BLUE ORIGIN LUNA-10
AN EXPEDITED APPROACH TO A COMMERCIAL LUNAR SURFACE ARCHITECTURE

BLUE ORIGIN

LSIC SPRING MEETING

APRIL 25, 2024

This researched was developed with funding from the Defense Advanced Research Projects Agency (DARPA)

Three Complementary Multi-Service Systems to Enable Viable Commercial Lunar Surface Infrastructure

Three Multiservice Elements

1. Lander Infrastructure Node and Host Platform
2. Laser and Power Framework for Energy, Communication
3. ISRU via Molten Regolith Electrolysis for Construction, Mining and Energy

Unique Insights

- Blue Origin is internally funding the development and two demonstration missions of the MK1 lander
- 1kW – 100 kW of reliable power is important for ISRU and other fixed assets and mobile elements
- As few as 3 properly situated power nodes near the lunar south pole can provide almost continuous power across hundreds of square km, potentially allowing individual end-user elements to re-allocate mass from energy storage to other functions
- Blue Alchemist ISRU technology, funded by NASA STMD Tipping Point to TRL6, breaks the paradigm of delivering elements from Earth to the Moon.
  - Enables lunar production and delivery of regolith derived materials such as O_2, iron, silicon, aluminum, and construction slag.
- Regolith derived materials can then be used in fabrication of solar panels, wires, radiators, radiation shielding, road surfaces, and delivered as propellants.

Completed Work

- The MK1 lander design completed and first vehicle integration under way under internal Blue Origin funding, flying on early New Glenn mission.
- PowerLight has conducted kilowatt-class laser power beaming TRL4 system demonstrations with the NRL.
  - Integrated transmitter, beam pointing , “safety sleeve”, and receiver technologies
- Honeybee LAMPS vertical solar array technology completed NASA STMD Phase 1 and executing on Phase 2.
- Blue Origin has developed Blue Alchemist ISRU technologies, including demonstrating each stage in the process from initial molten regolith kilns to solar array fabrication, with high fidelity ground demonstration units.

MK1 Can Support Early Demos and Sustained Operations

- **Flight Proven Before MVE –** At least two MK-1 missions will have resolved risk areas prior to Minimum Viable Experiment
- **3 ton Payload –** Will accommodate ISRU technology payloads and 1 kWe transmitted power across 10 km+ to various assets including enabling long-term rover operation in a PSR
- **Flexible Payload Accommodations –** MK1 has multiple interfaces for all foreseeable payloads to address DARPA Thrust Areas as well as NASA objectives
- **MK1 Minimum Viable Experiment Demonstrates MK1 Infrastructure Node –** MVE validates aspects of the MK1 acting as a long-life lunar surface power, communications, and PNT Node in the 2030's

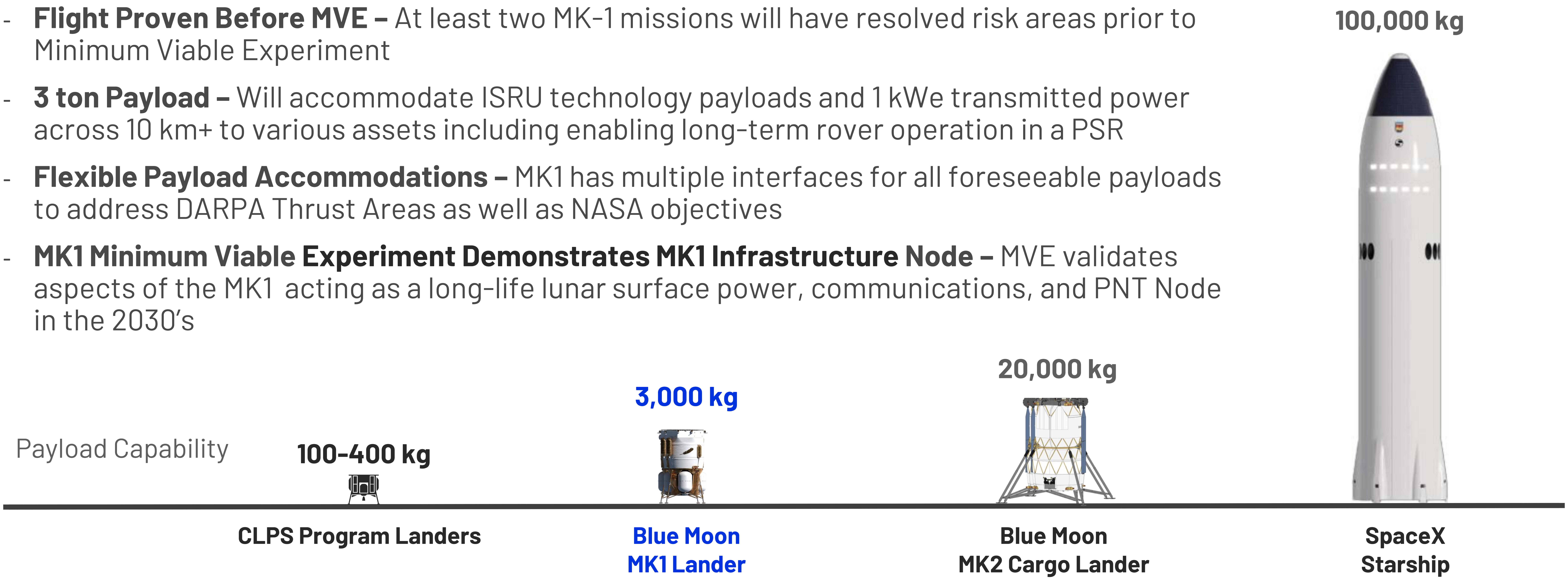

Image Source: Blue Origin

Our MK-1 lander is well sized both to host Minimum Viable Experiment demonstrations and act as a long-term node for lunar surface power, communications and PNT

Example Lunar Surface Infrastructure Relationships Between LunA-10 Teams

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Image Source: Blue Origin

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Infrastructure Concept - 2035

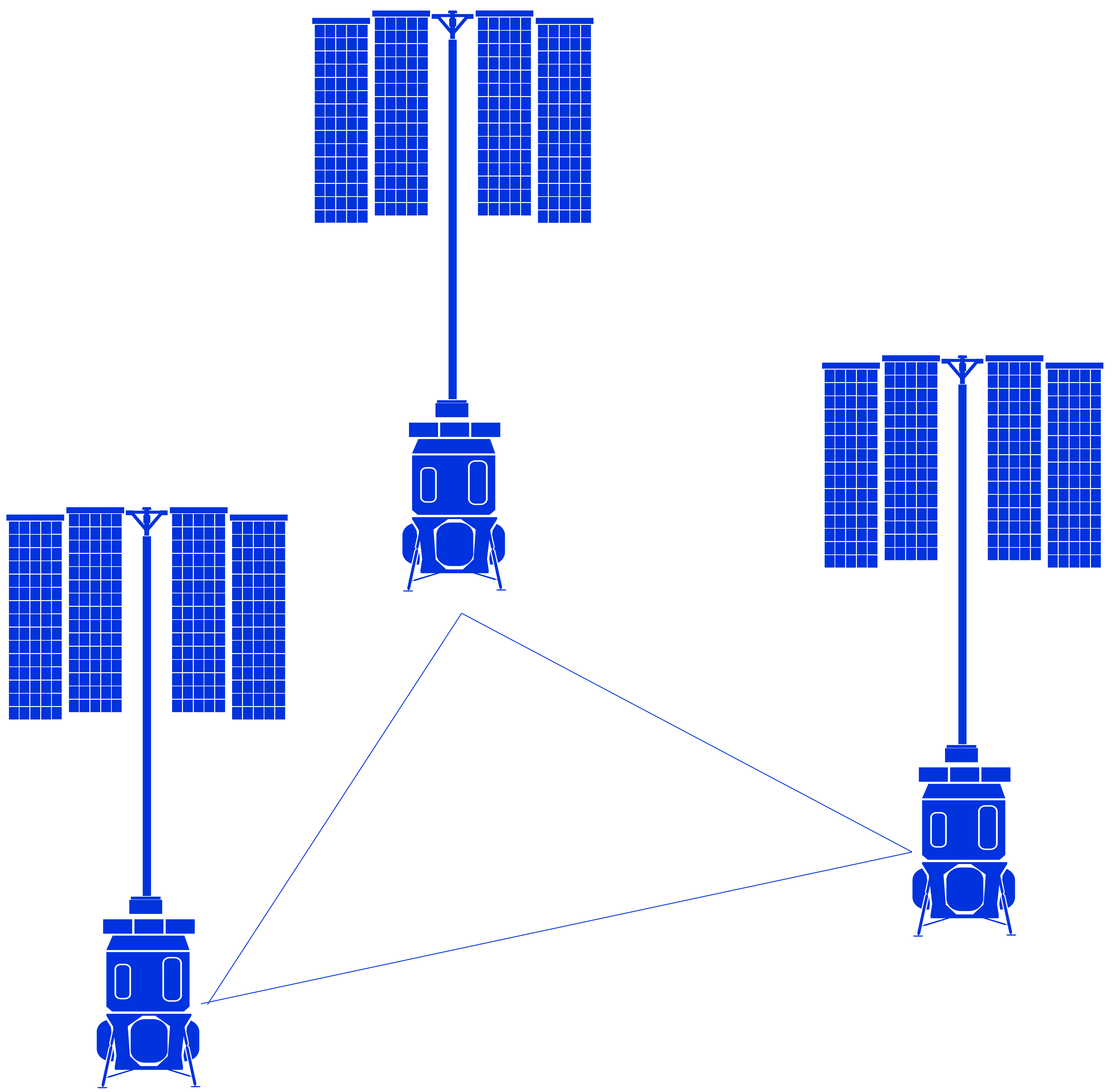
1) Power & Communications Utility service, 2) Cargo delivery service, 3) Materials Supply

Our concept may provide an infrastructure for the following services through a mesh network of landed assets:

1) Deliver cargo to lunar surface
2) Establish infrastructure node and host platform for other customer hardware
3) Provide day/night wireless power via laser power beaming to offboard users
4) Provide day/night wired power to hosted and adjacent users
5) Provide regolith-generated O_2, slag, and metals
6) Provide backhaul comms Direct to Earth and over surface

Blue's notional initial demonstration system demonstrates one node

- Mk1 Cargo Lander
- Power & Communications Infrastructure Payload Kit
    - Vertical Solar Array Technology (VSAT)
    - Power Storage System for overnight power
    - Laser Power Beaming
    - Radio and/or Optical. Comms
    - Power Conditioning
- Silicon extraction ISRU experiment using Molten Regolith Electrolysis (MRE)



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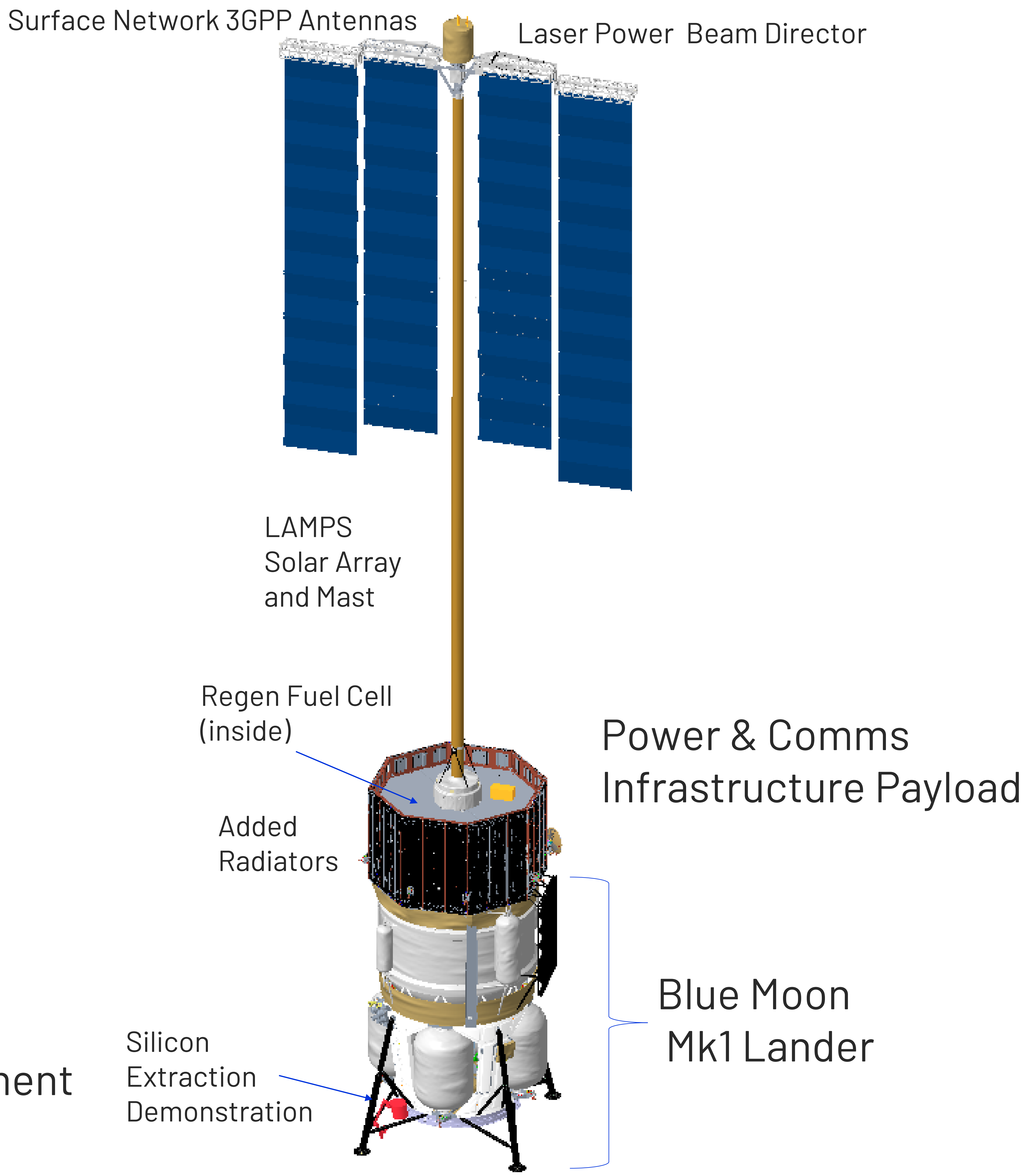
System Configuration

INITIAL DEMONSTRATION SYSTEM

Features	Capability
Solar Array	> 10 kWe
Mast	20 m mast on ~10 m lander (total 30 m above surface)
3GPP Telecom Service	25 Mbps bps up to > 10 km range, max range ~100 km
Regen Fuel Cell Augmentation Kit	1.5 MWh, 7.8 kW_e over 192 hrs
Laser Power Transmitter	~1 kW_e delivered to 10+ km,
Silicon Extraction Experiment	Demonstrate production of silicon from regolith
Heat Rejection Augmentation Kit	Added Radiator area for payload power

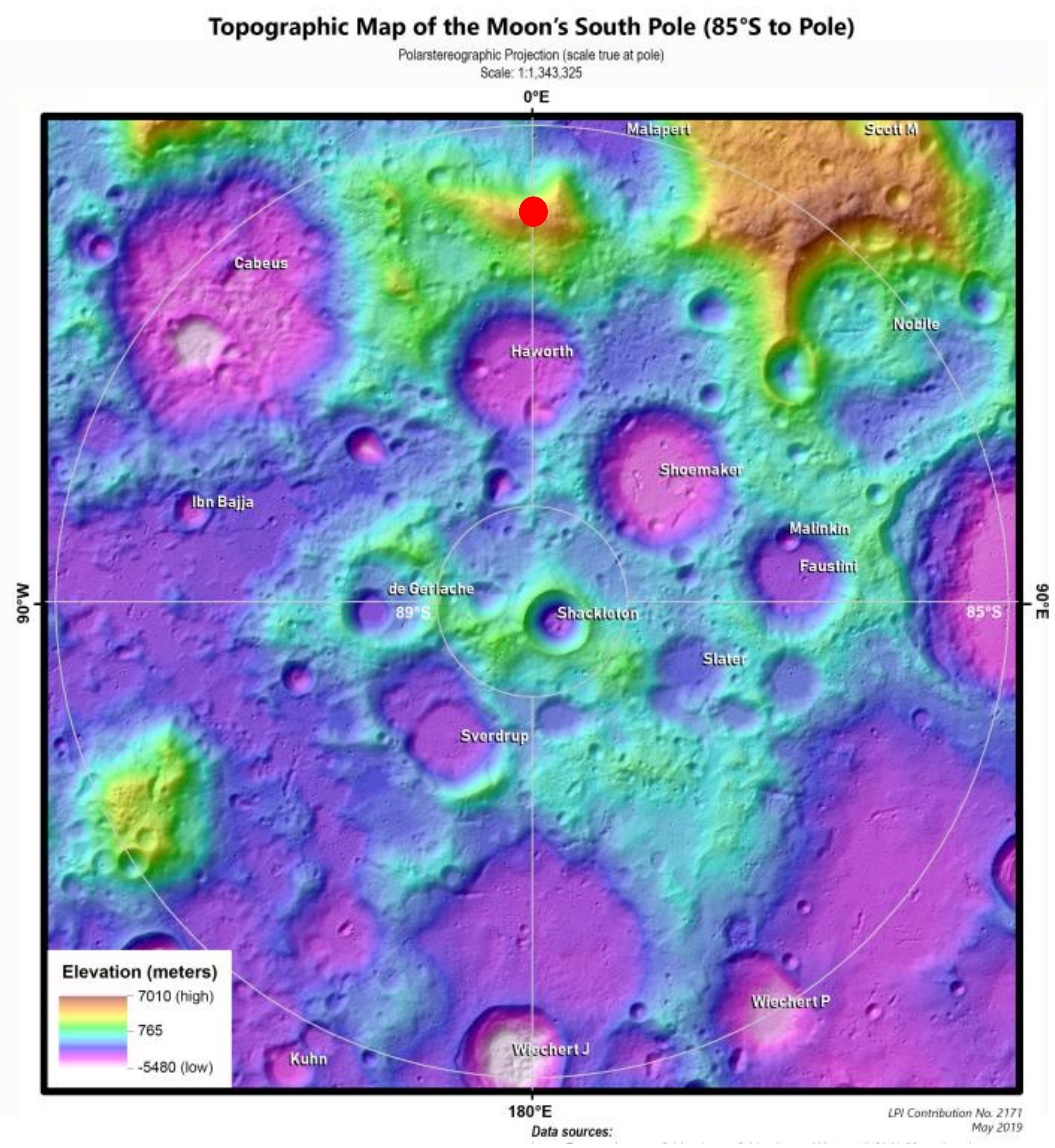


This is a study concept, not a product development commitment

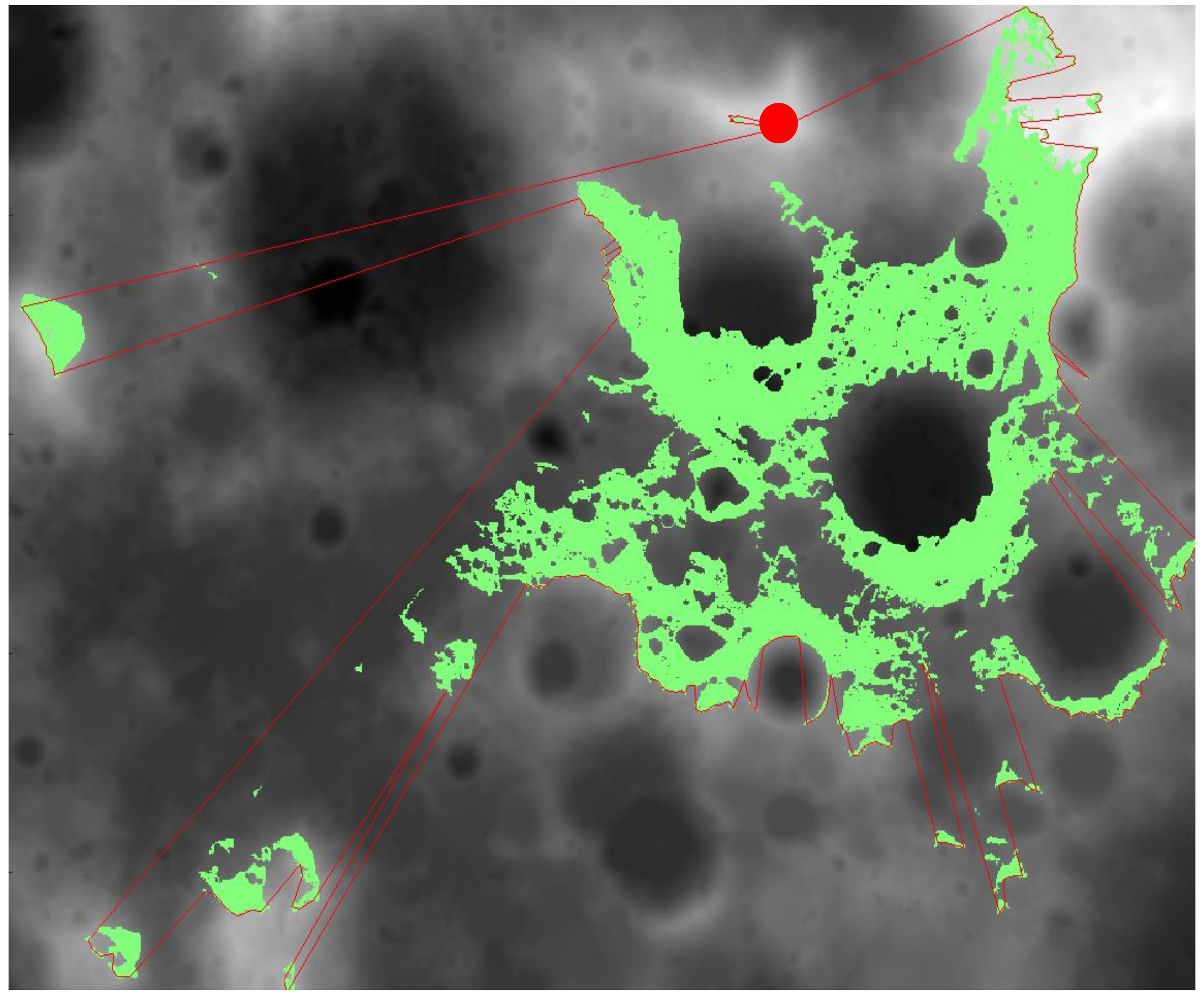
Image Source: Blue Origin

Viewshed from Utility Site at Malapert

Unlike on a theoretically smooth sphere, in mountainous terrain increasing the tower height doesn't (much) extend the max distance, instead it fills in gaps in the mid-field

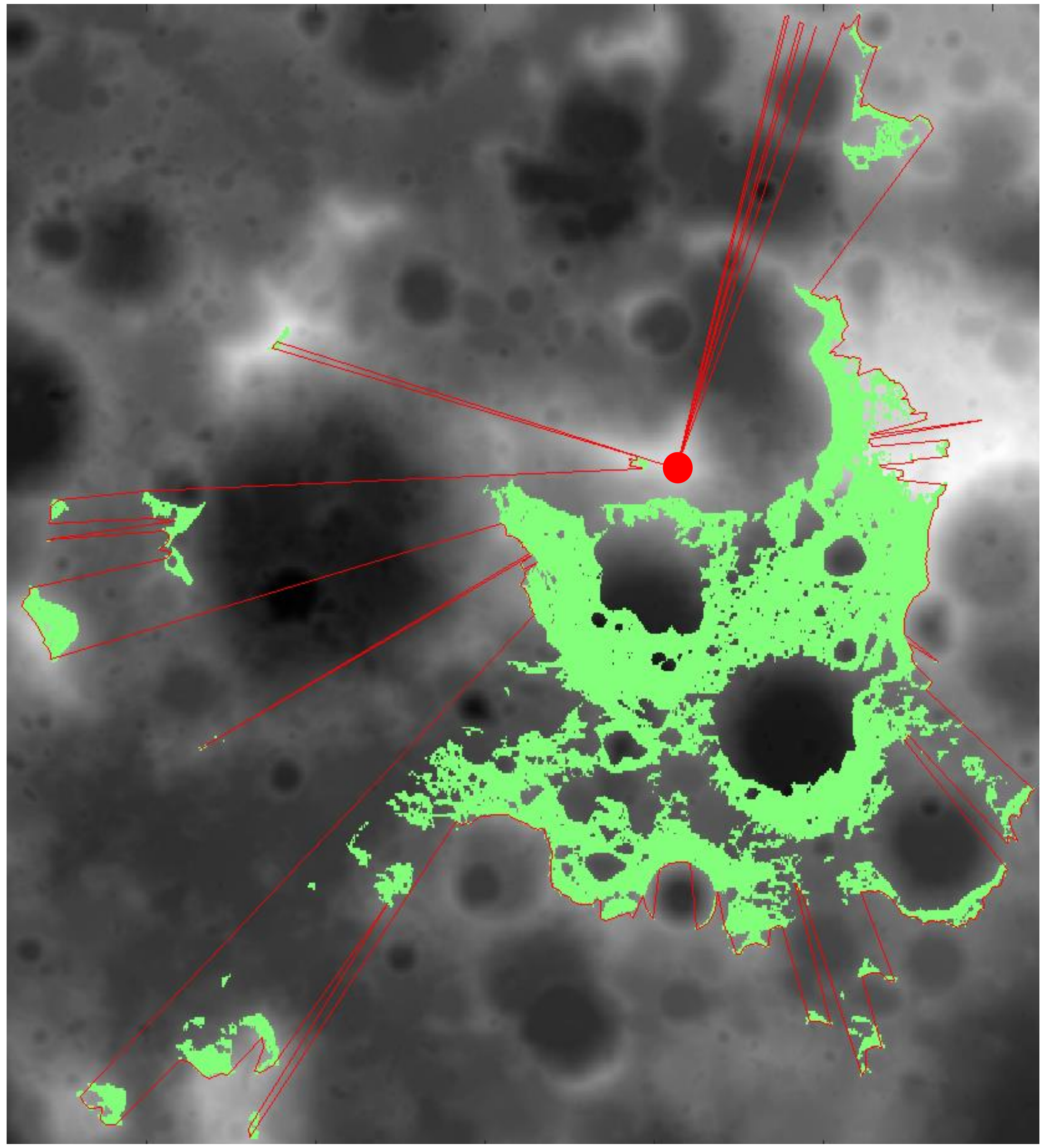


Source: Stopar J. and Meyer H. (2019) *Topographic Map of the Moon's South Pole (85°S to Pole),* Lunar and Planetary Institute Regional Planetary Image Facility, LPI Contribution 2171,



30 m tower to user 1 m above terrain

Source: Blue Origin



100 m tower to user 1 m above terrain

Source: Blue Origin

Max line-of-sight transmit distance for laser or RF is ~250 km

But most of the viewable area is <75-100 km

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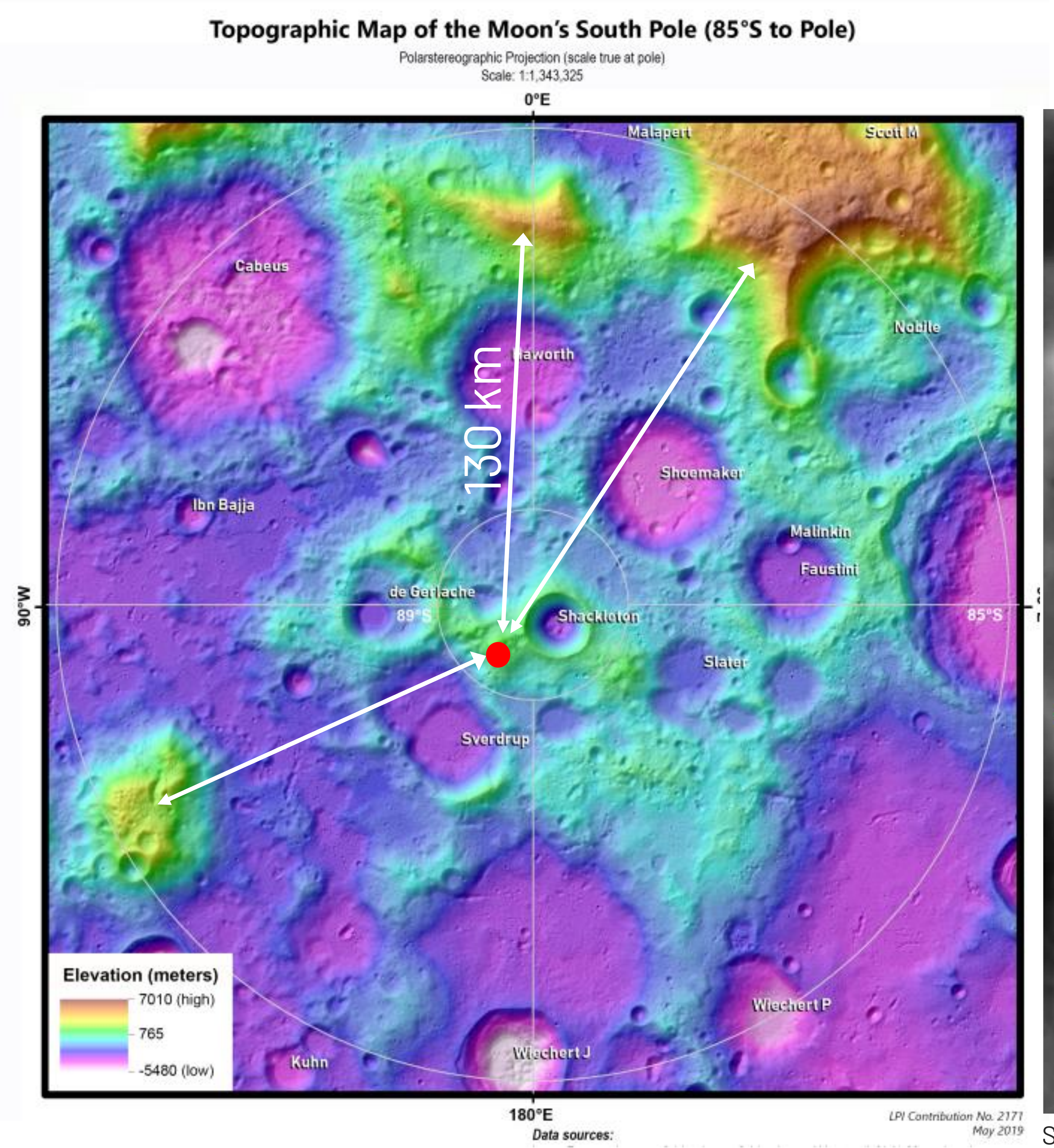
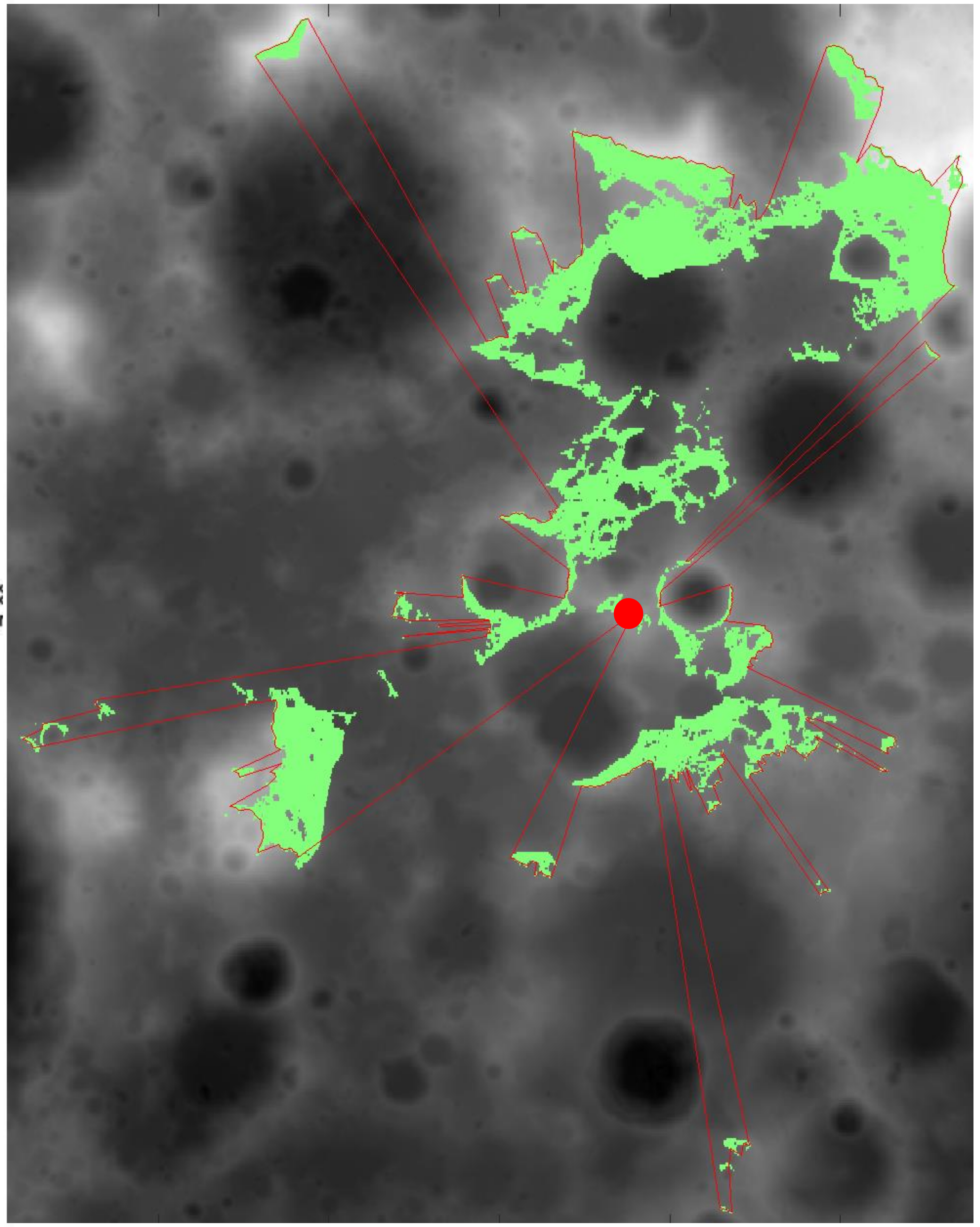
Viewshed from Utility Site at South Pole



