POWERLIGHT TECHNOLOGIES

Laser Power Beaming on the Moon

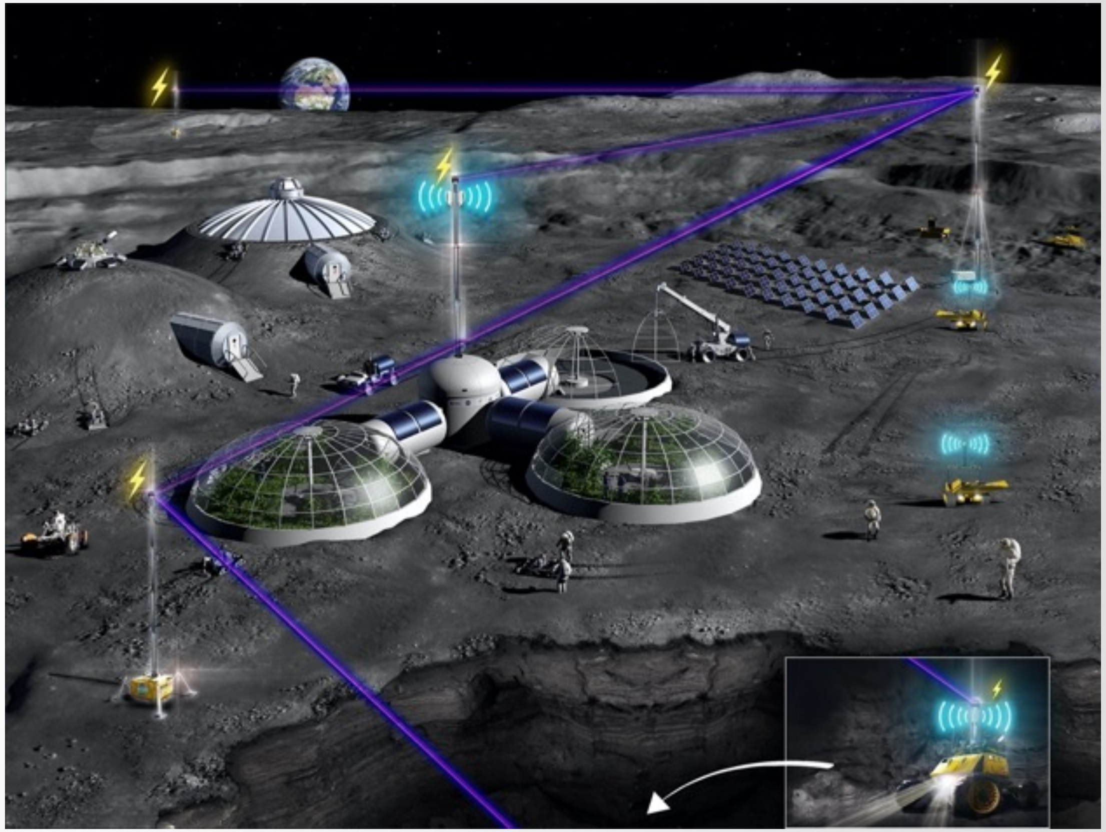
LSIC Surface Power Group meeting

May 23, 2024

Tom Nugent, Jr.

Overview

- Introduction to power beaming & PowerLight
- Performance metrics
- Lunar use cases and constraints
- Design trade-offs and modeling



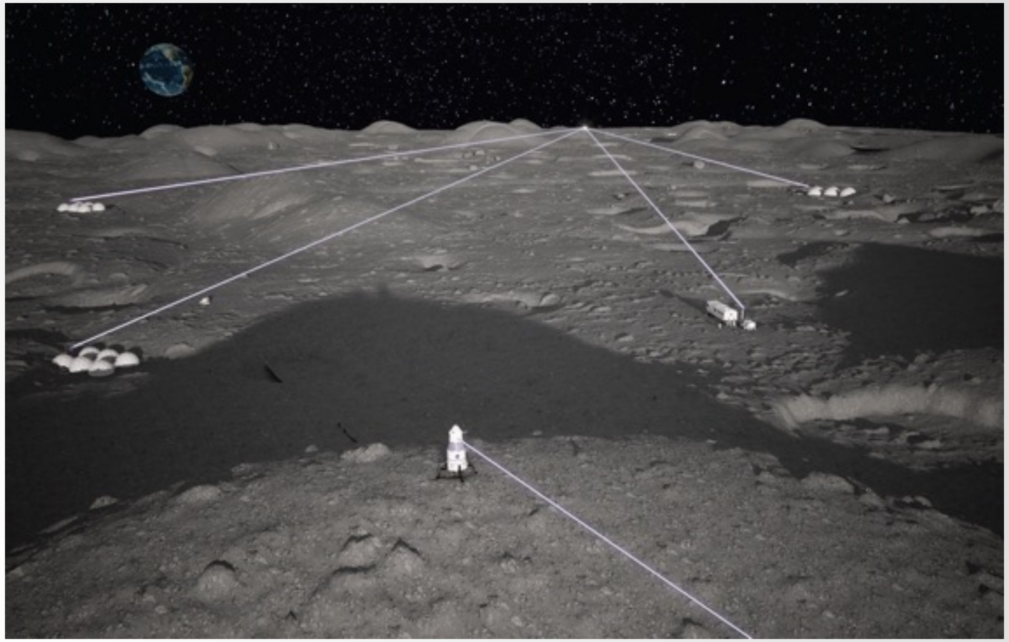
Key frontier markets demanding mobility & electrification have a power distribution problem:

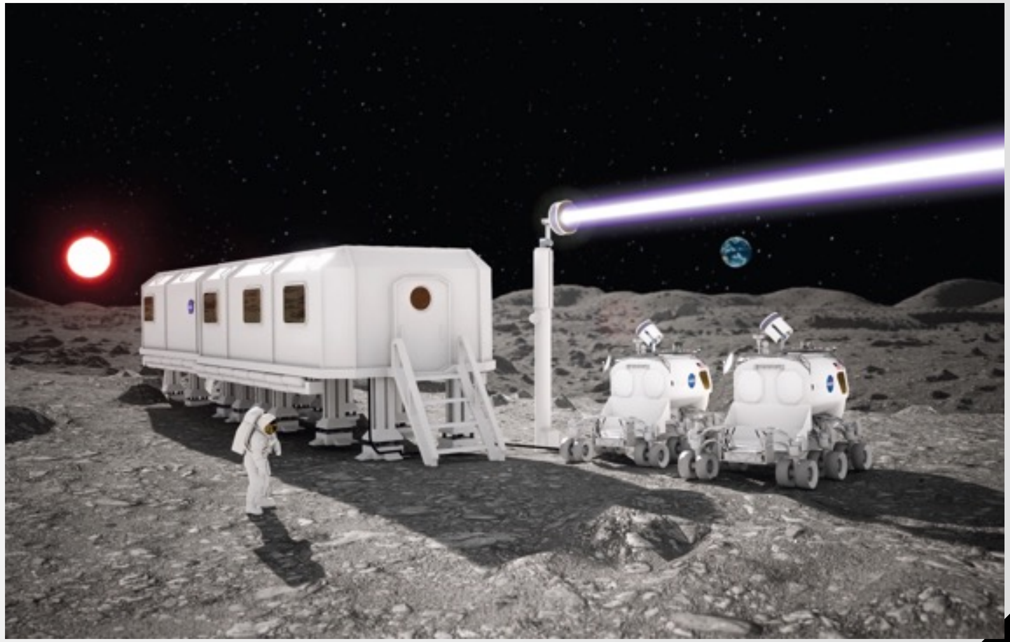
They need sustained power at the edge of the grid where loads are often mobile, vertical, in hard-to-reach areas, and need to be delivered with speed.

Traditional methods have proven too slow, too dangerous, too costly, or too damaging to the environment to satisfy these emerging demands.

