National Aeronautics and
Space Administration

NASA's Moon to Mars Architecture Workshop

Breakout Session: Technology and Infrastructure

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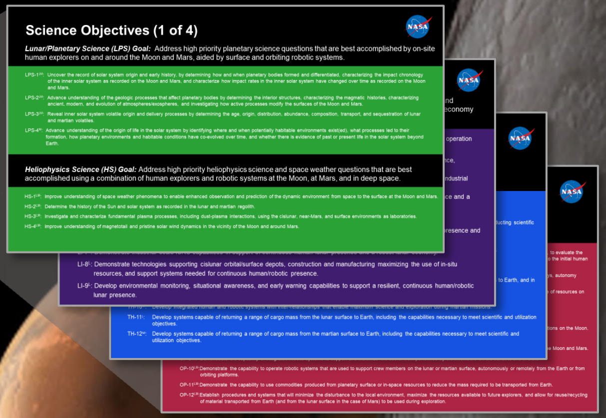
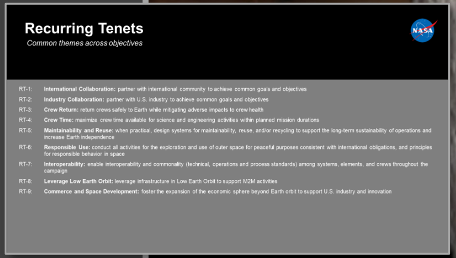
Revised M2M Objectives Roll-up

- **63 Top-Level Objectives across 10 Top-Level Goals**
  - 26 Science
  - 13 Infrastructure
  - 12 Transportation & Habitation
  - 12 Operations



- **9 Recurring Tenets (RT)**
  - Common themes across objectives

RT-1: **International Collaboration**
RT-2: **Industry Collaboration**
RT-3: **Crew Return**
RT-4: **Crew Time**
RT-5: **Maintainability and Reuse**
RT-6: **Responsible Use**
RT-7: **Interoperability**
RT-8: **Leverage Low Earth Orbit**
RT-9: **Commerce and Space Development**



- **Updated Glossary**

Lunar Infrastructure Goal and Objectives

Lunar Infrastructure (LI) Goal: Create an interoperable global lunar utilization infrastructure where U.S. industry and international partners can maintain continuous robotic and human presence on the lunar surface for a robust lunar economy without NASA as the sole user, while accomplishing science objectives and testing for Mars.

LI-1[L]: Develop an incremental lunar power generation and distribution system that is evolvable to support continuous robotic/human operation and is capable of scaling to global power utilization and industrial power levels.

LI-2[L]: Develop a lunar surface, orbital, and Moon-to-Earth communications architecture capable of scaling to support long term science, exploration, and industrial needs.

LI-3[L]: Develop a lunar position, navigation and timing architecture capable of scaling to support long term science, exploration, and industrial needs.

LI-4[L]: Demonstrate advanced manufacturing and autonomous construction capabilities in support of continuous human lunar presence and a robust lunar economy.

LI-5[L]: Demonstrate precision landing capabilities in support of continuous human lunar presence and a robust lunar economy.

LI-6[L]: Demonstrate local, regional, and global surface transportation and mobility capabilities in support of continuous human lunar presence and a robust lunar economy.

LI-7[L]: Demonstrate industrial scale ISRU capabilities in support of continuous human lunar presence and a robust lunar economy.

LI-8[L]: Demonstrate technologies supporting cislunar orbital/surface depots, construction and manufacturing maximizing the use of in-situ resources, and support systems needed for continuous human/robotic presence.

LI-9[L]: Develop environmental monitoring, situational awareness, and early warning capabilities to support a resilient, continuous human/robotic lunar presence.

Superscripts indicate applicability to Lunar (L), Martian (M), or both (LM)

Mars Infrastructure Objectives

Mars Infrastructure (MI) Goal: Create essential infrastructure to support initial human Mars exploration campaign.

- MI-1^{M}: Develop Mars surface power sufficient for an initial human Mars exploration campaign.
- MI-2^{M}: Develop Mars surface, orbital, and Mars-to-Earth communications to support an initial human Mars exploration campaign.
- MI-3^{M}: Develop Mars position, navigation and timing capabilities to support an initial human Mars exploration campaign.
- MI-4^{M}: Demonstrate Mars ISRU capabilities to support an initial human Mars exploration campaign.

Superscripts indicate applicability to Lunar (L), Martian (M), or both (LM)

Lunar Infrastructure Goal Rationale

Lunar Infrastructure (LI)

Goal: Create an interoperable global lunar utilization infrastructure where U.S. industry and international partners can maintain continuous robotic and human presence on the lunar surface for a robust lunar economy without NASA as the sole user, while accomplishing science objectives and testing for Mars.

Rationale: This goal articulates the foundational capabilities and services required to support continuous human presence and exploration of the Moon. The intention is to enable access and support across the entirety of the Moon's surface, not limiting exploration to one location or region that constrains scientific gain or extension to Mars. The language of this goal reinforces the important tenet of inviting industry and international partners to fully participate in and contribute to this endeavor. It supports the creation of markets and services that can endure with commercial value. Finally, this goal reinforces the key drivers for lunar exploration, which are scientific gains and practice for Mars.

