Science & Technology Office

Space-Based Solar Power
Enabling Lunar Exploration and Beyond

Christopher G. McKinney
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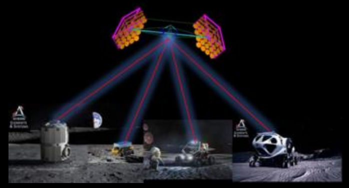


Power – The Key Commodity Needed to Explore the Lunar Surface

Illumination

The primary and scarce resource to produce power

- Equatorial Illumination Limits
  - Cyclical periods of 14 days illuminated; 14 days dark

- Polar Illumination Limits
  - Intermittent with up to 100s hours darkness
  - Highly dependent on location and elevation

The 14-day lunar night temperatures drop to ~-208°F (140K)

Most electronic systems will not survive

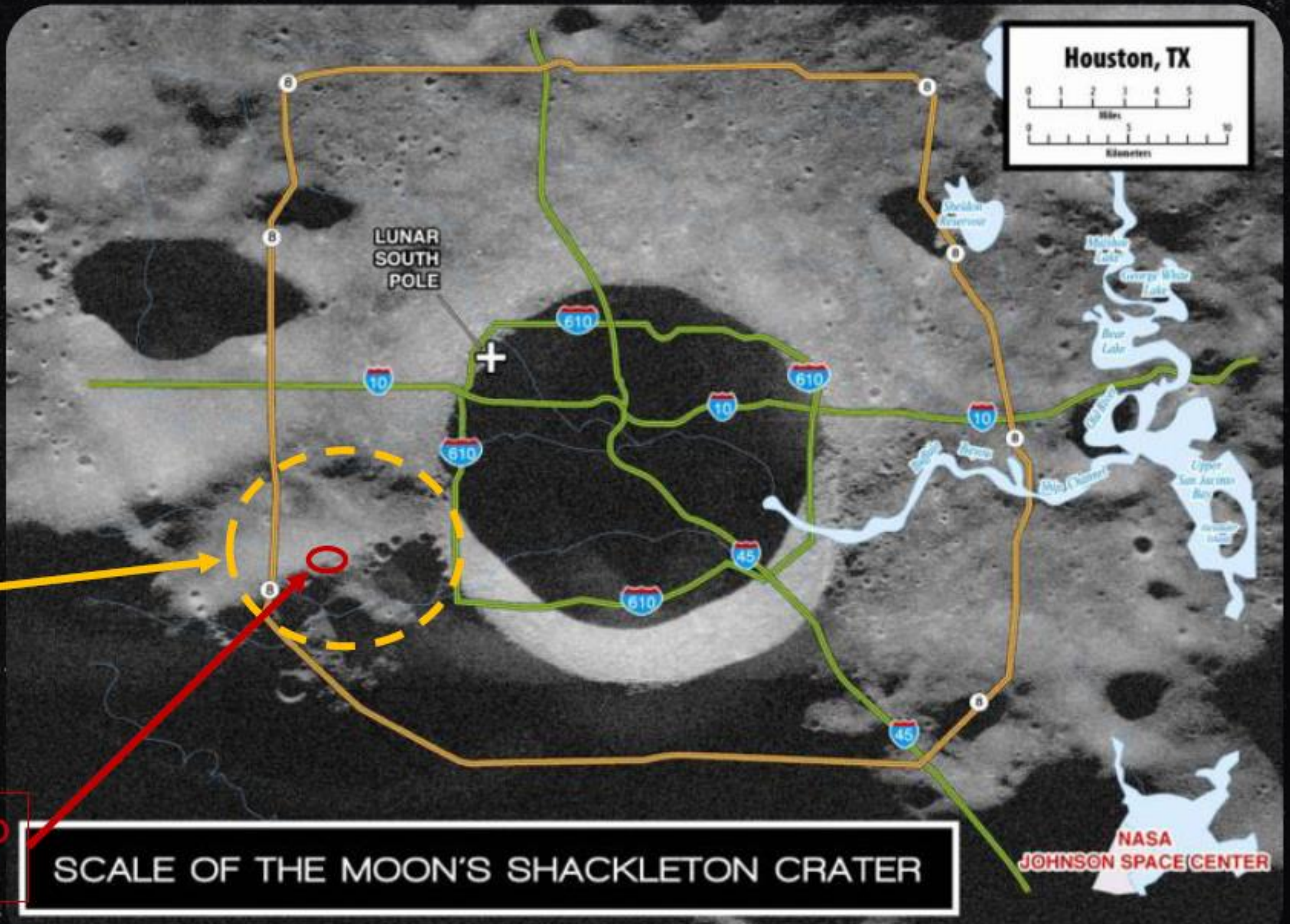
Life limiting factor for both robotic and human missions

Shackleton Crater – Likely Artemis Base Camp Location Has Near-Continuous Sunlight

- Located near Lunar South Pole
- ~20 km in diameter
- ~4 km deep
- Rim and Connecting Ridge are primary targets for future lunar landings
- α and Ω infrastructure phases expand outward from Artemis Base Camp

Phase α Infrastructure
(~10 km)

Artemis Base Camp
(~200 m)



But What About the Rest of the Moon?
Recent Landers Not Assured of Surviving the Lunar Night

ISRO tries to wake up Chandrayaan-3 after lunar night, no response yet

ISRO will continue to try to contact Chandrayaan-3 until it receives a signal or until it runs out of time.