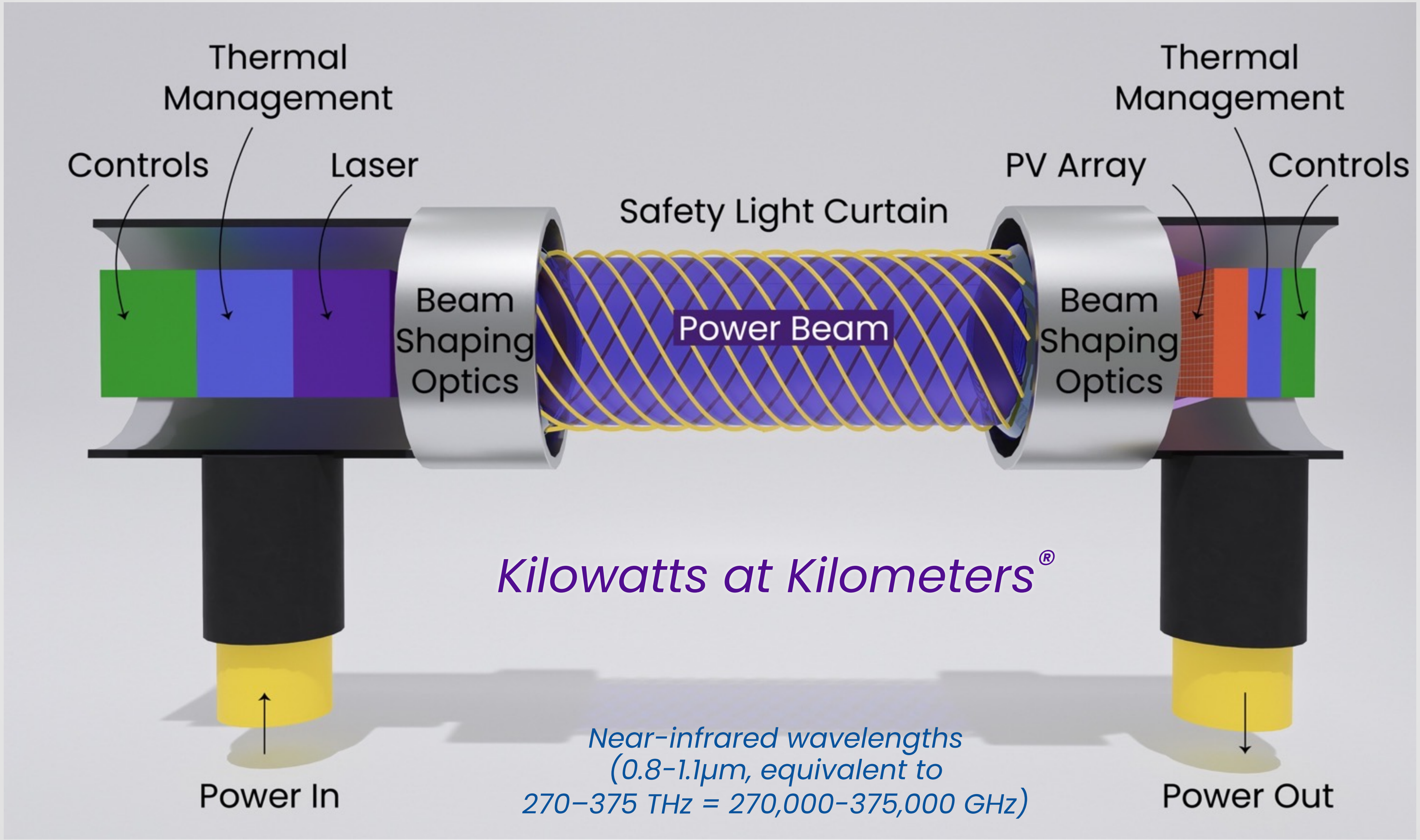
The Moon

- There is growing interest in lunar missions, including for long-term lunar infrastructure
- Power generation, distribution, and storage are key limiting factors
- Laser power beaming expands the range of possible operations, either in continual or fractional duty-cycled power, agnostic to the type of power source





What Is Laser Power Beaming?



Performance Metrics, Accomplishments, and Markets

Demonstrated Performance To-Date

A Systems Approach

Ensures optimal end-to-end performance and safety

Field Testing

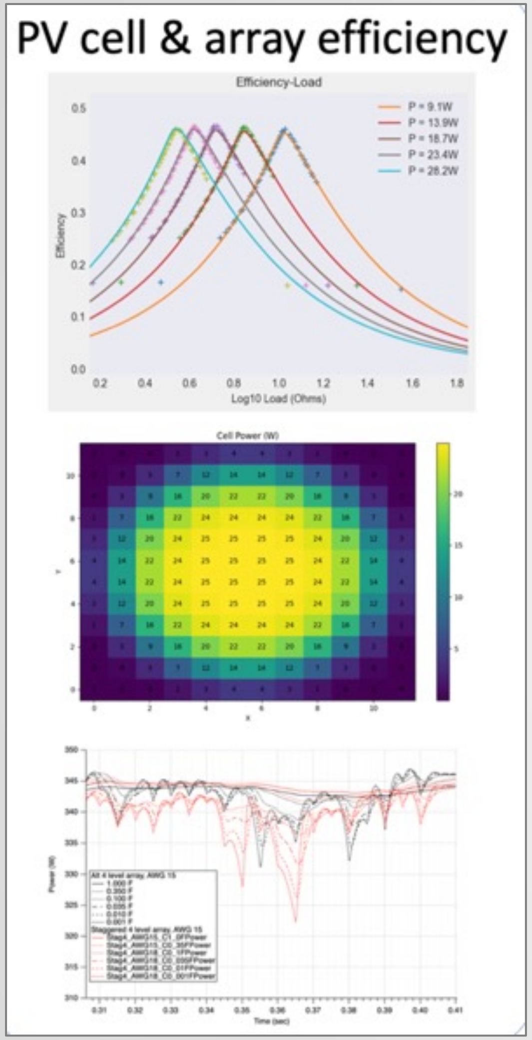
With the end-in-mind, our results are driven from field testing...not just theory, CAD models or ideal lab conditions that use selected "hero" results

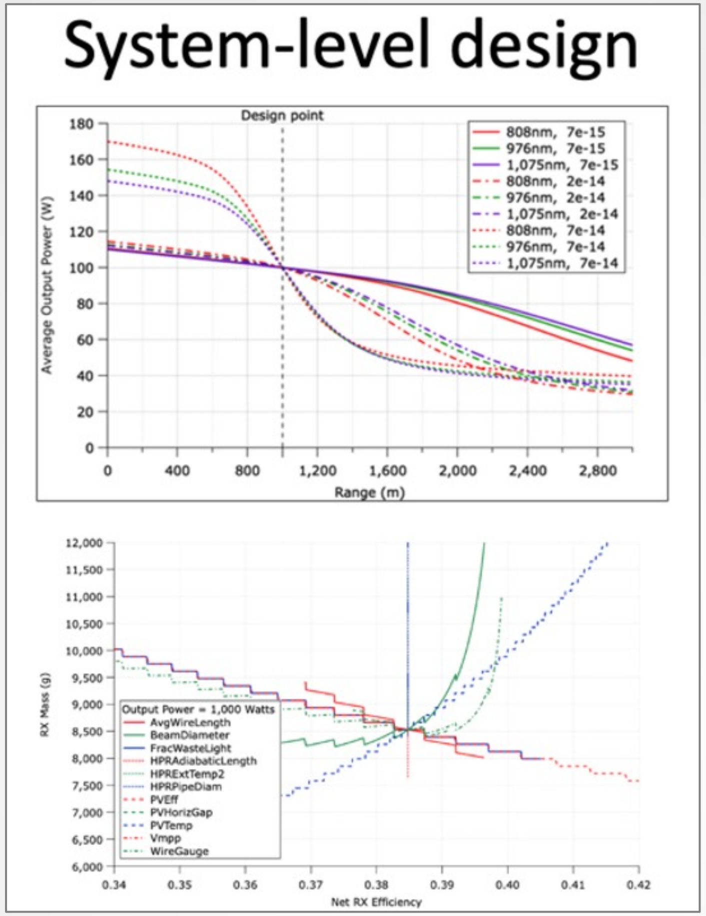
Other important metrics:

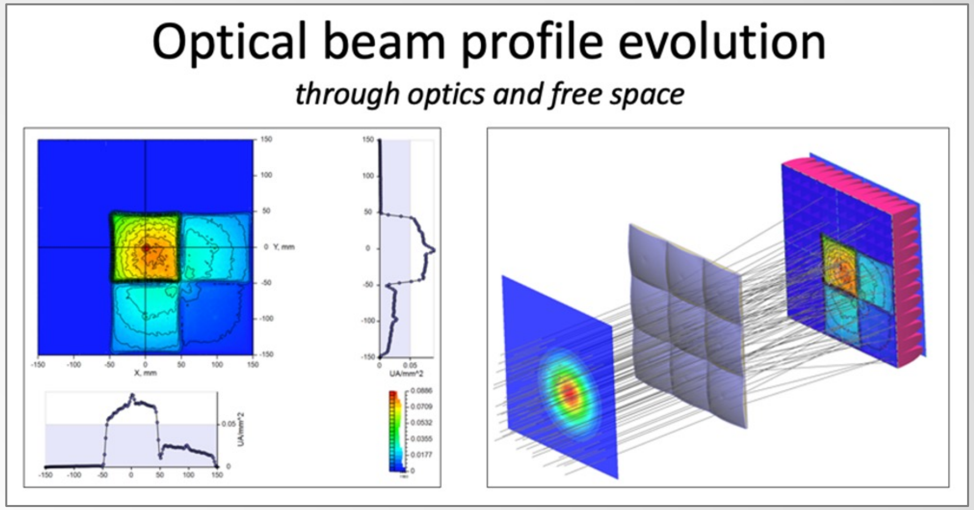
- End-to-end electrical efficiency
- Component efficiency (lasers, PVs, fiber)
- Non-PV receiver efficiency performance
- Cost & availability of components