One objective for each major infrastructure technology reflects the expectation that these capabilities will be achieved on different time scales and phased accordingly, and that their completion will be assessed by different metrics. **LI-1 through LI-3** address the overarching "utilities," that will be needed to support continuous lunar presence: power; communications; and position, navigation, and timing. These areas are fundamental elements that are essential to multiple scales of exploration throughout the build-up of assets on the lunar surface. **LI-4 through LI-6** describe additional primary capabilities that will enable robust exploration and sustained presence: mobility, precise landings, and manufacturing and construction. **LI-7 and LI-8** are the advanced capabilities that suggest industrial scale production and a fundamental shift to the use of lunar surface resources for sustainment and reduced logistics from Earth. **LI-9** explicitly calls out some of the functions that will provide resilience and situational safety for astronauts and assets.

Mars Infrastructure Goal Rationale

Mars Infrastructure (MI)

Goal: Create essential infrastructure to support an initial human Mars exploration campaign.

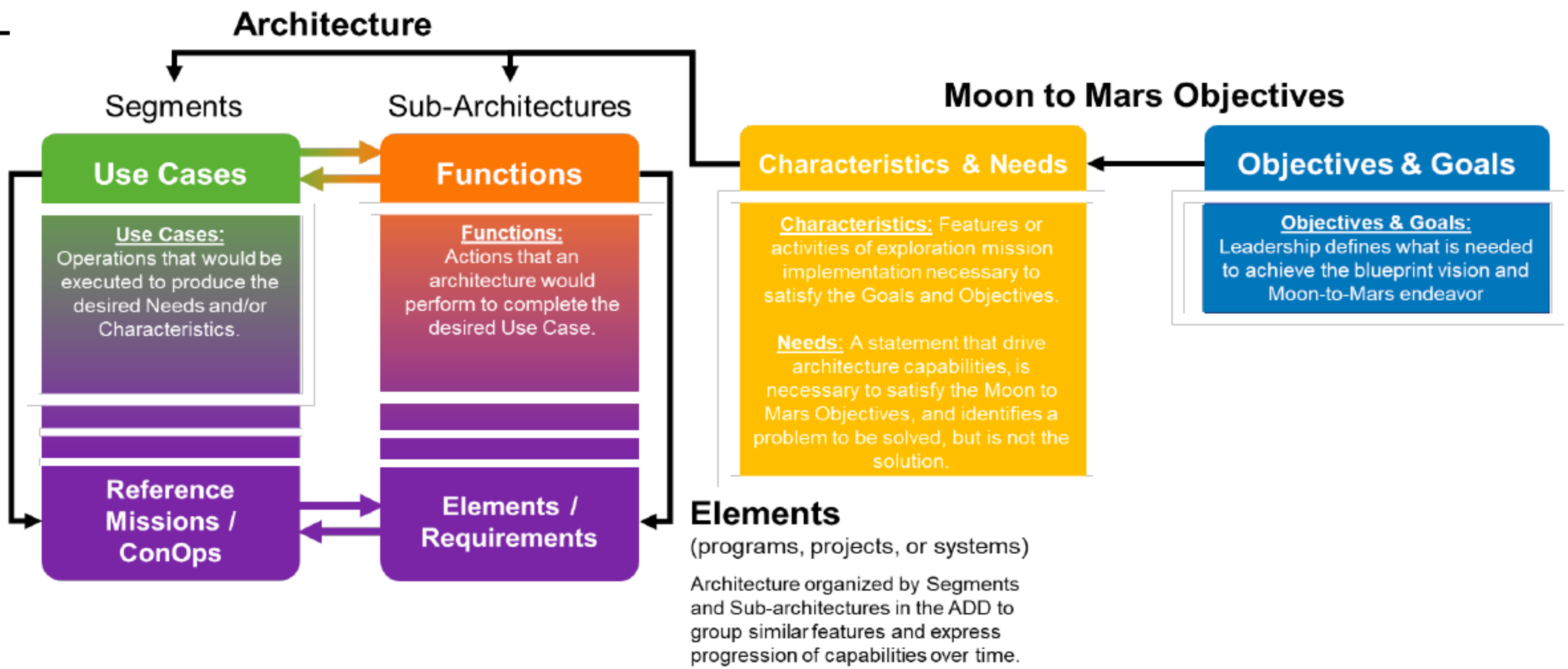
Rationale: To enable the potential for human presence and exploration of Mars beyond one mission, this goal acknowledges that foundational capabilities and services will be needed to properly prepare for and support this challenging endeavor. As technologies mature and the Mars architecture evolves, the exact meaning of the word "campaign" and the supporting objectives will be further defined.

As with the Lunar Infrastructure Objectives, the Mars Infrastructure Objectives are broken into specific functions that are foundational to efficient, safe, and sustained human exploration in **MI-1 through MI-3**: power; communications; and position, navigation and timing. **MI-4** reflects the importance of long-lead technology developments demonstrating the use of in-situ resources for repeated exploration missions and future sustained presence.