Region with line of sight from point on the Shackleton Connecting Ridge

30 m tower to user 1 m above terrain



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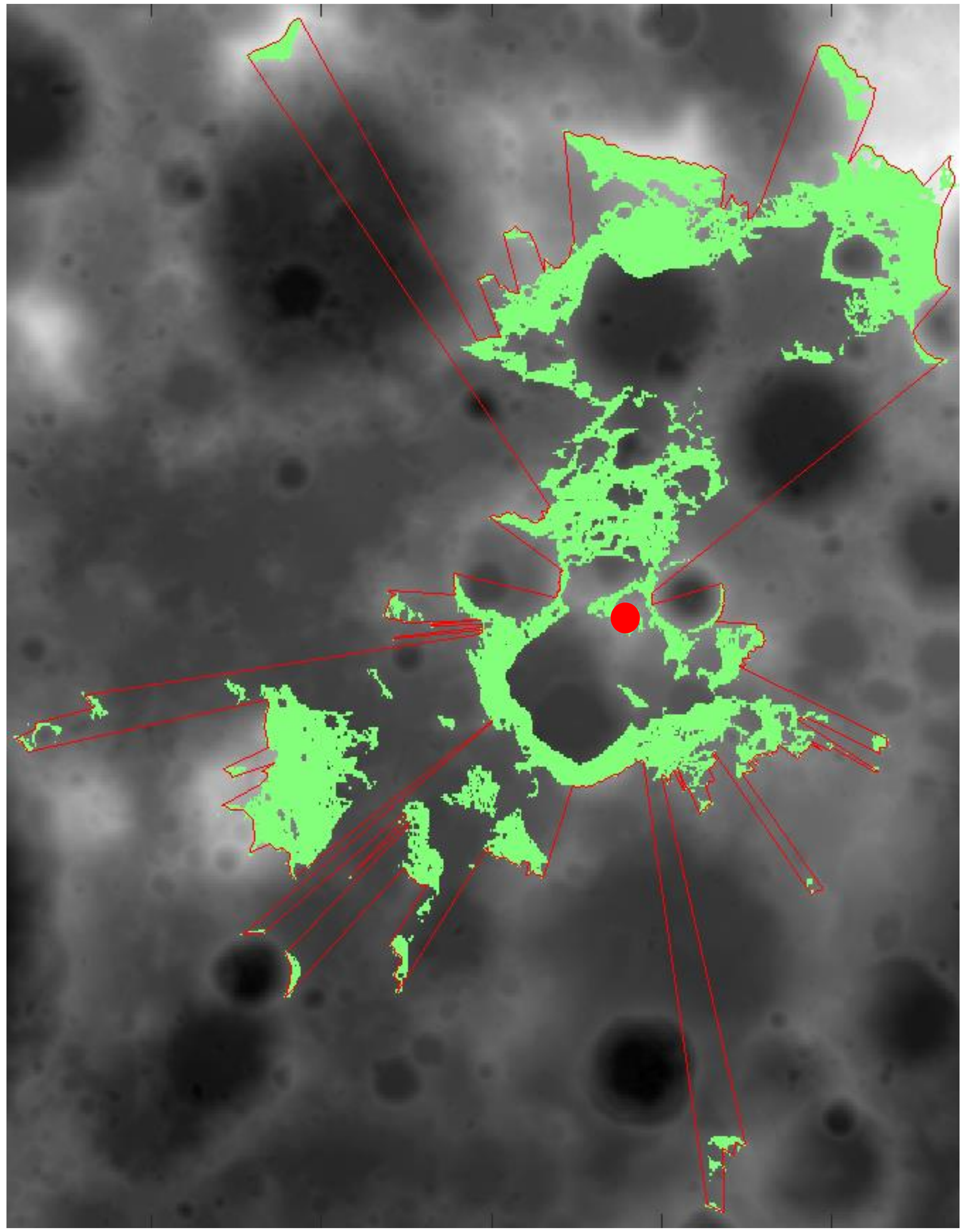

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The Blue Origin Mark 1 lander can deliver the basic building block of lunar power, telecom, and resource infrastructure


BLUE ORIGIN
FOR THE BENEFIT OF EARTH

CISLUNAR® INDUSTRIES

METAL - Material Extraction, Treatment, Assembly & Logistics

Prospecting	Mining	Processing	Refinement	Space Foundry	Logistics	Use/Sell
Surveying, Sampling, Feasibility	*Regolith Collection, Ore Concentration*	*Oxygen removal, Metal extraction*	*Metal Separation*	*Alloying, Casting, Extrusion, Shaping, Treatment*	*Storage, Distribution*	*Infrastructure, Commercial Customers*

Point of Contact
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LSIC Spring Meeting
April 25, 2024

About CisLunar Industries

Hardware For Sustainable Manufacturing, Mobility, and Industrial Development in Space

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Space Foundry

- Electromagnetic furnace system for metal processing in space

Lunar Applications

- Recycling
- Forming & Shaping
- Heat treatment
- Alloying

Power Converter

- Modular high-power converter for in-space applications

Lunar Applications

- Power distribution
- Power grid end points
- Mobile equipment
- Manufacturing

Partners

- NASA
- ISS National Laboratory
- Space Force
- Colorado School of Mines
- Colorado State University
- Sierra Space
- Axiom Space
- Nanoracks (Voyager Space)
- Astroscale U.S.
- Neumann Space
- Think Orbital
- KMI
- ZIN Technologies (Voyager Space)
- Safran

CisLunar Industries Lunar Space Foundry (LSF)

Building infrastructure and enabling sustainable mining operations

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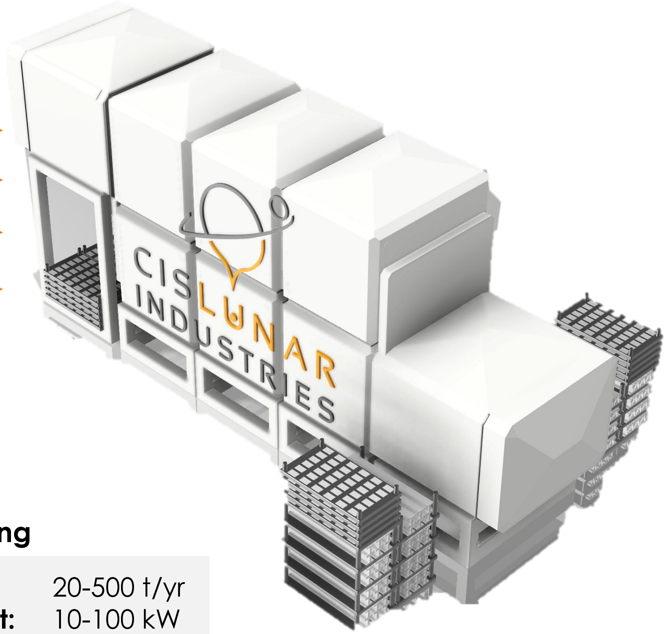
Inputs

- ISRU Metals — Aluminum, Iron
- Import — Alloying elements
- Scrap — Reclaimed metals
- Slag



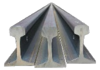
LSF Pilot Plant Sizing

Production rate:	20-500 t/yr
Power requirement:	10-100 kW
Size:	~10 m^3
Mass:	~5,000 kg

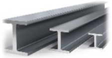
Products

Billets/Ingots

Rail

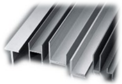


Beams



Sheet Metal

Extruded Profiles



Cables/Wire/ Additive Mfg.

Mining Equipment

500t builds:

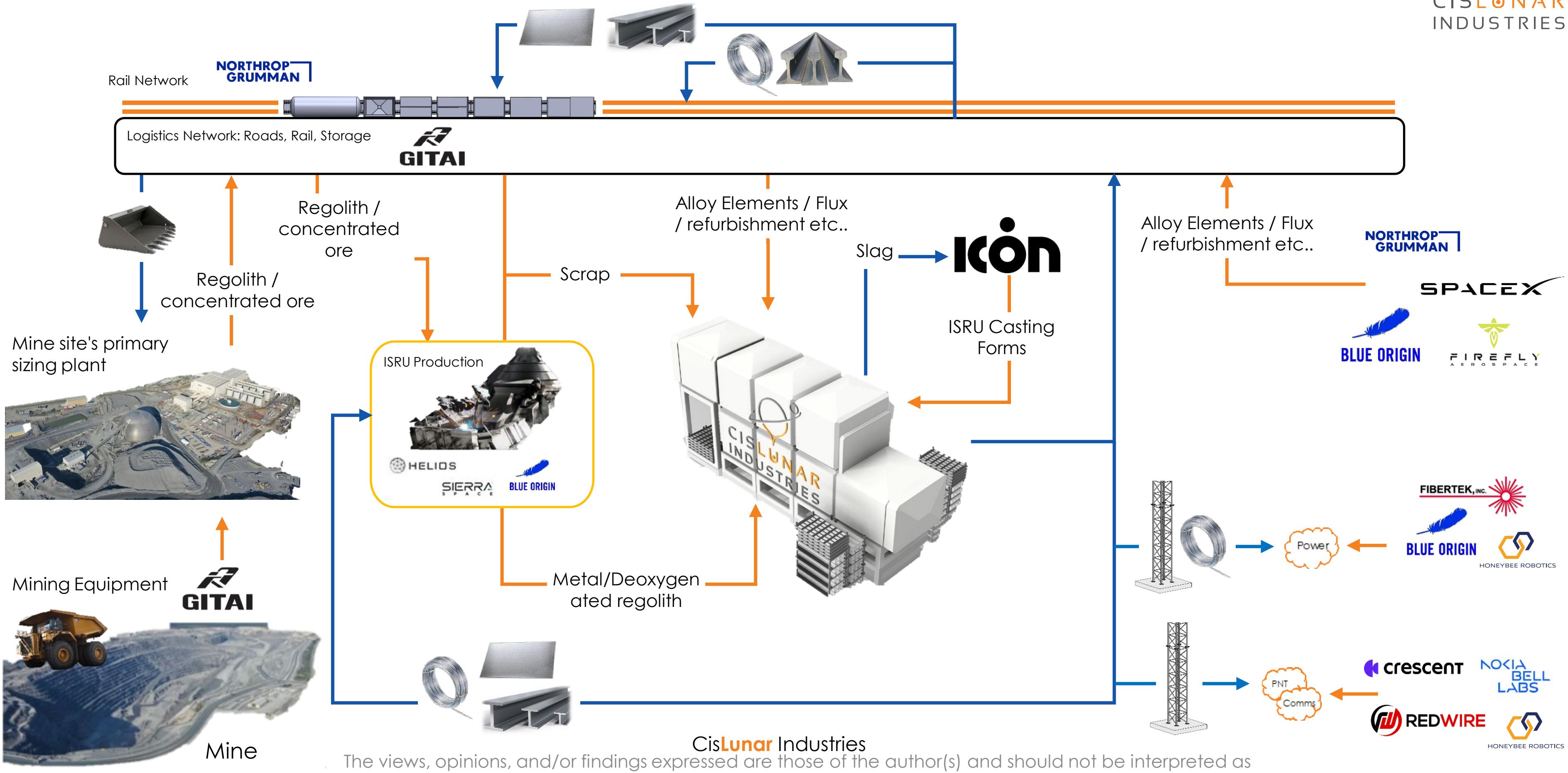
55km Railroad

33,000m² warehouse space

10MW Solar concentrator area

370km 1MW Transmission

ISRU Value Chain Overview



CisLunar Industries

The views, opinions, and/or findings expressed are those of the author(s) and should not be interpreted as representing the official views or policies of the Department of Defense or the U.S. Government.

Product Application Examples

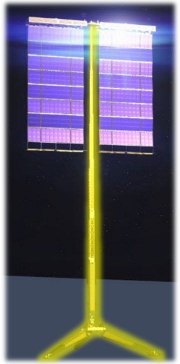
Power & Communications Infrastructure

Products

- Solar Array Structures
- Solar concentrator panels & Structures
- Transmission towers
  - Wired or Wireless
- Power lines

Customers

- Power Producers
- ISRU Refining and Manufacturing
- Other High-Power Consumers
- Infrastructure
- Connectivity



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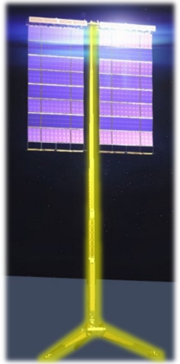

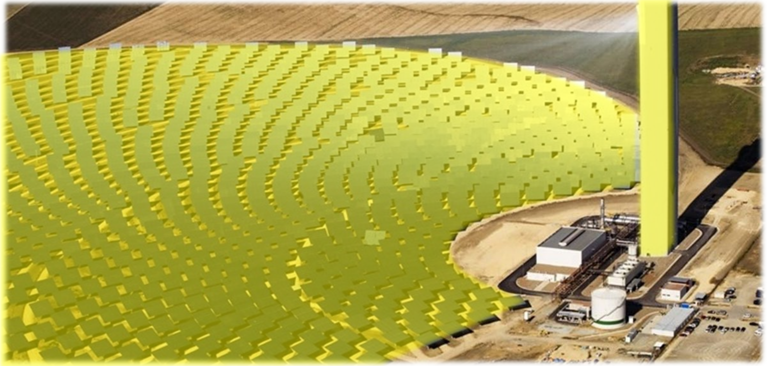

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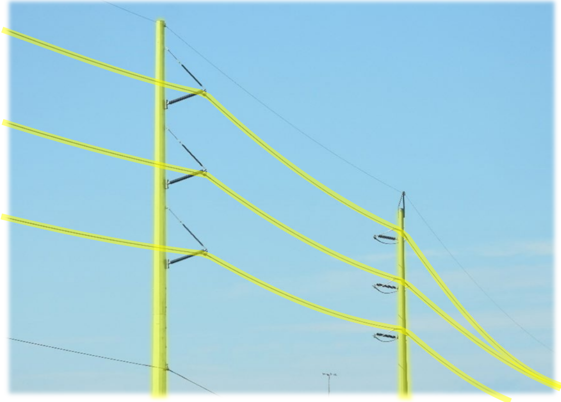

Product Application Examples

Lunar Transportation Infrastructure (Railroad)

Products

- Rails
- Fastening Hardware
- Rail Car Components
  - Wheels
  - Frames
  - Pannels
- Bridges
- Additive mfg. feedstock

Customers

- Logistics
- Infrastructure

Product Application Examples

Lunar Transportation Infrastructure (Railroad)

CISLUNAR INDUSTRIES

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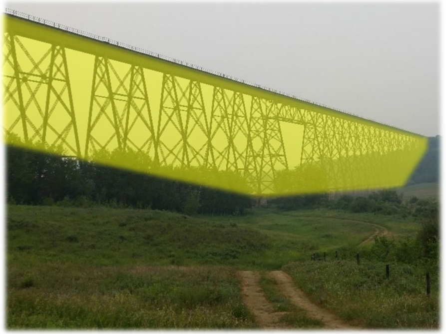
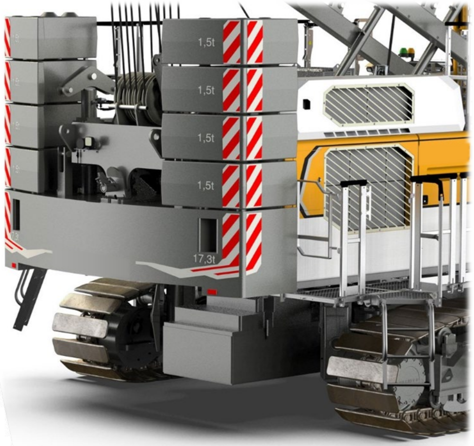


Product Application Examples

Heavy Equipment & Tooling

CISLUNAR INDUSTRIES

Products
- Wheels/track
- Crane Structures
- Mass blocks/ Counterweights
- Digging teeth
- Buckets/Blades
- Compacter rollers



Customers
- Construction
- Mining
- Logistics

Product Application Examples

Heavy Equipment & Tooling

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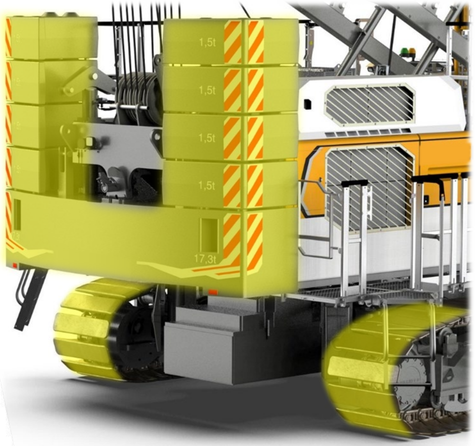
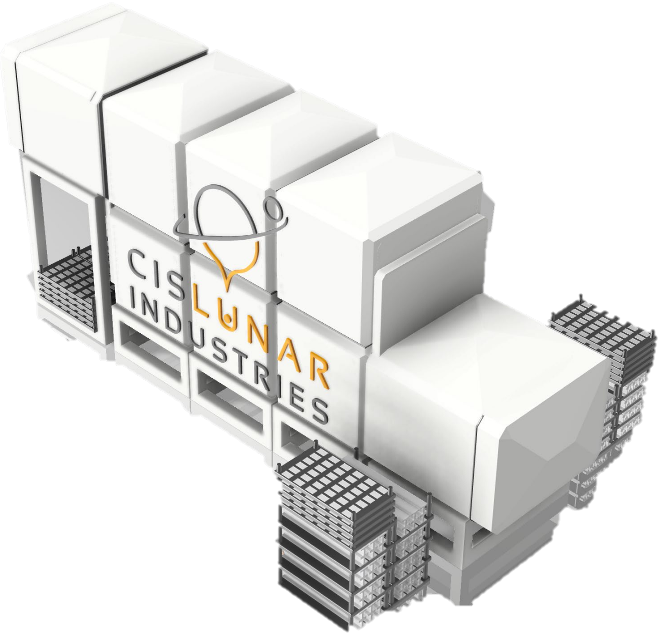


Commercialization

CISLUNAR INDUSTRIES

Key Cost Assumptions
- Transport cost: $50k/kg
- Energy cost: $36.26/kWh
- Deoxygenated Regolith: $2k/kg

Product Pricing
- Baseline at 1/2 of Earth-Moon transportation costs
- Average Product price: $25,000 /kg



Value proposition
- Large-Scale projects at reduced cost
- Sustainable & scalable economy
- On Demand Delivery
- De-risk transportation

Market
- $5B annual operating margin potential at 500t max capacity
- 5-year recap. at 18t/yr avg. sales

Economic Growth Accelerators

Sustainability

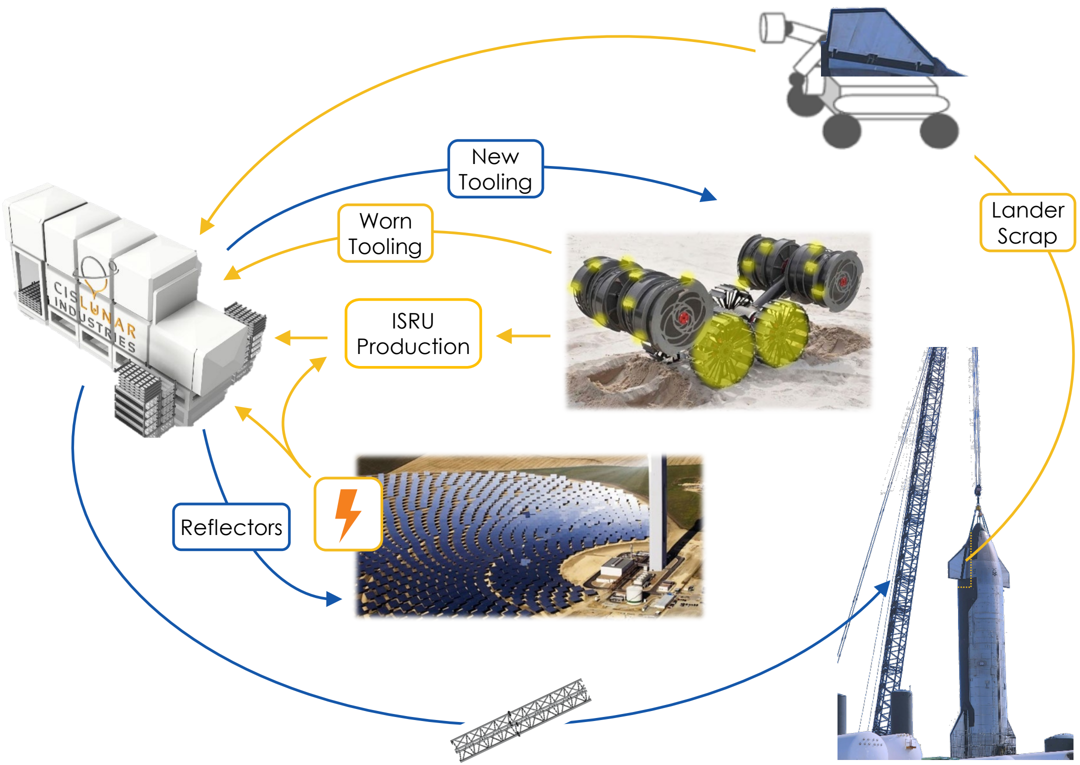
Cost savings and reduced reliance on Earth-sourced materials

- Recycling
  - Landers
  - Worn/broken components
  - Manufacturing Scrap
- Maintenance Economy
  - Robustness through replaceability/repairability

Scalability

Accelerate growth via sustainability, adaptability, and unique capabilities

- ISRU Power Infrastructure
  - Exponential scaling
- Modular Systems
  - Add capacity & capabilities to existing hardware
- Construct large and/or heavy vehicles
  - Enables Large scale construction
  - Increases stability & traction



Thank you!

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Mining Expert

Andy Young
Electrocatalytic Processing Expert

Dr. Andrew Petruska
Lunar Infrastructure Expert

Appendix

Scaling at reduced transportation costs

DARPA-EA-23-02 - 10-Year Lunar Architecture (LunA-10) Capability Study

crescent

ASTROBOTIC

SCOUT

LOCKHEED MARTIN

Source: Artist's Concept

Crescent's Multiservice Modular User Surface Terminal (MUST)

This research was developed with funding from the Defense Advanced Research Projects Agency (DARPA).

Crescent LunA-10 Team Introduction

- **Lockheed Martin is investing to develop a commercial services business model in advance of emerging mission needs** to provide US government agencies flexible and low-cost capabilities to support missions on and around the moon.

- **Crescent Space Services LLC ("Crescent")** is a Lockheed Martin subsidiary that provides **infrastructure-as-a-service for missions in cis-lunar space**, leveraging LM's deep heritage and reliability in space and combining it with the agility of a commercial services platform.

- Crescent is developing **a foundational service for lunar infrastructure, MUST, a lunar user surface terminal for communication, position, navigation and timing, space situational awareness and power** in direct response to government and commercial needs to procure capabilities as-a-service. Future service offerings will include **data storage & processing**.
  - **SCOUT Space:** Throughout the LunA-10 study program, Scout has been analyzing the lunar environment to determine suitability and performance for its line of high-performance gimbaled telescopes designed purposefully for space domain awareness on LEO and GEO platforms.
  - **Astrobotic:** In this LunA-10 effort, Astrobotic has scaled its NITE lunar night survival system to efficiently heat and power MUST terminals during the lunar night and serve as an emergency generator in case of a primary power system failure.
  - **Lockheed Martin Space:** Lockheed Martin provides decades of experience and their expertise in mission design, modeling, and simulation work which has been leveraged for LunA-10.

Crescent LunA-10 Team

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Deputy Program Manager

Josiah Gruber
SCOUT Space
VP of Engineering

Sean Bedford
Astrobotic
Director of BD

Christie Iacomini
Lockheed Martin Space
Senior Program Manager

MUST Introduction of Capabilities and Services

SCOUT

Surface & Space Situational Awareness

Capable of providing terrain-based navigation and tracking of health and status of surface and orbiting assets.

crescent

Position & Navigation

Informing assets and systems on the lunar surface of their precise location to keep missions on target.

Nighttime Integrated Thermal and Electricity

Provides external power and heat throughout lunar night(s).

ASTROBOTIC

Source: Astrobotic

Source: Artist's Concept

crescent

Earth Communications System

Provides high bandwidth communications and navigation services via relay services to Earth and Direct to Earth.

LOCKHEED MARTIN

SmartSat™

Software framework which enables reconfigurability and mission flexibility.

crescent

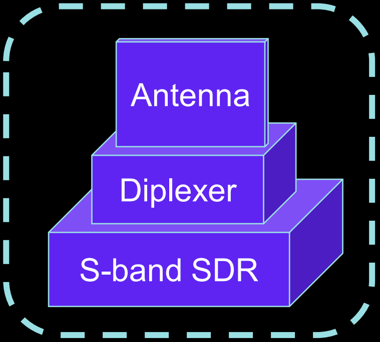
Surface Area Network

Scalable service providing communications and navigation services to lunar surface users.

MUST-MVP

- ECS & PNT only
  - Inputs: Power, Position and Timing Data
  - Outputs: Comm/PNT Data
  - Use Cases: Space-based user or dispersed missions operating independently

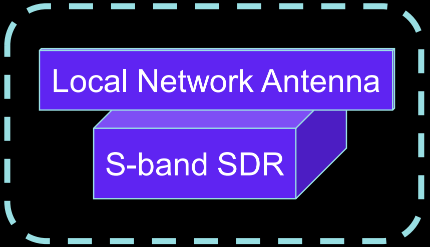
- **< 0.7kg**
- **< 20W (max consumption)**



MUST-SAN

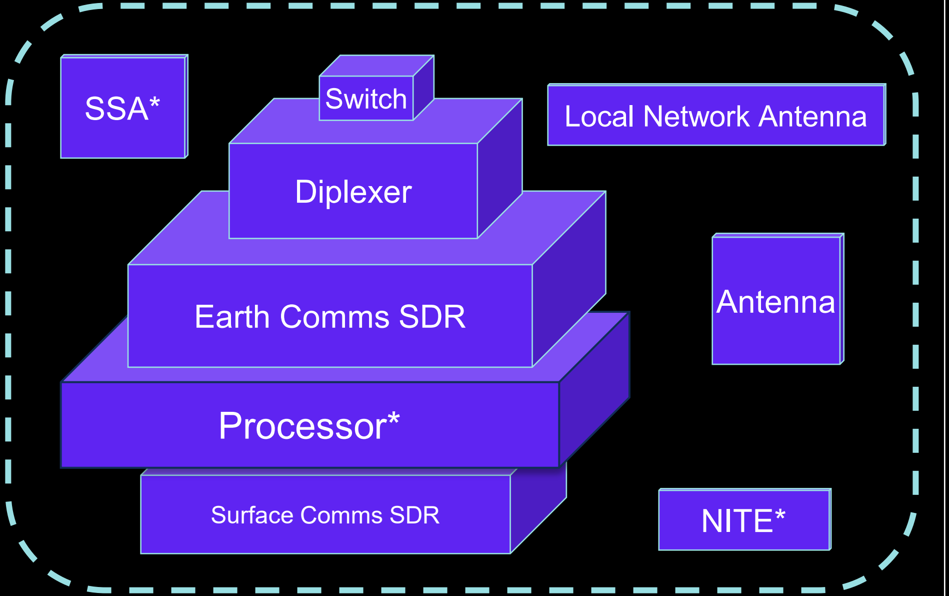
- SAN only
  - Inputs: Power
  - Outputs: Comm Data
  - Use Cases: Creates an independent SAN user (e.g. small rover)

- **< 0.75kg**
- **< 40W (max consumption)**



MUST

- Combination of MUST-MVP & MUST-SAN w/ optional SSA and NITE services
  - Inputs: Power, Position and Timing Data, Raw Pixel Data for Processor*, Payload Thermal Data for NITE*
  - Outputs: Comm/PNT Data, Processed Imagery from Processor*, Raw Pixel Data from SSA*, Heat and Power from NITE*
  - Use Cases: Small landers which enables localized SAN which can communicate with MUST-SAN units or with a dismounted astronaut OR larger rovers (e.g. LTVS)*



Base MUST model
- **< 1.5kg**
- **< 60W (max consumption)**

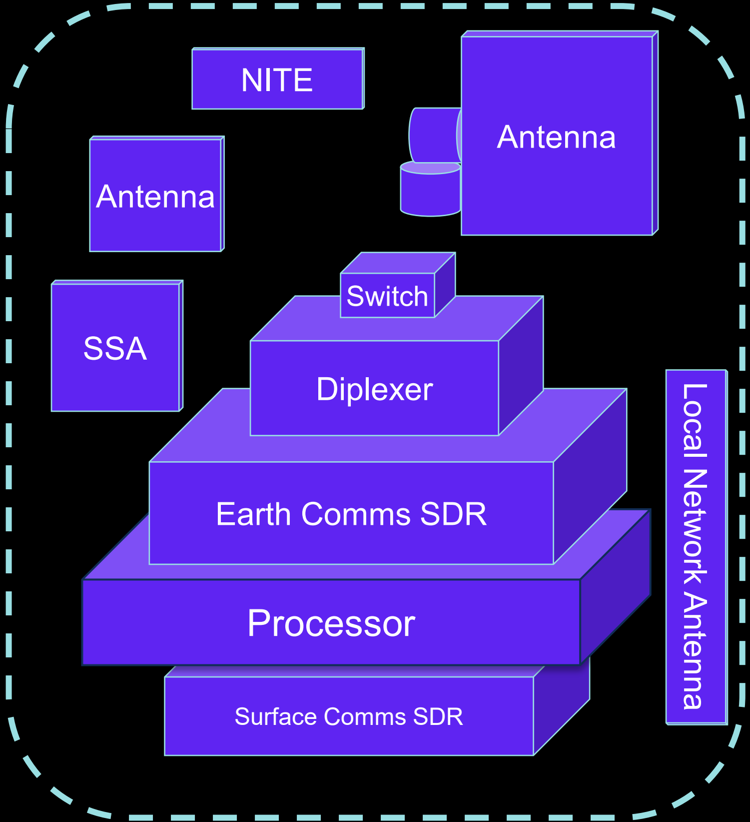
Optional Add-ons
- **< 12kg additional**
- **< 40W additional**

*optional add-ons/services

MUST-HEAVY

- MUST w/ the additional capability to survive and communicate throughout the lunar night
  - Inputs: Power, Position and Timing Data, Raw Pixel Data, Payload Thermal Data
  - Outputs: Comm/PNT Data, Processed Imagery, Heat and Power
  - Use Cases: Human Landing Systems; multi-node infrastructure now supported by SAN creating a mesh network

- **< 20kg**
- **< 125W (max consumption)**



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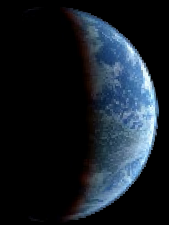
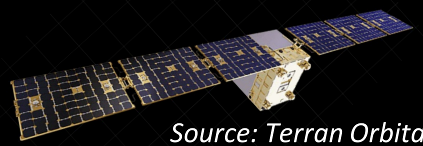
Source: Artist's Concept

Earth Communications System (ECS) Service



Relay-to-Earth



Source: Terran Orbital

Direct-to-Earth

ECS-to-Relay

- Hardware
  - Software Defined Radio
  - Radio Frequency Diplexer
  - Mission Specific Antenna Solution
    - Low Rates – S-band passive patch array
    - High Rate – Ka-band Electronically Steerable Array or Deployable reflector

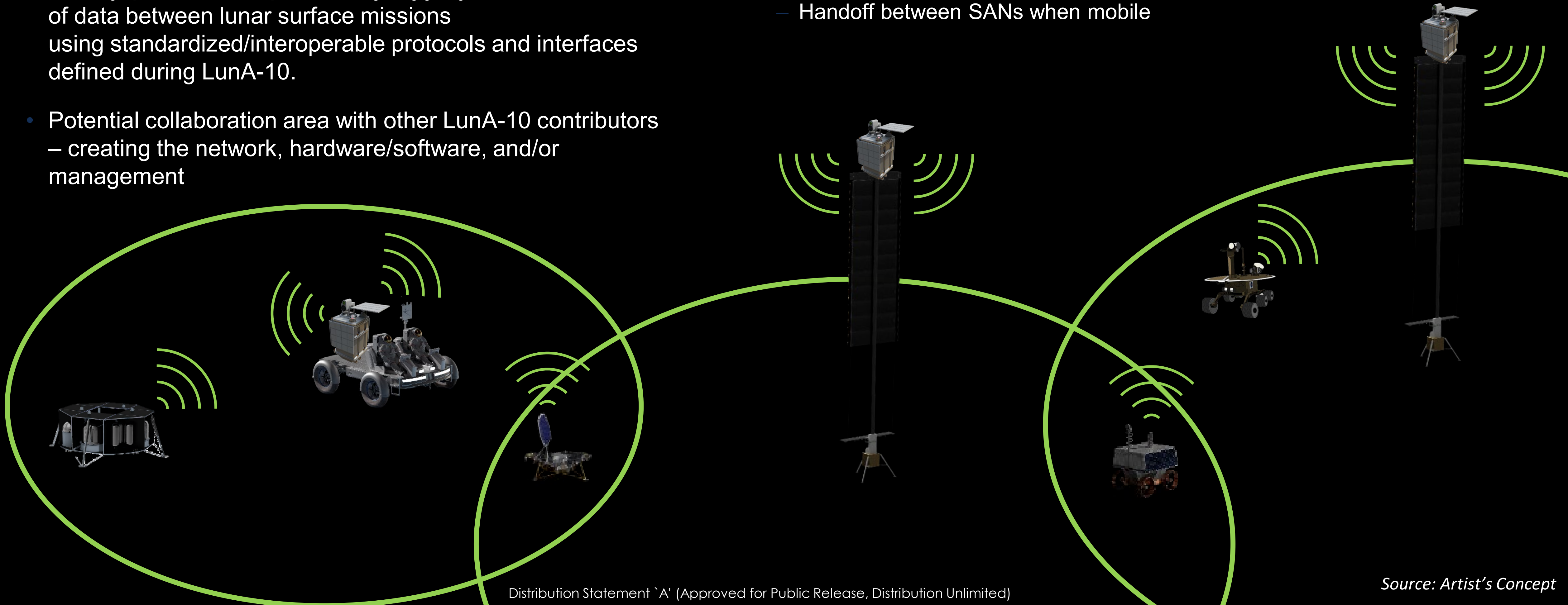
Source: Artist's Concept

- Utility of ECS
  - Direct-To-Earth
    - Scalable backhaul rates to commercial ground stations and/or Deep Space Network
  - Relay
    - LunaNet compliant signal for backhaul through Lunar Orbital Relay systems
  - Mesh
    - Surface Area Network supports local users
    - Extends coverage area with additional MUST terminals or MUST out of line of sight via orbital relay service.
  - Position, Navigation, Timing
    - Use of heritage Deep Space radiometric signals
    - Combined with imagery and local terrain knowledge for accuracy and reduced solution time

Surface Area Network (SAN) Service

- Surface Area Network is formed with a network terminal (radio, processor, antenna) within MUST.
  - Ex: 5G network
- The SAN system uses a millimeter-wave SDR and antenna to create a local communications network to enable routing, prioritization, processing, aggregation, and transfer of data between lunar surface missions using standardized/interoperable protocols and interfaces defined during LunA-10.
- Potential collaboration area with other LunA-10 contributors – creating the network, hardware/software, and/or management

- Utility of SANs:
  - Communication and PNT out to visible horizon
  - Simplifies user comm system which allows for lower SWaP on individual missions
  - Data aggregation to central hub
  - Surface Localization, rapid time-to-fix
  - Handoff between SANs when mobile