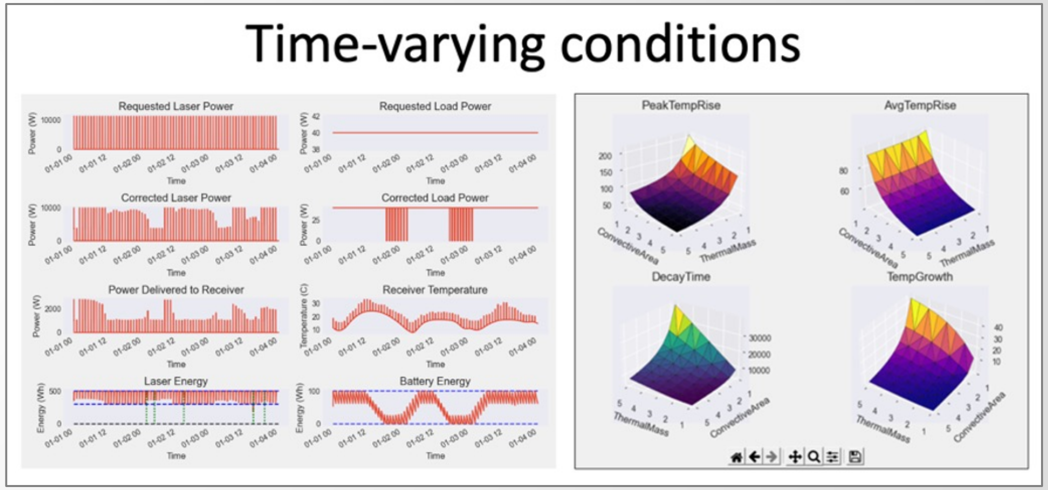
Factor	Performance
Power output	10 – 1,000 watts DC
Distance	FSP: 1.5 – 1,000 meters PoF: 5-100 meters
Specific power of flight receivers	300 – 800 W/kg
Output power/area	> 5,000 W/m^2 (>0.5 W/cm^2)
Passive safety	✅ (Reflections below ANSI & IEC)
Active safety shut-off (D^3 time)	1 ms
Range of active safety	~1,000 meters
Receiver design (non-PV) efficiency	Up to 97%
Laser Clearing House integration	✅
FDA/CDRH registration	In process
Environmental	Rain resistance; Day & night; Expanding temperature range