Rizwan Choudhury
Published: Sep 23, 2023 10:18 AM EST

SCIENCE

Chandrayan-3 and Pragyan rover.

Source: ISRO

LIVESCIENCE

SLIM lives! Japan's upside-down moon lander survives freezing lunar night, defying all expectations

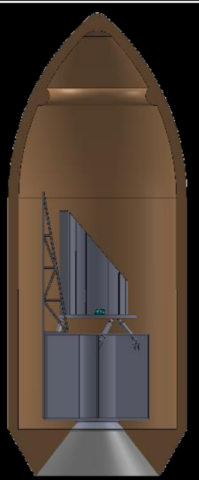
Brandon Specktor
Mon, February 26, 2024 at 2:55 PM CST · 2 min read

The Smart Lander for Investigating Moon (SLIM), taken by LEV-2 on the moon, released on January 25, 2024.

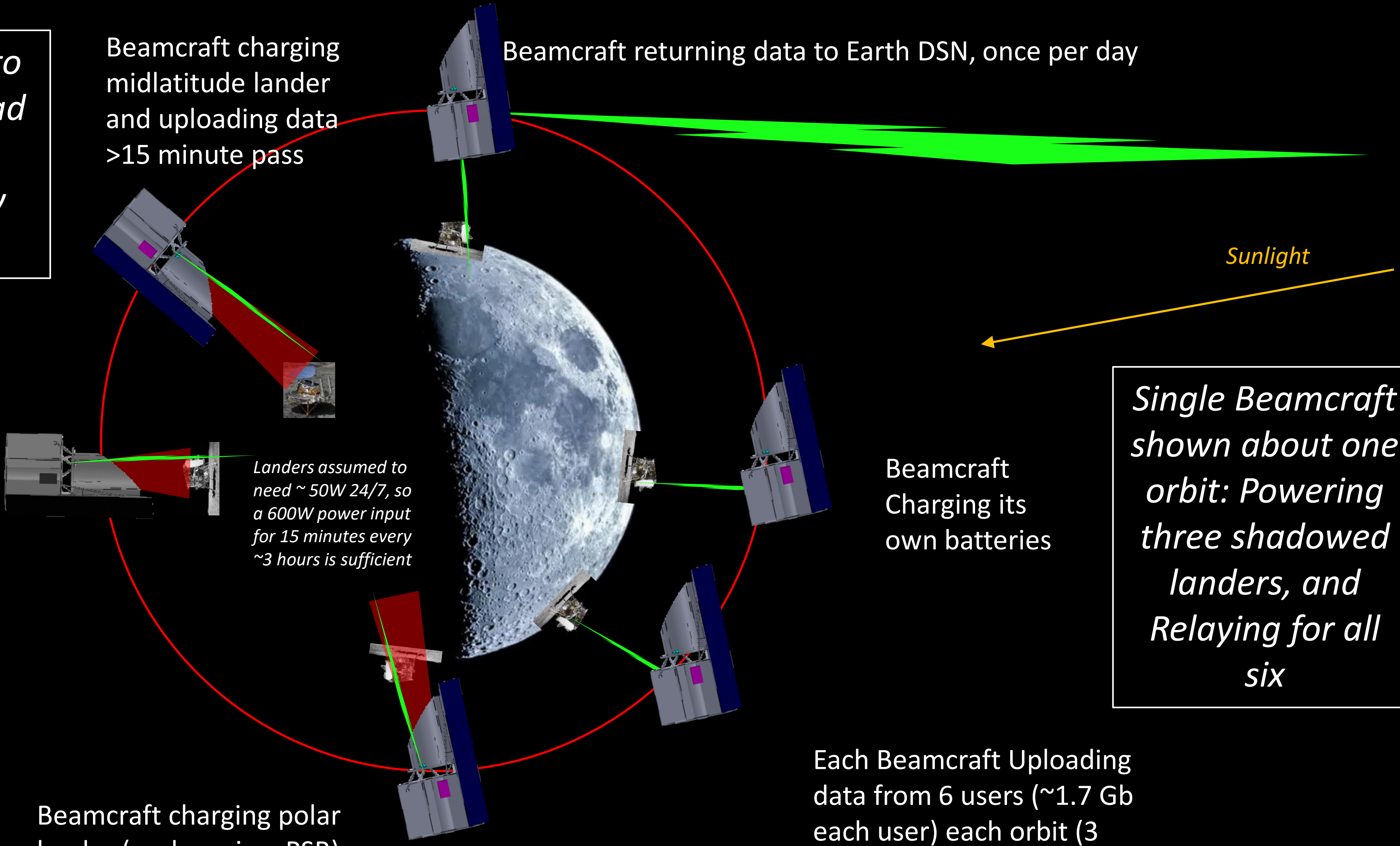
Conops

Three Beamcraft Power 18 science assets, equally spaced around the lunar surface

Each Beamcraft can provide power to 3 shadowed landers as well as upload data, provide housekeeping link, update PNT for 6 landers- especially important for farside users



Each Beamcraft launched on reusable Falcon H equivalent, ~ 40% additional payload for other lunar payloads available