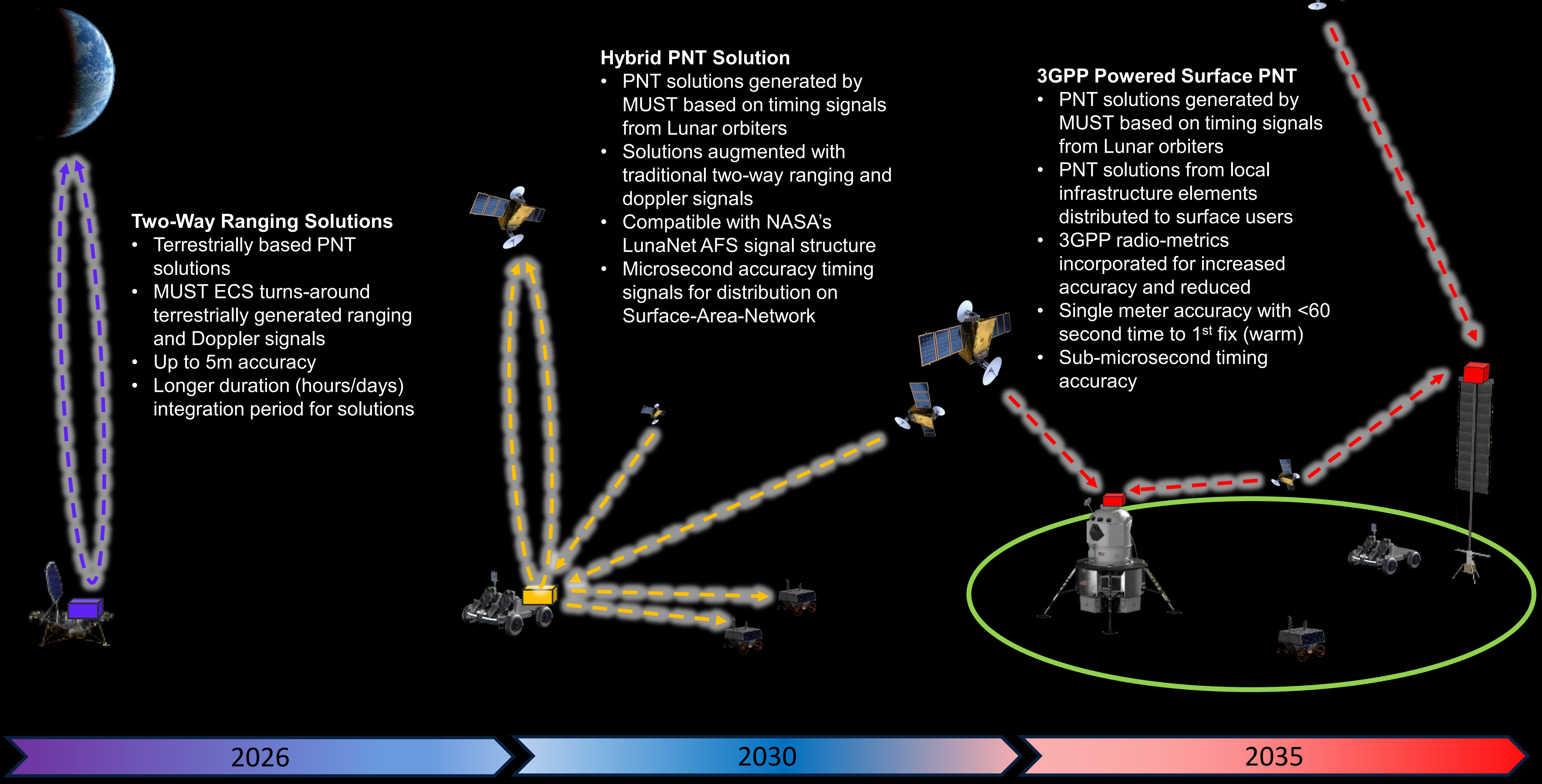
Source: Artist's Concept

Position, Navigation, and Timing (PNT) Service

Two-Way Ranging Solutions
- Terrestrially based PNT solutions
- MUST ECS turns-around terrestrially generated ranging and Doppler signals
- Up to 5m accuracy
- Longer duration (hours/days) integration period for solutions

Hybrid PNT Solution
- PNT solutions generated by MUST based on timing signals from Lunar orbiters
- Solutions augmented with traditional two-way ranging and doppler signals
- Compatible with NASA's LunaNet AFS signal structure
- Microsecond accuracy timing signals for distribution on Surface-Area-Network

3GPP Powered Surface PNT
- PNT solutions generated by MUST based on timing signals from Lunar orbiters
- PNT solutions from local infrastructure elements distributed to surface users
- 3GPP radio-metrics incorporated for increased accuracy and reduced
- Single meter accuracy with <60 second time to 1st fix (warm)
- Sub-microsecond timing accuracy



Source: Artist's Concept

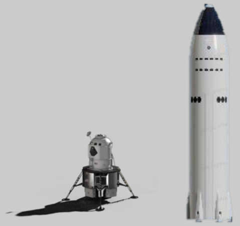
Scaling Capability and Demand

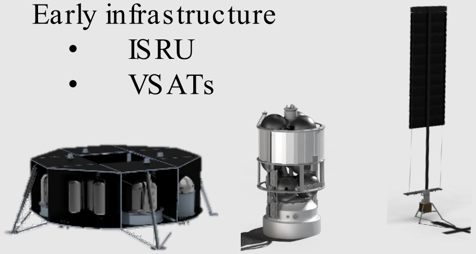
2026 MUST-MVP demonstration

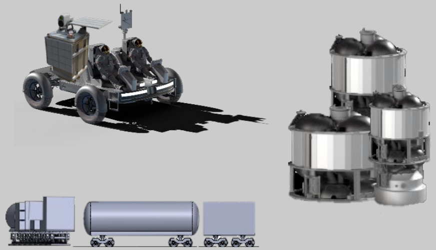
2026-2030 deployment of more capable MUST units (MUST-HEAVY)

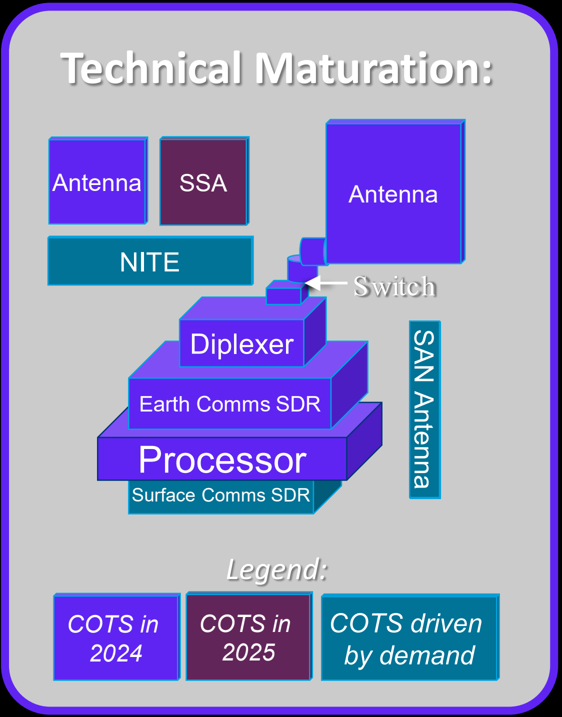
2030+ extend MUST network and implement 3GPP

Development	Demand

• MUST-MVP hardware is TRL-9
• Work to go is integration and productization
  • Developing commercial interfaces
  • Developing ICDs and User Guide
	• Focus on science landers, rovers, and limited Artemis missions
	

• Nearly all MUST-HEAVY hardware on track to be available COTS in 2025
• Definition of specific SAN requirements needed for minor modifications to existing COTS h/w
• Additional integration work required
  • Gimbal control
  • S/W applications
	• Expanded human and scientific exploration missions
	• Early infrastructure
	  • ISRU
	  • VSATs
	

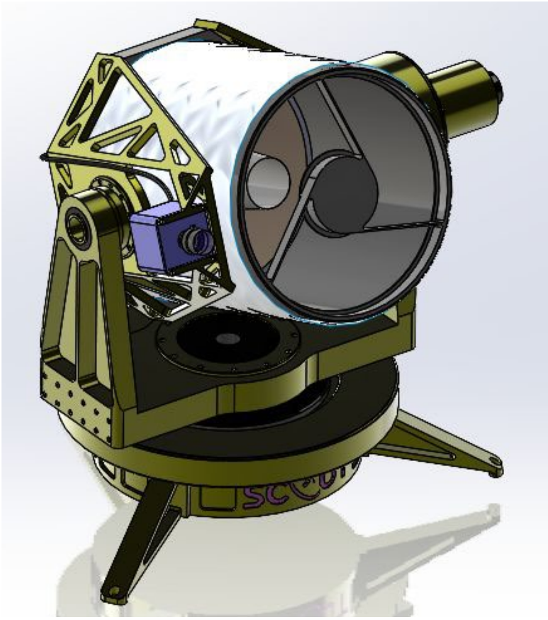
• Modifications needed to MUST units for 3GPP
  • Waveform modifications to SDRs
  • Potentially modifications to SAN Antenna
  • Network orchestration development
• Opportunity to continue updating and optimizing processing options and hosted s/w
	• Permanent human presence
	• Large scale infrastructure roll out
	

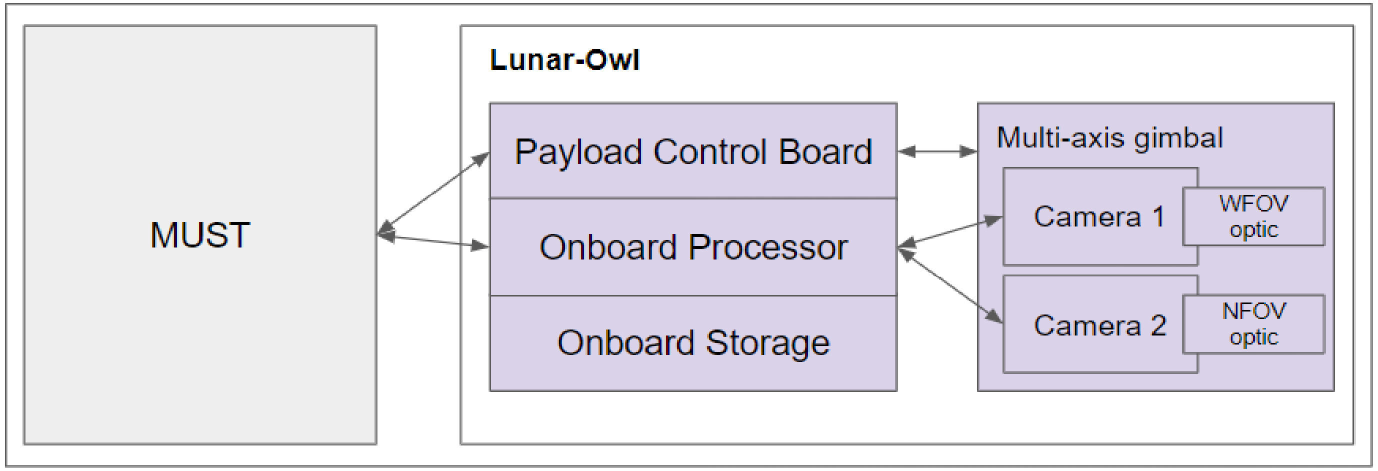


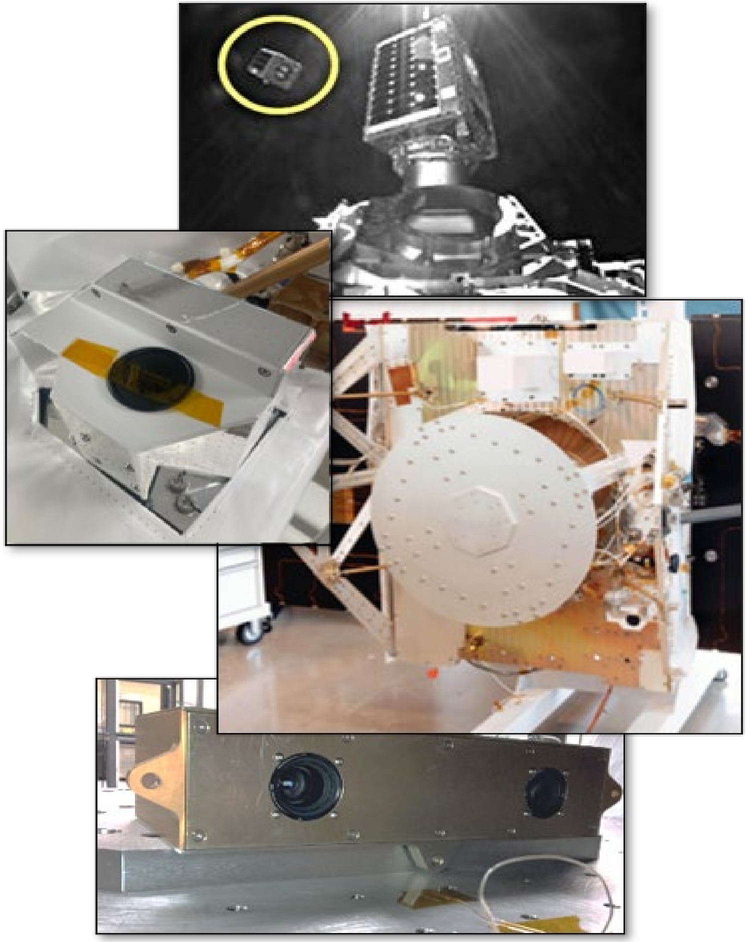
Source: Artist's Concept

Lunar-OWL Service Overview

- **Overview:** Owl is a high-performance, low-SWaP gimbaled optical system designed for long-range space domain awareness (SDA) missions. Lunar-Owl provides an SSA data-as-a-service via both taskable and opportunistic data collection methods, ensuring comprehensive coverage and real-time intelligence in the lunar environment.
- SWaP: <15-35kg, <55-75W
- Capabilities: Long-range lunar SSA, magnitude < 16-18



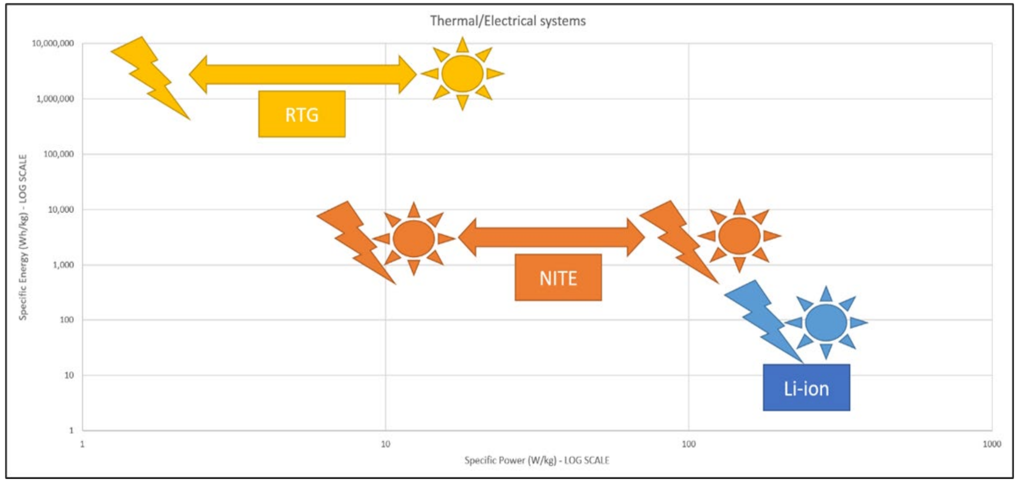




Source: SCOUT Space, Inc.

NITE Service Overview

- Astrobotic's Nighttime Integrated Thermal and Electricity (NITE™) system produces both heat and power in a non-nuclear system to allow MUST's continuous operations of critical systems during the cold lunar night
- Additional Applications:
  - Support access to other low temperature areas of interest such as PSRs
  - Deliver early-stage heat & power to enable standup of longer-term permanent operations
  - Provide backup heat and power
- Fills the gap between traditional heating/electric solutions
  - Specific energy goal of 1300 Wh/kg (combined heat and electricity); An order of magnitude higher than batteries
  - Specific Power (W/kg); Between low RTG levels and Li-ion battery levels; Depends on thermal/electrical ratio
- NITE is also throttleable
  - RTG's run continuously once activated and can produce excess heat that must be managed
  - NITE can be turned on and off or slowed down
- NITE also has regulatory advantages over RTG's, which require additional time & funding to address launch of nuclear materials

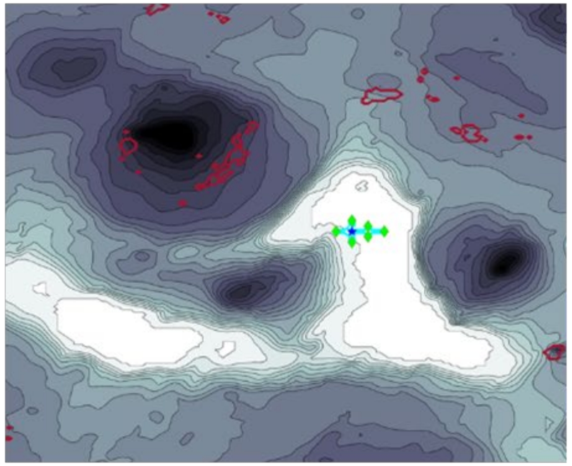


Specific Energy vs. Specific Power for Various Heating/Electric Solutions

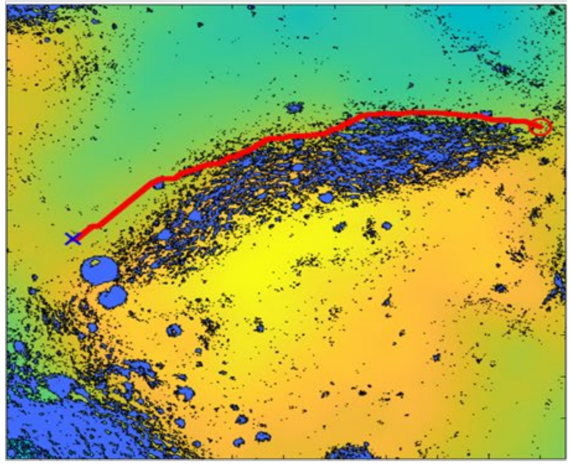
Source: Astrobotic

Lunar Economy Analysis Platform (LEAP) Overview

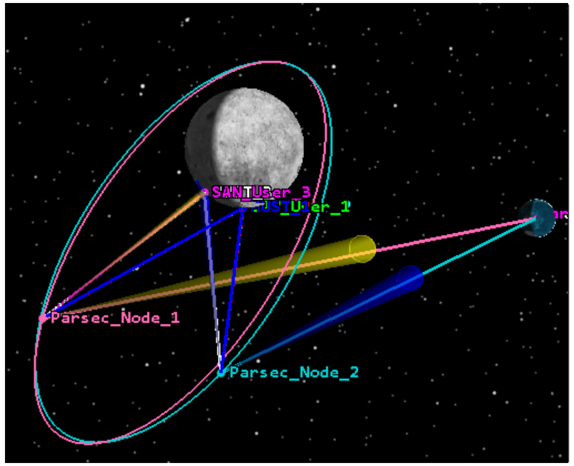
Optimize Power Grid Architecture



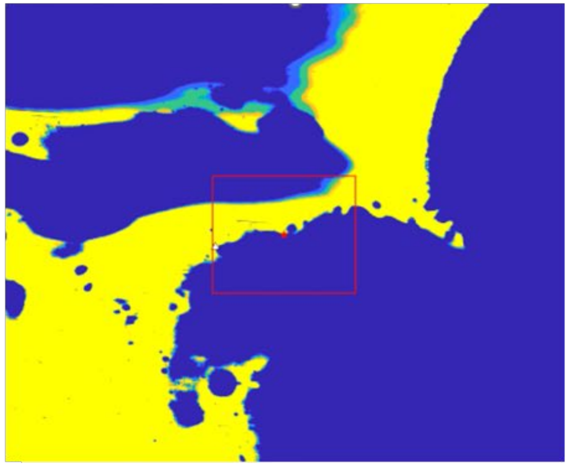
Multivariate Lunar Path Planning



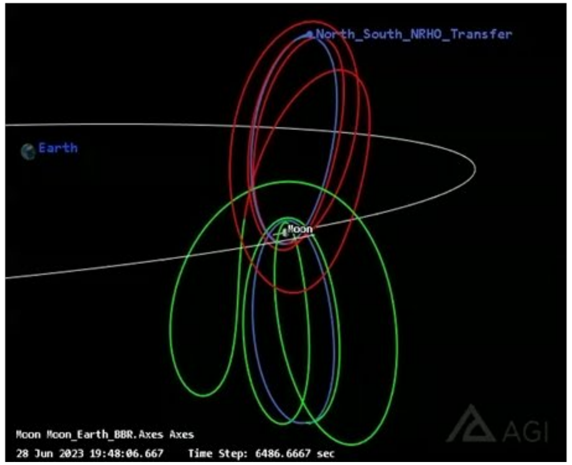
Model Lunar Comms Networks



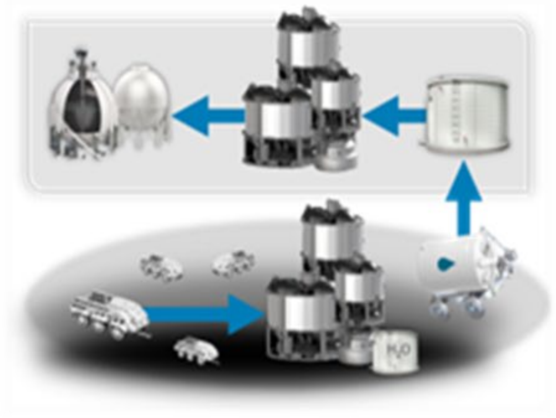
Analyze Illumination vs Height, Time



Model Propellant Demand and Refueling



Calculate ISRU Infrastructure Needs



Integrated lunar infrastructure system-of-systems analyses

Modular tools in a common environment

Object-oriented modeling

Common data structure

Design Features

Source: Lockheed Martin

QUESTIONS

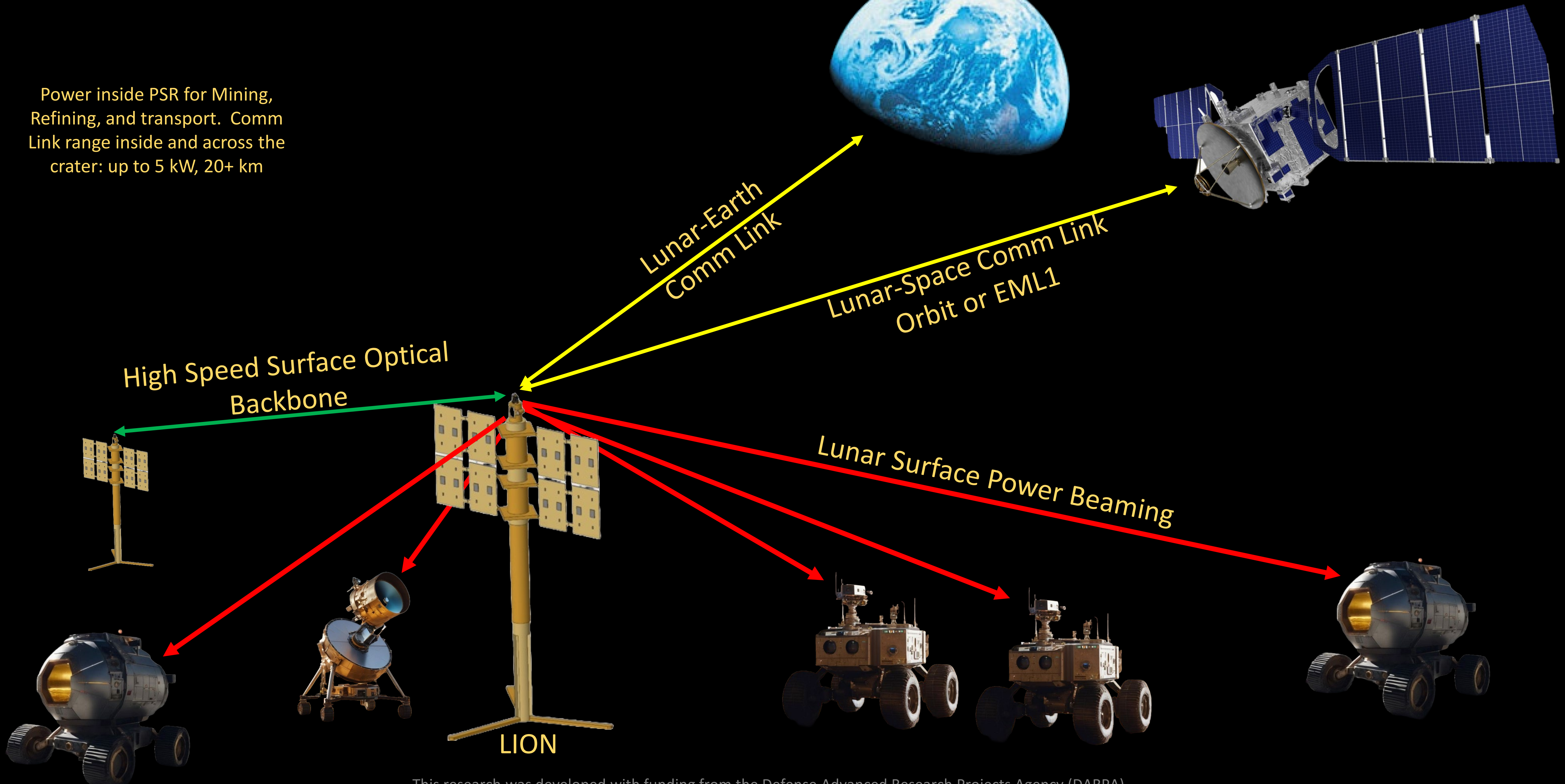
DARPA 10-year Lunar Architecture Capabilities Study (LunA-10)
Lunar Infrastructure Optical Node (LION)

FIBERTEK, INC.

25 April 2024 Mark Storm, Principal Investigator

This research was developed with funding from the Defense Advanced Research Projects Agency (DARPA).
The views, opinions and/or findings expressed are those of the author and should not be interpreted as representing the official views or policies of the Department of Defense or the U.S. Government.

Artist's Concept: sourced from
https://stock.adobe.com/images and Fibertek AI generated images



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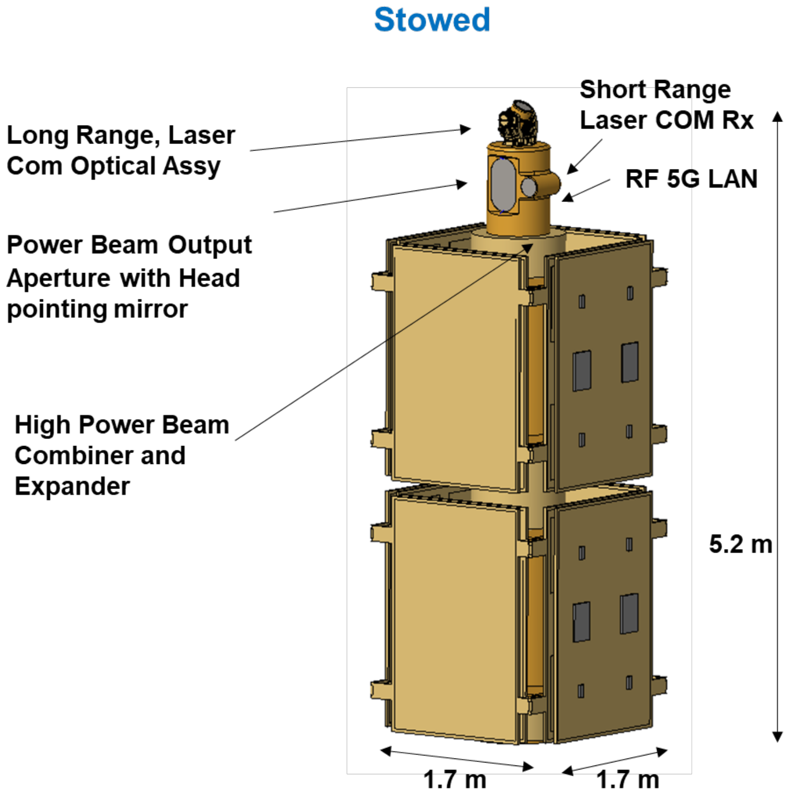
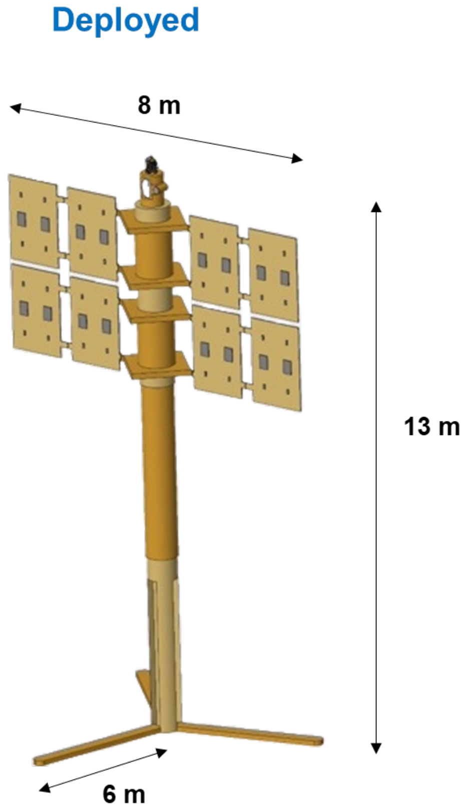
Lunar Infrastructure Optical Node (LION)

Key Hardware Features

- Low-mass, efficient thermal management
- Modular, configurable design for multi-service integration, scalability, inherent redundancy
  - Laser Power Beaming
  - Optical/RF Communications
  - Position, Navigation, & Timing (PNT)
- High-TRL component technologies





High-efficiency, sustained laser power beaming on the Lunar surface through low-mass and efficient thermal management

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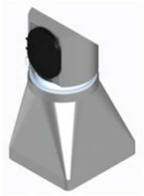
LION Scalability - SWaP Optimized Solutions

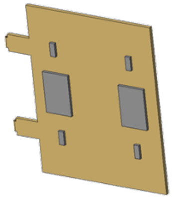
Regulated Power to User (kW)

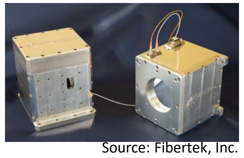
LION Nano

- **0.35 kW regulated power**
- Mass: <80 kg, *no tower*



Source: Fibertek, Inc.

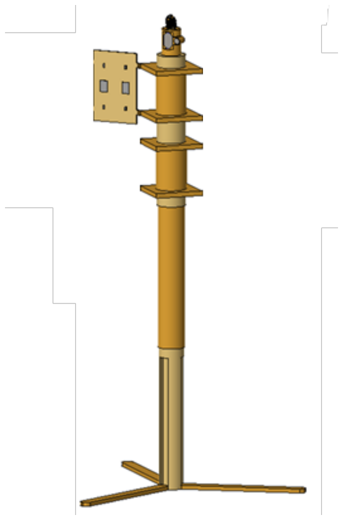




Source: Fibertek, Inc.

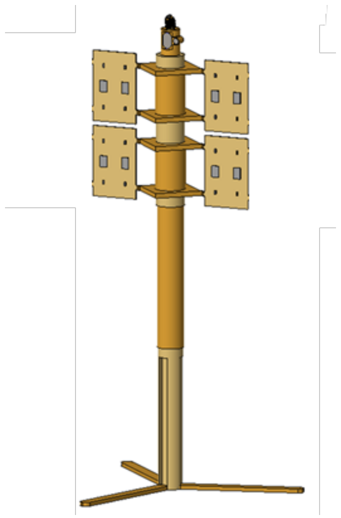
LION Micro

- **0.74 kW regulated power**
- Mass: 223 kg, including tower
- Tower height per application



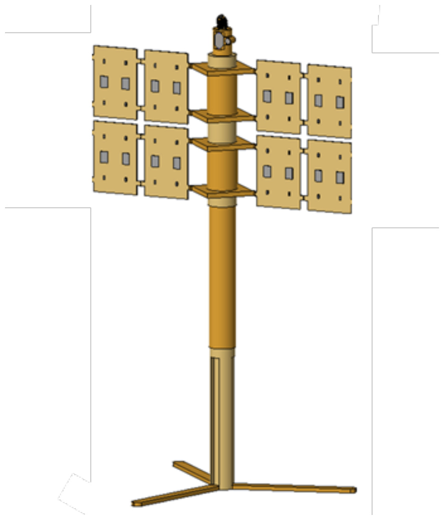
LION Mini

- **3.0 kW regulated power**
- Mass: 285 kg, including tower
- Tower height per application



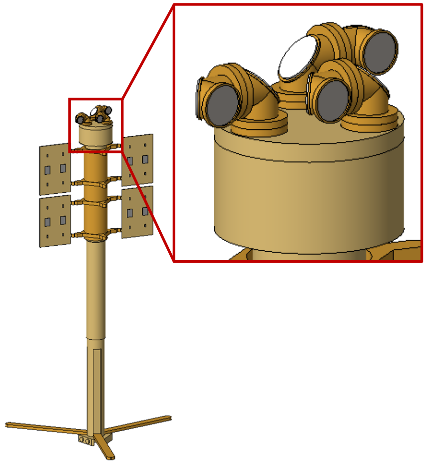
LION

- **5.9 kW regulated power**
- Mass: 360 kg, including tower
- Tower height per application



LION Multi

- **Individual beam directors per laser**
- **Power scalable**
- SWaP: Scalable, up to full LION
- Tower height per application

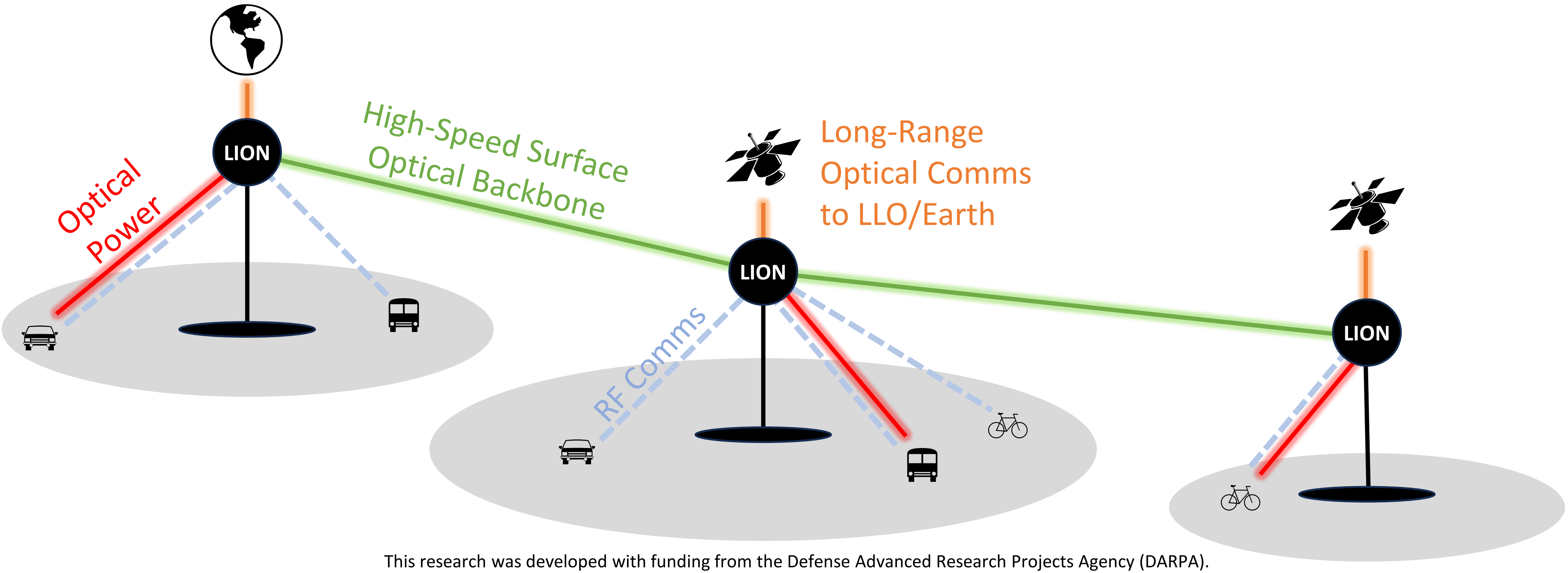


This research was developed with funding from the Defense Advanced Research Projects Agency (DARPA).