Modeling



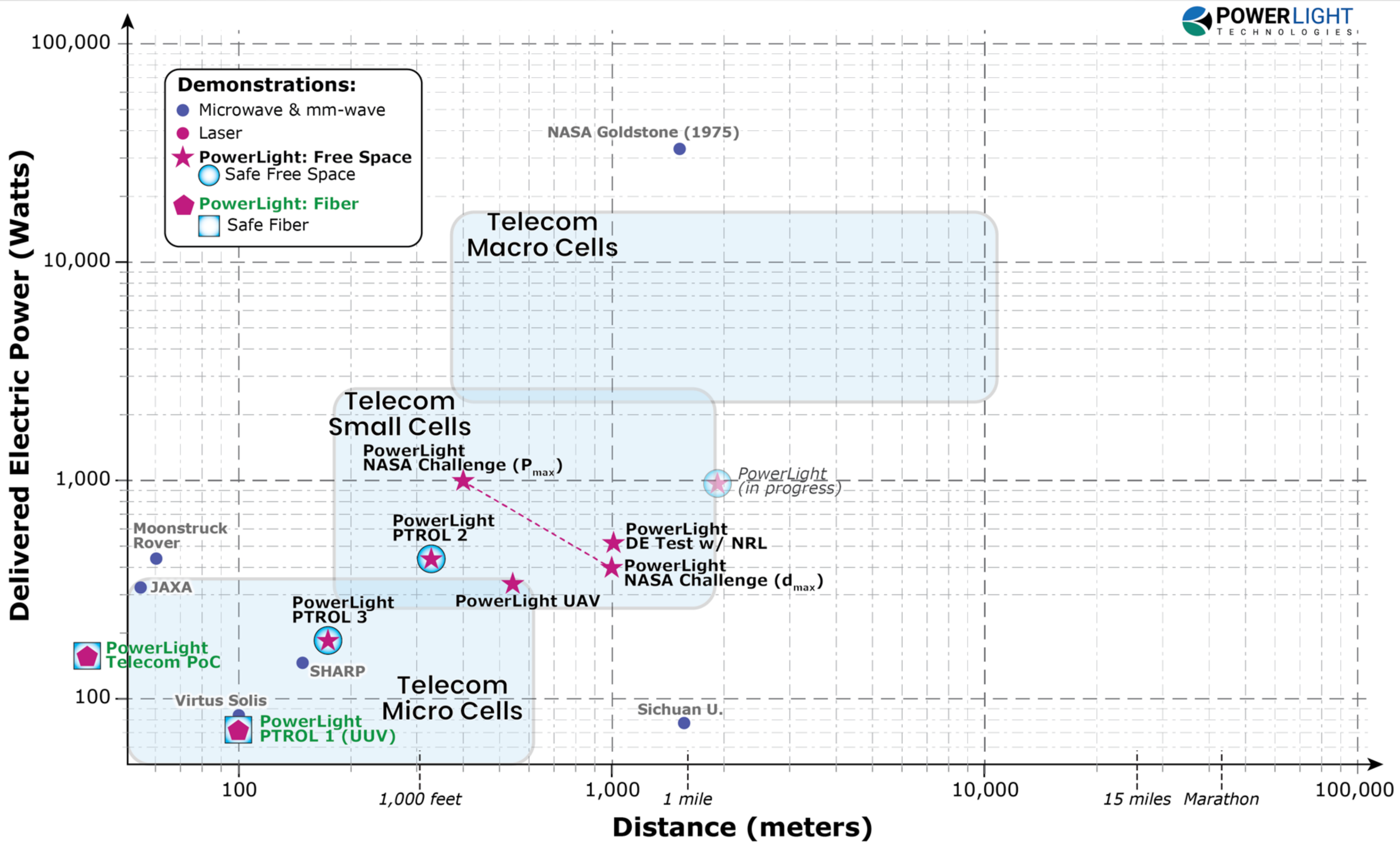




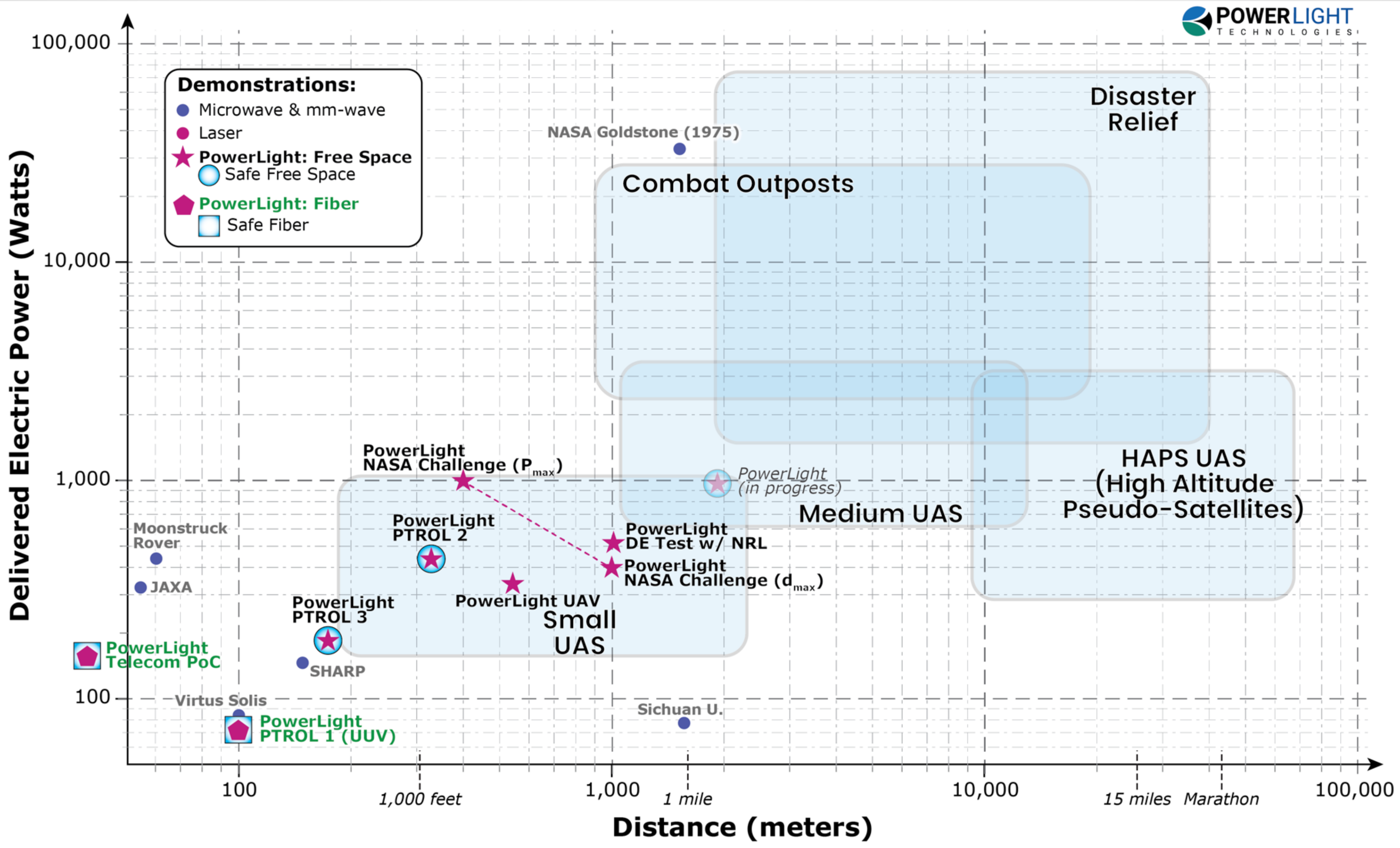


- System-wide optimization (for efficiency, size, weight, range, & cost) across many dozens of parameters: laser wavelength, beam size at the receiver, PV cell dimensions, beam intensity on the PV cells, PV cell grid line density, PV array electrical configuration, DC voltage boost, receiver maximum thermal resistance, beam intensity profile, tracking accuracy, transmitter optics quality, transmit aperture size, degree of environmental protection, and more.
  - Heavily prefer COTS or custom-COTS hardware.