Beamcraft charging midlatitude lander and uploading data >15 minute pass

Beamcraft returning data to Earth DSN, once per day

3 kW Laser beam provides ~ 600W to user for 15 minutes

Beamcraft in shadow charging equatorial lander and Uploading data >15min pass

Landers assumed to need ~ 50W 24/7, so a 600W power input for 15 minutes every ~3 hours is sufficient

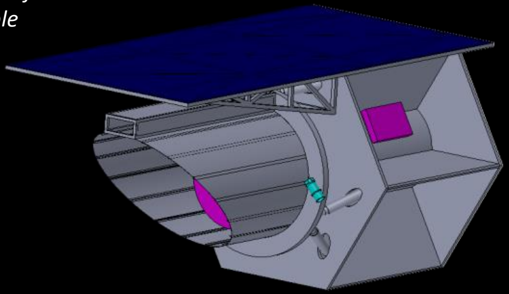
Beamcraft Charging its own batteries

Single Beamcraft shown about one orbit: Powering three shadowed landers, and Relaying for all six

Beamcraft charging polar lander (perhaps in a PSR) and Uploading data >15min pass

Each Beamcraft Uploading data from 6 users (~1.7 Gb each user) each orbit (3 assumed on farside)

Lander acquisition (<5mins) using search pattern using an enlarged laser beam (200m), lander laser sensors and X-Band link, option for lander beacon