LION Network Scalability

FIBERTEK, INC.

- Each LION terminal serves as a *fully capable* network node providing:
  - Optical Power Beaming
  - Long-Range Optical Comms (to Orbit or Earth)
  - Surface RF Comms (between users)
  - Short-Range Optical Network Comms (high-bandwidth users, LION terminals)



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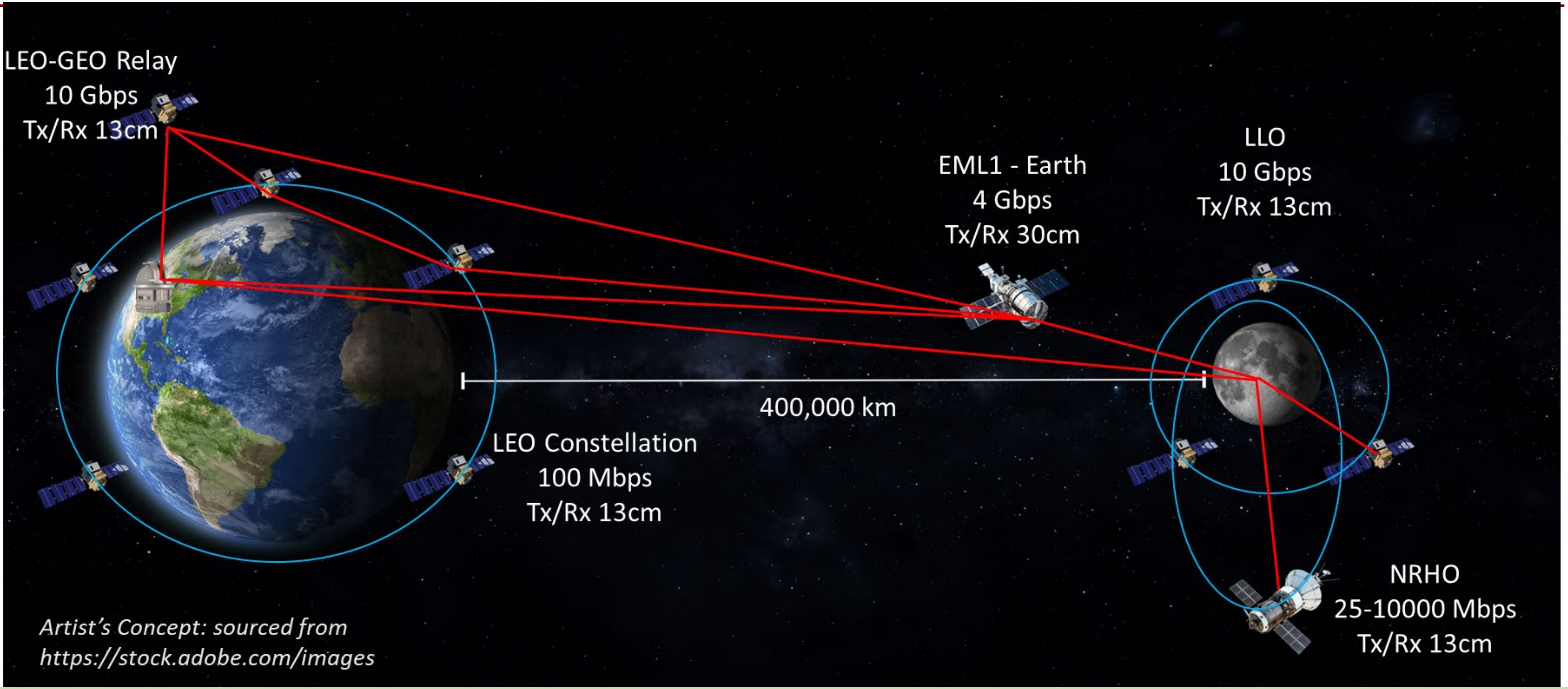
Off Surface Optical Links to support persistence



Long-range optical comms link budgets modeled from first principles and verified using commercial software enables key capabilities from lunar surface direct to Earth, satellite relays, and constellations.

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LION: Power & Data Costs

	Power Beaming ($/kWh)		Optical Communication to Earth/Orbiter ($/Gb)	
Input Power Cost (Daytime) ($/kWh)	Fully Loaded Production Price ($/kWh)	Distributed Launch Costs ($/kWh)	**Fully Loaded Production Price ($/Gb)**	Distributed Launch Costs ($/kWh)
Earth: 0.1	**1.4k – 1.8k**	432	0.6 – 0.9	0.15
10	**1.4k – 1.8k**		0.6 – 0.9	
CBE 100	1.8k – 2.2k		0.6 – 0.9	
1,000	6.4k – 6.8k		0.7 – 1.0	

- Operating costs are *low*, biggest unknown is input power costs
  - On Earth, power is ~ $0.10/kWh
  - Current Best Estimate (CBE) Lunar Daytime Input Power: $40 – $600/kWh
- Launch costs assumes $500,000/kg, tower is included in Power Beaming payload only
  - Users will have to purchase or provide their own laser power receiver & optical communications payloads
- Assumptions include:
  - 10-year mission
  - 90% operational duty cycle
  - 1 LION terminal
    - Power Beaming: 20% end-to-end efficiency
    - Laser Comms: 400 Mbps
- LION Nano: Cost is driven by launch (35 kg @ $500k/kg = $17.5m for expected 1 Lunar day, unknown operational time or input power costs)

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Logistics and the Design of a Lunar Harbor

Prepared for Lunar Surface Innovation Consortium
April 2024

POC: Kevin.Scholtes@fireflyspace.com

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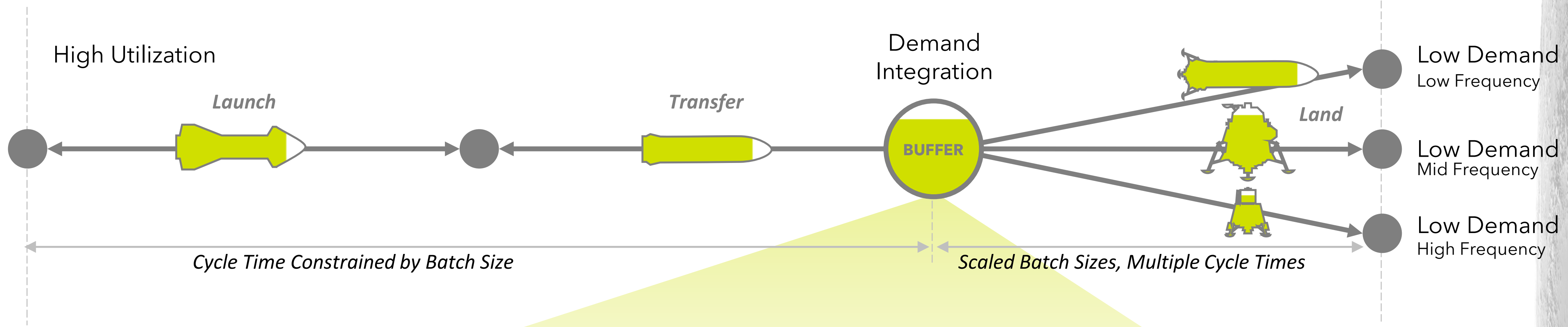
CONCEPT AGGREGATION HUBS

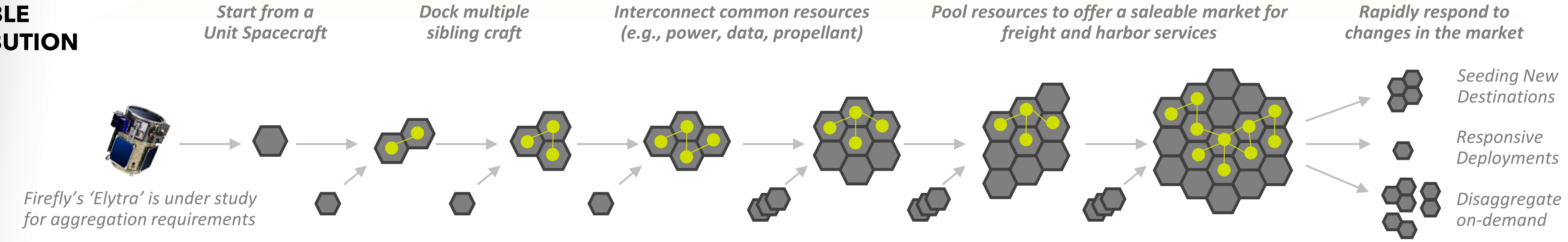
DECOUPLE SURFACE DEMAND FROM LAUNCH UTILIZATION

DEMAND INTEGRATION



Given a fixed system throughput, a buffer improves both utilization for upstream deliveries and frequency for downstream deliveries.

SCALABLE DISTRIBUTION



With lower per-unit commitment costs than a station, aggregations offer an incremental growth solution to meet traffic demand as it develops.

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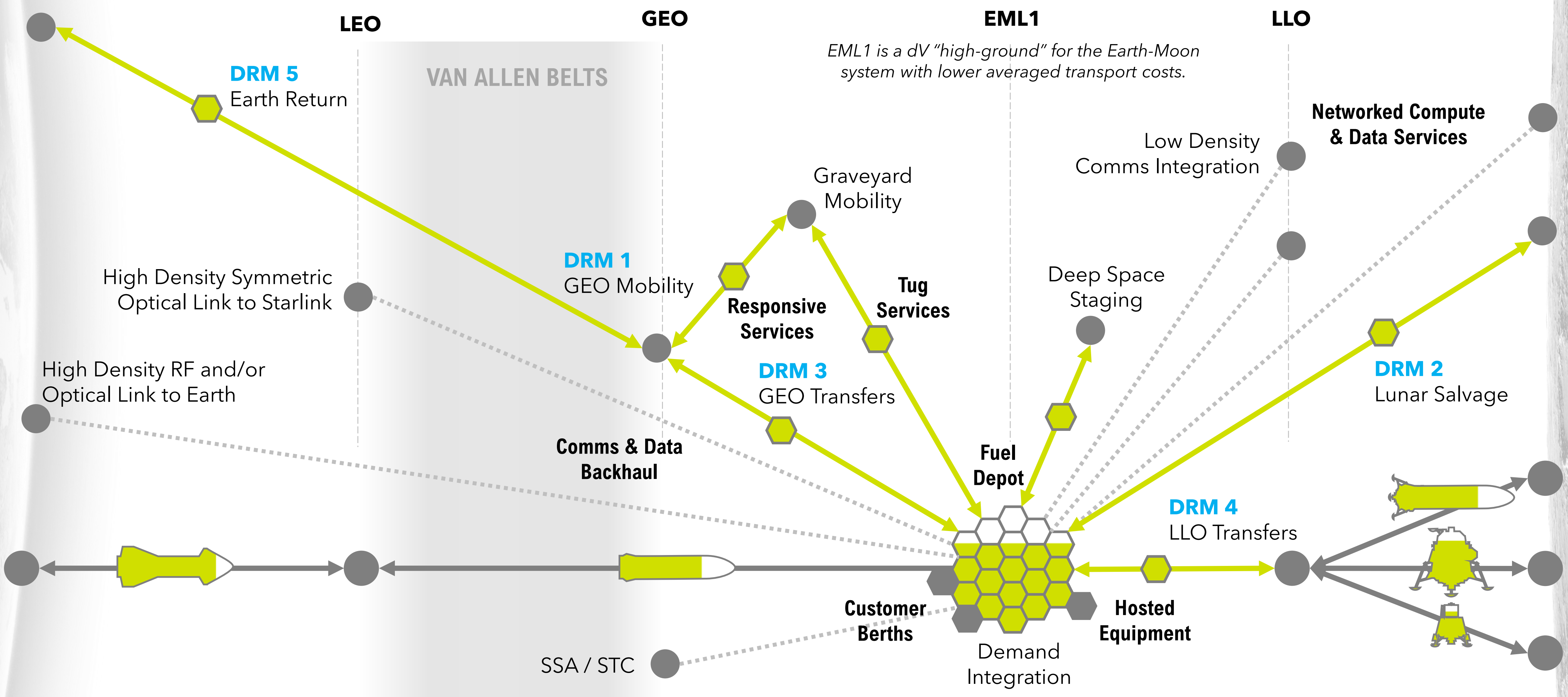
CONCEPT CORE SERVICES

CARGO FORMS THE ANCHOR MARKET FOR ANY HARBOR



As an EML1 aggregation grows it can offer increasingly more valuable services in cargo logistics, tugs, refueling, SSA, power, comms, data, and salvage.

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LOGISTICS DEMAND MODELING

SCALING THE ADDRESSABLE MARKET FOR THE LUNAR SURFACE

What should a model lunar population look like for a deeper exploration of supply chain assumptions?

CORE ASSUMPTION: The key demand metric is down-mass, (e.g., descent propellant, surface equipment, and maintenance/resupply cargo).

General Surface Equipment	Mass (kg)	LRUs (QTY)	Scrap Rate (LRU/year)
Small Ground Equip. (QTY)	50	10	0.1
Med Ground Equip. (QTY)	500	100	0.1
Large Ground Equip. (QTY)	5000	1000	0.1

Cargo is normalized and sampled as small, medium, or large demand signals.

General Lander Definitions	Propellant (kg)	Payload (kg)	Dry Mass (kg)
Small Class Lander	1000	150	500
Medium Class Lander	10000	1500	5000
Large Class Lander	100000	15000	50000

Landing is normalized and sampled as small, medium, or large delivery signals as well as propellant demand signals.

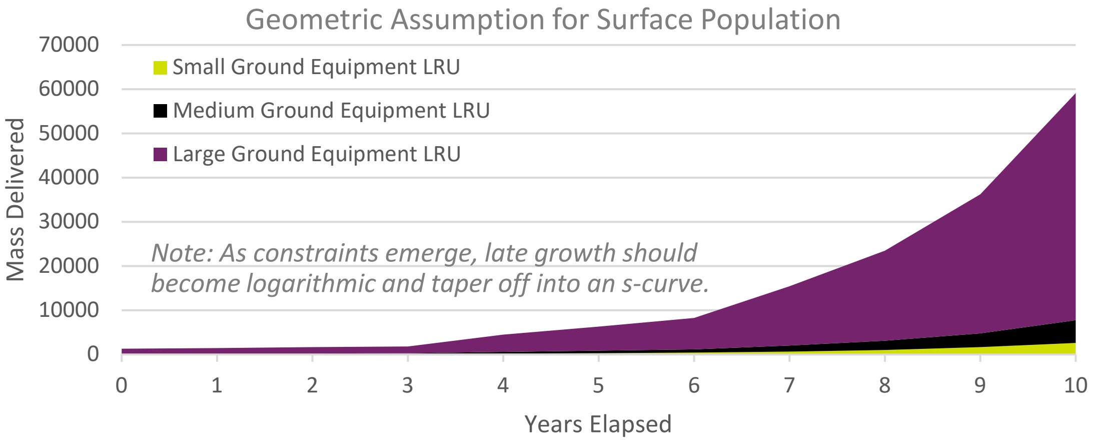
Years Elapsed	0	1	2	3	4	5	6	7	8	9	10
Cargo Received (MT) *at the Moon*	6.3	13	21	30	53	84	125	202	319	500	796
Cargo Launched (MT) *from the Earth*	221	321	438	603	951	1362	1894	2900	4370	6615	10274

This summation focuses exclusively on lunar down-mass demand and does not account for a lunar up-mass market in this specific context.

CORE ASSUMPTION: A proven market invites additional investments which compound, resulting in geometric growth during the early market phases.

Generalized Surface Population											
Years Elapsed	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Small Ground Equip. (QTY)	5	8	13	20	32	51	80	127	202	320	508
Med Ground Equip. (QTY)	1	2	3	4	7	11	16	26	41	64	102
Large Ground Equip. (QTY)	1	2	3	4	7	11	16	26	41	64	102

Years Elapsed	0	1	2	3	4	5	6	7	8	9	10
Equip. Demand (MT)	6.3	7.1	8.0	9.0	22	31	41	77	117	181	295
Prop. Demand (MT)	44	50	57	65	154	215	282	520	790	1220	1980



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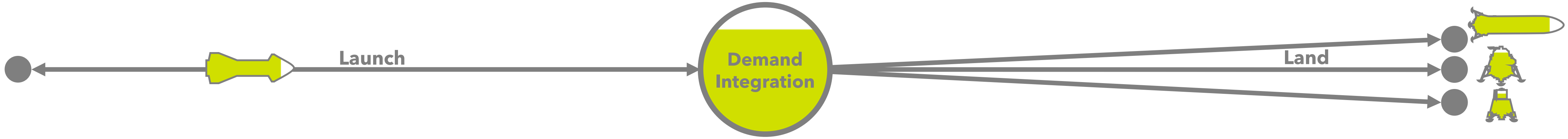
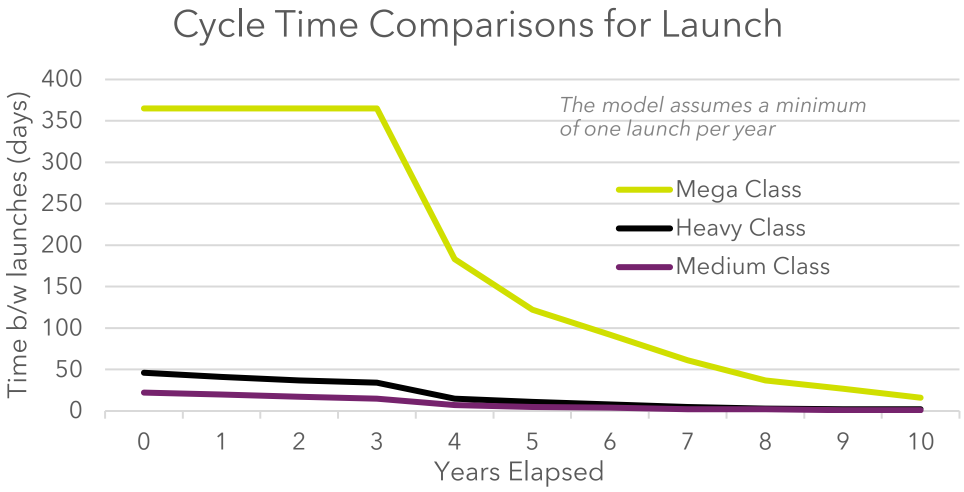
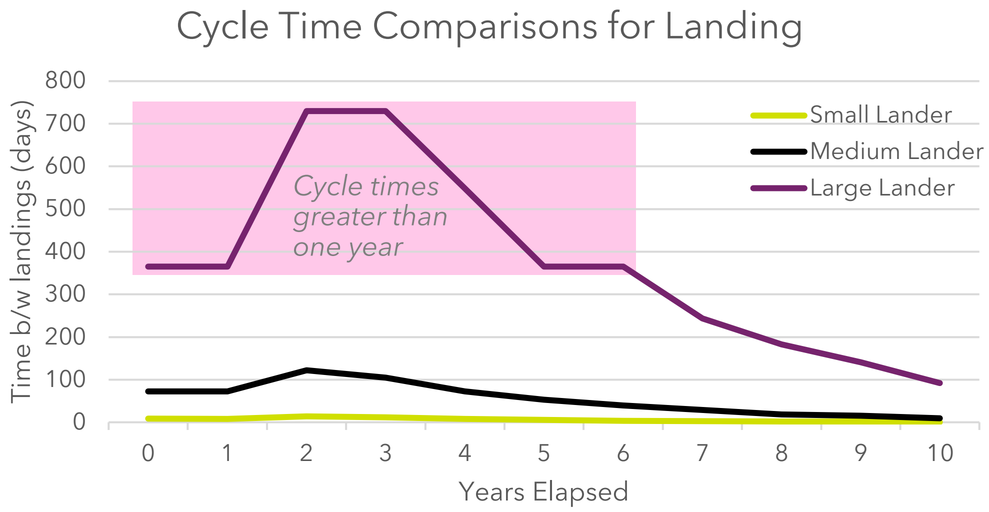
LOGISTICS INPUT/OUTPUT SCALING

UNDERSTANDNG BATCH SIZE WITHIN THE ADDRESSABLE MARKET







Launches Required to Meet Throughput (per launch class)

Years Elapsed	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Mega Lift Class	<1	<1	<1	<1	2	3	4	6	10	14	23
Heavy Lift Class	8	9	10	11	26	36	47	86	130	200	326
Medium Lift Class	17	19	22	25	59	82	108	200	303	466	759

Early market activity lacks the demand to fully manifest larger launch vehicles but will overwhelm medium and heavy launch vehicles as activity grows.

Landings Required to Meet Throughput (per Lander Class)

Years Elapsed	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Small Lander	43	48	54	61	149	209	276	513	782	1207	1970
Medium Lander	5	5	6	7	15	21	28	52	79	121	197
Large Lander	1	1	1	1	2	3	3	6	8	13	20

Early market activity lacks the demand to provide responsive shipping with large landers alone but too much demand for smaller landers to realistically support alone.

Years Elapsed	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Landing Sites	1	1	2	2	3	3	3	4	4	5	5

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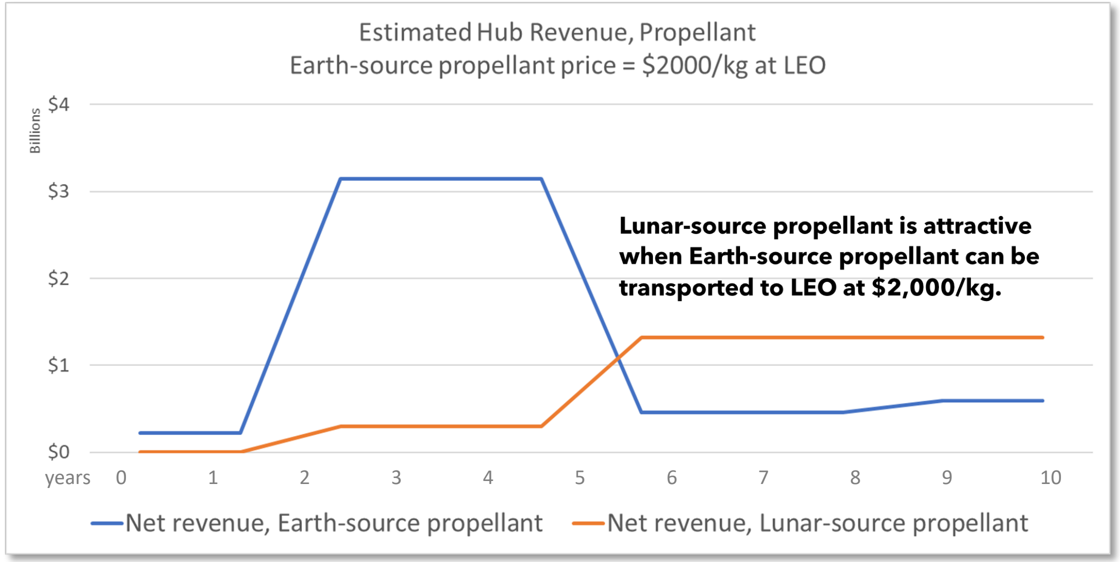
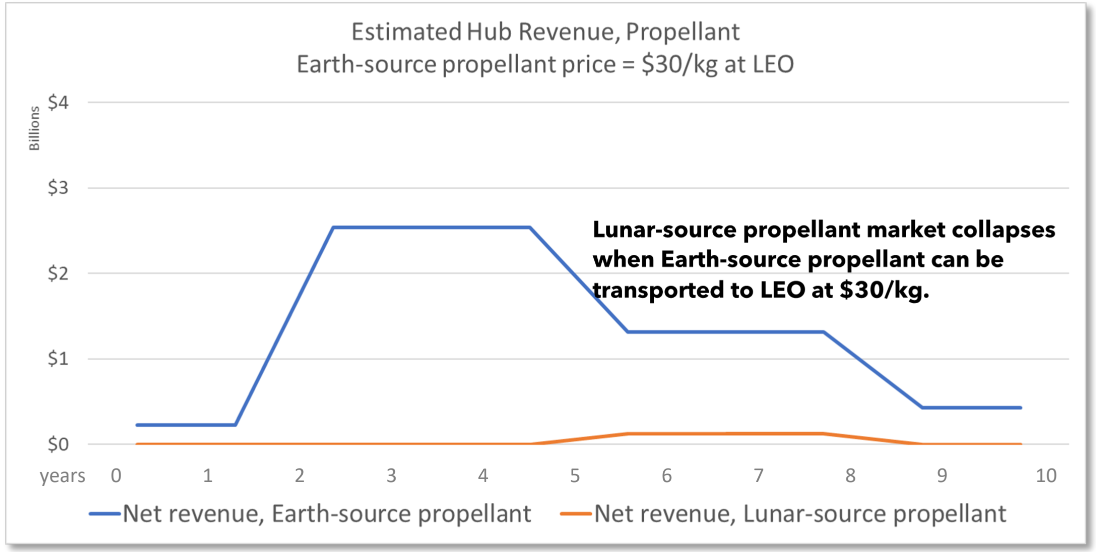
LOGISTICS PRELIMINARY INSIGHTS

REFUELING AND COUNTERINTUITIVE MARKET BEHAVIORS

As launch vehicles compete to lower the cost-to-orbit, how might that affect lunar industry?





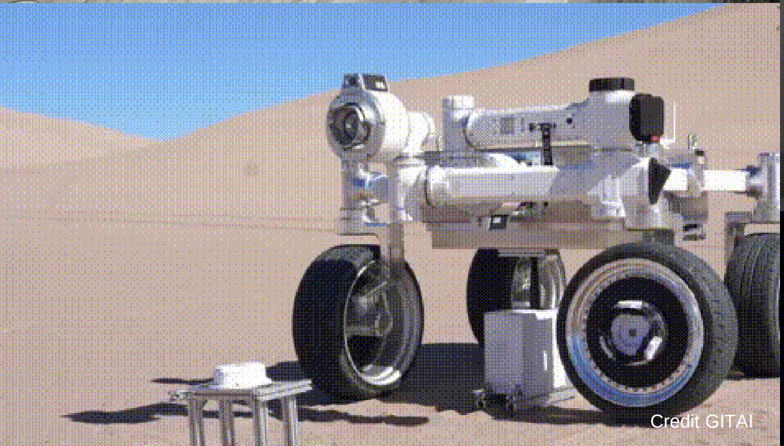
Unsurprisingly, the cost of acquiring Earth-sourced propellant will outcompete lunar-sourced propellant initially, especially with reductions in the cost-to-orbit from Earth. With sufficient lunar cargo traffic, a market can however favor lunar-sourced propellant.

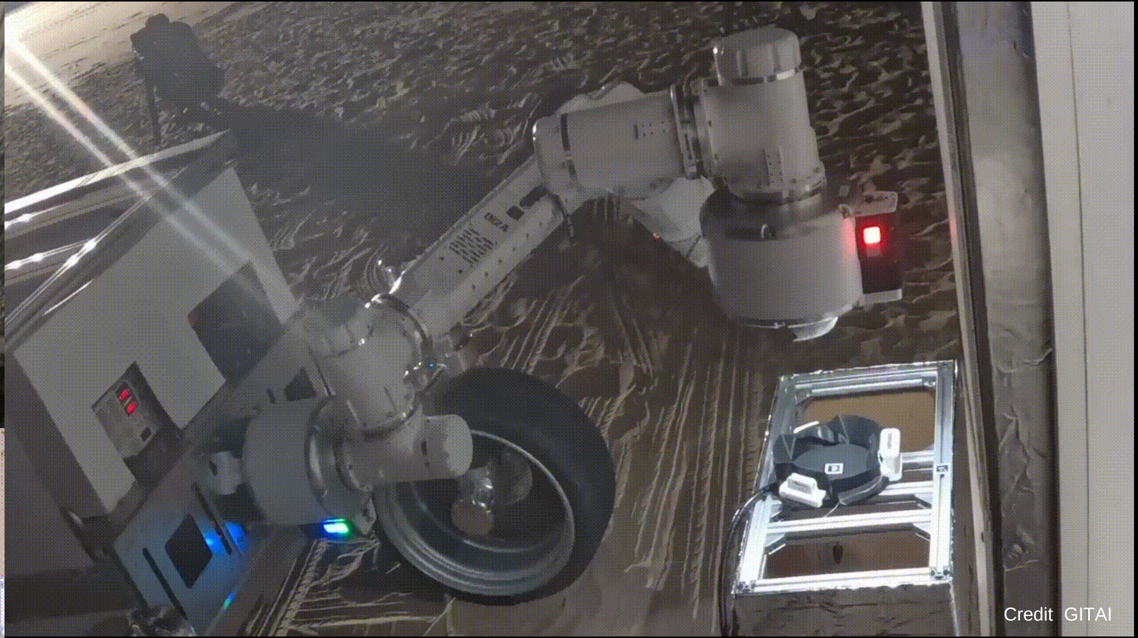
The further Earth cost-to-orbit is reduced, the harder it becomes for lunar-sourced propellant to compete. If reduced far enough, the same low launch costs that could accelerate industry on the Moon may also severely limit its development.

NOTE: *Due to the layering of assumptions, no values here should be treated as a specific forecast, the relative relationships are more significant. The provided tranches here assume the same time frame as the ten-year logistics model.*

GITAI's Robotics as a Service for Lunar Infrastructures

Providing Safe and Affordable means of labor in Space!





LSIC2024 Spring Meeting

DARPA 10-Year Lunar Architecture Capability Study (LunA-10)

Toyotaka Kozuki

GITAI, Chief Technology Officer

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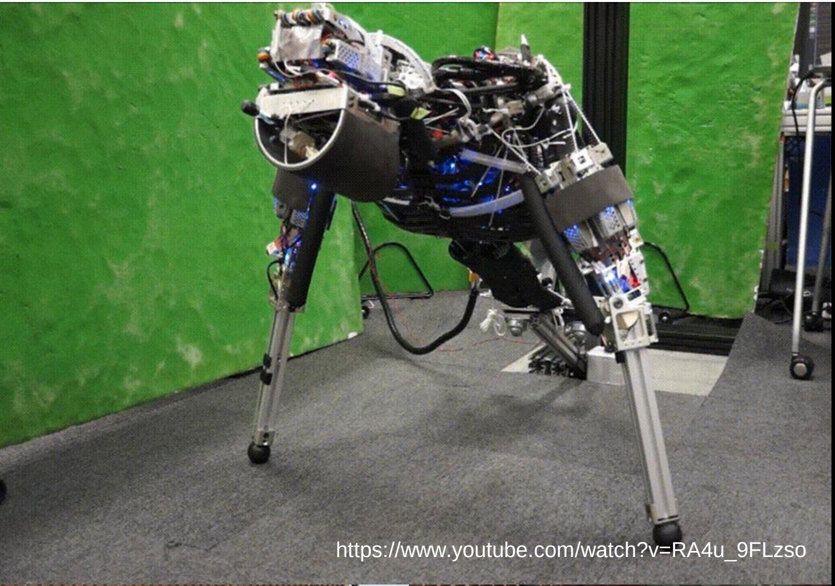
Why Robots in Space?!