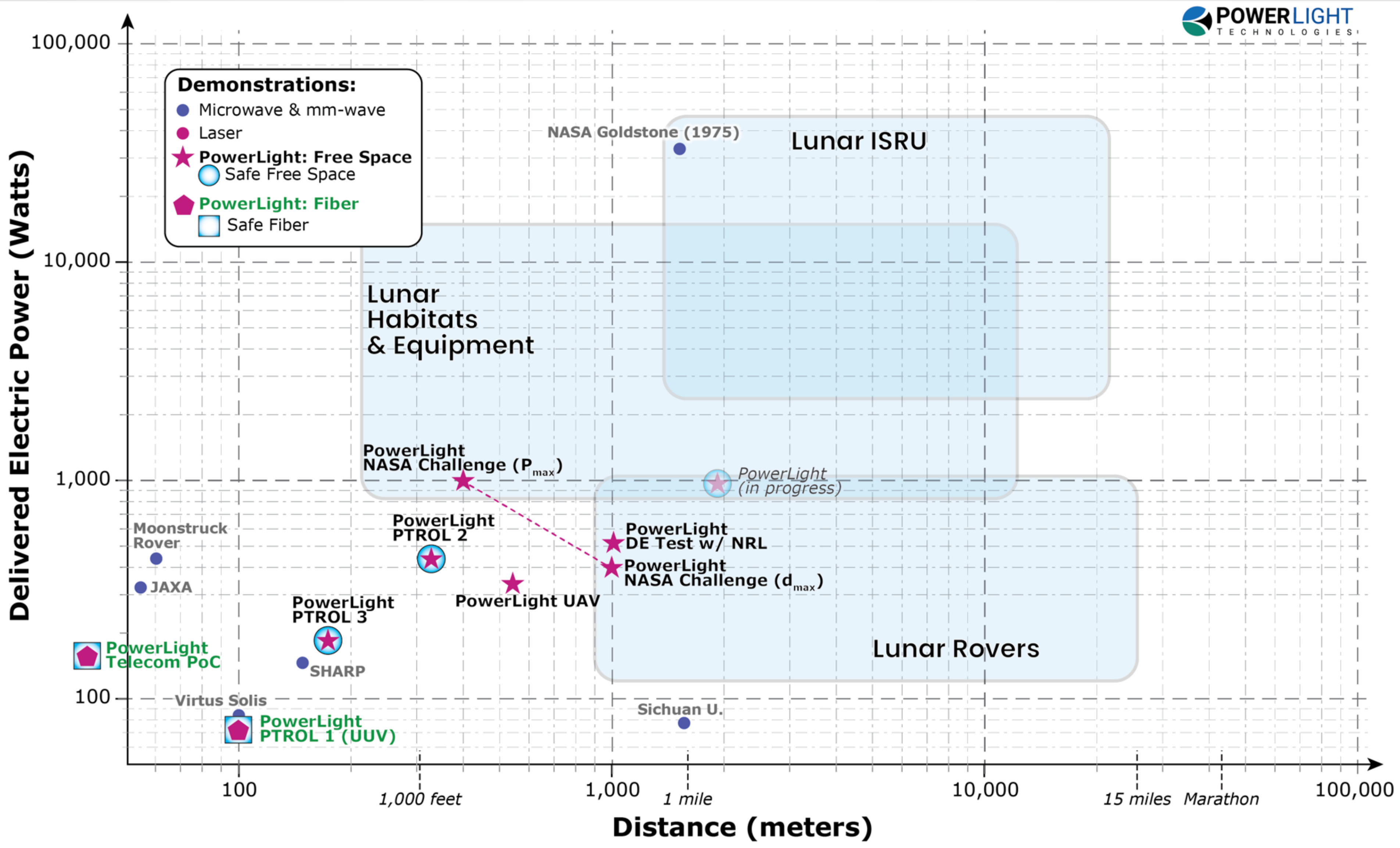
Power vs. Distance: Telecom Market



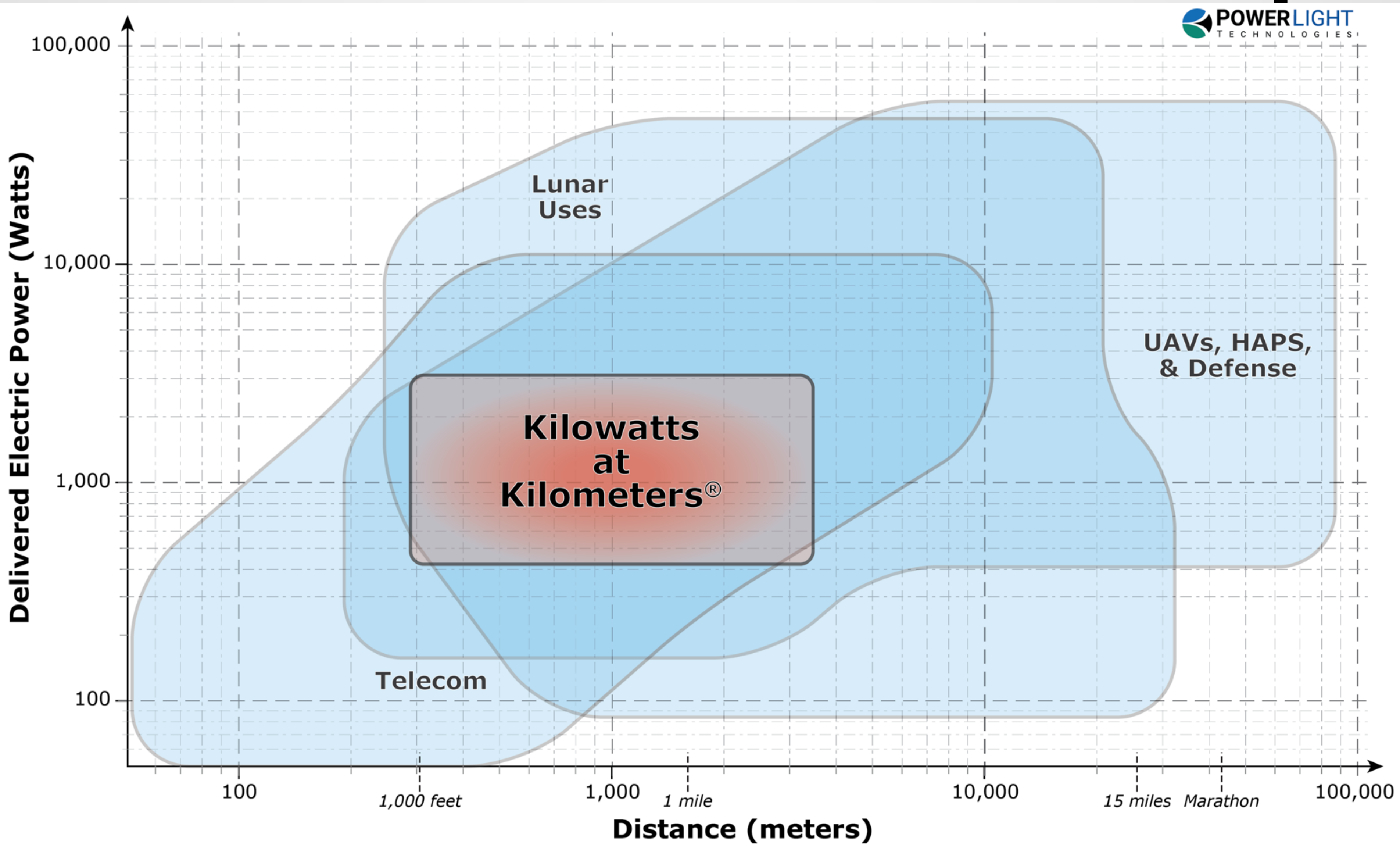
Power vs. Distance: UAS & Defense Market



Power vs. Distance: Lunar Market



Power vs. Distance: Market Overlap



Power on the Moon

Motivation for the Moon

Issues for Competition

- Kilowatt-class power sources are difficult to move due to size & weight
- Solar PV only works where (and when) the sun can reach
- Nuclear reactors are likely to have minimal shielding due to transport cost
- Electrical power cables are heavy (esp. to transport to the Moon) and difficult to deploy (and harder to move)
- Current cost estimate to soft-land mass on the Moon: US$1 Million/kg

Impacts for Power Beaming

- No atmosphere means:
  - No scintillation 👍
  - No air absorption losses 👍
  - No wind loading on structures 👍
  - No convective heat rejection 👎

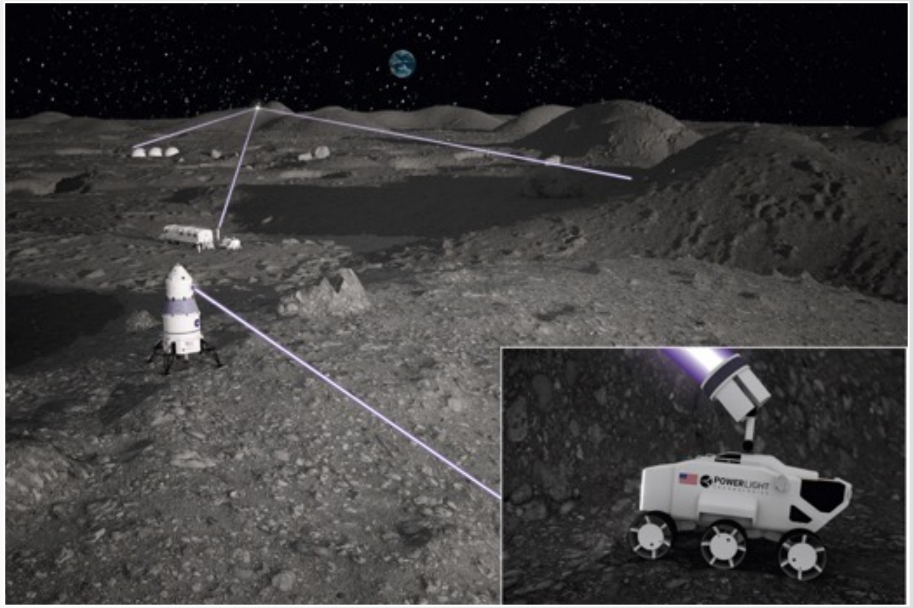
Alternatives Comparison

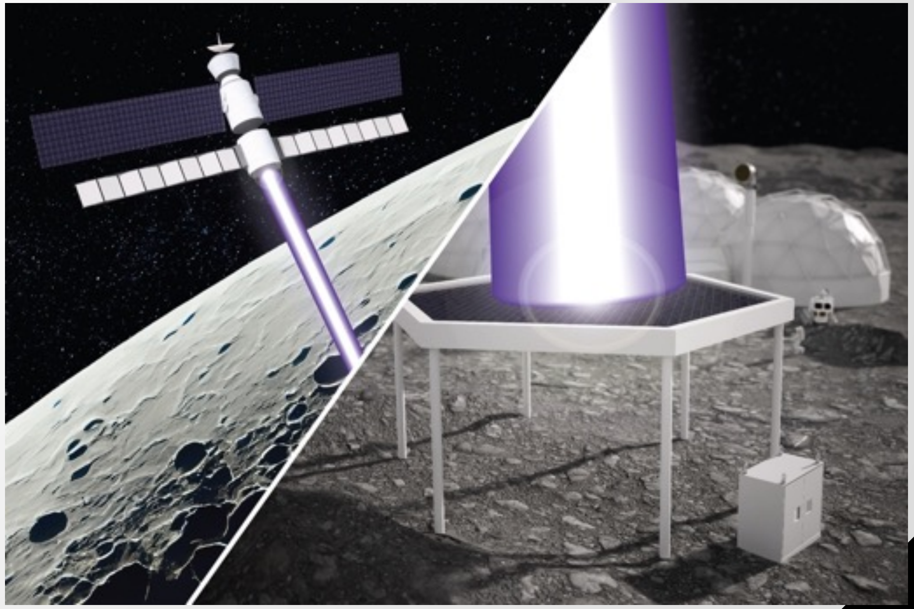
- The choice of how to distribute electrical power depends on subtle trade-offs between the following areas:
  - Up-front capital costs (includes launch mass)
  - Operational complexity (e.g., if manual processes for battery handling are needed)
  - Installation costs (e.g., of the hardware and/or services of running cables)
  - Flexibility (e.g., if the power usage location moves)
  - Expected lifetime
  - Efficiency
- These trade-offs are balanced against the value of the electrical power to the devices requiring it.

Metrics	Transmission			Generation @ point of use	
	Cables / wiring	Microwave	Laser	RTG	Solar (with batteries)
Effort-per-distance (logistics vs phase/time of lunar operations)	Terrible	Good	Very good	Very good	Very good
Size of Hardware	Very good	Terrible	Good	Good	Poor
Output Variability Rate	Very good	Good	Good	Poor	Good
Mass-per-Distance (incl. deployment hardware)	Poor	Very good	Excellent	N/A	N/A
Efficiency	Very good	Good	Good	N/A	N/A
Cost of Hardware	Very good	Good	Good	Poor	Good
Power-per-Volume	Excellent	Poor	Good	Good	Poor
Mass-per-Power	Very good	Poor	Good	Poor	Good
Rovers in Permanently Shaded Regions?	Extremely difficult	Yes	Yes	Yes	No
Other Concerns	Poor mobility	RF interference	Thermal management	Nuclear politics	Low intensity, intermittent