Beamcraft slews to each user using reaction wheels

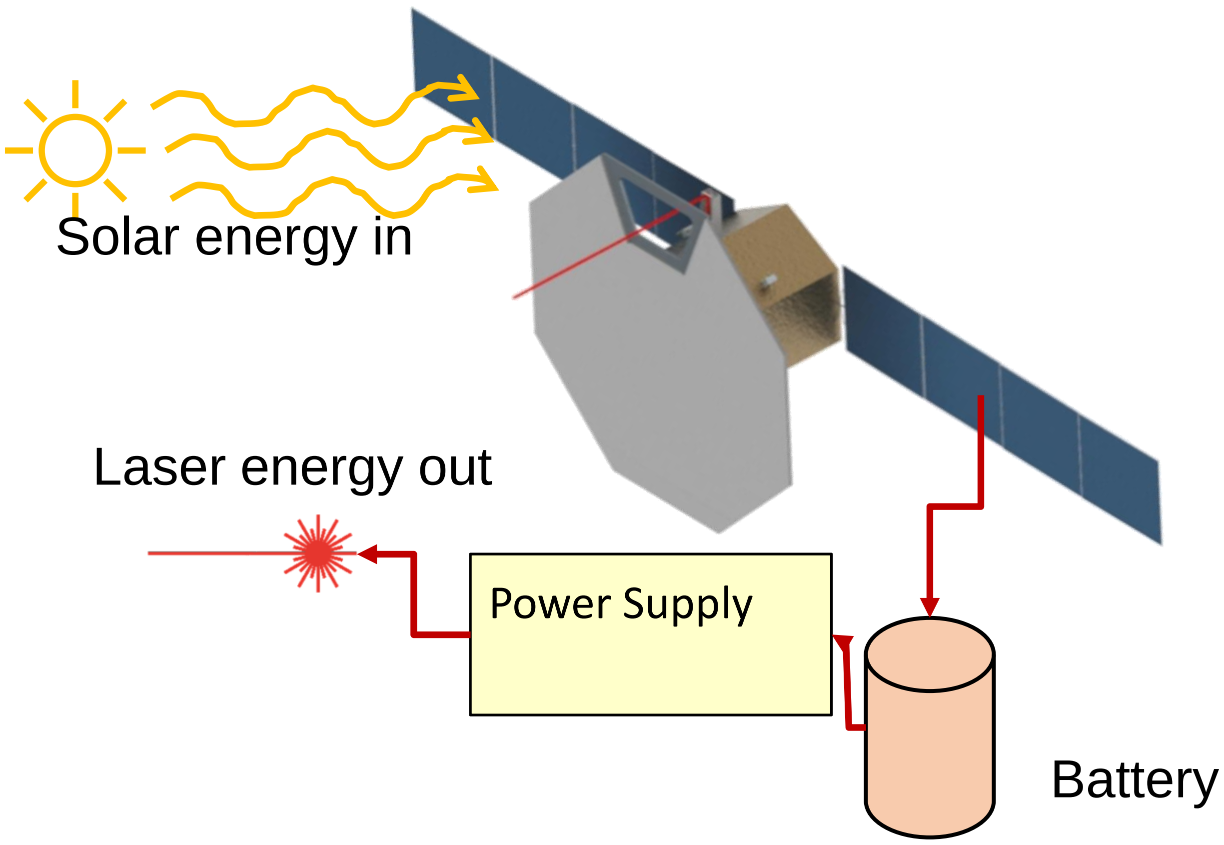
Courtesy of GRC

Higher Resolution – The Beamcraft

Several Key Components

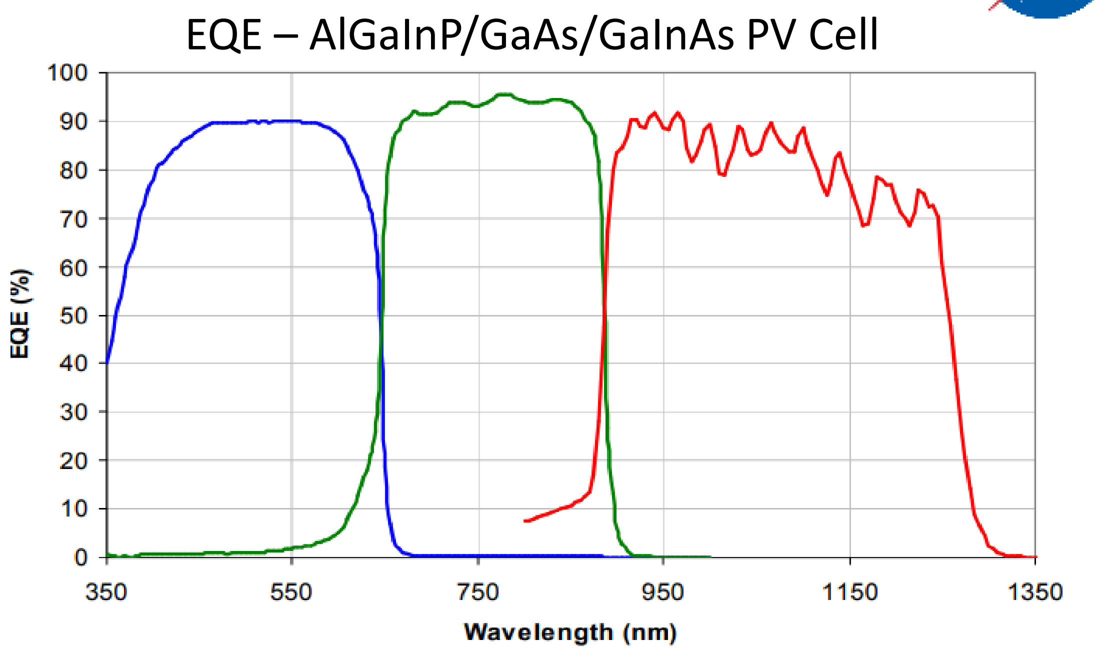
- Solar PV – high-TRL COTS
- Propulsion system for orbit maintenance – high-TRL COTS chemical, maybe SEP in future
- Battery System – high-TRL COTS
- Power Supply – high-TRL COTS
- Laser System – mid-TRL COTS
- Cooling System – high-TRL COTS
- Communications System – high-TRL COTS
- Satellite bus – high-TRL COTS

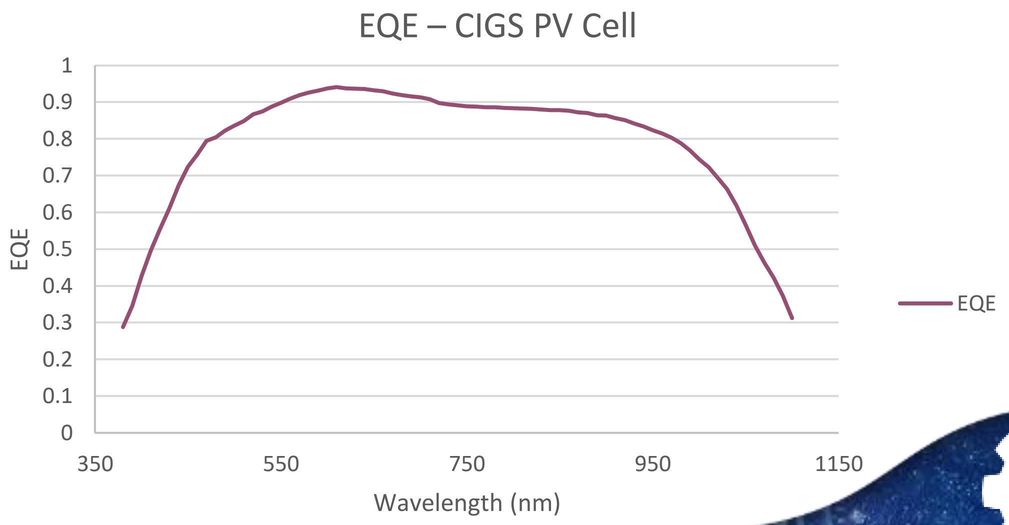
- Sizing for each above component driven by laser and number of surface assets to be powered
    - Craft must be capable of recharging AND dumping excess heat between power cycles



Receiving Monochromatic Infrared Power

- High-TRL COTS Si-based multi-junction PV receivers are not tuned to receive monochromatic infrared energy
- Multi-junction PV receivers are limited by the layer generating the least amount of energy – all layers must be activated to generate considerable energy
  - The sun outputs energy in a broad wavelength range
- However, since CIGS cells incorporate only a single activation layer, they are responsive to monochromatic illumination AND broad-spectrum solar illumination
- Additionally, CIGS cells are fairly robust; capable of surviving very low and reasonably high temperatures
- Substrate flexibility allows movement, stowage, and deployment
- Some risk of tearing or delamination





IEEE Xplore Full-Text PDF:

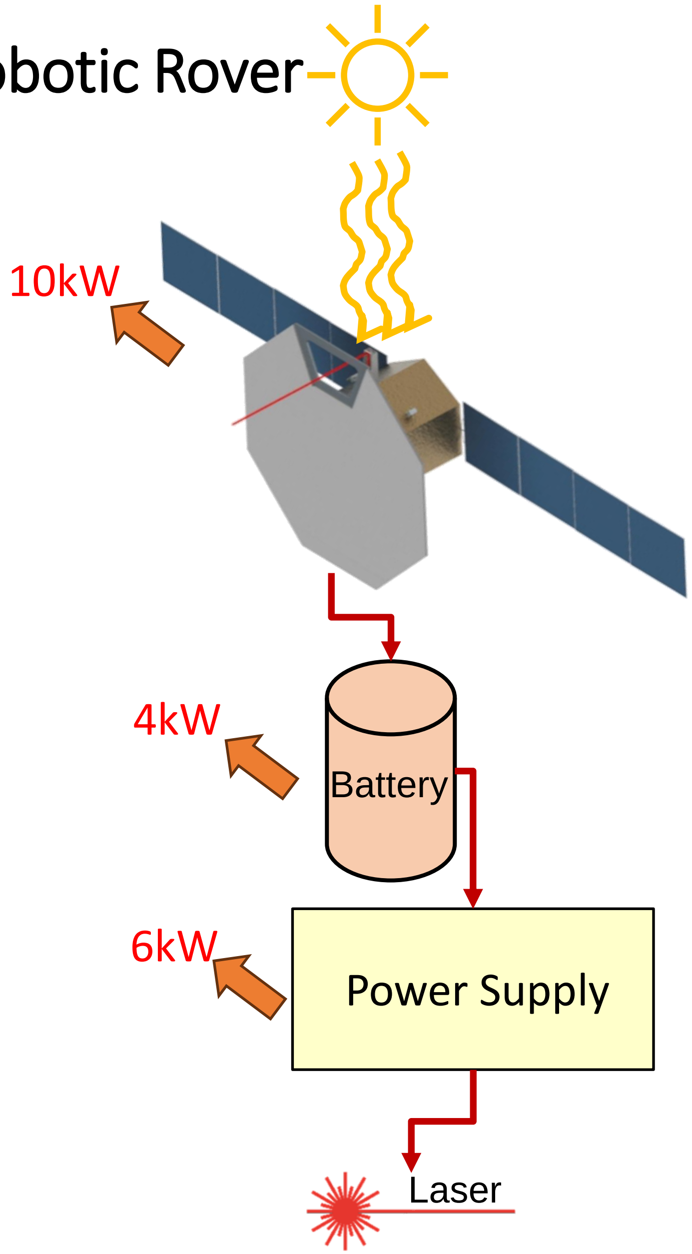
Lunar Surface Asset Power Requirements Estimates

	Small Robotic Rover		Large Robotic Rover		Lunar Base	Crewed Rover	
	Survival	Operating	Survival	Operating	Operating	Survival	Operating
Power Required	5 W	30 W	100 W	450 W	30,000 W	2,000 W	6,000 W
Total Daily Energy Required	120 Whr	720 Whr	2,400 Whr	10,800 Whr	720,000 Whr	48,000 Whr	144,000 Whr
Continuous Power Delivery Required*	40W	240W	800W	3,600W	240,000W	16,000W	48,000W

* Based on 3 hours of power delivery time per 24-hour period

Heat vs Power – Delivering Power to a Large Robotic Rover

- 500W continuous power requirement (for easy math)
- 12kWhr daily power
- 4kW continuous average received power during beam time
  - 15 minutes of beam time per 2-hour orbital period; 3 hours total beam time per earth day
- 8kW continuous average power *on target* from laser
  - Benchmark 50% laser receiver efficiency
    - 3kW heat rejection (receiving asset)
  - Note: potential additional losses due to jitter, surface obscurations, etc.
- 16kW continuous laser power required from battery
  - Benchmark 50% laser efficiency
    - 6kW heat rejection (beamcraft)
- Battery must be capable of providing ~20kW continuous during beam time, and storing *at minimum* 4kWhr to service a single surface asset
  - Benchmark ~80% battery efficiency
    - 4kW heat rejection (beamcraft)
- PV must be able to receive ~10kW continuous; 1 hour per orbit
  - Benchmark 50% solar receiver efficiency
    - 10kW heat rejection (beamcraft)