MI-1[M]:	Develop Mars surface power sufficient for an initial human Mars exploration campaign.
MI-2[M]:	Develop Mars surface, orbital, and Mars-to-Earth communications to support an initial human Mars exploration campaign.
MI-3[M]:	Develop Mars position, navigation and timing capabilities to support an initial human Mars exploration campaign.
MI-4[M]:	Demonstrate Mars ISRU capabilities to support an initial human Mars exploration campaign.

Objectives Decomposition Process

Objective Decomposition Process Flow



Characteristics & Needs:

C&Ns are the first level of decomposition of the objective, from the objective owners, to provide additional context/details on the objective's intent. This enables the architecture teams to provide direct traceability of the Use Cases and Functions to C&N statements.

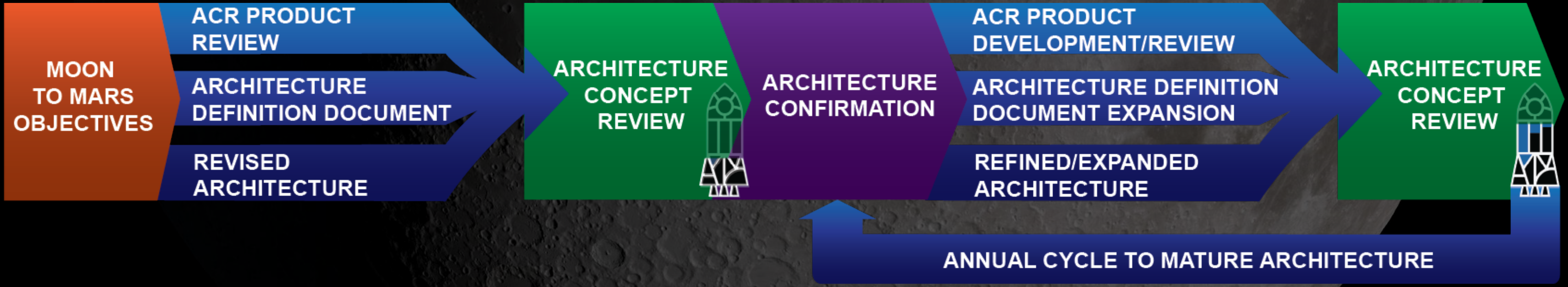
Architecture Processes

Strategic Analysis Cycle

- Moon-to-Mars Campaign
- Campaign and Architecture Development
- Element Formulation
- Modeling and Simulation
- Rapid Prototyping and Human in the Loop Testing

Evolutionary Architecture Process

Formulating architecture and exploration strategy based on objectives



Architecture Segments and Sub-Architectures

Segment: A portion of the architecture, identified by one or more notional missions or integrated use cases, illustrating the interaction, relationships, and connections of the sub-architectures through progressively increasing operational complexity and objective satisfaction.

Human Lunar Return

Initial capabilities, systems, and operations necessary to re-establish human presence on the Moon.

Foundational Exploration

Expansion of operations, capabilities, and systems supporting complex orbital and surface missions to conduct utilization and Mars forward analogs.

Sustained Lunar Evolution

Enabling operations, capabilities, and systems to support regional and global utilization, economic opportunity, and a steady cadence of human missions on and around the Moon.

Humans to Mars

Initial capabilities, systems, and operations necessary to establish human presence on Mars and continued exploration.

Sub-architecture: A group of tightly-coupled systems, functions, and capabilities that perform together to accomplish architecture objectives.

Communication, Positioning, Navigation, and Timing • Habitation • Human Systems • Logistics • Mobility Systems • Power • Transportation • Utilization Systems

ESDMD Treatment of Infrastructure Objectives

DRAFT Lunar Infrastructure Objective Decomposition (1 of 2)

Lunar Infrastructure (LI) Goal: Create an interoperable global lunar utilization infrastructure where U.S. industry and international partners can maintain continuous robotic and human presence on the lunar surface for a robust lunar economy without NASA as the sole user, while accomplishing science objectives and testing for Mars.

ID	Objective	Original ADD Language	Updated Language	Notes
LI-1	Develop an incremental lunar power generation and distribution system that is evolvable to support continuous robotic/human operation and is capable of scaling to global power utilization and industrial power levels.	Emplace power generation and power storage capabilities on the lunar surface	Emplace scalable power generation, energy storage, and power distribution system(s) on the lunar surface	Do we need continuous power for crew critical event here too?
		Emplace power distribution and storage capabilities on the lunar surface to allow power utilization at multiple locations around exploration sites	Emplace scalable power generation, energy storage, and power distribution system(s) on the lunar surface to allow power utilization at multiple locations around exploration sites	
LI-2	Develop a lunar surface, orbital, and Moon-to-Earth communications architecture capable of scaling to support long term science, exploration, and industrial needs	Implement communications systems to enable high bandwidth, high availability communications between Earth-based personnel, surface crew, and science packages on the surface	Implement scalable communication system(s) to enable high bandwidth, high availability communications between Earth-based personnel, surface crew, and payloads/assets/science packages on the surface.	
			Implement scalable communication system(s) to enable high bandwidth, high availability communications between Earth-based personnel, in-space crew, and in-space payload/assets/science packages	
			Implement scalable communication system(s) to enable high bandwidth, high availability communications between In-space personnel, surface crew, and payload/assets/science packages on the surface	
LI-3	Develop a lunar position, navigation and timing architecture capable of scaling to support long term science, exploration, and industrial needs.	Implement navigation and timing systems to enable high availability navigation on the surface	Implement scalable navigation, positioning, and timing system(s) to enable high availability navigation and tracking in cislunar space and on the lunar surface	
			Implement system(s) to enable accurate location tracking of collected surface samples	
LI-4	Demonstrate advanced manufacturing and autonomous construction capabilities in support of continuous human lunar presence and a robust lunar economy.	Deliver and demonstrate autonomous construction demonstration package(s) to the lunar South Pole	Deliver autonomous construction demonstration package(s) to the lunar surface to demonstrate scalable capabilities and applications	
			Deliver advanced manufacturing demonstration package(s) to the lunar surface to demonstrate scalable capabilities and applications	
LI-5	Demonstrate precision landing capabilities in support of continuous human lunar presence and a robust lunar economy.	Demonstrate ability of lunar landers to reliably land within a defined radius around an intended location.	Demonstrate the capability for lunar landers to reliably and safely land within a defined radius around an intended location	