Musculoskeletal humanoid robots as academic career



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Credit GITAI

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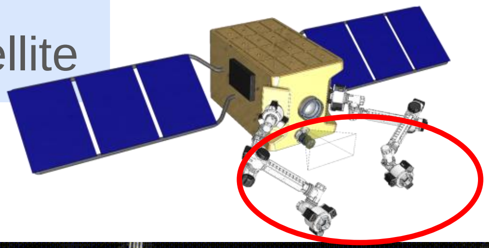
Product intro<INCHWORM ROBOT>

OSAM domain

Inchworm on Satellite

Credit GITAI

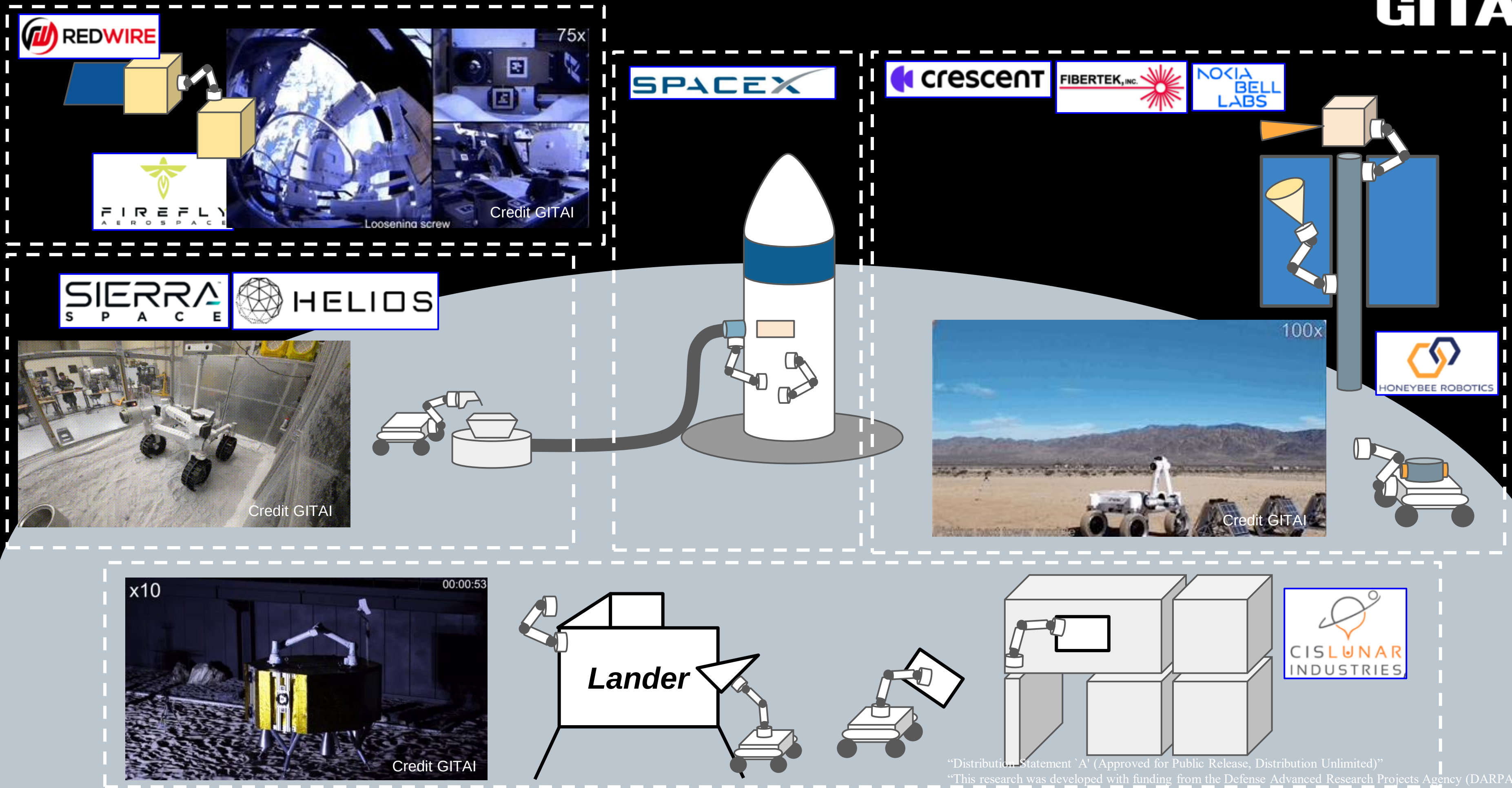


Lunar domain

Inchworm on Rover

RaaS on lunar economy

GITAI



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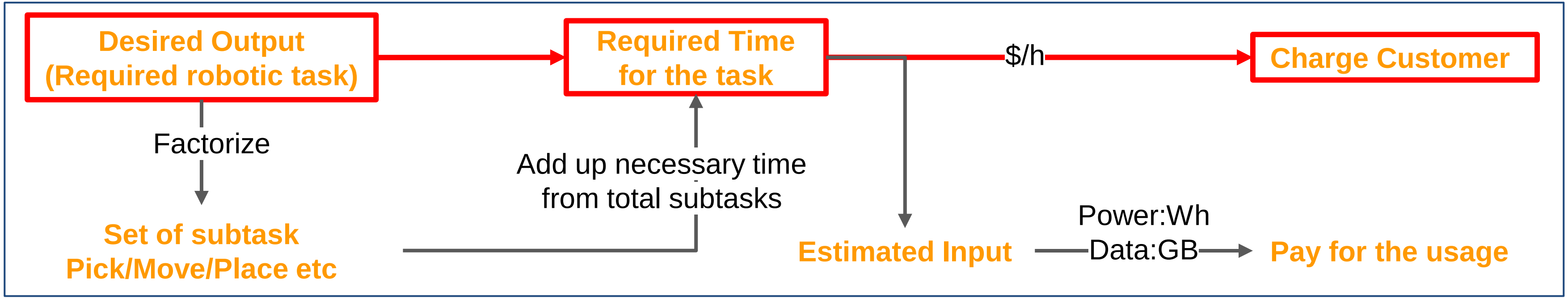
Executive Summary

We propose the concept of **Robotics as a service(RaaS)**.

The metrics we'd like to propose for our service is **$/hour**

1 Pick	2 Move	3 Place
Perception(Computer Vision) Robust Fiducial Marker Detection	**Motion Planning** Joint Angle Limit Avoidance Self Collision Avoidance Trajectory Caching	**Verification** Joint Angle Sensor Contact sensor Camera View



"This research was developed with funding from the Defense Advanced Research Projects Agency (DARPA)."

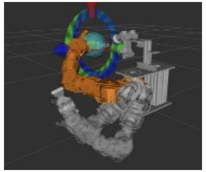
Issues in Space Industry

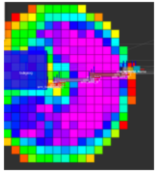
- Cost of transportation has been improving.
- What next? → Issue of high cost for labor

[All pictures on this page belong to GITAI]

Vertically Integrated Design

Software





Avionics

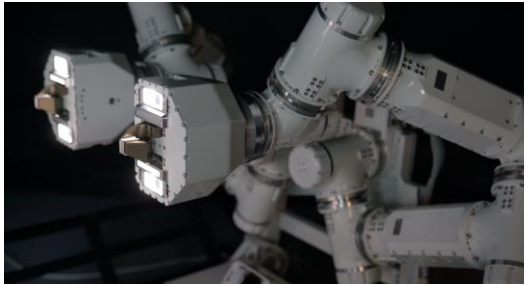


Mechatronics


Design/Production/Testing in LA

Mature Key components

Technology verified at ISS



Lunar measures(TRL4)

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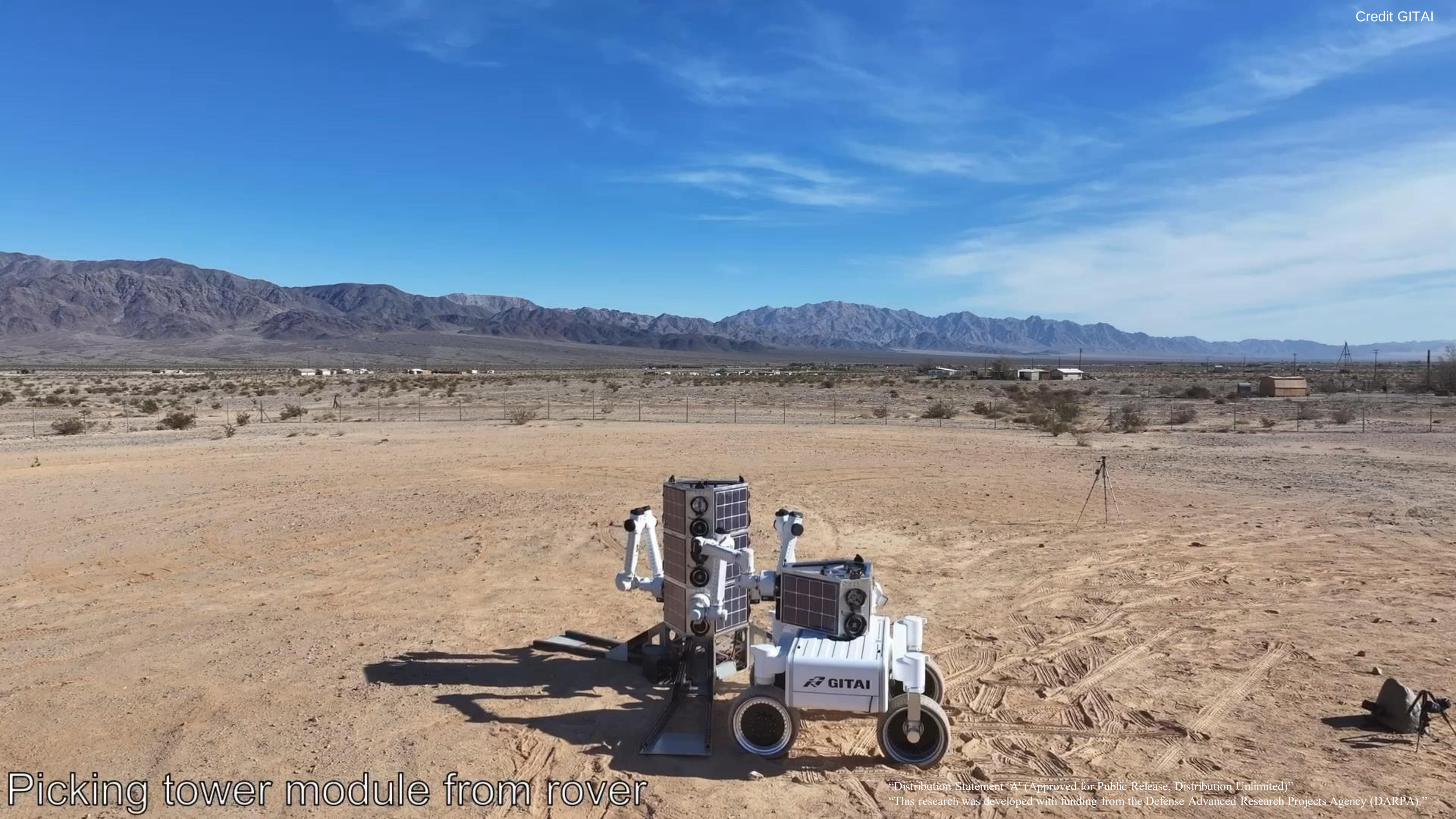

Picking tower module from rover

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HELIOS

DARPA 10-Year Lunar Architecture (LunA-10) TA-1

Oxygen Production from Lunar Regolith

LSIC Spring Meeting

April 23 - 25, 2024

HOW WILL WE GET BACK TO THE MOON TOGETHER?

HELIOS

- Helios is developing novel technology for the direct production of oxygen out of lunar regolith, where it is both ubiquitous and 42% of the total regolith weight.
- Helios's technology does not require consumables brought from Earth.
- Technology performs at a lower temperature than direct Molten Regolith Electrolysis (MRE).
- Produces high purity oxygen (above 99.6%) by physically separating the oxygen creation zone from the regolith melt zone.

What we contribute:

Oxygen gas for life support and LOX propellant

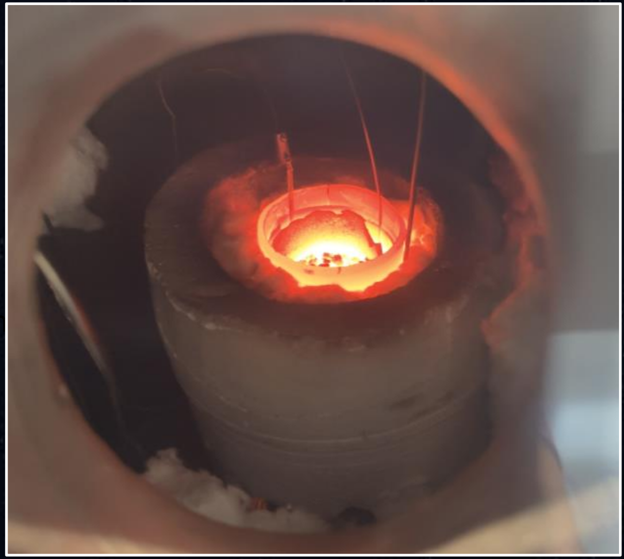
Source: [Helios]

Construction raw Materials Heated Metal and de-oxygenated regolith

Source: [https://www.freepik.com]

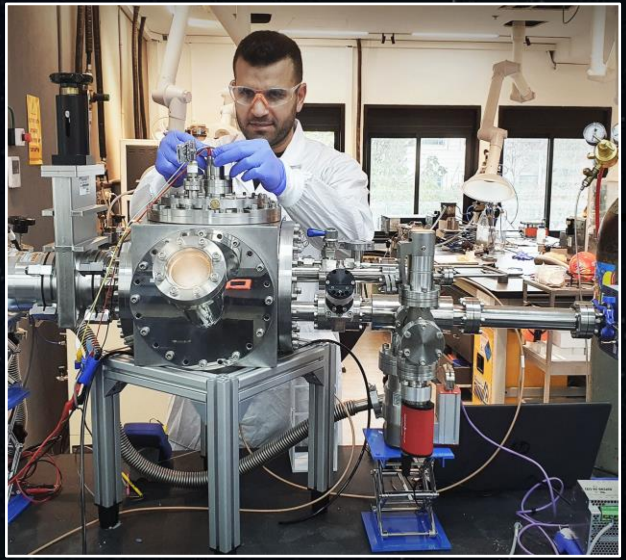
OUR TECHNOLOGY

- After years exploring MOE, Helios gravitated to developing cells based on solid-oxide electrolyzer cell (SOEC) technology.
- Currently, Helios is focusing on developing "scaleup friendly" SOEC tubular cells.



Source: [Helios]

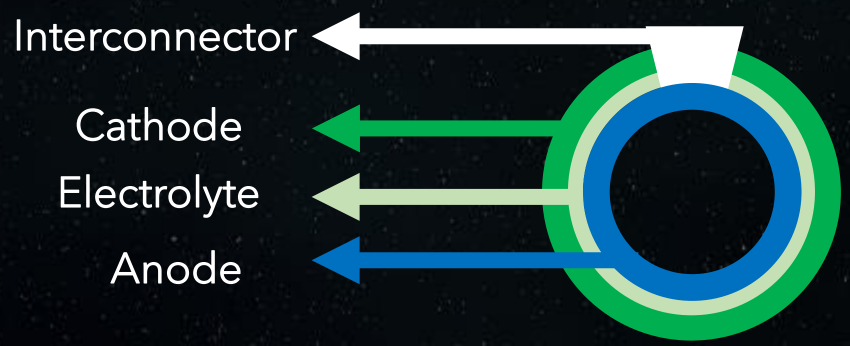
Maturing technology



Source: [Helios]

Monitoring abilities and upscaling

Tubular cell Top view



Source: [Helios]

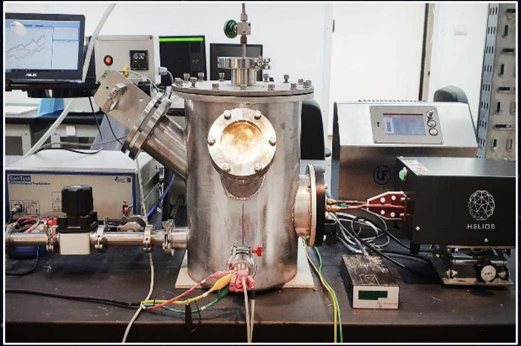
OUR SCALE-UP APPROACH

HELIOS

Timeline

2022 2023 2028 2030 2035

MVP in Lab on Earth



Source: [Helios]

MVP on the Moon

Source: [https://www.freepik.com]

Maximum Performance Unit (MPU) on the Moon

Source: [https://www.freepik.com]

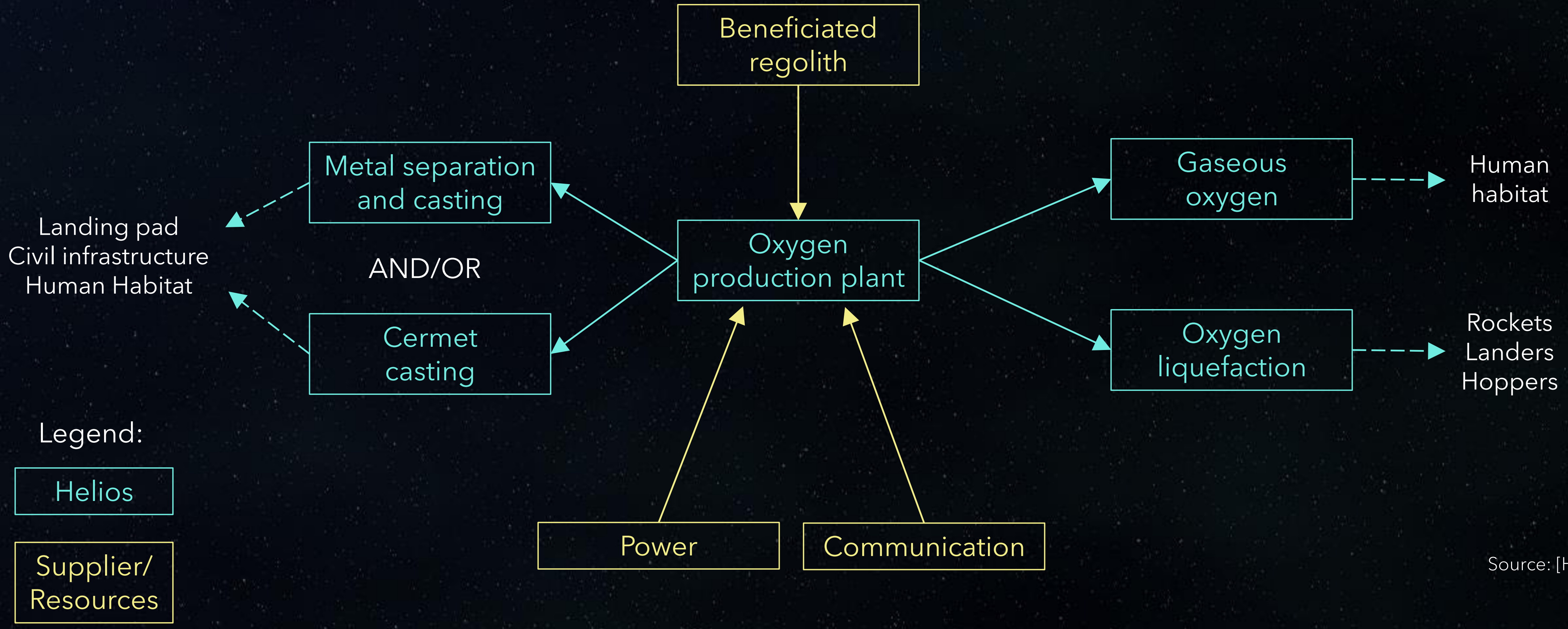
Oxygen Production Plant (MPUs) on the Moon

Source: [Helios]

10^{-3} 10^{-1} 10^{2} 10^{3} 10^{5}

Kg O_2 per month

OUR INITIAL INTEGRATED SYSTEM CONCEPT

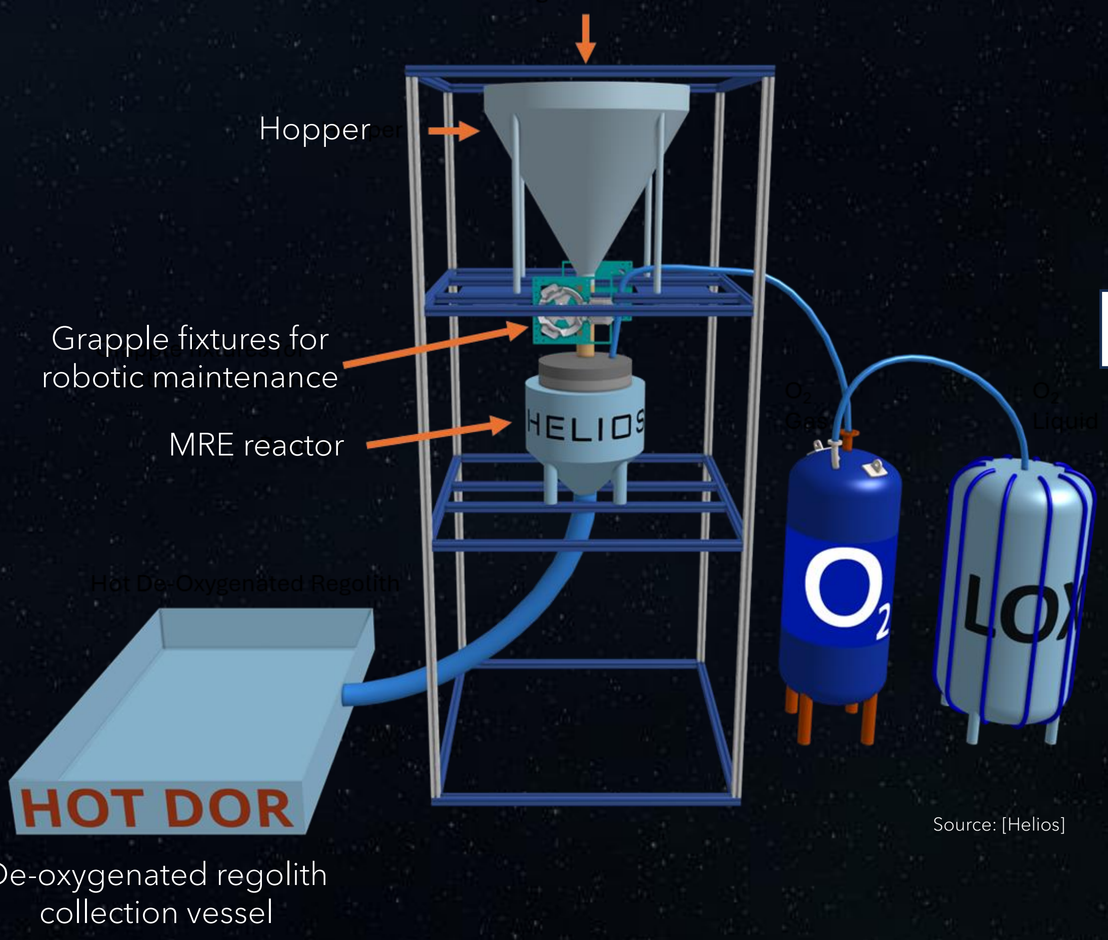


Source: [Helios]

FROM MVP TO ROBUST OXYGEN PRODUCTION PLANT

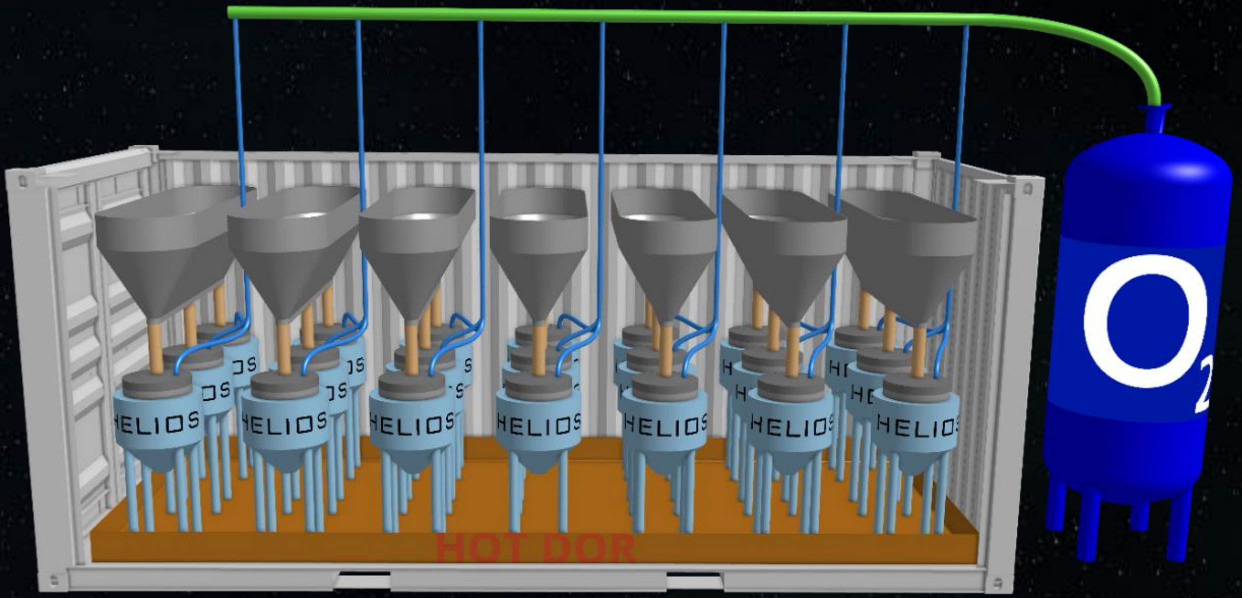
HELIOS

250 Kg/month crew life support system



Source: [Helios]

~120 ton/month container equiv. system



Source: [Helios]

OUR OPPORTUNITIES AND CHALLENGES

HELIOS

Lunar Dust

Lunar dust, a combination of highly abrasive and electrostatically charged particles, poses a significant threat to the functionality and longevity of any system deployed on the lunar surface

Lunar Gravity

Lunar gravity is anticipated to impact the dynamics of the molten regolith flow within the MRE reactor on the lunar surface, which must be understood to optimize reactor design and performance

System Lifespan

Unique lunar environment with periods of intense sunlight and extreme heat juxtaposed with cooled lunar nights devoid of sunlight will impact the activity vs. stability of a lunar MRE system

Standardization

Standardization of system interfaces (regolith handling, power, comms etc.) ensures different systems work together seamlessly, simplifies maintenance, and reduces risk, paving the way for a robust and sustainable lunar future.

Economics

To achieve a sustainable presence on the Moon, economics must be sustainable. For commercial companies, this means that lunar business opportunities must generate a profit and a return on investment

HELIOS

Thank you!

DARPA LunA-10 TA-1
LSIC Spring Meeting, Initial SCR Summary

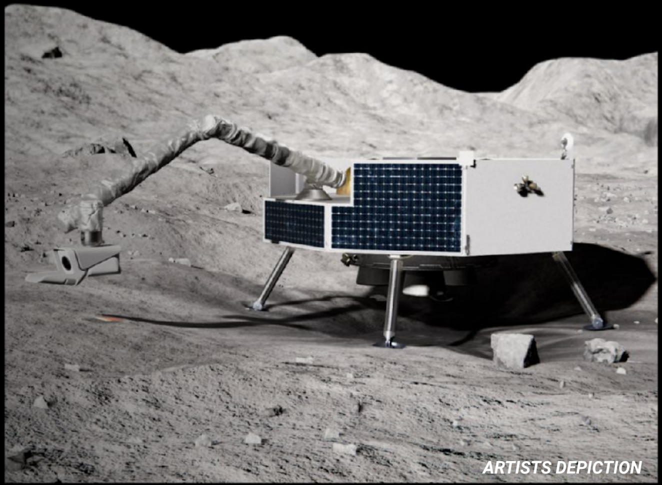
April 25, 2024

Table of Contents

ICON's Olympus system is a multi-purpose construction system primarily using local Lunar resources as building materials to further the efforts of NASA as well as commercial organizations to establish a sustained Lunar presence.

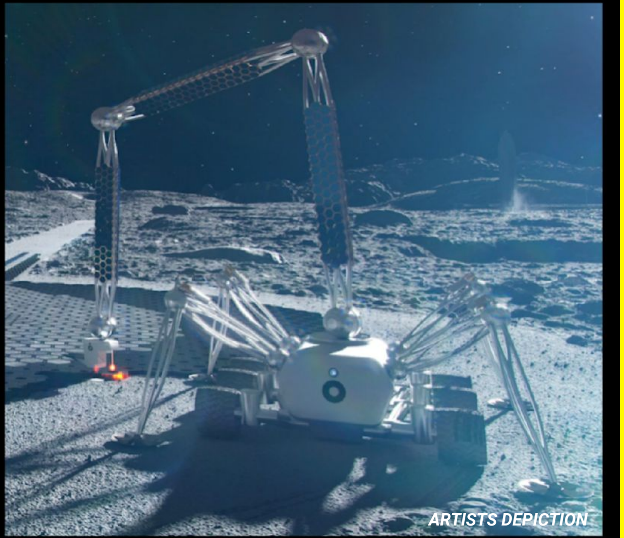
ARTISTS DEPICTION

Our goal is to build infrastructure off-planet…
…starting with the moon.

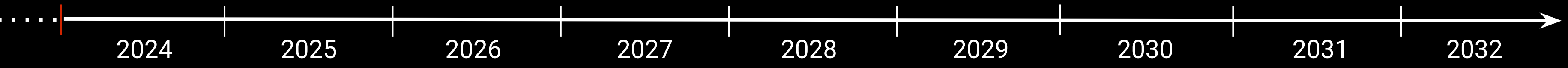


Lunar demonstration to close lab testing

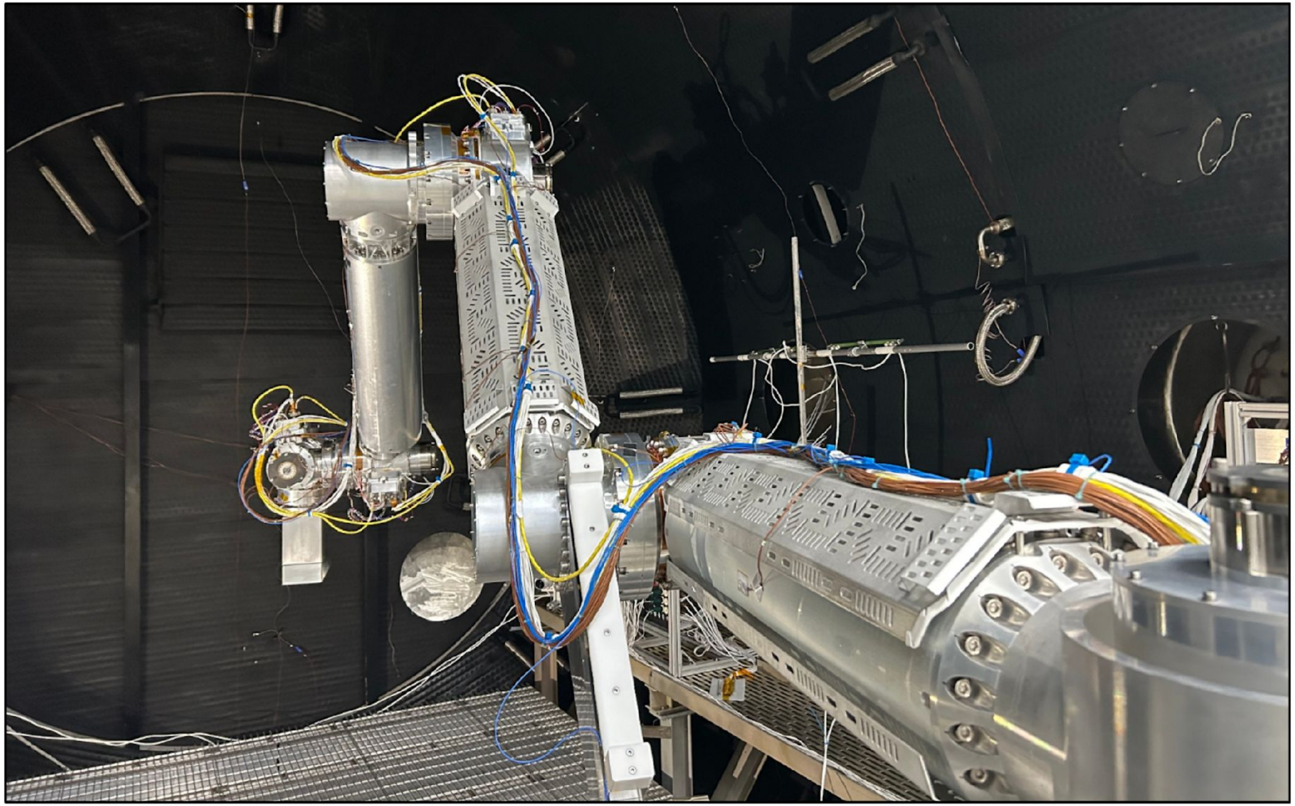
Going “off lander” for extended build volumes



Commercially scalable hab-capable system



ICON's Laser VMX Lunar Construction System



ICON's Laser VMX robotic prototypes are capable of autonomously 3d printing with lunar regolith.

Results from Laser VMX Structural Testing

Testing and analysis show that the prints can survive the thermal conditions of the south pole and withstand the forces generated during launch and landing of an HLS class lunar lander. NASA corroborated our findings and selected Laser VMX as the primary process for its additive construction needs.

Compression
24 C: 348 MPa
57 C: 334 MPa
-184 C: 339 MPa
Thermal cycled: 252 MPa

Tension
24 C: 8.69 MPa

CTE
-184 C to 57 C:
-3.15×10^{-6}

Plasma Torch
Degradation: discoloration only

4-Point Bend
24C: 68.9 MPa

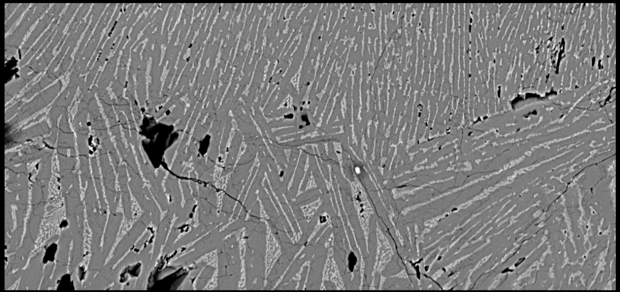


Figure: SEM imagines of Laser VMX grain structure

Figure: Cross section of printed Laser VMX sample

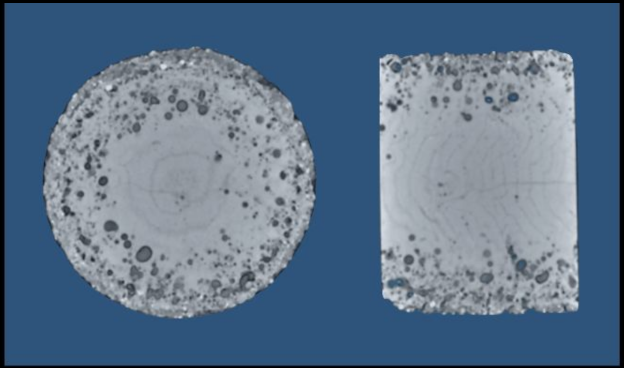


Figure: CT Images from Post-test ablation testing

Figure: Plasma Torch Testing (3MW/m2)

ICON’s Company Centered Lunar Framework

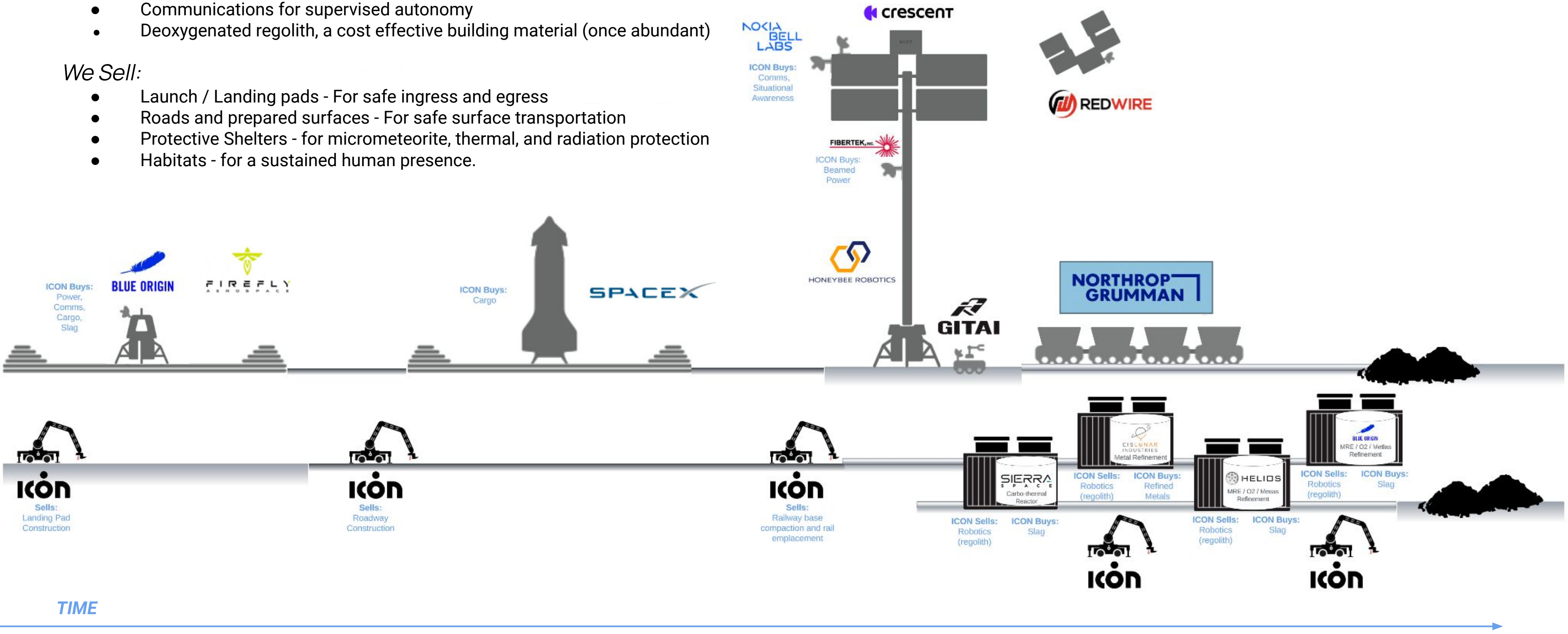
We Buy:

- Transit for our robots to the lunar surface
- Energy for our robots and processes
- Communications for supervised autonomy
- Deoxygenated regolith, a cost effective building material (once abundant)

Note: Primary Connections, Buys and Sells shown in blue.