10kW continuous received
1 hour per orbit

5kWhr stored

20kW continuous discharge

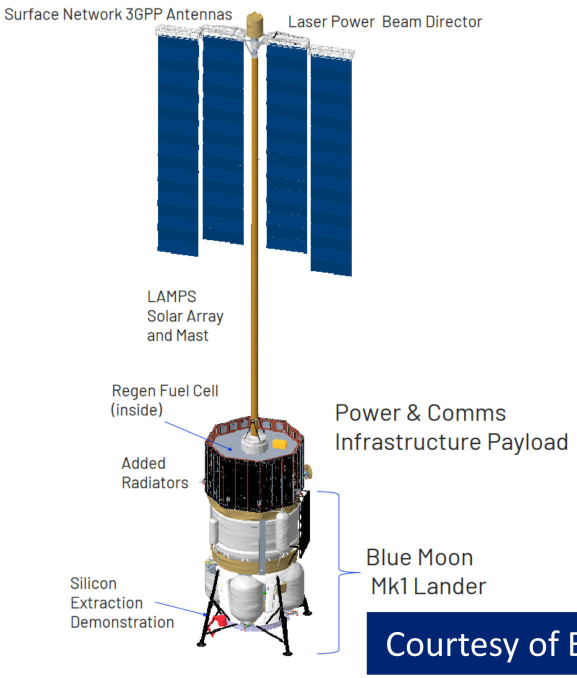
16kW continuous during beam time

8kW continuous laser out

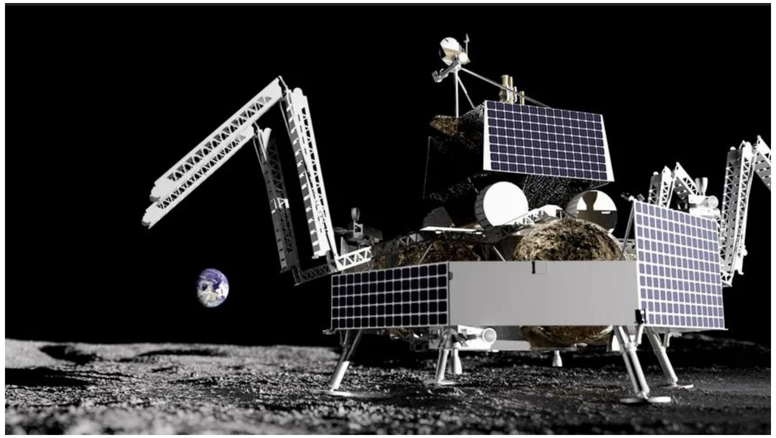
Current Lunar Power Trades

- Most lunar power studies are focused on nuclear power in the form of RTGs or solar power in the form of VSATs (Vertical Solar Array Technology)
  - RTG technology is robust and mobile, but expensive
  - VSAT orientation is not ideal for steady-state power beaming, not easily mobile

- Surface assets designed for beamed power reception could be equipped with a dual-use articulating PV panel capable of tracking the beamcraft to optimize power reception
  - Angular losses can be quantified, may not be worth the extra cost/complexity
- What about size?
  - 8kW continuous at 0.1 W/cm^2 requires 1.6m^2 receiver area
    - Benchmark 50% receiver efficiency
    - Beam focusing and shaping may be required
  - CIGS cells experience rapid degradation around 70C
    - Larger receivers may be easier to cool but more difficult to stow and deploy



Courtesy of Blue Origin



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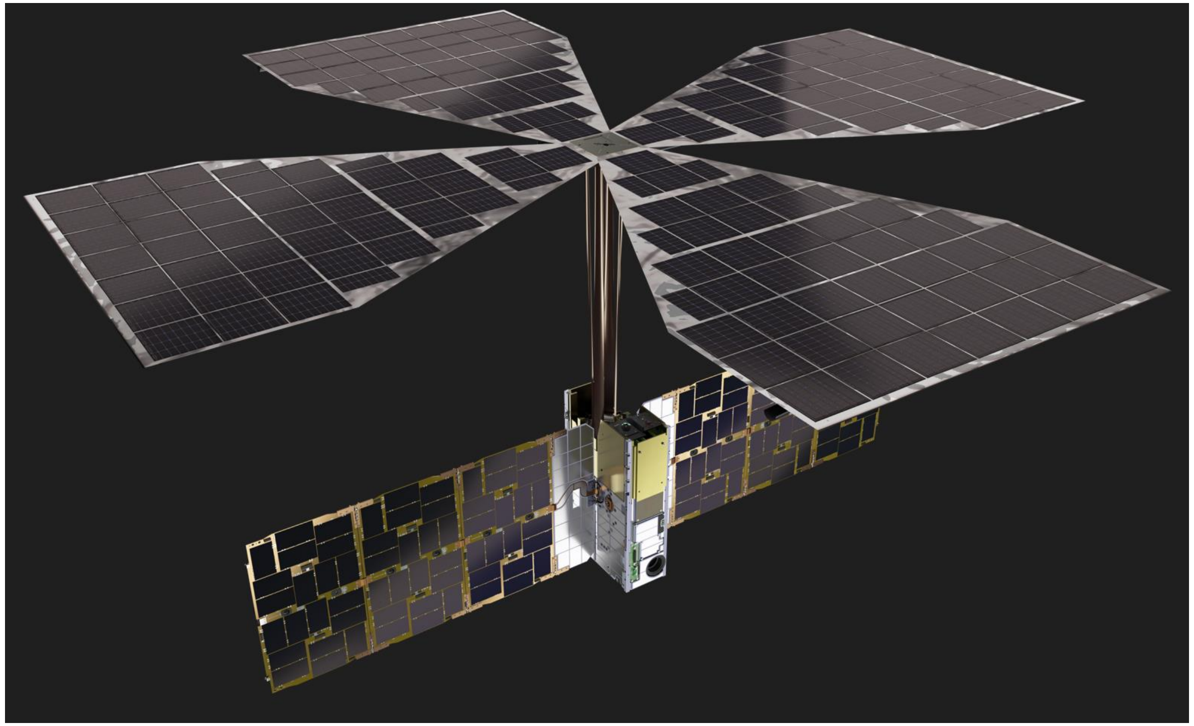
https://www.sciencedirect.com/science/article/pii/S0927024824003489