DRAFT Lunar Infrastructure Objective Decomposition (2 of 2)

ID	Objective	Original ADD Language	Updated Language	Notes
LI-6	Demonstrate local, regional, and global surface transportation and mobility capabilities in support of continuous human lunar presence and a robust lunar economy.	Demonstrate the ability to allow crew to move locally around landing sites to visit multiple locations of interest.	Demonstrate the ability to allow crew to move locally around landing sites to visit multiple locations of interest	
			Demonstrate the ability to relocate surface elements to regional locations around the lunar surface during crewed and uncrewed phase of missions	
		Demonstrate the ability to relocate surface elements to locations around the lunar South Pole between crewed surface missions.	Demonstrate the ability for crew to access surface assets across the lunar globe	
LI-7	Demonstrate industrial scale ISRU capabilities in support of continuous human lunar presence and a robust lunar economy.	Deliver and demonstrate ISRU demonstration package(s) to the lunar South Pole	Deliver scalable ISRU demonstration package(s) to the lunar surface	
			Demonstrate scalable capabilities to collect, produce, store, and transfer commodities for potential system and crew usage on the lunar surface	
			Demonstrate the capability to identify and locate potential site(s) for resource utilization	
LI-8	Demonstrate technologies supporting cislunar orbital/surface depots, construction and manufacturing maximizing the use of in-situ resources, and support systems needed for continuous human/robotic presence.	Demonstrate capability to transfer propellant from one spacecraft to another in space	Demonstrate the capability to transfer propellant from one spacecraft to another in space	
			Demonstrate the capability to transfer propellant from one element to another on the lunar surface	
		Demonstrate capability to store propellant for extended durations in space	Demonstrate the capability to store propellant for extended durations in space	
		Demonstrate capability to store propellant on the lunar surface for extended durations	Demonstrate the capability to store propellant for extended duration on the lunar surface	
			Demonstrate the capability to use surface-born resources for potential construction and/or manufacturing on the lunar surface	
LI-9	Develop environmental monitoring, situational awareness, and early warning capabilities to support a resilient, continuous human/robotic lunar presence.	Emplace systems to monitor solar weather and to predict SPEs	Emplace system(s) to monitor cis-Lunar space and lunar surface natural environments and provide early warnings to in-space and surface assets and crew	Specification on which environment variables to monitor should be at the Use Case Level
			Emplace system(s) to monitor cis-Lunar space and lunar surface induced environments and provide early warnings to in-space and surface assets and crew	

DRAFT Mars Infrastructure Objective Decomposition

Mars Infrastructure (MI) Goal: Create essential infrastructure to support initial human Mars exploration campaign.				
ID	**Objective**	**Original ADD Language**	**Updated Language**	**Notes**
MI-1	Develop Mars surface power sufficient for an initial human Mars exploration campaign.	NA	Emplace high availability power generation, energy storage, and power distribution system(s) on the Martian surface.	
			Provide continuous power availability during crew safety critical mission operation.	
MI-2	Develop Mars surface, orbital, and Mars-to-Earth communications to support an initial human Mars exploration campaign	NA	Implement communication system(s) to enable high bandwidth, high availability communication between Earth-based personnel, in-space crew, surface crew, and payloads/assets/science packages on the surface.	
			Implement communication system(s) to enable high bandwidth, high availability communication between Earth-based personnel, in-space crew, surface crew, and in-space payloads/assets/science packages.	
MI-3	Develop Mars position, navigation and timing capabilities to support an initial human Mars exploration campaign.	NA	Implement navigation and timing system(s) and processes to enable high availability navigation, positioning, tracking, and Mars timing on the surface.	
			Implement navigation, positioning, and timing system(s) to enable high availability navigation and tracking in deep space and in Martian orbit.	
			Implement system(s) to enable accurate location tracking of collected surface samples.	
MI-4	Demonstrate Mars ISRU capabilities to support an initial human Mars exploration campaign.	NA	Deliver ISRU demonstration package(s) to the Martian surface.	
			Demonstrate capabilities to collect, produce, store, and transfer commodities for potential system and crew usage on the Martian surface.	
			Demonstrate the capability to identify and locate potential sites for resource utilization.	