We Sell:

- Launch / Landing pads - For safe ingress and egress
- Roads and prepared surfaces - For safe surface transportation
- Protective Shelters - for micrometeorite, thermal, and radiation protection
- Habitats - for a sustained human presence.



Notional ICON VMX-Enabled Landing Pad for Starship - Loads / Design

Assumed Pad Material Properties: Replicate sintered regolith using a low CTE ceramic material

- Compressive Strength = 345.0 MPa
- Tensile Strength = 17.3 MPa
- Modulus of Elasticity = 68.9 GPa
- Density = 2.6 g/cm³ (2,600 kg/m3)
- Poisson's Ratio = 0.25
- Coefficient of Thermal Expansion = 4.0x10-7 1/C

Applied Loading:

Dead Loads (D):
- Self-weight (Lunar Gravity)

Live Loads (L):
- Rocket plume pressure
- Landing leg bearing
- Off-nominal pad-edge landing analyzed

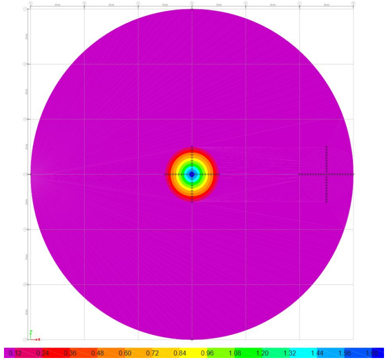


Figure: Loading Information – Plume Pressure

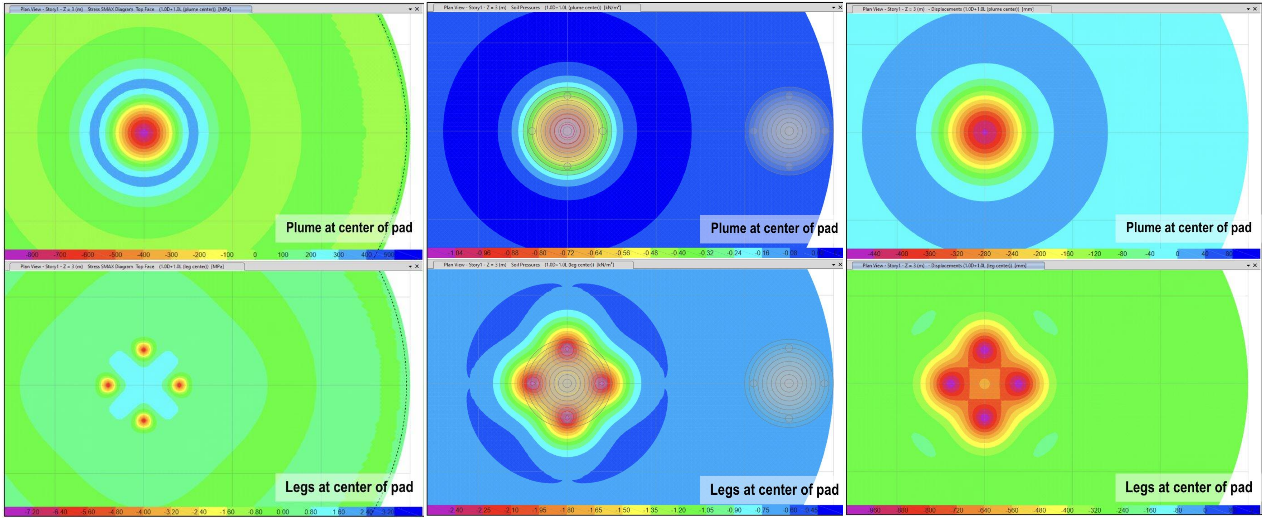


Figure: Model Example Results – Pad Stresses, Soil Bearing Stress, Vertical Deflection

Notional ICON VMX-Enabled Landing Pad for Starship - Dust / Analysis

Rocket landings propel regolith, gravel, and rocks at high velocities—potentially damaging or even destroying spacecraft, scientific instruments, and other critical lunar infrastructure. Given the absence of atmospheric drag and reduced gravity, lunar ejecta will travel great distances with minimal energy loss, creating an atmosphere of pollution that could enshroud the Moon and inhibit future travel.

For this study, a nominal plume-surface interaction was used for loading. Landing accuracy drives the design rather than apron size to mitigate for dust.

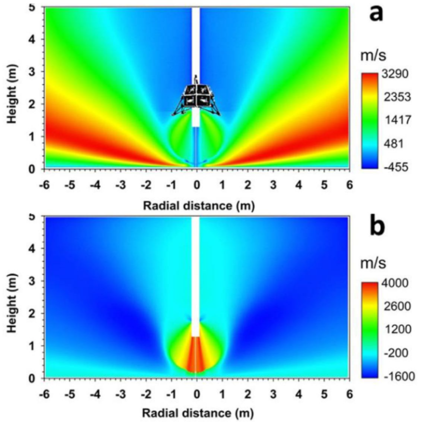


Figure A: Plume gas horizontal velocity profile at h = 1.5 m.
Figure B: Plume gas vertical velocity profile at h = 1.5 m.
(Mishra et al., 2022)

Distance from centroid of vehicle (m)	Percent of plume pressure	Plume Pressure (kPa)
0	100%	1700
1	90%	1530
2	80%	1360
3	70%	1190
4	60%	1020
5	50%	850
6	40%	680
7	30%	510
8	20%	340
9	10%	170
10	0%	0

Figure: Plume-surface interaction assumptions

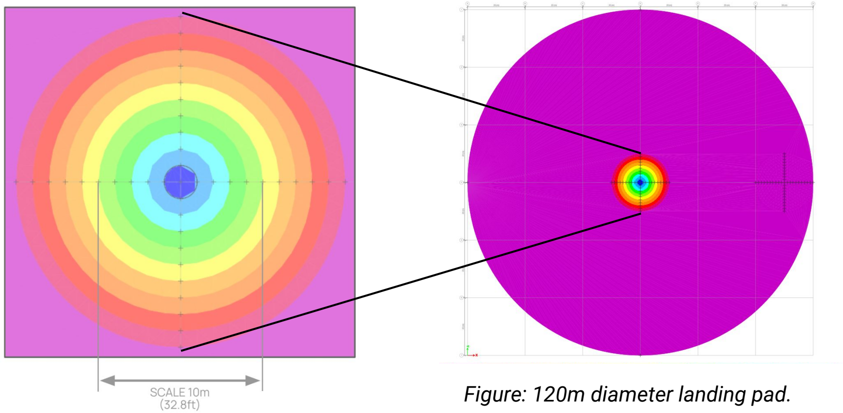


Figure: 120m diameter landing pad.

Notional ICON VMX-Enabled Landing Pad for Starship - Scaling Model

The whitespace chart to the right reflects the Laser VMX landing pad production vs. time for pad classes, with 1cm average thickness.

Smaller pads can be produced in relatively short timescales, less than 1 year with a single landing and robot.

When going for larger pads, like what would be required for a reusable Lunar starship, robotic parallelism are likely to be required to bring production to reasonable time-scales. (Multiple robots per pad, road, etc).

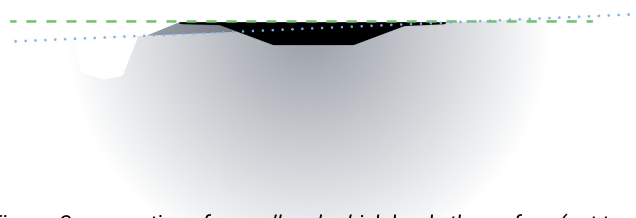


Figure: Cross section of a small pad, which levels the surface (not to scale).

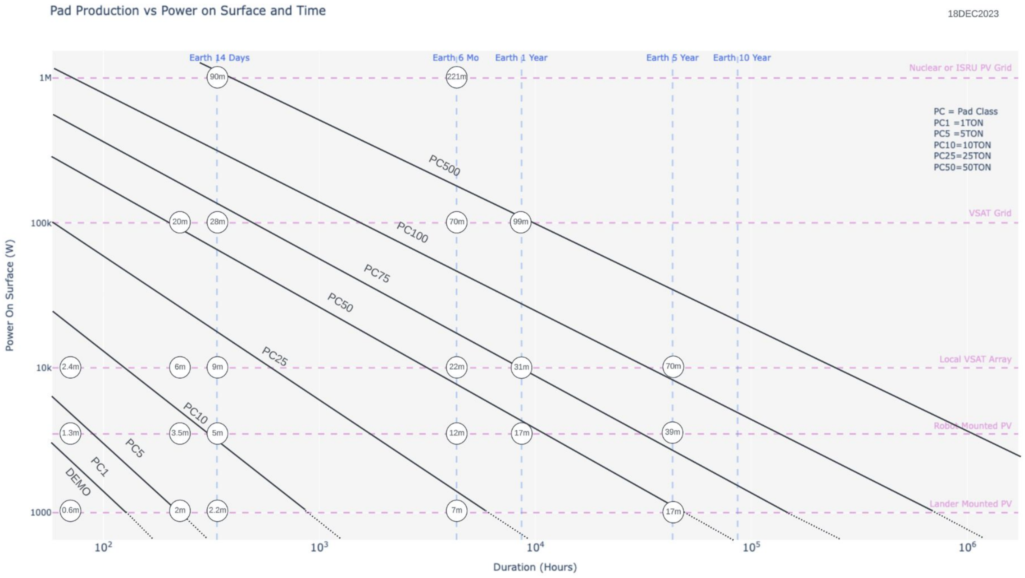


Figure: An larger pad's nominal shape scales, needing much more material throughput and energy.

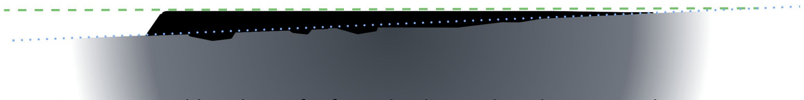


Figure: A possible solution for faster landing pad production is to locate areas of large rock, and product only the pad-surface required to make the rock flat, and suitable for landing.

Notional ICON VMX-Enabled Landing Pad for Starship – Economics

The first full scale construction robot on the surface is ideally capable of completing at least 4 CLPS Class landing pads, with connecting roads for ingress and egress.

The cost structure will consist of landing, launch, and occupancy fees for the duration the pad is in use. As the lunar economy grows, so will the number and, likely, size of rockets on the lunar surface. As demand increases, so will the value of the landing pads and other horizontal infrastructure.

An initial construction-scale system is assumed to make one or two small landing pads near a region of interest, and should be able to recover the investment as the rate of launches and landings increases.

When scaling up, the robot reliability and throughput will go up, without a substantial increase in launch costs, resulting an outlook for profitable pad, road, and eventually habitat construction into the late 2030s.

The "Notional Reusable Starship Pad" is particularly large due to the incredibly large loads seen during landing, so additional considerations and designs are required to fully assess the financial viability.

ICON Olympus Construction System 1			
2027-2030 Era	500-1000kg class		
Item	**Cost**		**unit**
Engineering / Management	$	24,000,000	usd
Flight Hardware	$	15,000,000	usd
Launch / Landing Services	$	200,000,000	usd
Operation	$	1,000,000	usd
	$	**240,000,000**	**usd**
Robots Operational On Surface		1	
Pads created per robot		2	
Pads created		2	
Pad lifetime		20	yr
Launch-Landings / Year / Pad (Avg)		12	
Launch-Landings / Lifetime (per Pad)		240	
Launch-Landings / Lifetime		480	
Cost / Landing	$	500,000	usd
Revenue over n years	$	240,000,000	usd
Profit	$	-	usd

ICON Olympus Construction System Critical Mass			
2030 - 2035 Era	1000-2000kg class		
Item	**Cost**		**unit**
Engineering / Management	$	24,000,000	usd
Flight Hardware	$	60,000,000	usd
Launch / Landing Services	$	800,000,000	usd
Operation	$	4,000,000	usd
	$	**888,000,000**	**usd**
Robots Operational On Surface		4	
Pads created per robot		10	
Pads created		40	
Pad lifetime		20	yr
Launch-Landings / Year / Pad (Avg)		12	
Launch-Landings / Lifetime (per Pad)		240	
Launch-Landings / Lifetime		9600	
Cost / Landing	$	250,000	usd
Revenue over n years	$	2,400,000,000	usd
Profit	$	1,512,000,000	usd

Off-board Heat Rejection System - Problem Summary and Potential Solutions

High-Power lunar operations will rely on an ability to remove thermal energy from the system

Terrestrial applications can reject heat via conduction fed convection processes [fig: A].

Cis-Lunar and other spacecraft rely solely on radiators.

Future Lunar missions may not be able to rely on radiative cooling alone, dumping heat into a thermal mass allows that heat to be used when needed either during lunar night or for power generation [fig: D].

Using lunar regolith as a storage medium, whether to dump waste heat or to store thermal energy, is not a new concept

Using regolith in the following ways:

- Loose
- Compacted
- Sintered
- Loose material contained in a vessel (made of melted and solidified regolith or other materials)

Some have even considered water or other media as storage media, either brought from Earth or extracted locally

Can we use ICON VMX material as a thermal mass/battery and take advantage of its relatively high thermal conductivity [b] and heat capacity and insulate the mass using loose regolith (with it's very low net thermal conductivity [Fig: C])

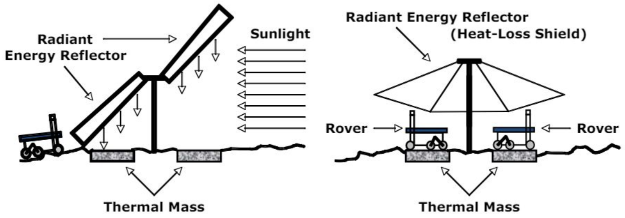


Image: Balasubramaniam, R., Gokoglu, S.A., Sacksteder, K.R., "An Extension of Analysis of Solar-Heated Thermal Wadis to Support Extended-Duration Lunar Exploration", 48th Aerospace Sciences Meeting, Orlando, FL, January 4-7, 2010.

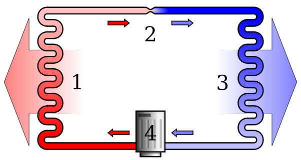


Figure: A

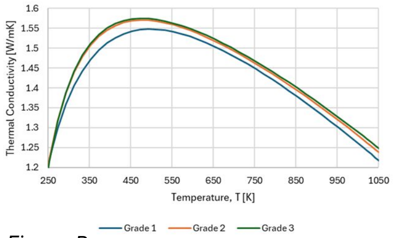


Figure: B

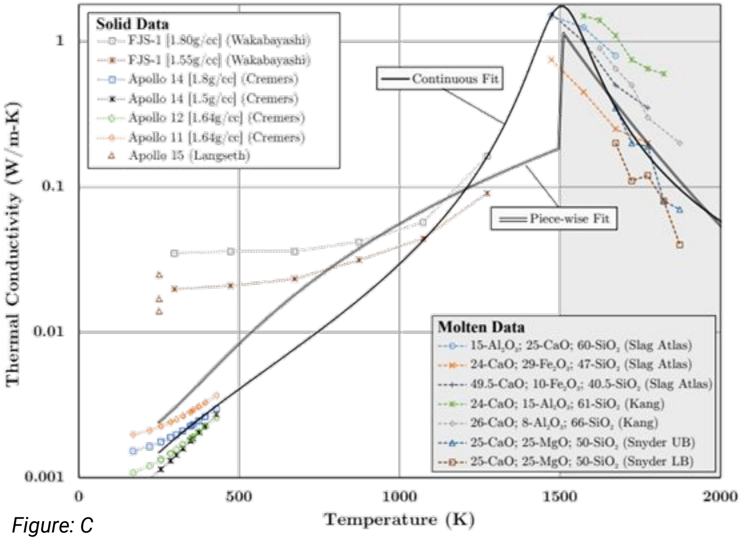


Figure: C

Off-board Heat Rejection System - Design Examination

Three (3) thermal models were created

[a] Thermal mass in regolith flush with surface with "blanket" covering exposed surface.
[b] Mass buried in regolith 0.2 m, below surface.
[c] (not shown) as [a] but with a layer of graphene strips (tendrils) between layers of VMX,
[d] as [b] but with graphene tendrils

Assumptions:

All model versions use a VMX thermal mass: 1 m x 0.5 m x 0.2 m, initial temperature 240 K (~235 kg)

Regolith region into which VMX mass is set: 2 m x 2 m x 0.5 m, initial temperature 240 K

Regolith surface initial temperature 50 K

Graphene thermal strap is used to connect mass to a point on the regolith surface at which a thermal "connector" is envisioned

Two scenarios analyzed: case 1 with connector held to 800 K, and case 2 with 1 kWt applied to SC interface connector

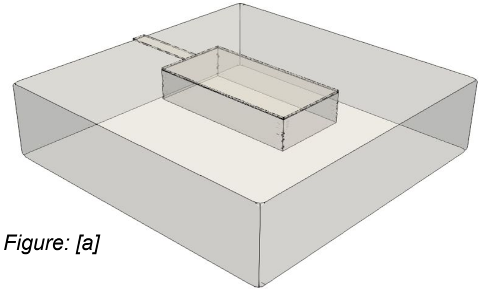


Figure: [a]

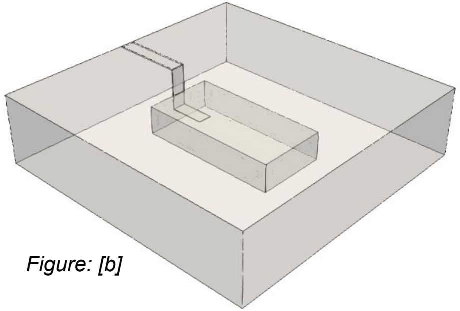


Figure: [b]

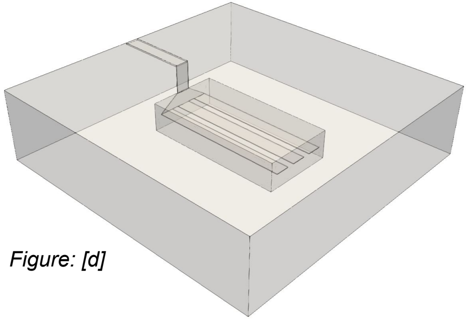
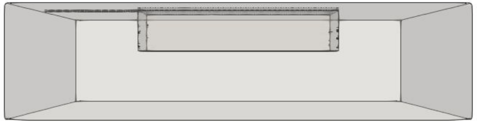
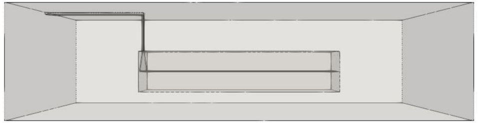


Figure: [d]





Off-board Heat Rejection System - Constant Temperature Results

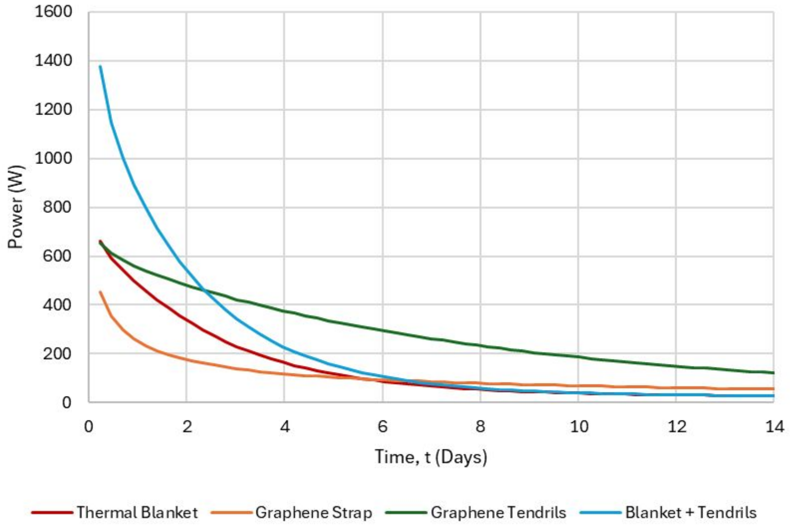
Selected results for configurations A->D run with constant temperature interface

Shown here are detailed results for the blanket on monolithic VMX Grade 1 and summary results for all configurations exposed to the 800 K interface BC

Evaluations for other VMX grades were done, results are very similar, with more detail will be provided in the SCR report

Temperature evolution of the mass over time is shown below with the VMX block becoming near isothermal at day 14

Graph to the right shows power flowing into the battery as a function of time for all configurations evaluated. Used as a heat sink case 1C offers the highest cooling flux initially while case 1D provides the most consistent sink



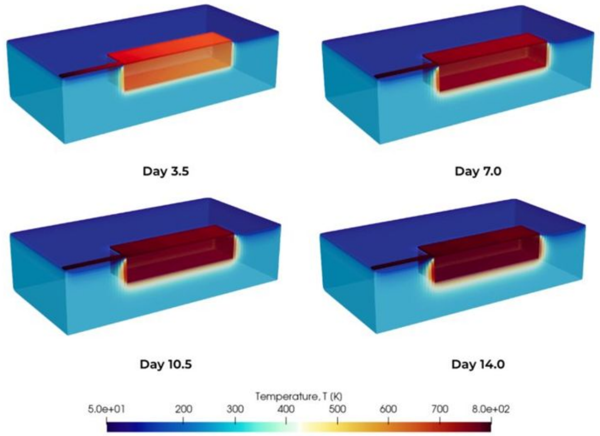


Figure: Example of a simulation-set run in CFD, 14 Earth days, 800 K Input

	CASE 1A: Thermal Blanket	CASE 1B: Graphene Strap	CASE 1C: Blanket + Tendrils	CASE 1D: Graphene Tendrils
Input Energy	48.0 kWh	38.0 kWh*	74.4 kWh	99.1 kWh
Ave. Temp	780 K	643 K*	788 K	691 K

Figure: Table and graph of input energy and average temperature.
** extreme non-uniform temperature*

Commercialization Model - Business Model

The first full scale construction robot on the surface is ideally capable of completing at least 4 CLPS Class landing pads, with connecting roads for ingress and egress.

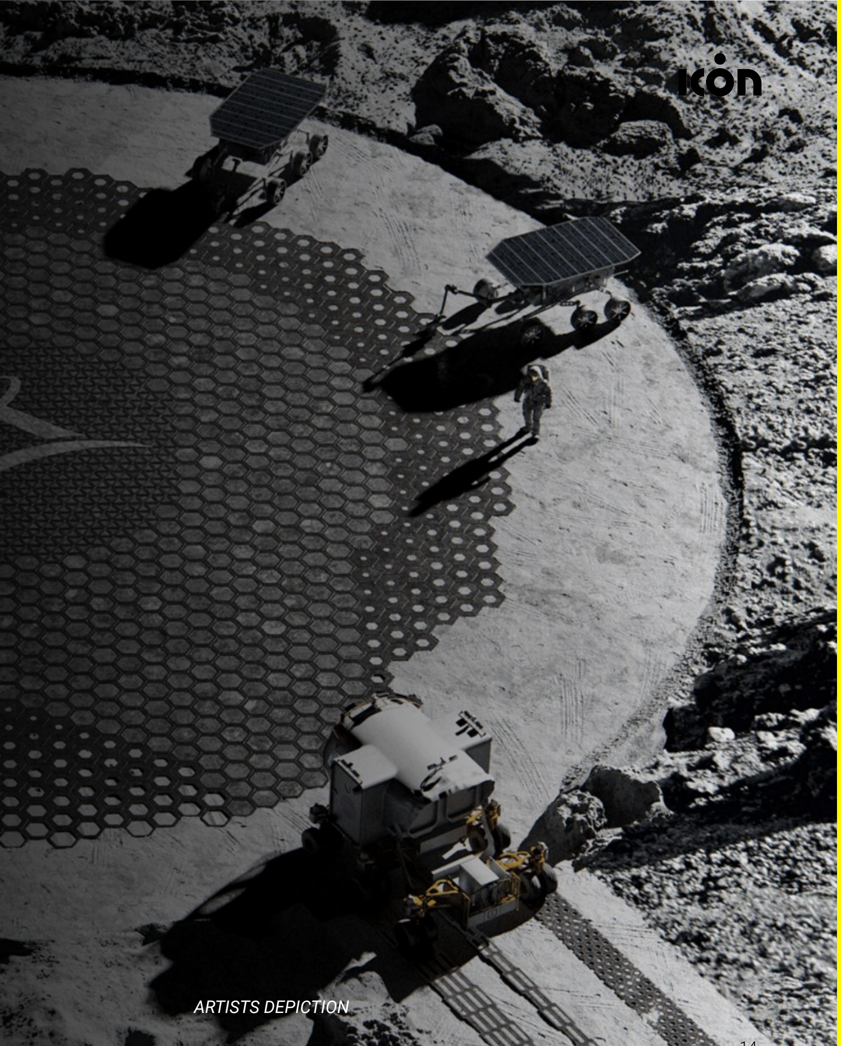
Since the launch / landing pad production cost can be amortized over a large volume of uses, the owner of a landing pad could foreseeably charge per use. It is worth emphasizing that the cost to spacefaring entities using the pad is negligible when compared to the program and launch costs to arrive, as well as mitigated risks and the ability to service areas that are highly adjacent to other lunar assets for commercial purposes.

The cost structure will consist of landing, launch, and occupancy fees for the duration the pad is in use. As the lunar economy grows, so will the number and, likely, size of rockets on the lunar surface. As demand increases, so will the value of the landing pads and other horizontal infrastructure.

Just as planes must use runways, rockets must use landing pads on the lunar surface to contain lunar ejecta. Operating landing pads, therefore, is analogous to ownership of other critical "gateway" infrastructure, such as airports, ports, and railways.

Foundational infrastructure is one of the greatest economic multipliers*.
An investment into this technology will multiply across the value chain and provide a strong return on investment for the creation of a sustainable lunar economy.

*Foster , Vivien, Maria Vagliasindi, and Nisan Gorgulu . "The Effectiveness of Infrastructure Investment as a Fiscal Stimulus: What We've Learned." World Bank Blogs, February 2, 2022.



ARTISTS DEPICTION

ARTISTS DEPICTION

10-Year Lunar Architecture (LunA-10) Capability Study

A Multi-Service Cislunar Commercial Constellation

Presented at LSIC

April 23-25th, 2024

REDWIRE
- Study lead
- RF apertures
- Mission CONOPs

RADAR APPLICATIONS
- SAR/MTI SME

Axta Space Corporation
- Comms SME

CACI EVER VIGILANT
- PNT SME

Advanced SPACE
- Orbital Mechanics SME

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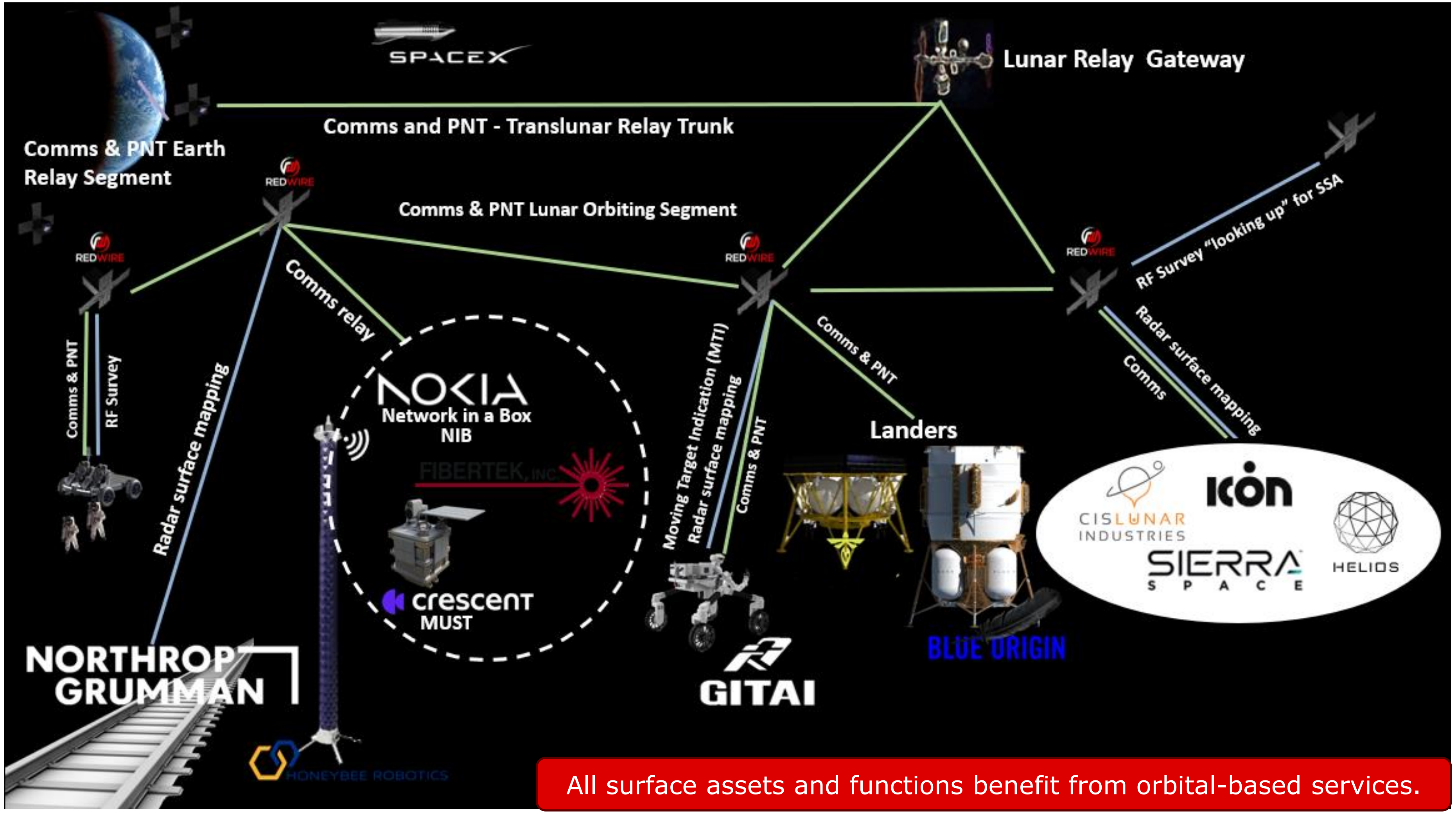
Redwire LunA-10 Introduction

Redwire proposes a constellation of cislunar orbiters providing multiple RF-based services:

- Communications
- Position, Navigation, and Timing (PNT)
- RF Survey
- SAR/MTI
- Microwave space-based solar power beaming



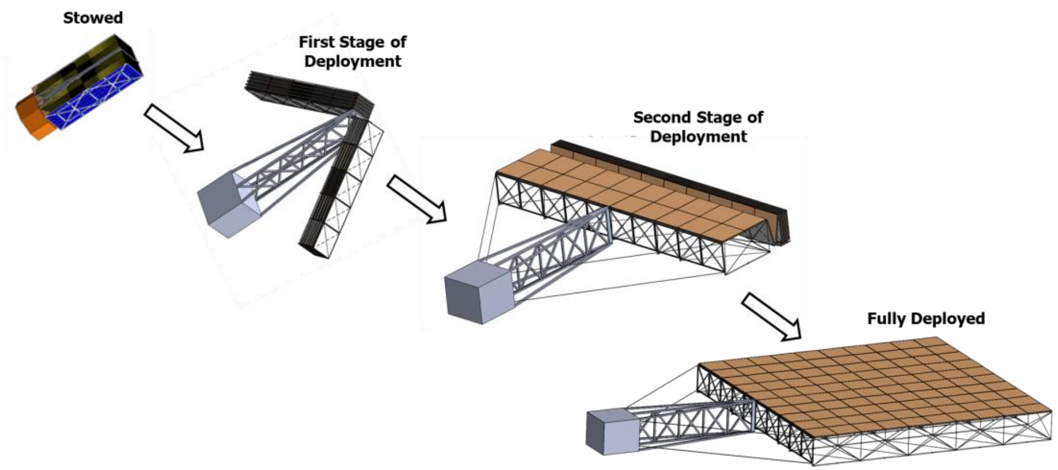
Source: Redwire

This research was developed with funding from the Defense Advanced Research Projects Agency (DARPA).

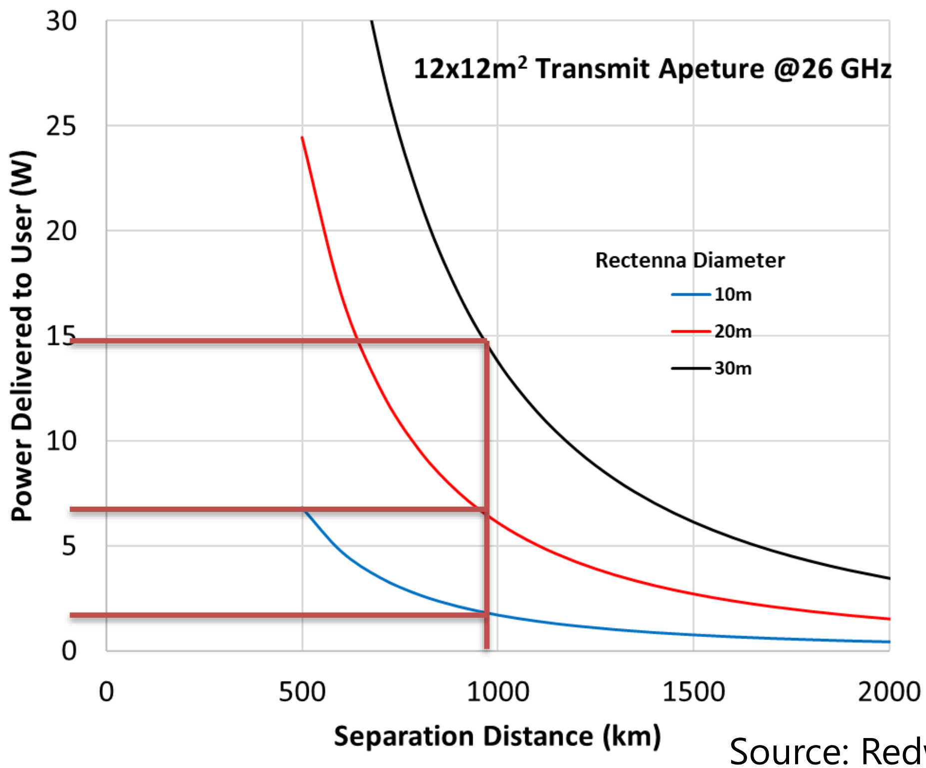
Microwave Power Beaming is Feasible, but not Commercially Viable…

Conclusion: While technically feasible, microwave power beaming from cislunar orbit does not appear to be commercially viable due to aperture size/mass/cost that would be required for meaningful energy delivery

Formation of 12m x 12m aperture



Source: Redwire



Source: Redwire

Tx antenna >19mx19m could realize a useful amount of power (>500 Whr) with the standard efficiencies @26 GHz and a 30m diameter rectenna

This research was developed with funding from the Defense Advanced Research Projects Agency (DARPA).