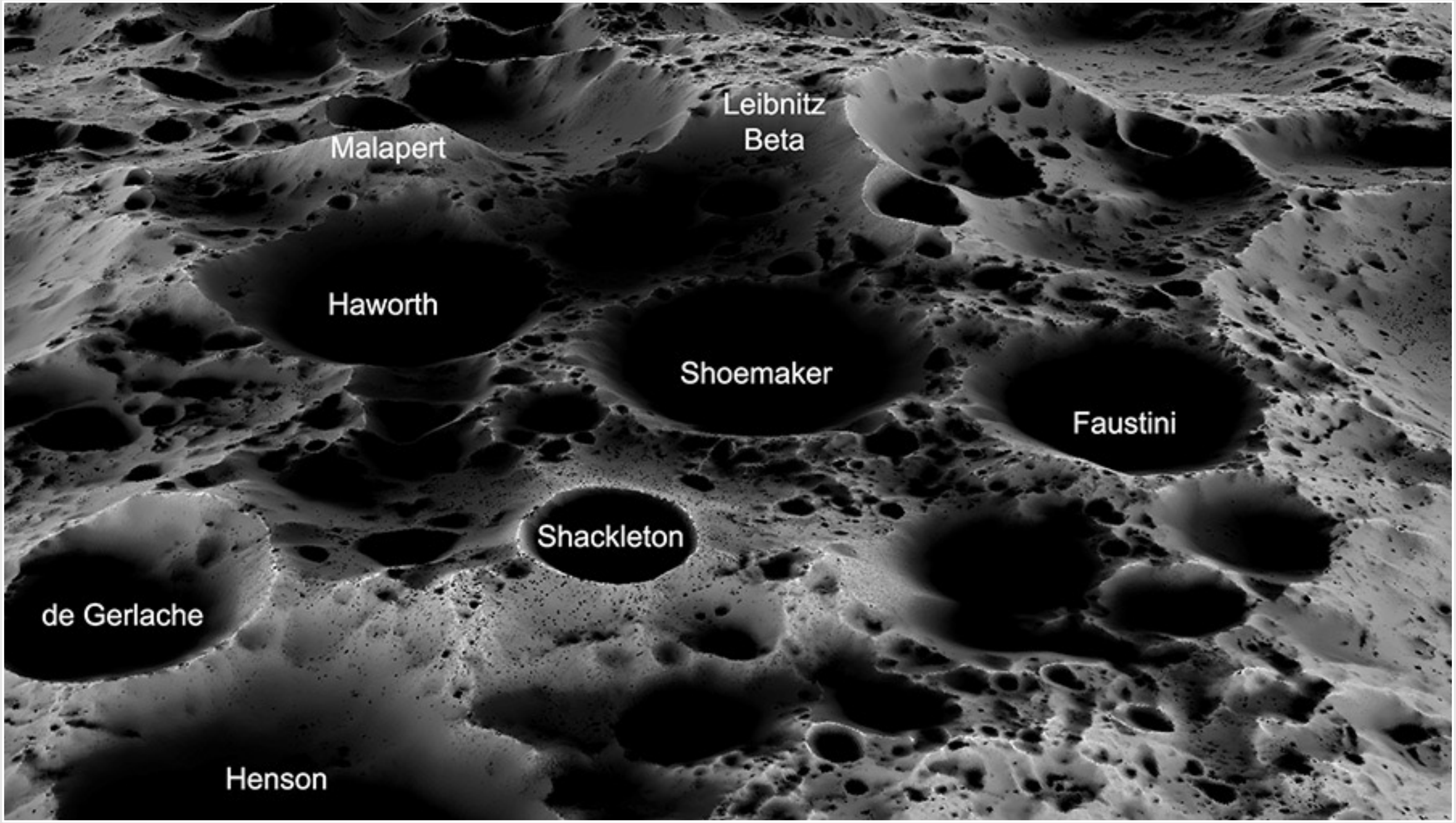
Use Case-based Ranges

- Ground-to-ground
  - Range out to 10-20 km
    - Rovers, vehicles, sensors, habitats
  - Long range out to ~150+ km
    - Ridge-to-ridge to cover shadowing
- Orbit-to-ground
  - 200km-10,000+km
  - Help with night-time challenges
  - Unstable orbits





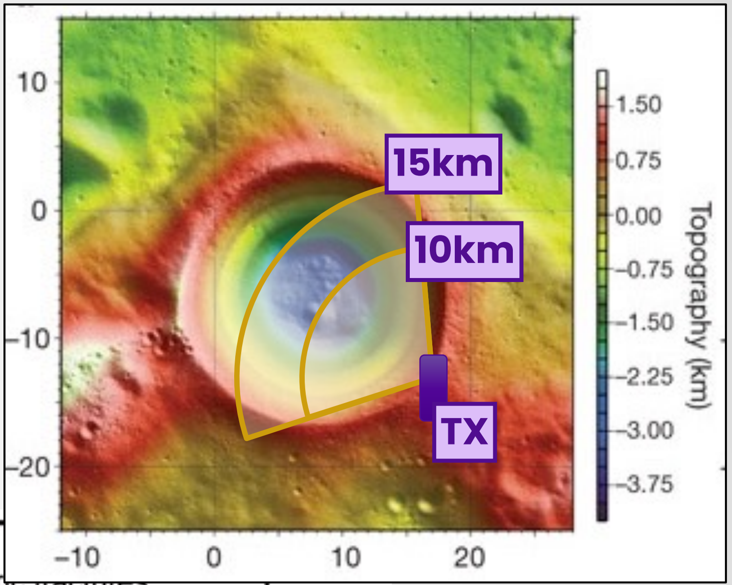
Lunar South Pole

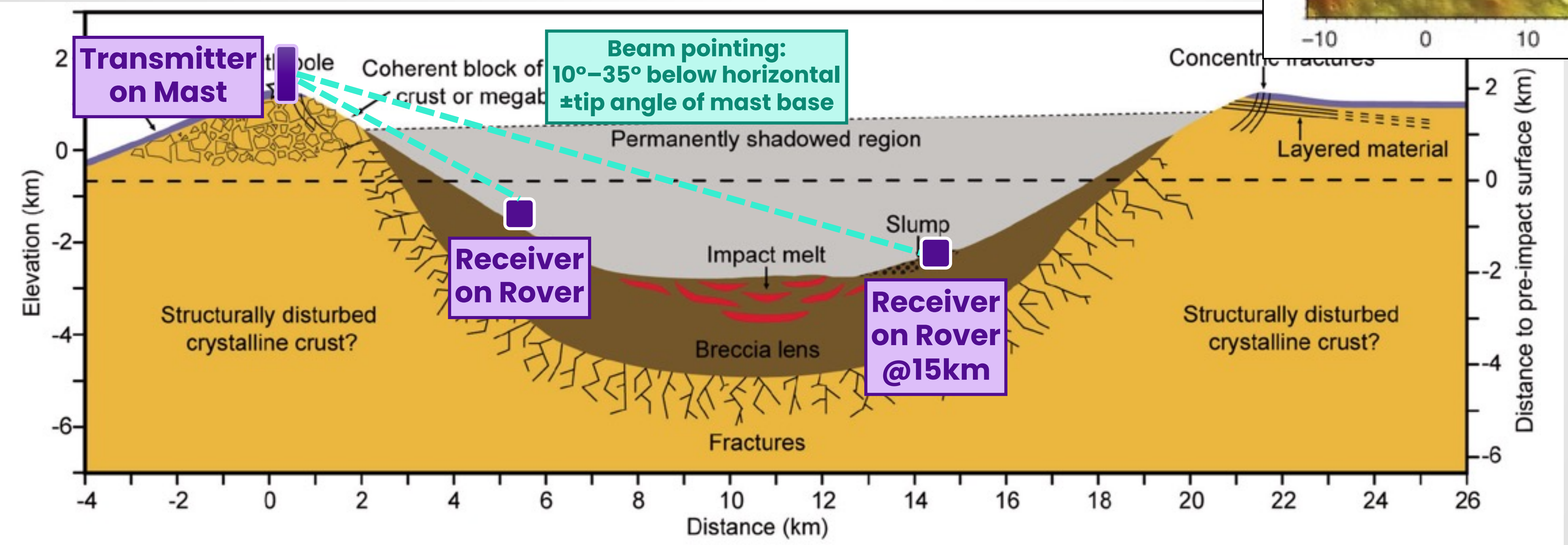


https://www.lpi.usra.edu/lunar/lunar-south-pole-atlas/

Rovers in Shadowed Craters

- Beaming power to exploration rovers in permanently shadowed regions overcomes limits of solar & nuclear power
- Shackleton Crater, for example, is >20km in diameter.
  - Slope can be >30° ⇒ range of TX beam tilt angle affects field of regard
  - One TX to reach past the center of the crater