Power Envisioned Future

Sustainable Living and Working Further from Earth

Developing sustainable power sources and other surface utilities to enable continuous Lunar and, ultimately, Mars surface operations.

Power Generation

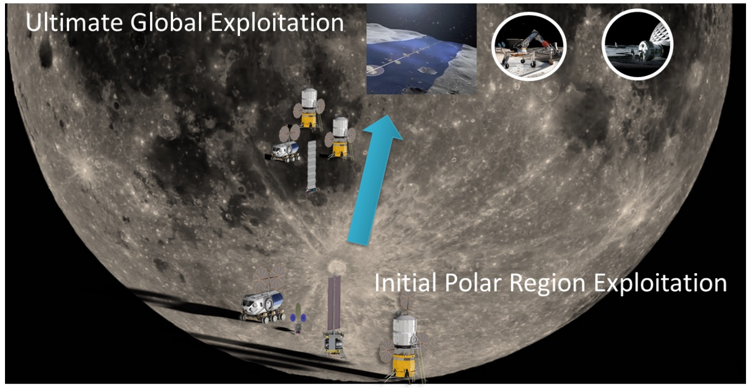
- Up to 50 kW_e-class modular Earth-sourced Photovoltaic Arrays for Lunar Polar surface outposts and ISRU prospecting/production plants.
- 40 kW_e-class mobile Fission Power Systems to support Lunar Polar operations, bootstrap a global Lunar surface power grid to support Lunar industrialization at lower latitudes, and support Mars surface exploration

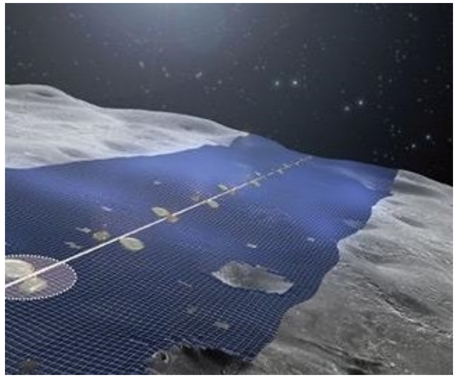
Energy Storage

- Up to 50 kW_e-hr Secondary Batteries for mobility
- Up to 1 MW_e-hr Regenerative Fuel Cells for Polar Outpost/ISRU energy storage
- Large scale energy storage systems gathered from Lunar-sourced minerals

Power Distribution

- 1000 V, radiation-hard, high reliability power electronics
- Up to 10 kW_e–class low mass Cables and spools for multi-km power distribution grids
- Up to 10 kW_e-class Power Beaming for up to 5 km line-of-sight.
- High power, long distance transmission lines printed from Lunar-sourced aluminum.





Not all activities depicted are currently funded or approved. Depicts "notional future" to guide technology vision.

EXPLORE: Develop Next Generation Communications and Navigation Technologies

Develop communications, navigation, and sensing infrastructure capable of handling high data volumes with near real-time communication (cislunar), and increased onboard navigation and time-keeping autonomy

QUANTUM COMMUNICATIONS

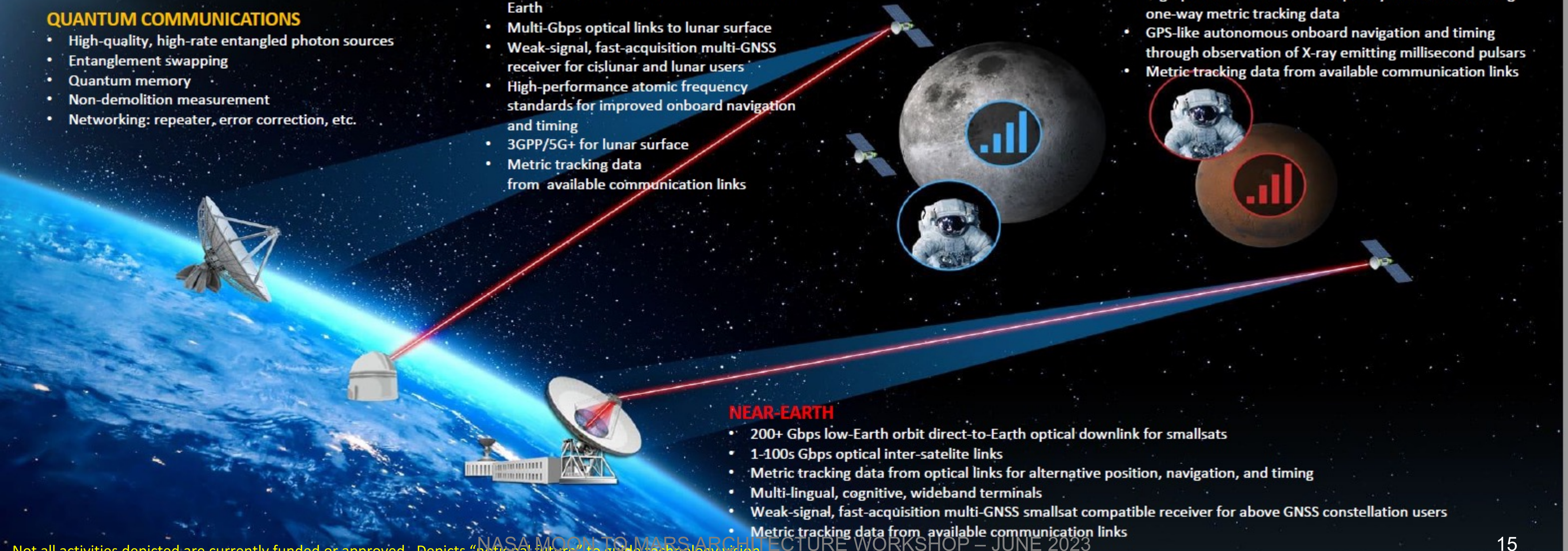
- High-quality, high-rate entangled photon sources
- Entanglement swapping
- Quantum memory
- Non-demolition measurement
- Networking: repeater, error correction, etc.