Full End-to-End Communications and PNT Solution Devised

Summary of Proposed Lunar Comms Architecture

Lunar Surface Segment: **NTE/5G RF last mile**

- Nokia proposed LTE/4G/5G supported solution, 10km, **100mbps**

Lunar Orbiting Segment: **mid/high lunar**

- Constellation 16 sats, ubiquitous coverage, leveraging sustainable frozen lunar orbits, optimized for comms capability, 3000-13000km, **1-10 Gbps**
- PNT hosted on same constellation

Lunar Relay Segment: **NRHO**

- Lunar orbiters to NRHO, 3000-70000km, **1-10Gbps**

Translunar Trunk Segment: **Earth orbiting, high-rate data**

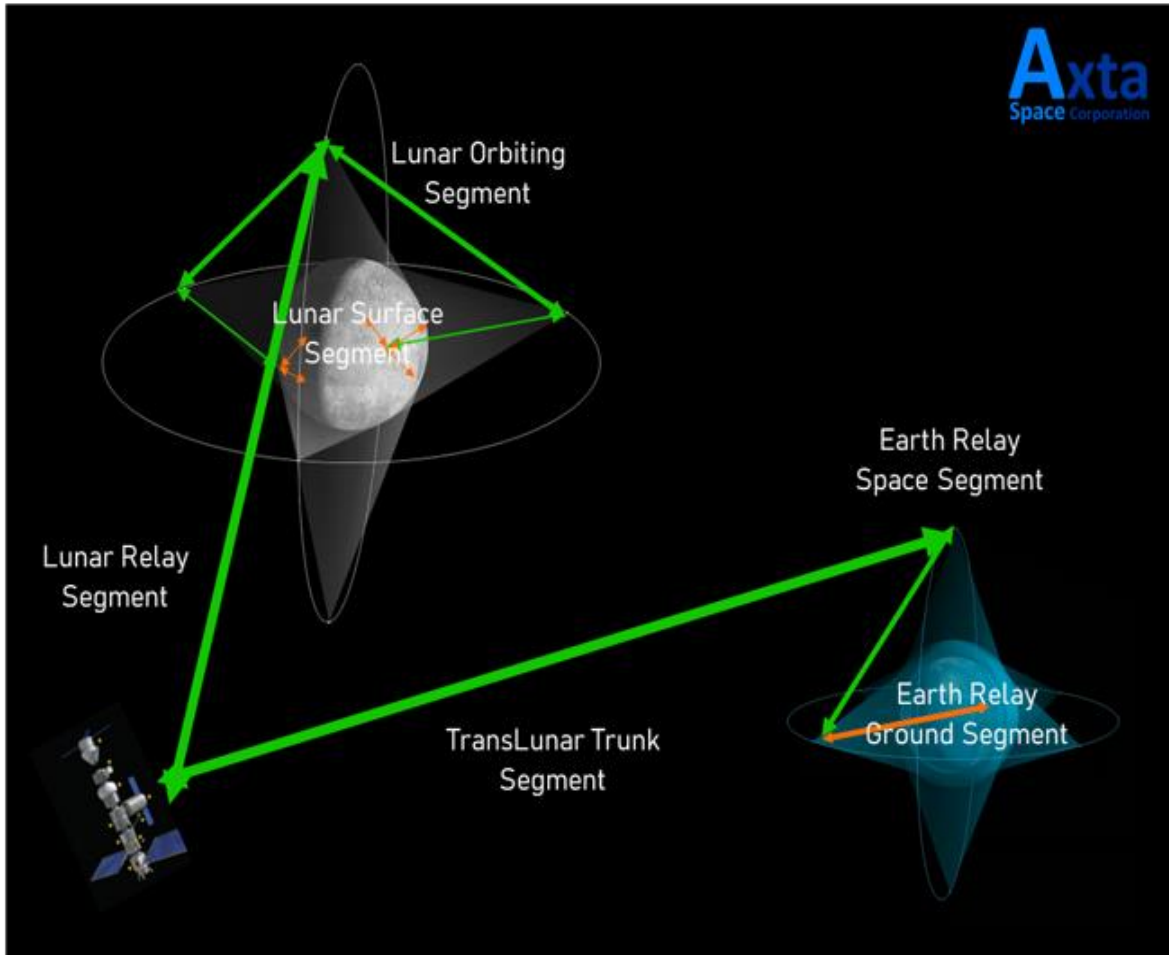
- Long link distance, 390,721km, optical data link, **100Gbps**

Earth Relay Space Segment: **Earth orbiting (prior to atmospherics)**

- Constellation, 3 GEO sats, constant link, 40000km, **100Gbps**

Earth Relay Ground Segment: **Earth-Ground, traditional RF links**

- Gateway into Cloud distribution to any site, optical terrestrial, **1-10Gbps**



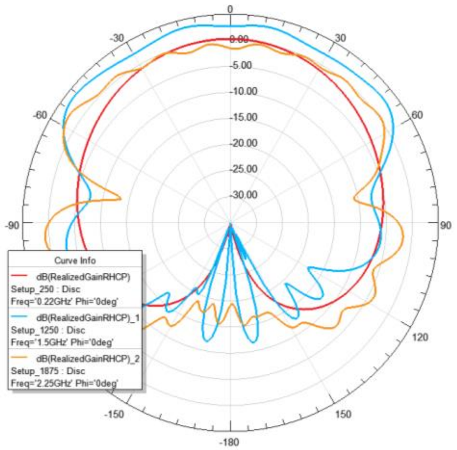
Source: Redwire

This research was developed with funding from the Defense Advanced Research Projects Agency (DARPA).

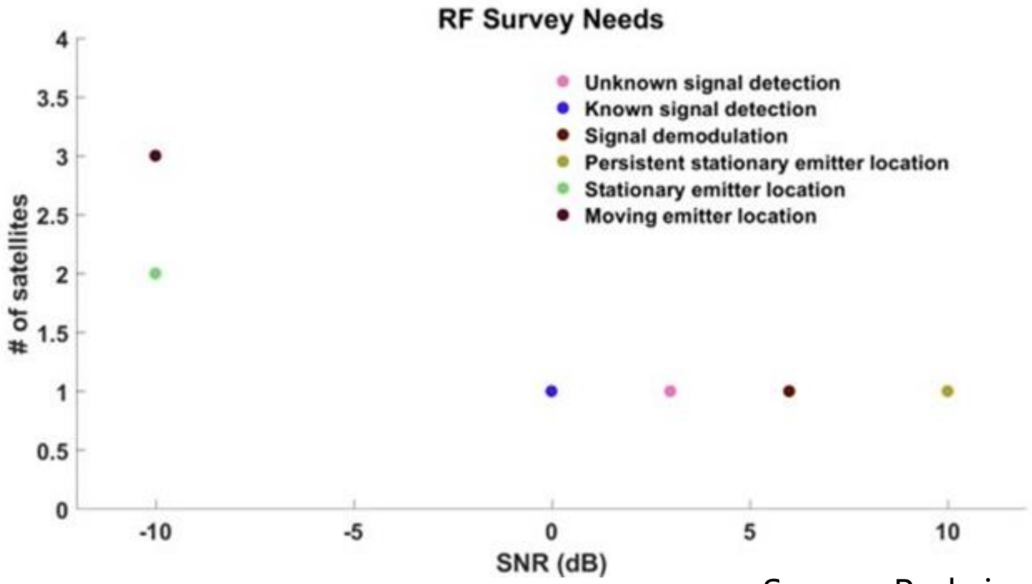
Same Aperture Can Be Used for Both PNT & RF Survey

- An ultra-wideband “Vivaldi” antenna can be used for both PNT and RF survey functions
- For RF Survey mode, system can either “look down” to detect RF sources on the lunar surface, or “look up” at orbiting objects for Space Situational Awareness (SSA)
- Signal strength that can be identified for a given separation distance has been assessed
- System could be used to cue the pointing of a high-gain, narrow beam antenna for signal localization and characterization.

Source: Redwire



Source: Redwire



Source: Redwire

This research was developed with funding from the Defense Advanced Research Projects Agency (DARPA).

PNT Performance

Predicted Position and Timing Performance for LPS

Clock Technology	Allan Deviation @65000 sec (Hz/Hz)	σ_{pos} (m)	σ_{time} (ns)
Rb-lamp	5×10^{-14}	20.9	30.2
Cesium beam	1.5×10^{-13}	21.5	31.0
DSAC	2×10^{-15}	20.9	30.1

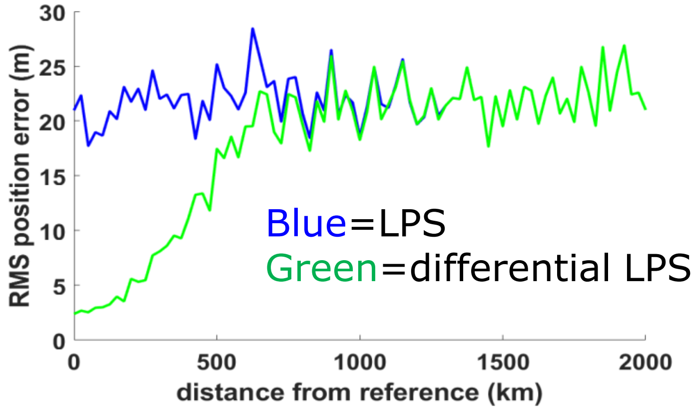
Source: Redwire

Conclusions

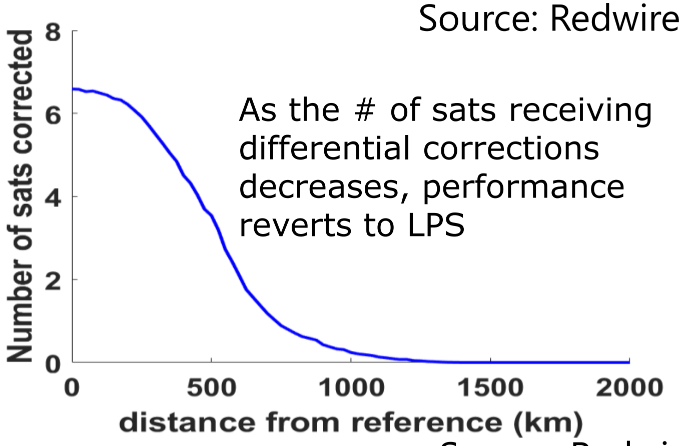
- User 3D RMS position errors are expected to be about 21 *meters*
- RMS timing error expected to be about 30 *ns*
- Both position and timing error are limited by ephemeris position error

Navigation performance can be improved by employing a differential LPS system (DLPS)

- This system uses a fixed lunar reference station to compute pseudorange corrections for each satellite
- The corrections are then uplinked to the satellites and broadcast as part of the LPS messages



Source: Redwire



Source: Redwire

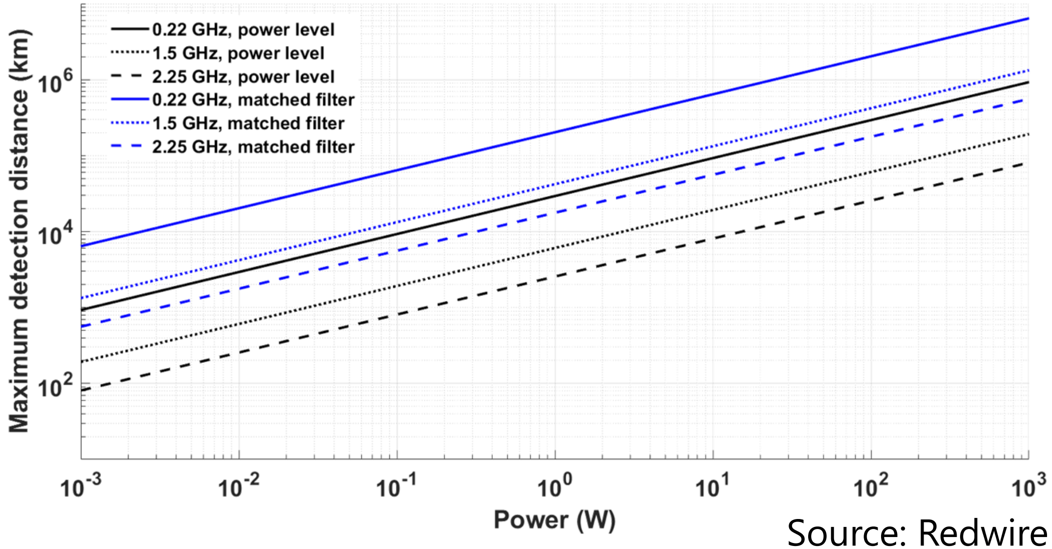
Conclusions

- User 3D RMS position errors are expected to be about 2.2 *meters* near the reference station
- This best-case error is limited by the random pseudorange error, not the ephemeris error
- Increasing the satellite power to 100W from 1W would decrease the best-case error by a factor of 10 to 0.22 *meters*.

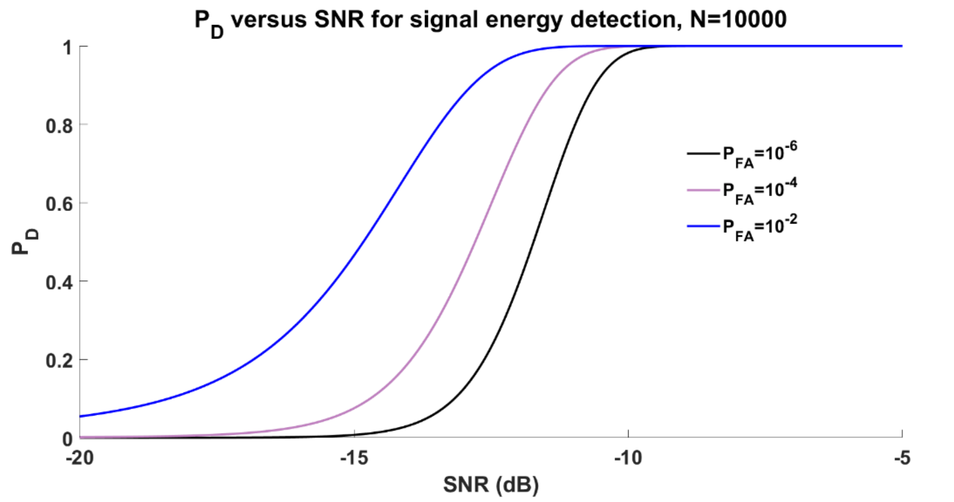
This research was developed with funding from the Defense Advanced Research Projects Agency (DARPA).

RF Survey Performance

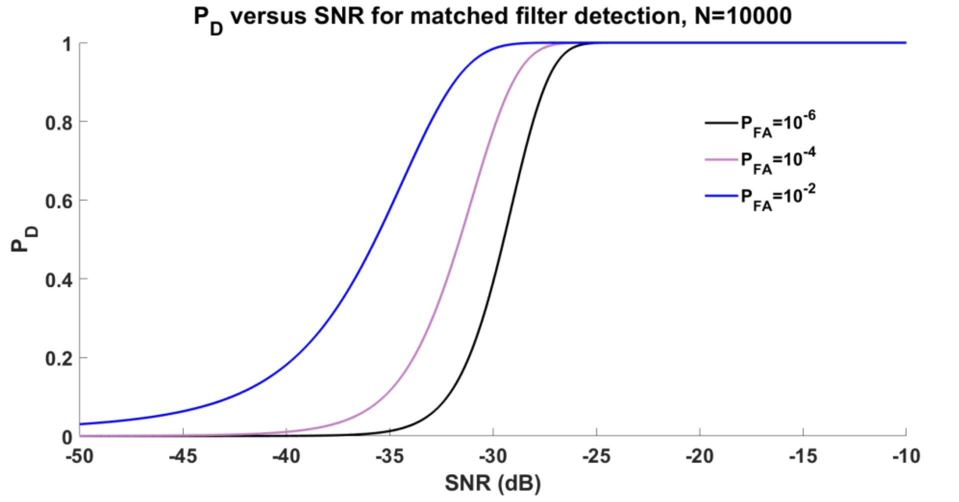
- RF signals can be detected via energy or matched filter methods.
- For three frequencies we computed the expected SNR for a $B = 10kHz$, $P = 1W$ signal versus distance (below).
- The probability of detection for different false alarm probabilities P_{FA} for each method is shown on the right for a 1.0 *sec* duration segment.



Source: Redwire



Source: Redwire



Source: Redwire

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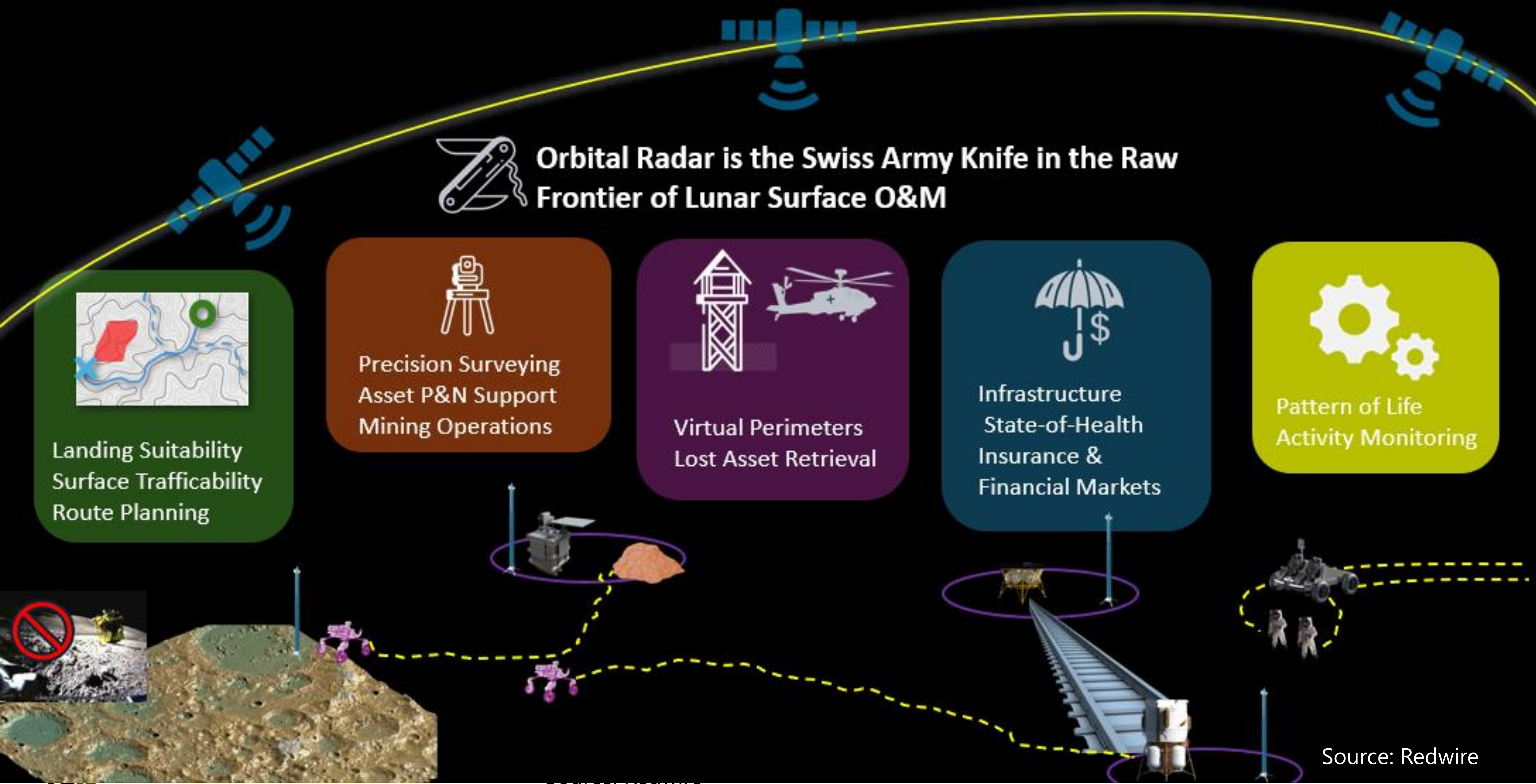


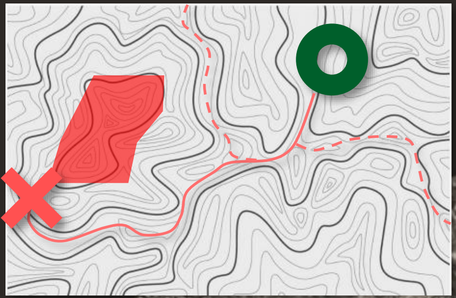
This research was developed with funding from the Defense Advanced Research Projects Agency (DARPA).

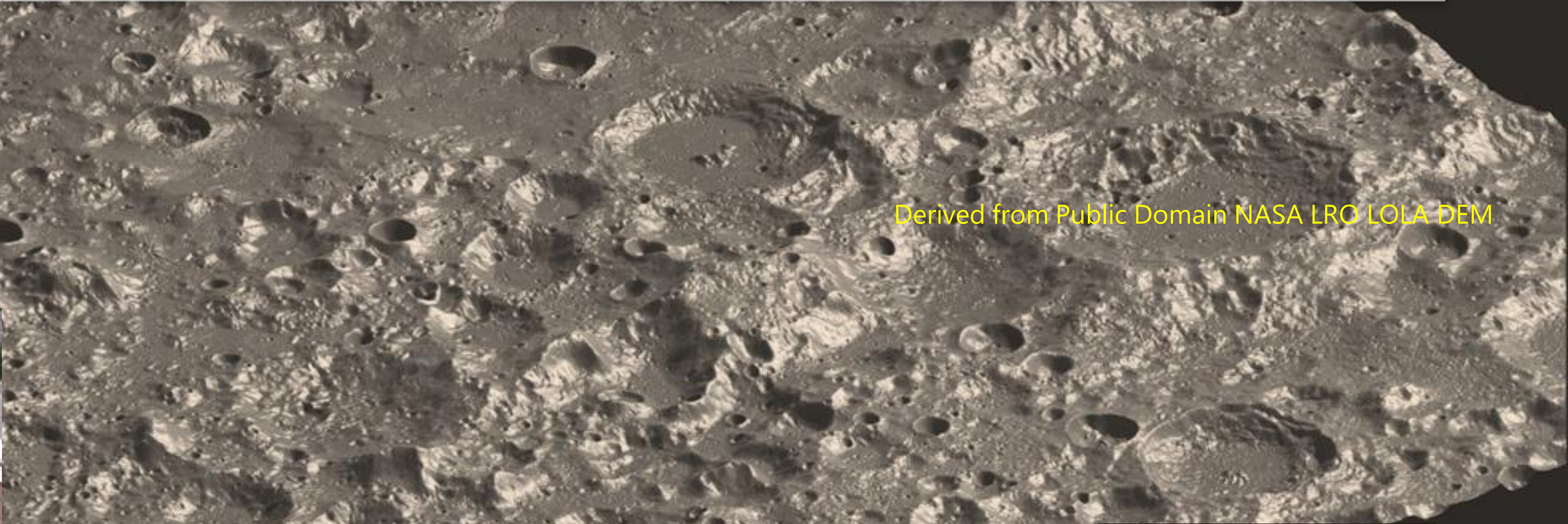
At every scale the lunar surface is very rough, fractal in nature

Precision knowledge at a broad & fine level of detail will be required to enable:

- Near-term landing and site staging (even “small” rocks are problematic!)
- Efficient routing / trafficability for surface rovers (“Google Maps for Moon”)
- Where to emplace pads, route rails, LoS Comms and roadways for longer term economy
- Prospecting and forensics

Orbital Radar imaging can provide lunar terrain detail at the scale of 0.3m or finer





Best available DEM of Lunar South Pole is only 30m post spacing

Source: Redwire

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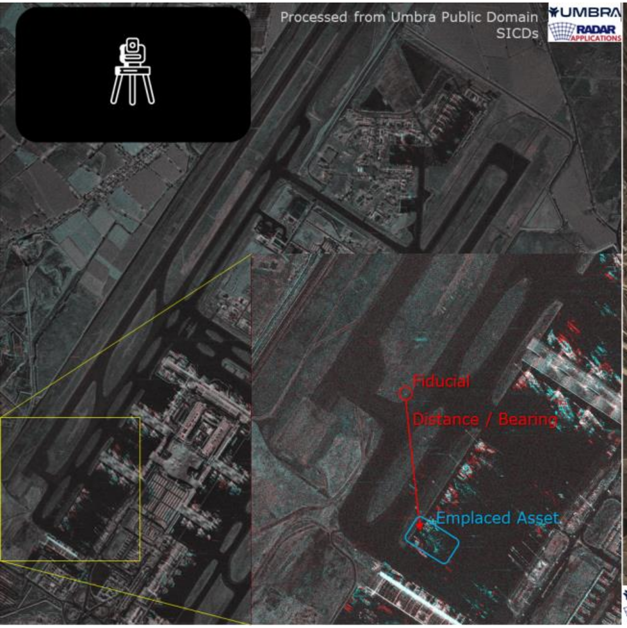
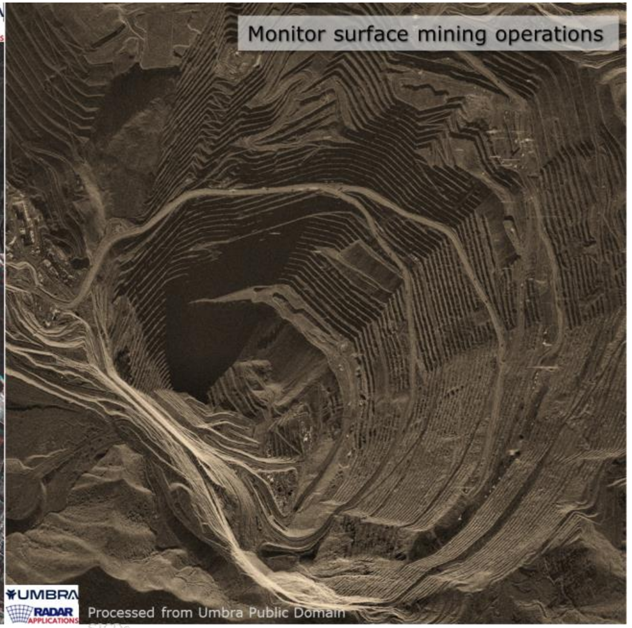
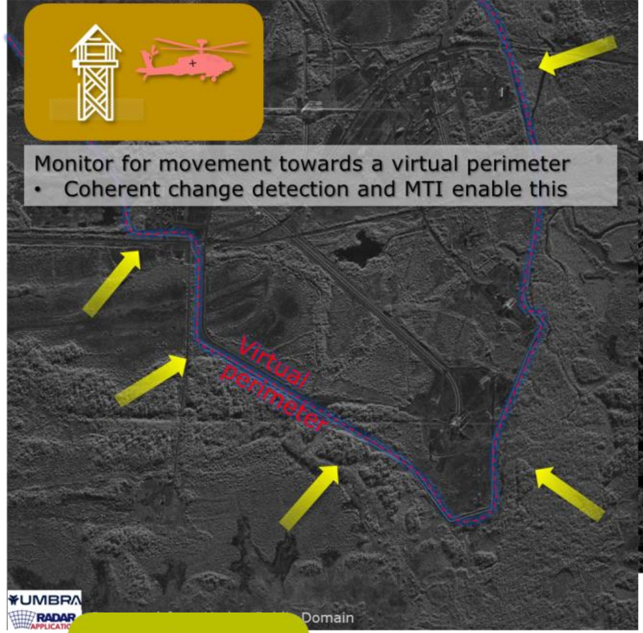
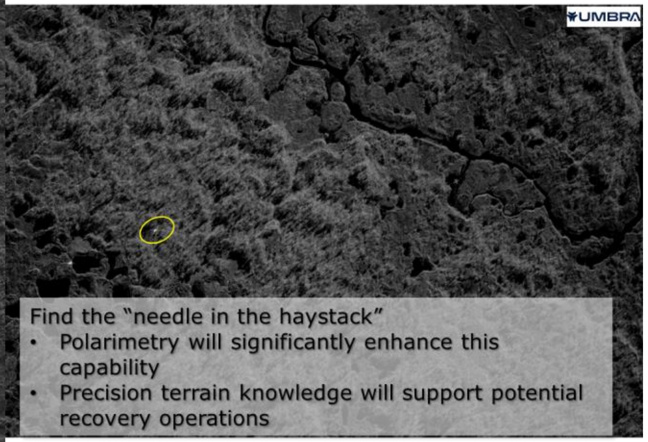
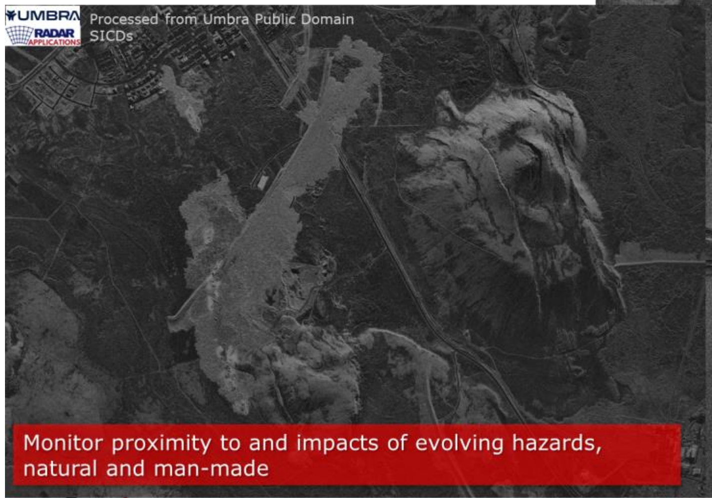


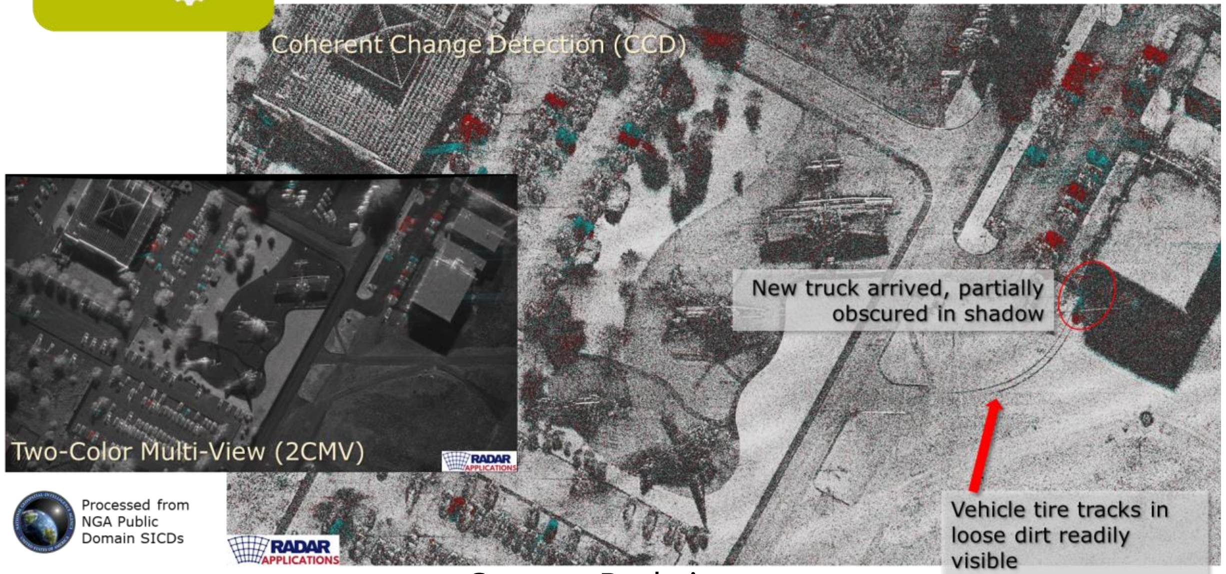








Utilize MTI "dots on map" and SAR CCD to monitor overall patterns-of-life



Source: Redwire

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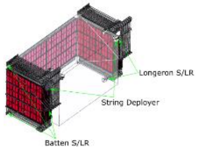
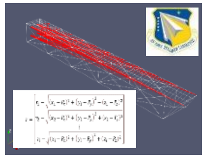
Redwire's Deployable Planar Phased Array Architectures

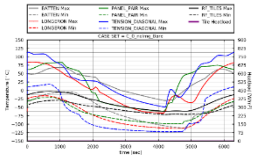
Planar array architectures supporting SAR/MTI have been ground demonstrated.



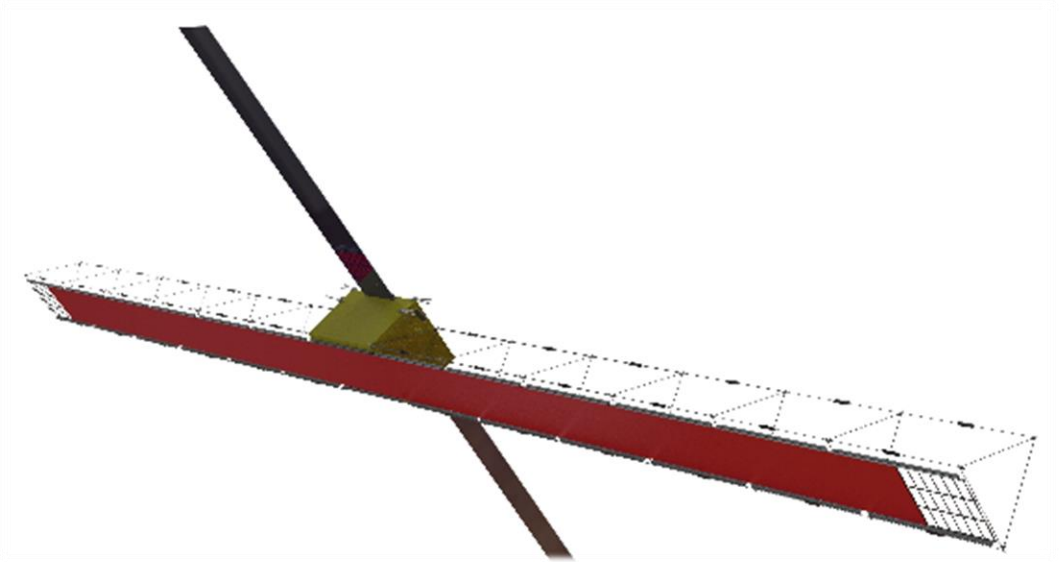
✓ ESPA Compliant for deployment on low-cost platform



✓ Instantaneous metrology enabling active phase correction



✓ On-orbit thermal and structural stability



Source: Redwire

This research was developed with funding from the Defense Advanced Research Projects Agency (DARPA).