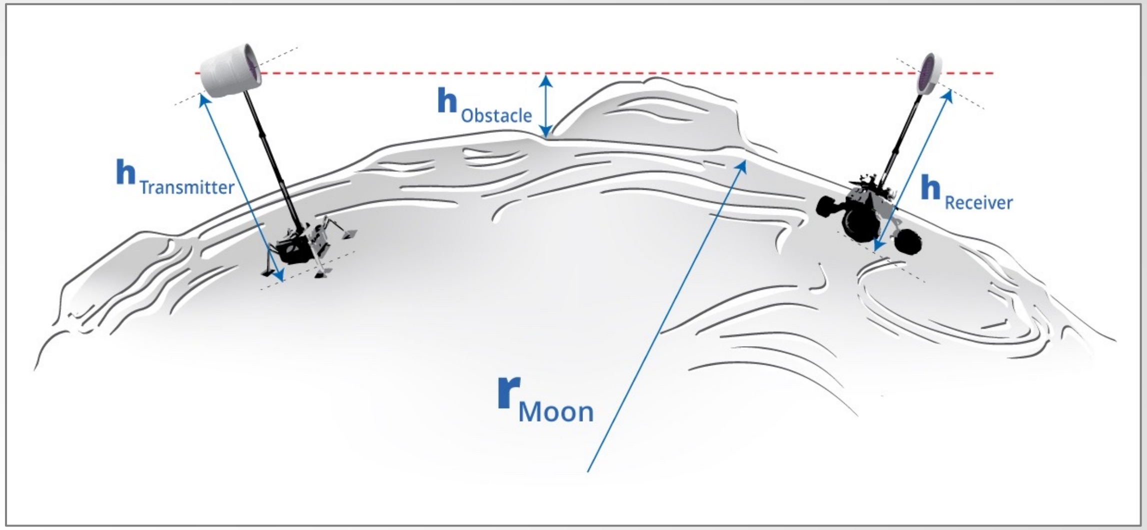


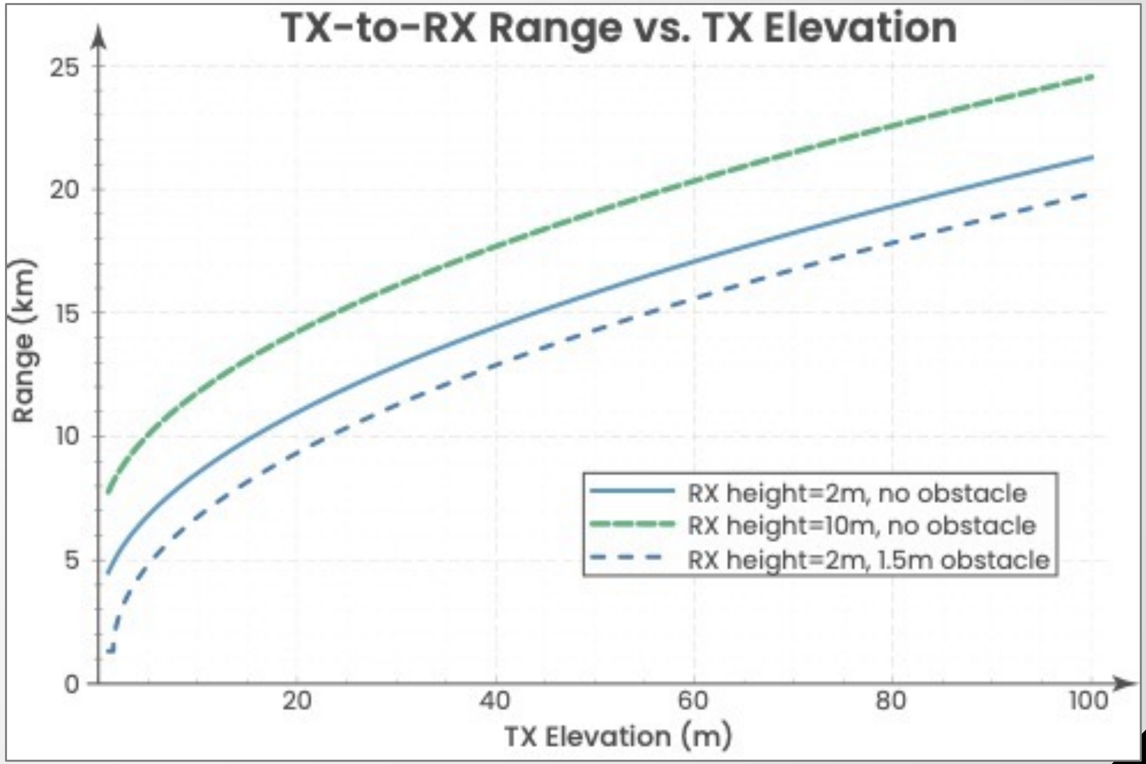


Challenges

Horizon Distance

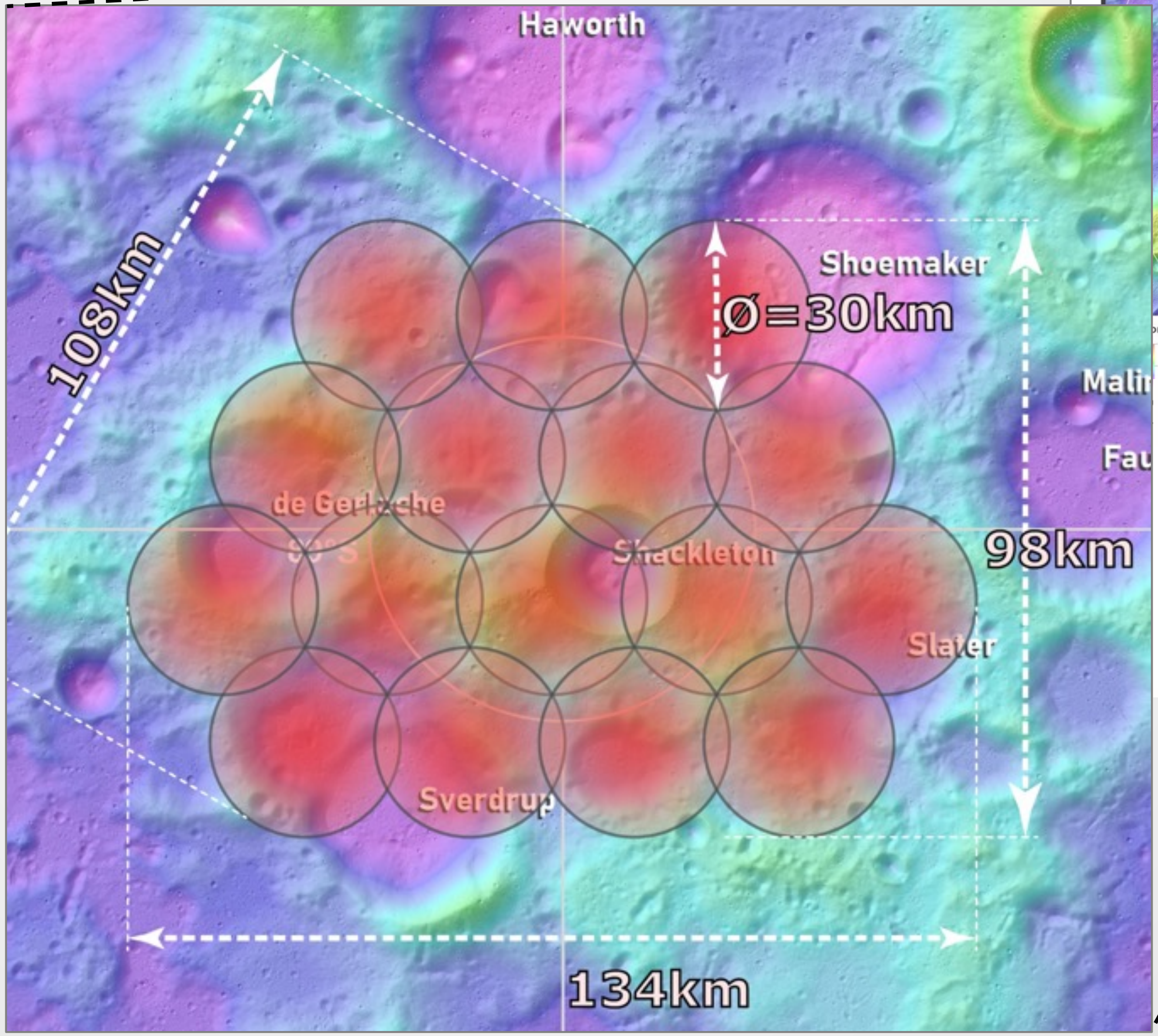
- Moon has a smaller radius than the Earth, with the result that the distance to the horizon is much shorter.
    - Graph is for spherical Moon
- The distance to the horizon varies as a function of the elevation of the transmitter aperture.
    - Topography of the Moon (hills, valleys, boulders, etc.) reduce the actual ranges, creating "holes" in coverage due to shadows from taller features.
- To reach 10s of kilometers can require very tall mast for the beam director.