CISLUNAR AND MOON

- LunaNet framework for interoperable and resilient communication and navigation
- 1-10+ Gbps coherent optical links direct-to-Earth
- Multi-Gbps optical links to lunar surface
- Weak-signal, fast-acquisition multi-GNSS receiver for cislunar and lunar users
- High-performance atomic frequency standards for improved onboard navigation and timing
- 3GPP/5G+ for lunar surface
- Metric tracking data from available communication links

OTHER CELESTIAL BODIES AND DEEP SPACE

- Extension of LunaNet framework beyond Earth-Moon for interplanetary and deep space network
- High Photon Efficiency optical links for 100s Mbps direct-to-Earth downlink
- High-performance atomic frequency standards enabling one-way metric tracking data
- GPS-like autonomous onboard navigation and timing through observation of X-ray emitting millisecond pulsars
- Metric tracking data from available communication links



NEAR-EARTH

- 200+ Gbps low-Earth orbit direct-to-Earth optical downlink for smallsats
- 1-100s Gbps optical inter-satelite links
- Metric tracking data from optical links for alternative position, navigation, and timing
- Multi-lingual, cognitive, wideband terminals
- Weak-signal, fast-acquisition multi-GNSS smallsat compatible receiver for above GNSS constellation users
- Metric tracking data from available communication links

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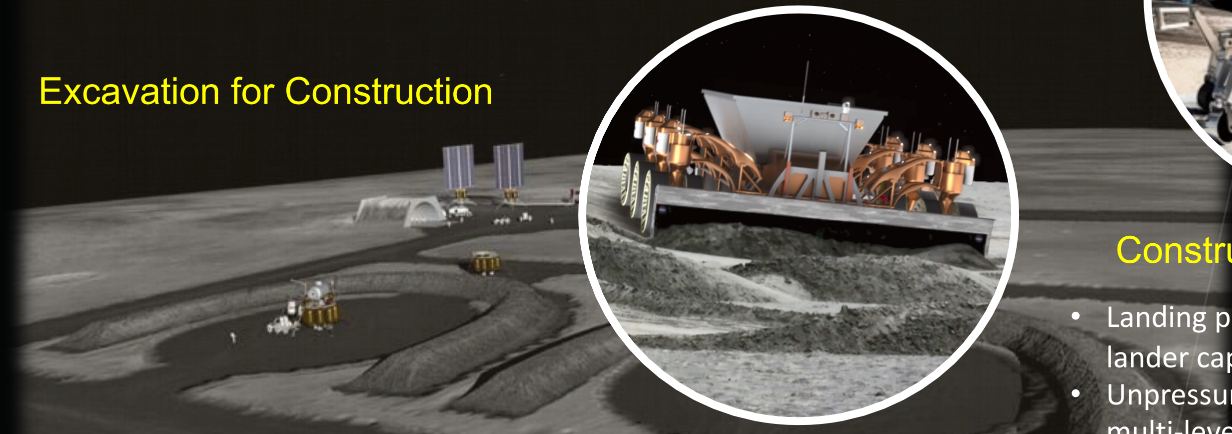
Autonomous Lunar Excavation, Construction, & Outfitting

targeting landing pads, structures, habitable buildings utilizing in-situ resources

Excavation for ISRU-based Resource Production

- Site surveying, resource prospecting
- Ice mining & regolith extraction for 100s to 1000s metric tons of commodities per year

Excavation for Construction



- Site preparation for construction: obstacle clearing, leveling & trenching
- Construction materials production utilizing in-situ resources
  - 100s to 1000s metric tons of regolith-based feedstock for construction projects
  - 10s to 100s metric tons of metals and binders

Construction and Outfitting

- Landing pad construction demo scaling to human lander capable landing pads
- Unpressurized structure evolving to single and then multi-level pressurized habitats
- Outfitting for data, power & ECLSS systems
- 100-m-diameter landing pads, 10s km of roads, 1000s m^3 habitable pressurized volume

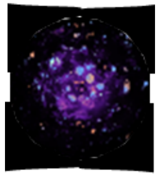
Sustainable Off-Earth Living & Working

- Commercial autonomous excavation and construction of landing pads, roads and habitable structures
- Fully outfitted buildings to support a permanent lunar settlement and vibrant space economy
- Extensible to future SMD missions and Mars settlement