Commercialization/Economic Outlook and Mission Timeline

- Deploying a commercially-viable cislunar service presents several economic challenges, primarily driven by the high initial investment required and the need to secure financing where market potential and ROI are uncertain/undemonstrated.
- Pricing is being developed with following assumptions: <5-yr ROI, inclusive of hardware NRE/RE, launch costs, financing and insurance fees, and yearly operational costs.

Service	Considered Independent Service or Infrastructure?	Pricing Strategy
Communications	Infrastructure	yearly subscription
PNT	Infrastructure	yearly subscription
RF Survey	Independent Service	per RF survey
SAR and MTI	Independent Service	per km^2 scanned

Source: Redwire

<table>
<tr><th>Year/Task</th><th>2025</th><th>2026</th><th>2027</th><th>2028</th><th>2029</th><th>2030</th><th>2031</th><th>2032</th><th>2033</th><th>2034</th><th>2035</th></tr>
<tr><td>Age</td><td colspan="3">Exploration Age</td><td colspan="3">Foundational Age</td><td colspan="4">Industrial Age</td><td>Jet Age</td></tr>
<tr><td rowspan="2">Redwire Mission Phasing</td><td colspan="2">TRL 4</td><td colspan="3">Pathfinder Minimum Viable Experiment (MVE)</td><td colspan="3">Minimum Viable Product (MVP) Constellation - South Pole Services</td><td colspan="3">Constellation Expansion</td></tr>
<tr><td colspan="2">Focus is on further analysis, development, detailed design, and demonstration (ground) of hardware and software. This is supported by prototyping of SAR sub arrays (tiles), the full SAR aperture, the PNT/RF Survey aperture, and data processing hardware and algorithms.</td><td colspan="3">A single Pathfinder is designed, produced, and deployed to cislunar orbit to demonstrate SAR/MTI capabilities as well as PNT/RF survey services. With one spacecraft, data will be limited, particularly for PNT. However, data produced will demonstrate full functionality and performance, and ultimately validate models for constellation-based services.</td><td colspan="3">The Pathfinder is augmented with additional assets to form a constellation capable of providing adequate spatial and temporal coverage/resolution for SAR/MTI and PNT/RF survey to South Pole locations. Subscription services will be available to government and commerical customers at South Pole locations.</td><td colspan="3">Assets are added to provide coverage to other Lunar locations (e.g., far side). Subscription services are expanded to include increased coverage.</td></tr>
</table>

Source: Redwire

THANK YOU!

Contact: Dana Turse, Space Systems Architect

Dana.turse@redwirespace.com, (303)908-7649

REDWIRE
- Study lead
- RF apertures
- Mission CONOPs

RADAR APPLICATIONS
- SAR/MTI SME

Axta Space Corporation
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CACI EVER VIGILANT
- PNT SME

Advanced SPACE
- Orbital Mechanics SME

This research was developed with funding from the Defense Advanced Research Projects Agency (DARPA).

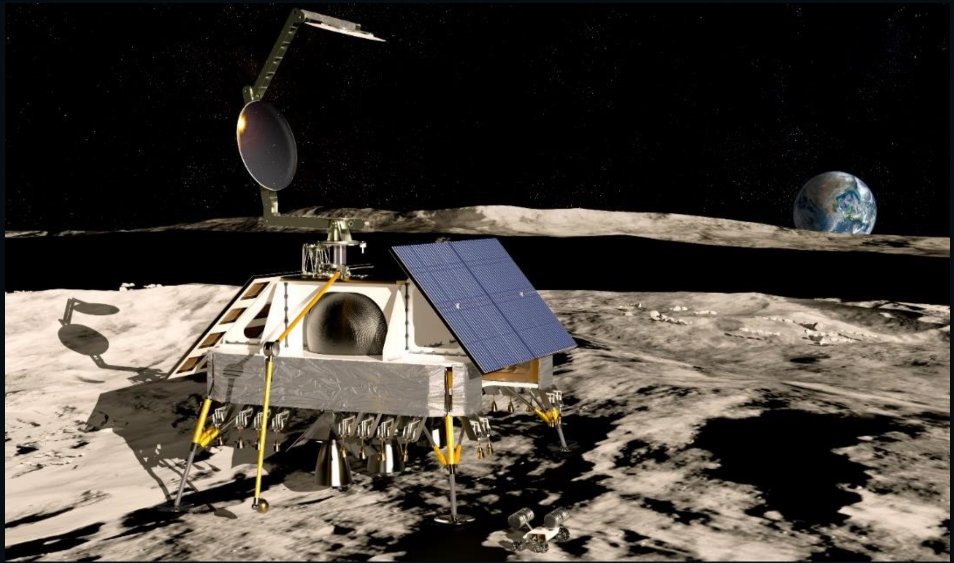
2024

Lunar Oxygen Production and Energy Storage Node

This work was conducted under the DARPA 10-Year Lunar Architecture Capability Study (LunA-10) under contract HR0011-24-3-0310

Lunar Oxygen Production and Energy Storage Node

- Three Main Functions
  - Oxygen Extraction from Regolith
    - Direct Solar Power Input
  - Fuel Cell Energy Storage
    - Lunar Night Survival
  - Chemical Conversion
    - Waste Stream Recycling
    - Energy Efficient Long-Term Propellant Storage



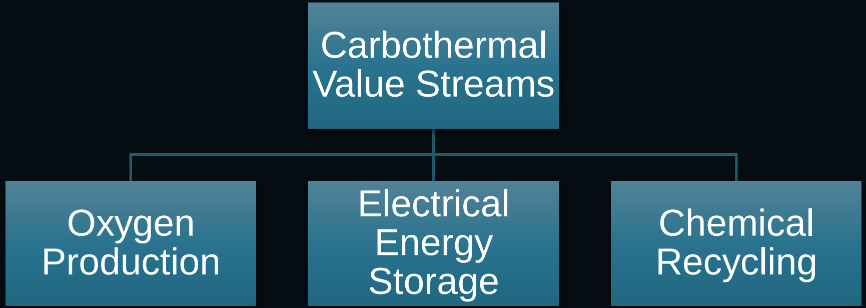
Source: Sierra Space

Artist concept of a carbothermal oxygen production plant

Carbothermal Oxygen Production Process

$MO_x(l) + xCH_4(g) \rightarrow M(l) + xCO(g) + 2xH_2(g)$	Carbothermal & Pyrolysis
$xCO(g) + 3xH_2(g) \rightarrow xH_2O(g) + xCH_4(g)$	Methanation
$xH_2O(l) \rightarrow xH_2(g) + 0.5xO_2(g)$	Water Electrolysis
$\boldsymbol{MO_x(l) \rightarrow M(l) + 0.5xO_2(g)}$	**Net Reaction**

- Carbothermal reduction uses methane and heat to extract oxygen from the metallic oxides within lunar regolith to produce CO/CO_2
- The oxygen is stored, the hydrogen is recycled back into the system



Source: Sierra Space

Lunar Oxygen Production

- Sierra Space’s carbothermal oxygen production process (TRL 6) extracts oxygen from lunar regolith.
    - Could operate anywhere on the moon
- Produces reduced metallic slag which could be refined into pure metals or used as construction material
- Uses direct solar heating to significantly reduce electricity usage
    - Could substitute electrical energy

Source: Sierra Space (*Artist concept)*

Regolith is delivered to the ISRU plant

Recycled Carbon

Regolith

Source: Sierra Space

Regolith simulant actively undergoing carbothermal reduction

Source: Sierra Space

Slag

Oxygen

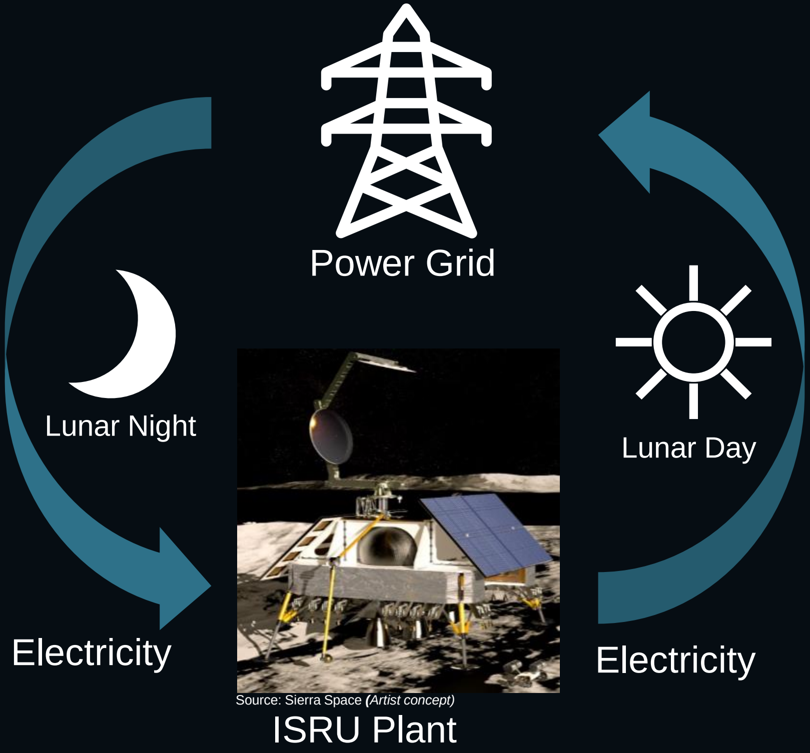
Source: Sierra Space

Fuel Cell Energy Storage

- Electrolysis is used to store energy during the lunar day and a fuel cell provides electricity during lunar night

- Uses electricity to split water into hydrogen and oxygen during the day
    - Oxygen is extracted from lunar regolith to reduce launch mass

- The fuel cell reacts the hydrogen and oxygen to produce electricity during lunar night



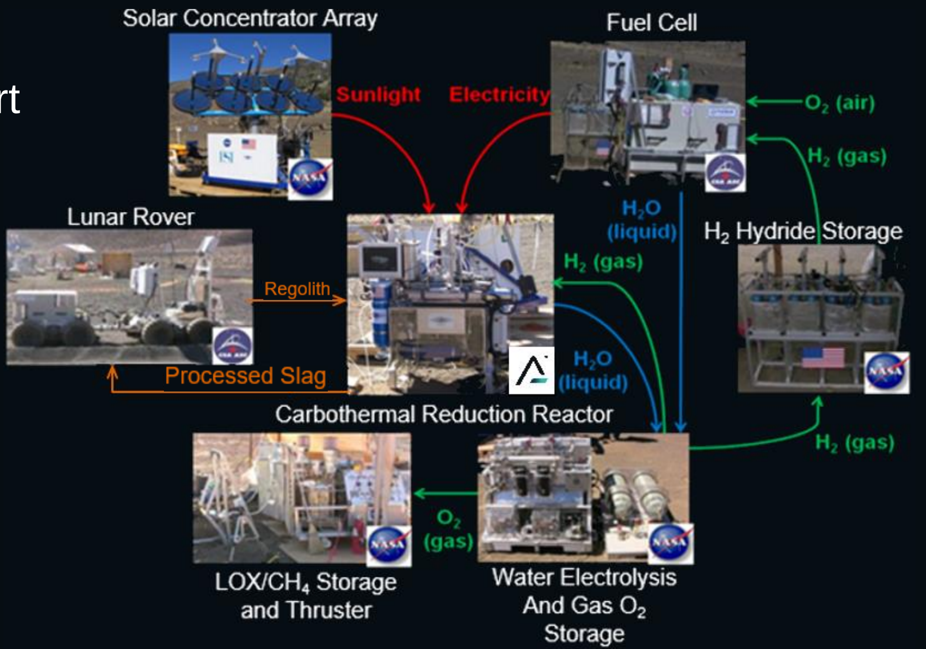
Chemical Conversion

- Could recycle and reuse chemicals
  - Convert chemicals for storage or transport
  - Reduce resupply requirements
- Examples:
  - Propellant waste (ullage, boil-off)
  - Fuel cell waste (water)
  - ECLSS waste (carbon dioxide, biological)

$$Methane \Leftrightarrow Carbon + Hydrogen$$

$$Water \Leftrightarrow Hydrogen + Oxygen$$

$$Carbon\ Dioxide \Leftrightarrow Carbon + Oxygen$$



Brass board architecture test has demonstrated functionality

Source: https://ttu-ir.tdl.org/server/api/core/bitstreams/11c6ddf9-b539-47b8-8b36-0bd618320ea9/content

Value Stream Inputs and Outputs

Oxygen Production

Inputs

- Lunar Regolith
- Electricity (day)
- Communications
- Carbon
  - Propulsion ullage
  - ECLSS Waste
- Hydrogen
  - Propulsion ullage

Outputs

- Oxygen
  - Propulsion
  - ECLSS
- Slag
  - Construction feedstock
  - Metals refinement

Energy Storge

Inputs

- Electricity (day)
- Communications

Outputs

- Electricity (Night)
  - Night survival
  - Night ops

Chemical Recycling

Inputs

- Water
  - Fuel cell rovers
- Hydrogen
  - Propulsion ullage
- Oxygen
  - Propulsion ullage
- Methane
  - Propulsion ullage
  - ECLSS waste
- Carbon Dioxide
  - ECLSS waste

Outputs

- Water
  - ECLSS
  - Fell cell rovers
  - Cold Gas propellant
  - Long term storage
- Hydrogen
  - Fuel cell rovers
  - Propellant
- Oxygen
  - Propellant
  - ECLSS
- Methane
  - Propellant
- Carbon
  - ISRU Steel
- Carbon Dioxide
  - Coolant (Scaling phase only)

SIERRA SPACE

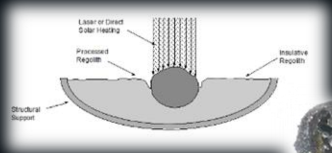
Carbothermal Development

Source: Sierra Space

Source: Sierra Space

1993

Hot-wall furnace experiments



Source: Sierra Space

Source: Sierra Space

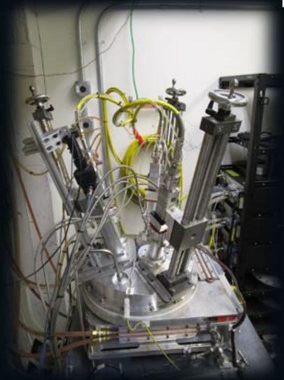
1998

Direct energy processing approach developed to allow long duration reactor operation

Source: Sierra Space

2010

End-to-end carbothermal field test with solar energy, Sabatier reactor, electrolysis & thruster



Source: Sierra Space

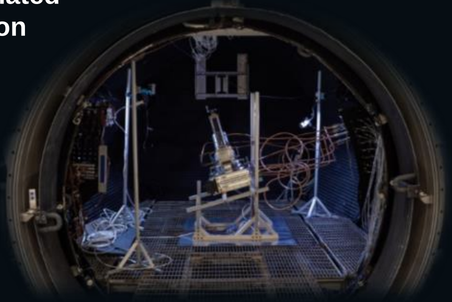
2020

Scaling Design & Testing

Source: Sierra Space

2022

Large scale fully automated reactor demonstration



Source: https://www.fox13seattle.com/news/nasa-extracts-oxygen-from-lunar-soil-simulant-for-the-first-time

2023

Thermal vacuum test to TRL 6

Source: Sierra Space

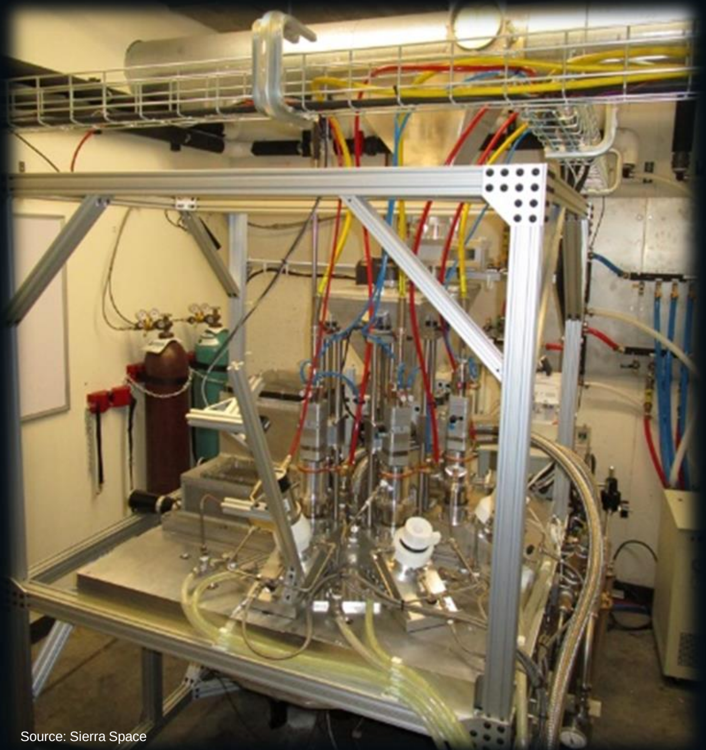
2021-2024

Flight forward, automated reactor demonstrator development

Carbothermal Reactor Strategy


Source: Sierra Space

Optimize performance (Complete)


Source: Sierra Space

Show how process scales (Complete)


Source: Sierra Space

Flight forward demonstrator (Current effort)

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Demand to and from ISRU plant

X denotes the demand exists but has not been quantified or is proprietary

* Denotes rough number of the correct order of magnitude

All values are estimated and noncommittal

Demand to ISRU Plant

	Electricity, Day, (Surge, watts)	Electricity, Night Survival (W)	Electricity (Night Operations, Kw)	Oxygen (MT/launch)	Hydrogen (kg/year)	Slag (kg/Day)	Carbon (kg/year)	Heat (watts)	Water (kg/year)	Liquification Services (kg/year)	Water	CO2
Blue Origin	X	1000	10*	X	X					X	X	
Cislunar Industries		150*	10*			50*	X					
Crescent Space Services		30	.13*									
Fibertek		200	5*									
Firefly Aerospace		10	.04*	0.6					X		X	
GITAI		10*										
Helios Project Ltd												
Honeybee Robotics												
ICON Technology, Inc.		10*	5*			720						
Nokia		100										
Northrop Grumman		X	X									
Redwire Space												
SpaceX				200								X

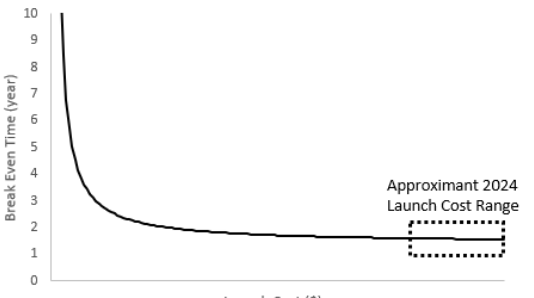
Source: Sierra Space & companies indicated

Demand From ISRU Plant

	Communication to Earth (Mbps)	Communication to Moon (Kbps)	Electricity, Day (watts)	Electricity, Night (Watts)	Methane (MT/Landing)	Hydrogen (Mt/Launch)	Lunar Regolith (kg/day)	Water (kg/year)	Oxygen (Only in specific scenarios)	Empty Tankage Rental	Transport to Lunar Surface
Blue Origin	2-5	30	X			X			X	X	X
Cislunar Industries											
Crescent Space Services	2-5	30									
Fibertek	2-5	30									
Firefly Aerospace											
GITAI USA							50*				
Helios Project Ltd									X		
Honeybee Robotics			X								
ICON Technology, Inc.											
Nokia	2-5	30									
Northrop Grumman											
Redwire Space			X								
SpaceX	2-5	30			10					X	X

Source: Sierra Space & companies indicated

Commercialization



Source: Sierra Space

	Estimated Price	Rationale
Sell Oxygen	~500-750 $k/kg	Based off a ~25% discount of landing cost
Sell Slag	~15-50 $K/kg	Estimate based on how much it costs to purchase regolith, robotic costs to remove, and added value of reduced metals
Sell Nighttime Electrical	~20-30X Day time cost	Covers fuel cell use, electrolysis, re-liquification of oxygen and storage of hydrogen
Rent Oxygen/Hydrogen Rental	~300 $k/kg	Based off a ~25% discount of landing cost. Quantities limited based on methane/hydrogen supply
Sell Water	~500-750 $k/kg	Rent hydrogen/oxygen for fuel cell use and accept it back in the form of water. Fee if not returned. Assumes 1% of rental is lost.
Buy Daytime Electrical	Market Rate	Electricity needs to be sold cheaper than it costs to develop and ship panels from earth
Buy communications	Market Rate	Priced by supply and demand of communication suppliers

Source: Sierra Space

- ISRU Commodities expected to track with launch and landing cost
  - Materials sold at a discount to launch and landing costs
  - Currently at ~$1M/kg

SpaceX 10-Year Lunar Architecture Capability Study (LunA-10)

Lunar Surface Innovation Consortium (LSIC) Spring Meeting

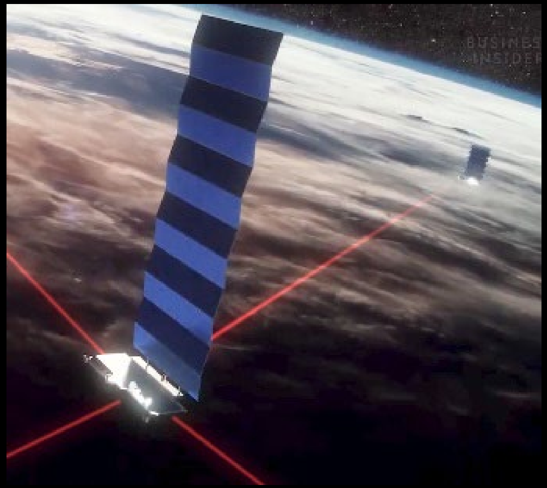
23-25 Apr 2024

This research was developed with funding from the Defense Advanced Research Projects Agency (DARPA).

SpaceX designs, manufactures and launches the world's most advanced rockets and spacecraft.

STARSHIP

HUMAN LANDING SYSTEM



STARLINK AND STARSHIELD

Unique SpaceX competencies & technology to be leveraged to enable LunA-10 and other commercial partners

- Transportation - Starship will enable affordable and reliable access to the Moon for very large amounts of cargo and crew
- Surface Platform – Post landing, Starships are large surface platforms that can provide services and host third-party equipment
- Communications and Operations – SpaceX brings its experience operating a fleet of 6,000+ laser-linked Starlink satellites to lunar operations

STARSHIP SYSTEM

The Starship system is designed to revolutionize human activity in space, providing Earth orbit and interplanetary crew and cargo transportation. The cornerstones of the Starship system are full reusability and in-space propellant transfer.

Starship is the world's most powerful launch vehicle ever developed and is designed to carry more than 100 metric tons to the lunar surface

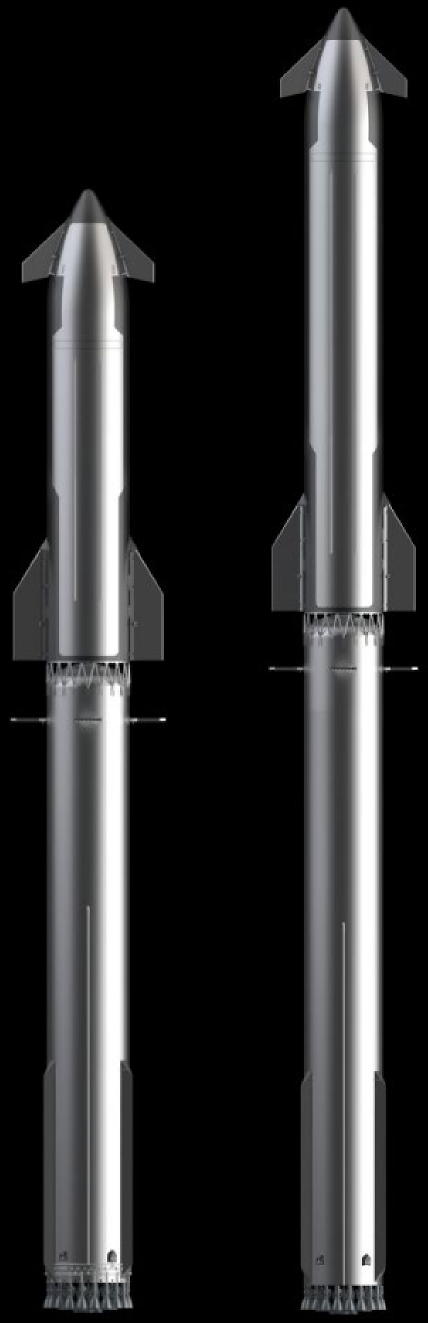
	Starship 2	Starship 3
TOTAL HEIGHT	**124.4 m** / 408 ft	**150 m** / 492 ft
DIAMETER	**9 m** / 30 ft	**9 m** / 30 ft
THRUST	**8240 tf** / 18 Mlbf	**9220 tf** / 20 Mlbf

SHIP "STARSHIP"

IN-SPACE TRANSPORTATION
VERTICAL LANDING
FULLY REUSABLE

BOOSTER "SUPER HEAVY"

REQUIRED FOR ORBITAL MISSIONS
VERTICAL TAKEOFF
VERTICAL LANDING
FULLY REUSABLE



For more information, download the Starship Users Guide here

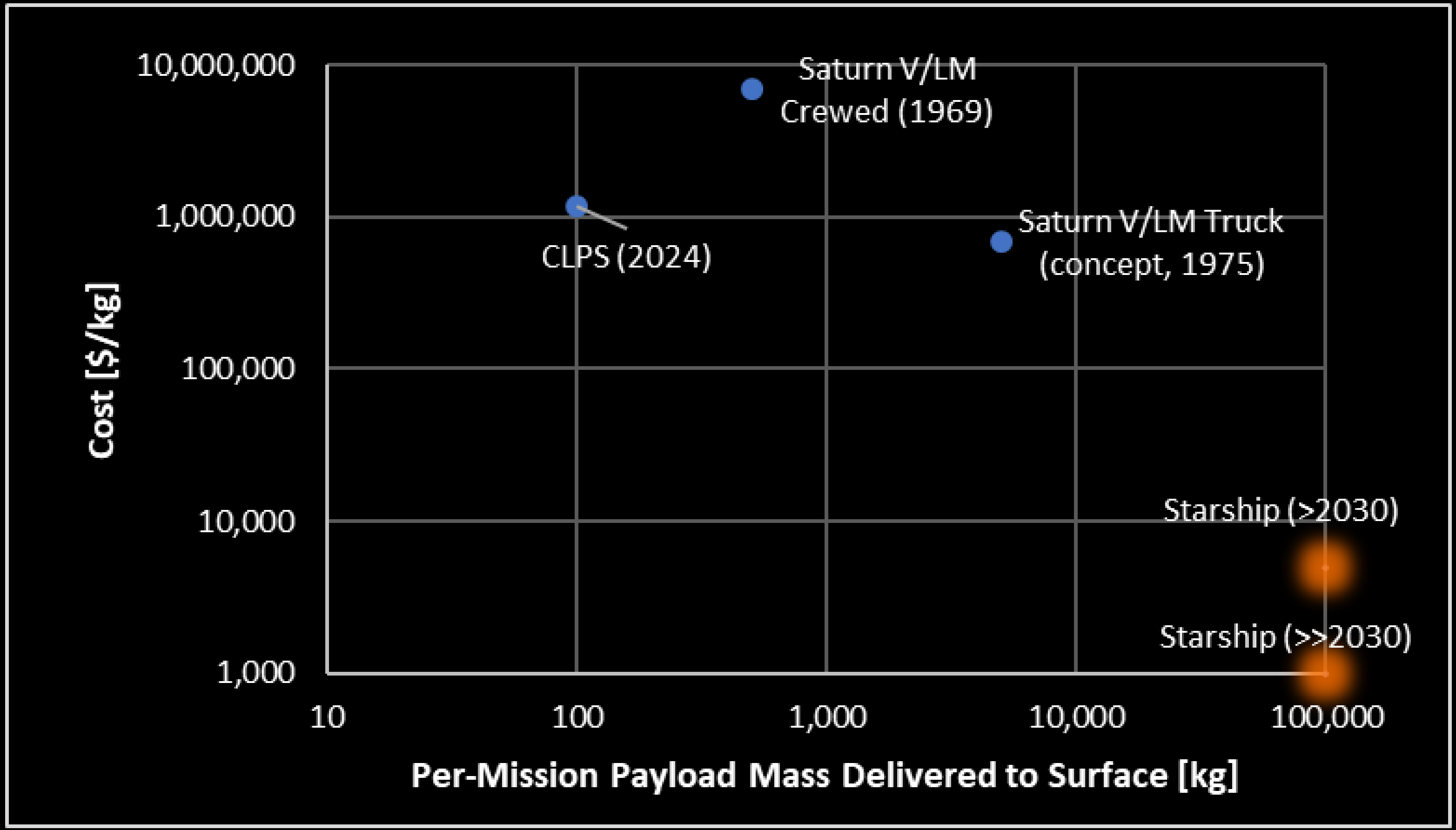
SPACEX LUNAR FRAMEWORK

Transit & Mobility

Communications

Third-Party Hosting & Services

TRANSIT & MOBILITY (EARTH-MOON): ECONOMIC OUTLOOK



- Affordable mass transfer between Earth & Moon is foundational to enabling sustainable lunar access.
- Starship will recoup R&D investments via a variety of use cases including terrestrial satellite launches.

3 STARSHIP LANDINGS BEGIN A ROBUST LUNAR BASE

1. **Utility Starship**
   Hub for power, communication, data, commodities storage

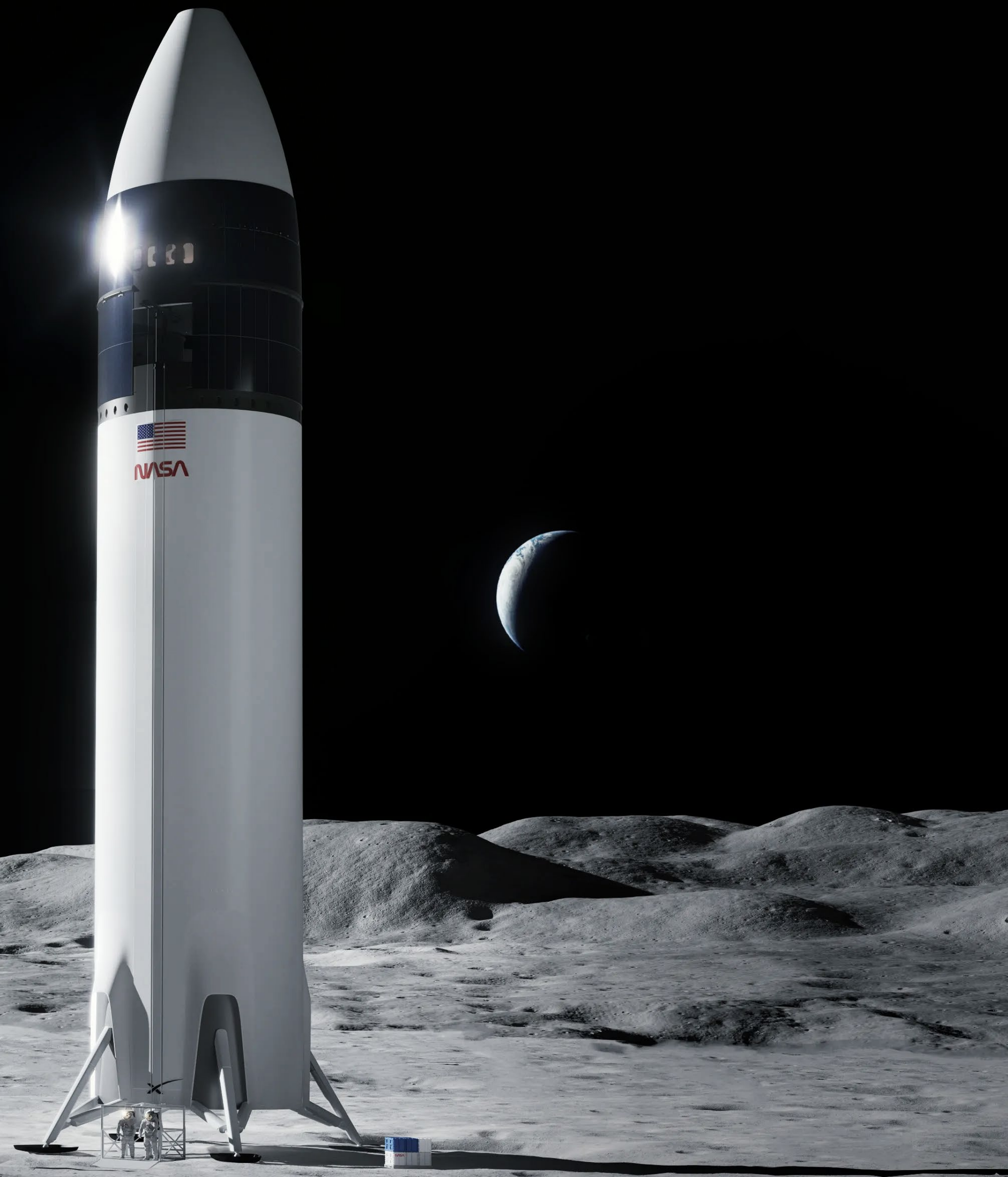
2. **Rolling Stock Starship**
   Rovers, construction equipment, ISRU plants, and other site-specific payloads

3. **Habitation Starship**
   Serves as crew hab for the site

Artist Concept ~ Moon Base | SpaceX

UTILITY STARSHIP

- Starship lands, deploys cargo & services
- Provides backhaul between Moon and Earth
- Local connectivity through hosted payloads
    - Starship provides ~55m height
- Provides on the order of tens of kW to hosted payloads & surface users
    - Can provide 100+ kW if configured



Artist Concept ~ Lunar Landing | SpaceX

POST-LANDING UTILITY OF LUNAR CARGO DELIVERY STARSHIPS

STARSHIP CAN DELIVER 100+ TONS OF LUNAR CARGO AND REMAIN AS A SURFACE ASSET ITSELF

- Propellant and Fluid Storage
  - Empty prop tanks provide fluid storage space
  - Oxygen tanks hold ~1,000 tons LOX
  - Could use tanks to store other liquids or gases
  - Ullage methane/boil-off available for lunar surface users

Unneeded components (such as engines) on landed Starship can be harvested and processed into raw feedstock material

Artist Concept ~ Moon Base | SpaceX

Starship enables affordable, reliable cislunar transportation by significantly reducing delivery cost per kg and significantly increasing payload delivery capability.

Landed Starship surface, platforms provide:

- Power
- Habitation
- Communications connectivity
- Fluid and commodity storage
- Components and materials

SpaceX's extensive experience with optical and RF comms in space can be leveraged to connect Earth and Lunar networks

Questions?