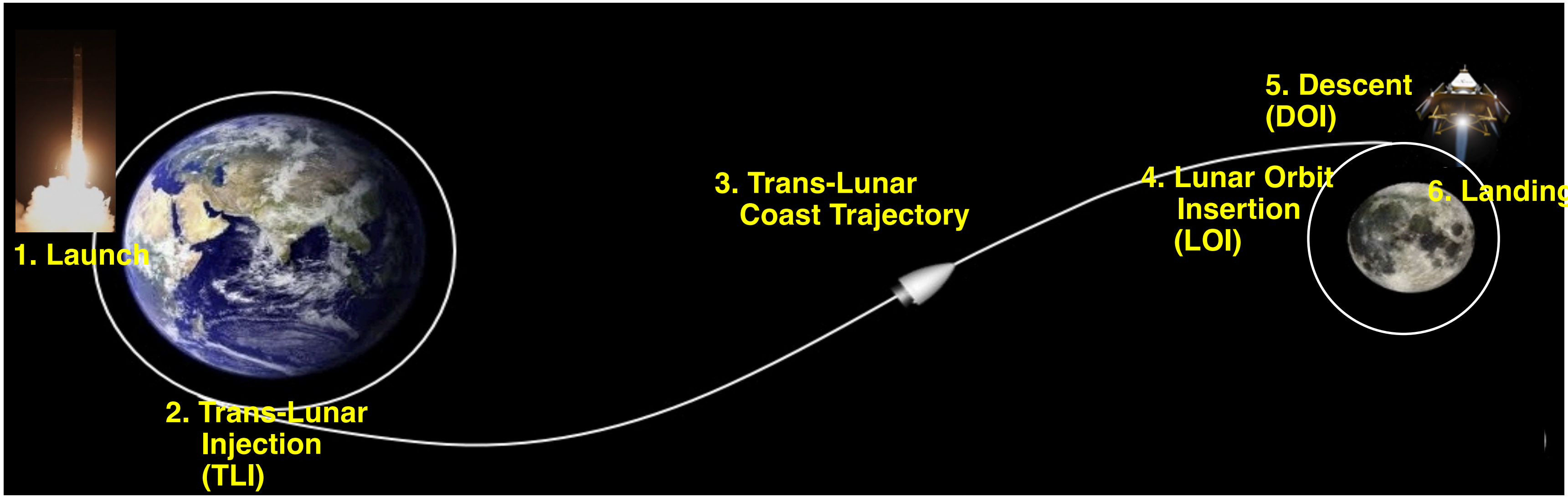
Launch Vehicle Capabilities

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

Draft Mission Timeline

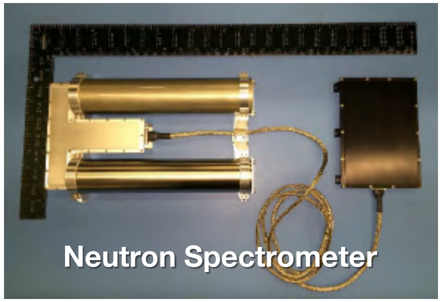
	Min	Max	
Launch	-15	-115	Minutes
TLI	0	0	Minutes
LOI Begins	4.5	5.5	Days
LOI Ends	6.5	7.5	Days
DOI	7.5	14.5	Days
Landing	7.55	14.55	Days