LIVE: Develop exploration technologies and enable a vibrant space economy with supporting utilities and commodities

Scalable ISRU production/utilization capabilities including sustainable commodities on the lunar & Mars surface*

Commercial Scale Water, Oxygen, Metals & Commodity Production

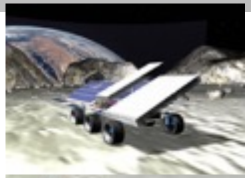

- Lunar resources mapped at meter scale for commercial mining
- 10's of metric tons of commodities per year for initial goal commercial usage
- Scalable to 100's to 1000's metric tons per year

Commodities for Habitats & Food Production

- Water, fertilizers, carbon dioxide, and other crop growth support
- Crop production habitats and processing systems
- Consumables for life support , EVAs, and crew rovers/habitats for growing human space activities

In Situ Derived Feedstock for Construction, Manufacturing, & Energy






- Initial goal of simple landing pads and protective structures
- 100's to 1000's metric tons of regolith-based feedstock for construction projects
- 10's to 100's metric tons of metals, plastics, and binders
- Elements and materials for multi-megawatts of energy generation and storage
- Recycle, repurpose, and reuse manufacturing and construction materials & waste

Commodities for Commercial Reusable In-Space and Surface Transportation and Depots


- 30 to 60 metric tons per lander mission
- 100's to 1000's metric tons per year of for Cis-lunar Space
- 100's metric tons per year for human Mars transportation

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*Commodities are items and consumables that can be eventually sold

LAND: Enable Lunar/Mars global access with ~20t payloads to support human missions.

Developing landing capabilities that support unique requirements for both the Moon and Mars, to allow for landing greater payload capacity with greater accuracy

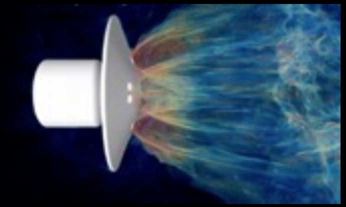
Lunar Capabilities (feeding forward to Mars)

Precision Landing and Hazard Avoidance

Safely and precisely land near science sites or pre-deployed assets *(see details in separate package)*

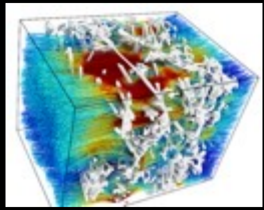
Retropropulsion

Understand flow physics and vehicle control through wind tunnel testing of Mars-relevant configurations; advance CFD modeling



Plume Surface Interaction

Reduce risks to landers and nearby assets by understanding how engine plumes and surfaces behave



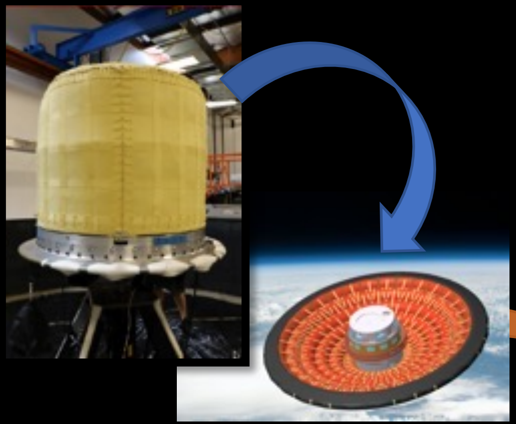
Foundational Modeling, Testing, Instrumentation, and Computing

Measure EDL flight system performance and update/develop unique, critical simulations for EDL/DDL systems

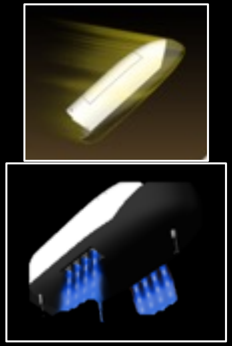
Mars Capabilities

Large Scale Demonstrations

Large structures, including deployables, that can slow down a 20t payload in the thin Mars atmosphere