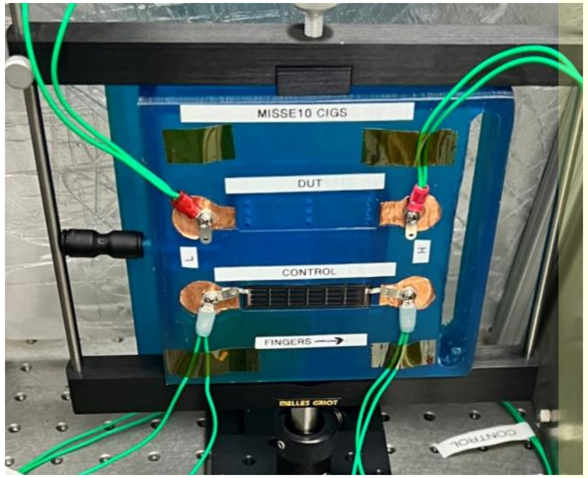
The Lightweight Integrated Solar Array and anTenna – LISA-T

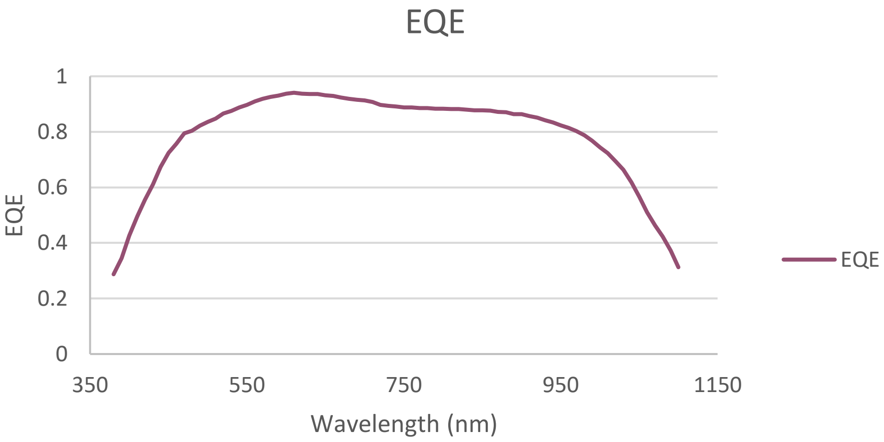
- 6U cubesat launched August 15, 2024
- Began deployment August 27, 2024
- 2 ‘petals’ equipped with ASTI CIGS cells
  - 2 petals with thin-film triple junction cells
- Will demonstrate and benchmark CIGS cells for solar power reception