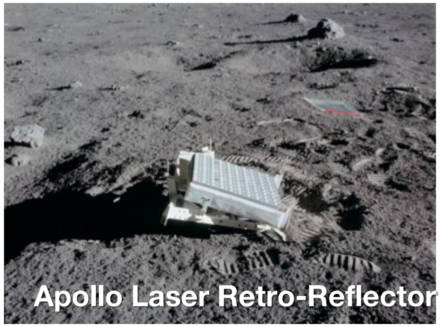
Note: Mission Timeline Ranges. TLI = 0



Draft Instrumentation Options

Sample Instrumentation Options	Key Measurements
Neutron Spectrometer System (NSS)	Senses hydrogen-bearing materials (eg. Ice) in the top meter of regolith.
Near-Infrared Volatile Spectrometer System (NIRVSS)	Identify volatiles, including water form (e.g. ice bound) in top 20-30 cm of regolith. Also provides surface temperatures at scales of <10 m
Camera, LEDs plus NIR spectrometer	Provides high fidelity spectral composition at range.
Radiation sensors	Measure radiation shielding by lunar regolith in lava tubes.
Mole	Measures heat flux
Magnetometer	Measures variations in the strength of the Moon's magnetic field.
Seismometer	Measures propagation of seismic waves through the Moon to help understand the Moon's internal structure.
Laser Retro-Reflectors	Improved knowledge of Moon's orbit, variations in the rotation of the Moon and rate at which Moon is receding from Earth.





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.

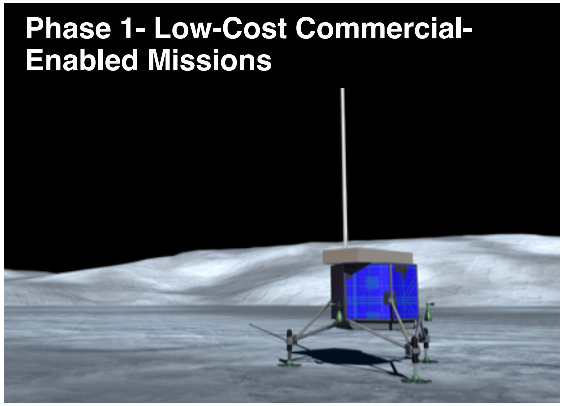
Govt's Role

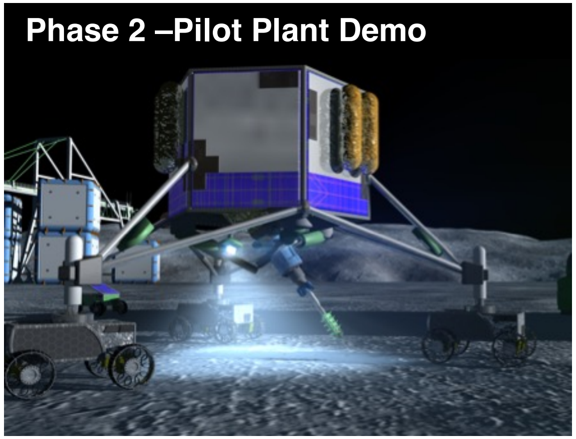
- No one company can industrialize the Moon alone. Investments to enter market are too huge and risky to enter alone.
- Govt can play key role by establishing Public-private partnerships to help accelerate infrastructure development.
- Other govt incentives should be explored to lower barriers of entry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

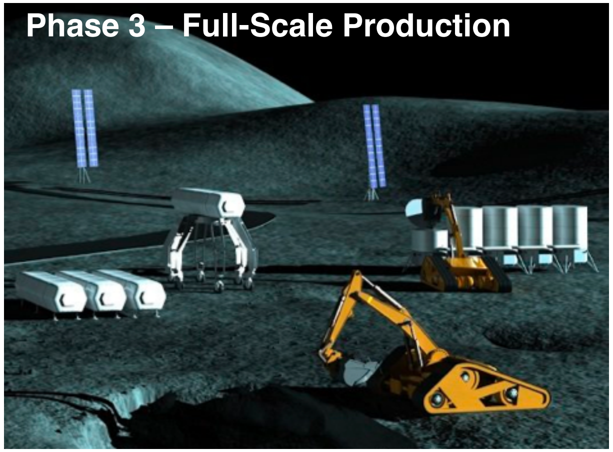
The Moon can serve as a Gateway to the rest of the Solar System and beyond.

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.







For more information contact:

Dr. Allison Zuniga
Project Development Manager
NASA Ames Space Portal Office
Phone: 650-604-2017
Email: allison.f.zuniga@nasa.gov

Dr. Dan Rasky
Manager, NASA Ames Space Portal Office
Phone: 650-604-1098
Email: daniel.j.rasky@nasa.gov