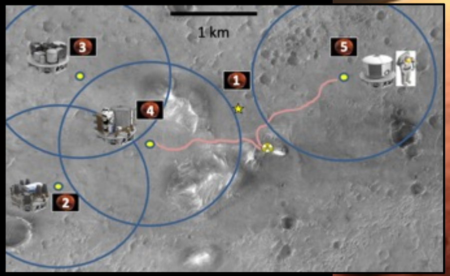


Earth Flight Tests, such as LOFTID



Assess Alternatives

Aggregate Assets



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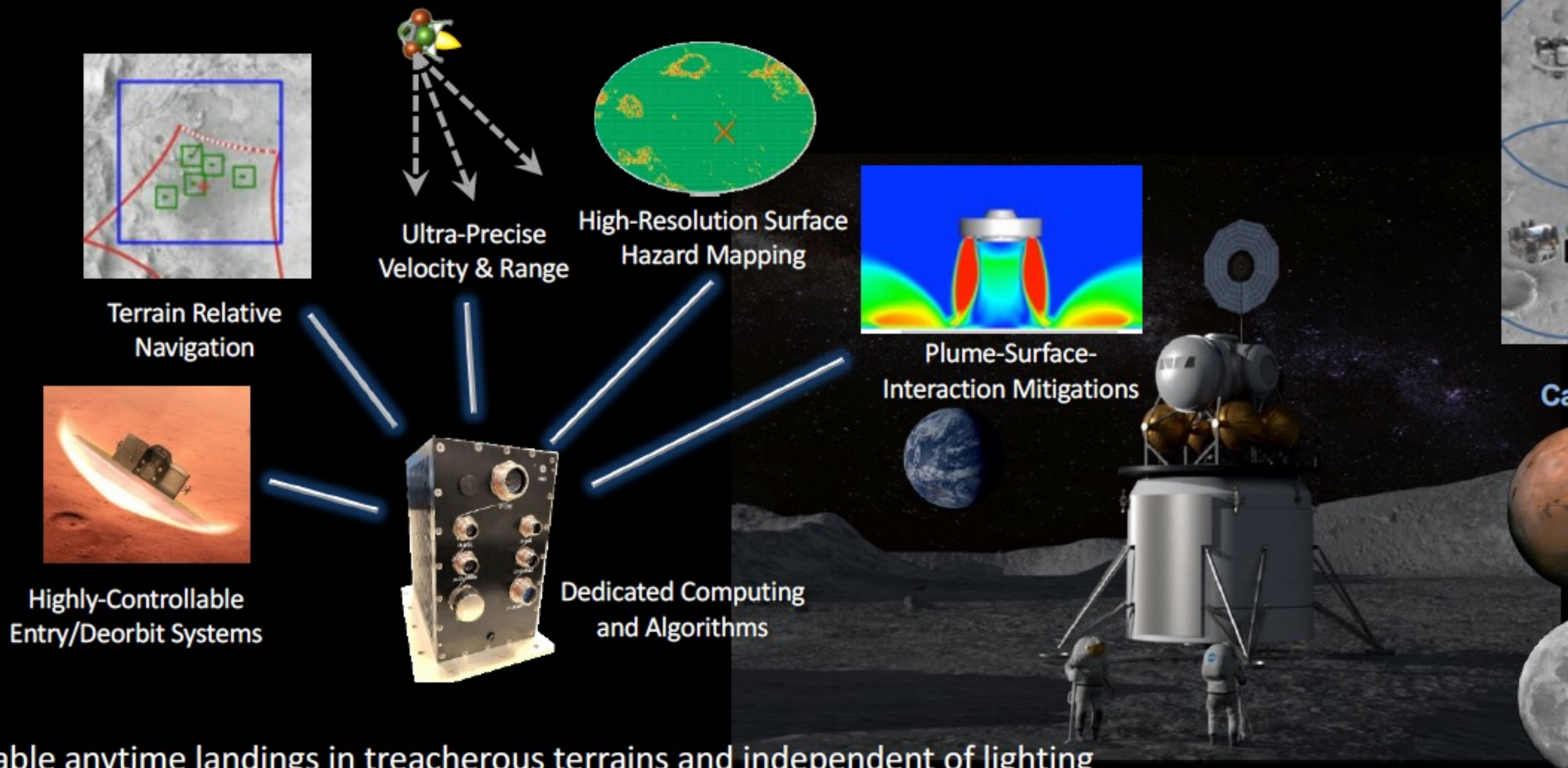
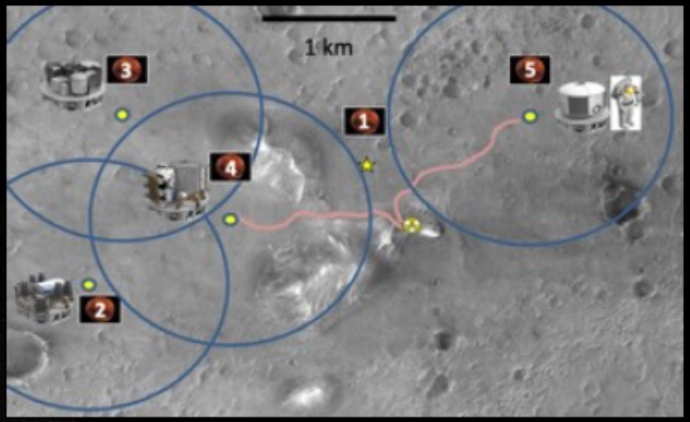
LAND: Technologies to Precisely Land Payloads and Avoid Landing Hazards

Developing entry, descent and landing technology to enhance and enable small spacecraft to Flagship-class missions across the solar system



Aggregated and Sustainable Sites on the Moon and Mars



Capabilities evolvable for many solar-system destinations

<u>Enable</u> anytime landings in treacherous terrains and independent of lighting

<u>Reduce the risk</u> of the landing for human and robotic missions to many destinations

<u>Reduce operations time</u> for a rover or human to reach an interesting site

<u>Aggregate resources</u> in one surface region for missions requiring multiple landings

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Questions

1. **Questions or comments on the Lunar or Mars Infrastructure Goal Rationales or objectives?**
2. **NASA is engaging with U.S. industry partners and asking for feedback on sustainable business cases. How are other Agencies engaging their industries?**
3. **Which objectives align with your Agency's interests?**