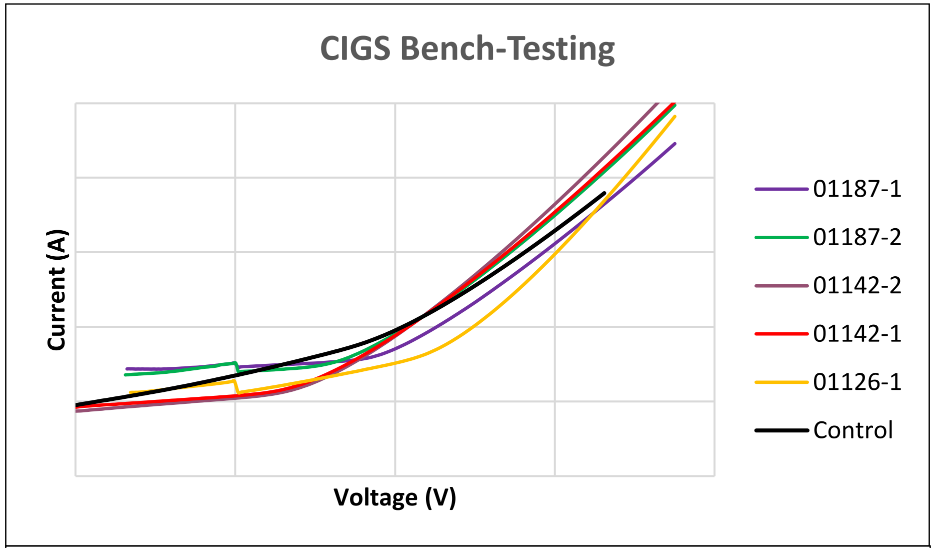


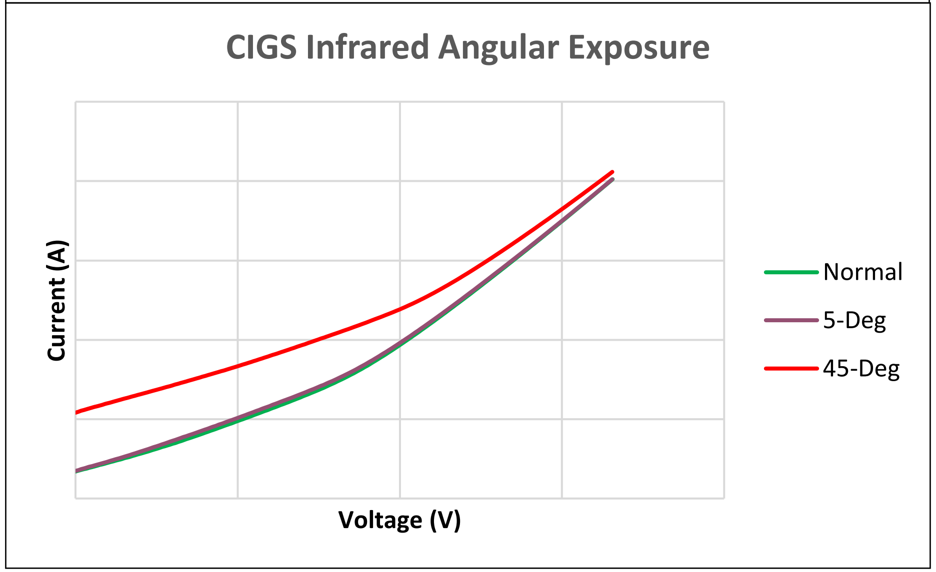
- Other capabilities
  - X-band antenna
  - Cells embedded into a solar sail polyimide substrate

Progress - MSFC Power Beaming Bench Testing









Evaluation of CIGS PV for Laser Power Transmission

Ascent SOLAR

Offeror: Ascent Solar Technologies, Inc

Principal Investigator: Julian Miller, ASTI Director of Space Solutions

Technical Leader: Christopher G. McKinney, NASA MSFC

Technology Alignment:

A.4.8 Cross-Cutting Technologies; A.4.1 Advanced Space Transportation Systems; A.4.1.1 In-Space Transportation Systems; A.4.1.2.2 Propellant-less Propulsion Systems; A.4.5.5 Planetary Science; A.4.7 Surface Technologies & Systems; A.4.7.1 Extreme Environments; A.4.7.2 In-Situ Resource Utilization (ISRU); A.4.7.3 In-Space Assembly & Manufacturing (ISAM); A.4.8.3 Autonomous Systems & Robotics (ASR); A.4.8.7 Power & Energy Systems

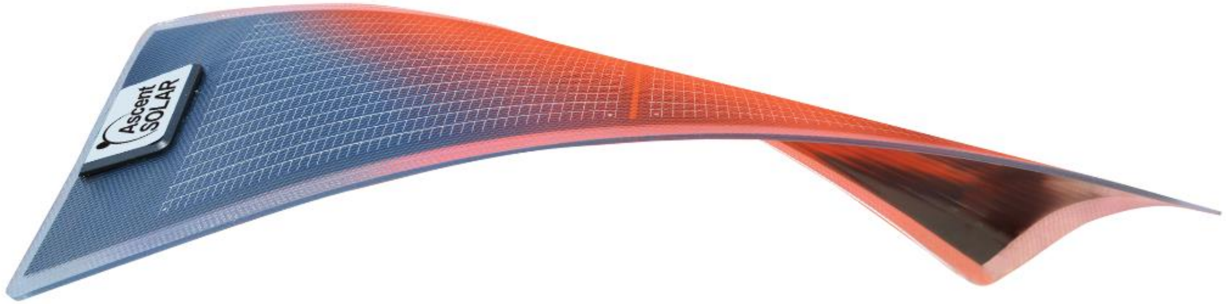
Brief Description

1. Initial PV Module Power Beaming & Test Evaluations
2. Test Data Analysis and Module Design Iteration
3. Improved Module Power Beaming & Test Evaluations

This new technology stands to benefit MSFC Planetary Missions Program office by enabling a means for delivering power to lunar surface assets operating in PSRs and other extreme environments where highly mass and volume efficient means of power generation are required and/or enabling survival or continuous operation during the lunar night.

Benefits to partner

The proposed technology development benefits ASTI by verifying, validating, and maturing of capabilities for receiving monochromatic beamed power with low cost, mass producible PV modules. Test data results from the first round of testing will inform an iteration to a tipping point readiness level, increasing viable government program and customer opportunities that could lead to commercialization and wide scale civil & commercial mission adoption.



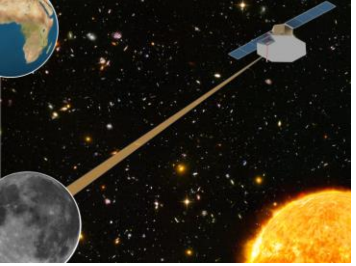
Expectations for the Future

- More industry and OGA partnerships
  - Dual-use receiver technology development
  - Quick, automated, optimized beam adjustment
    - Shape (irradiance distribution), shape (circular, square, custom), beam diameter/focus

- Component and system-level testing
  - Important to advance the TRL of specific technologies, but need to lean on MSFC SE expertise to integrate and benchmark the performance of the system

- Architecture integration
  - Optical power beaming is a flexible power solution capable of enabling not only lunar night survival, but continued science and exploration during the lunar night, in permanently shadowed regions (PSRs), and at large distances away from settled regions
  - This technology is NOT meant to be a replacement to FSP, RTGs, or other power solutions, SBSP will help ‘bridge the gap’ to a more permanent power solution at the lunar south pole – providing reliable power to automated assembly systems

- NASA HQ support
  - HQ exploring a multi-center study for lunar orbital SBSP



Questions?