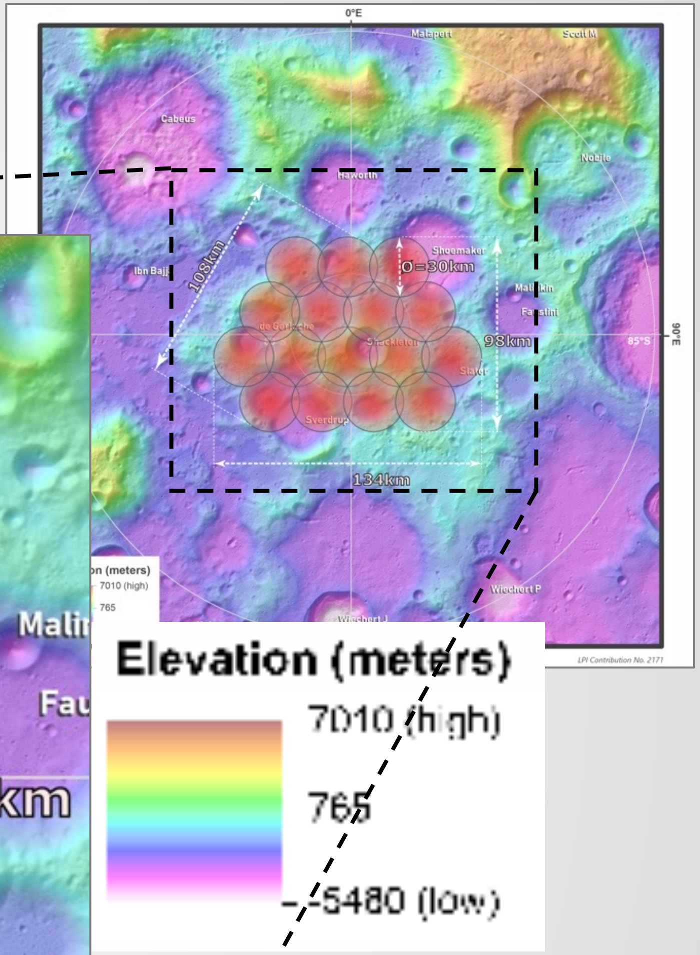




Coverage of South Pole

- Small number of transmitters can provide wide-area coverage
    - Example: assume 15km maximum range from TX to RX





https://www.lpi.usra.edu/lunar/lunar-south-pole-atlas/

Example of Terrain Shadowing

- Green areas have line of sight to 30m high TX at red dot
- More areas fill in as the TX elevation gets higher

Note: This is only an example, and its inclusion does not imply any endorsement by Blue Origin.

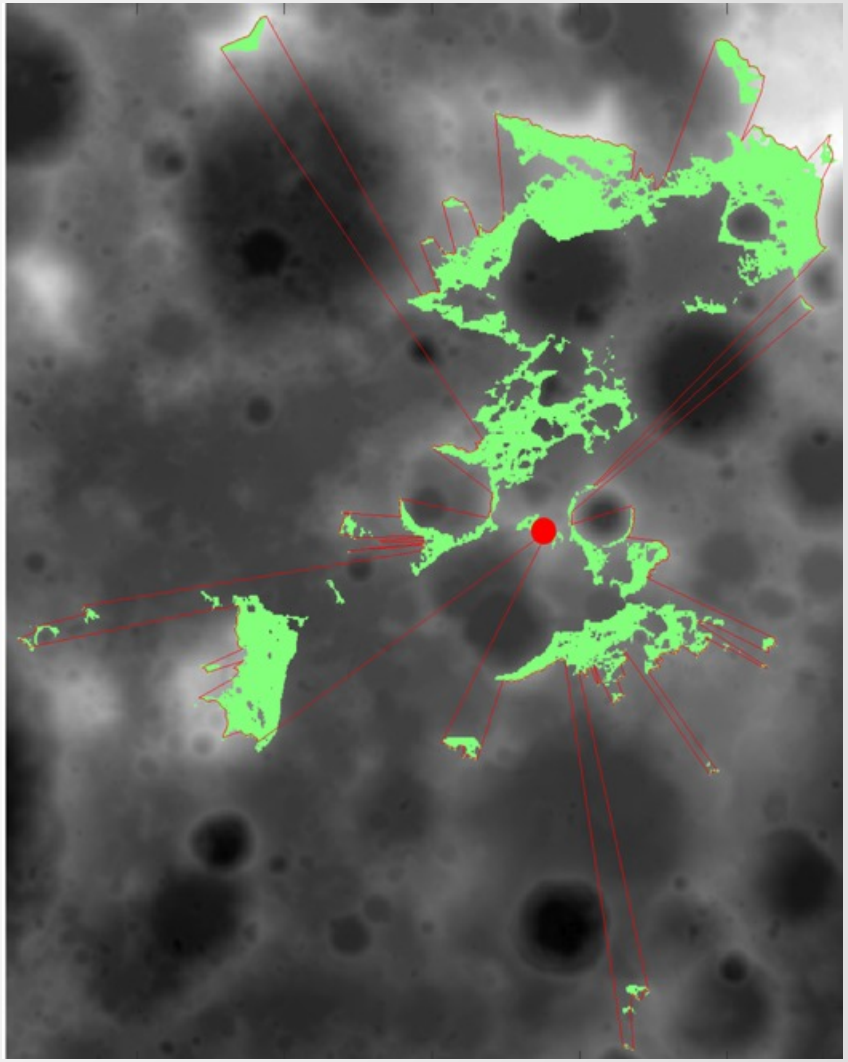
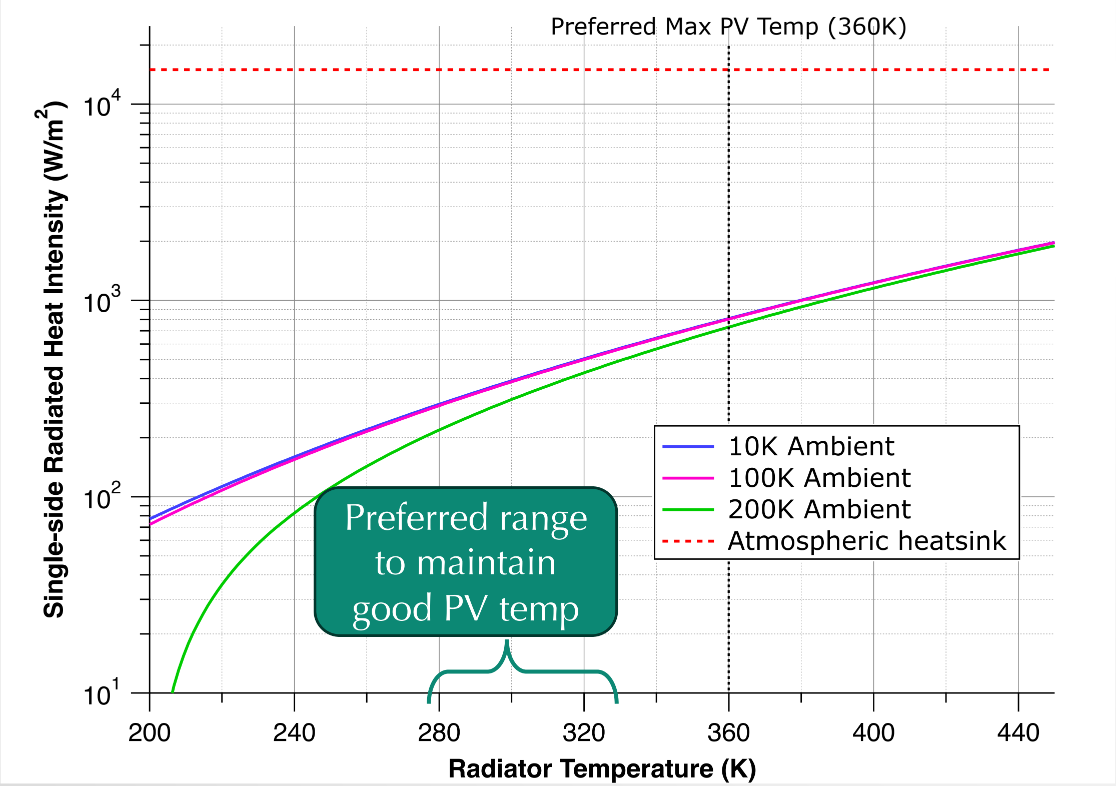
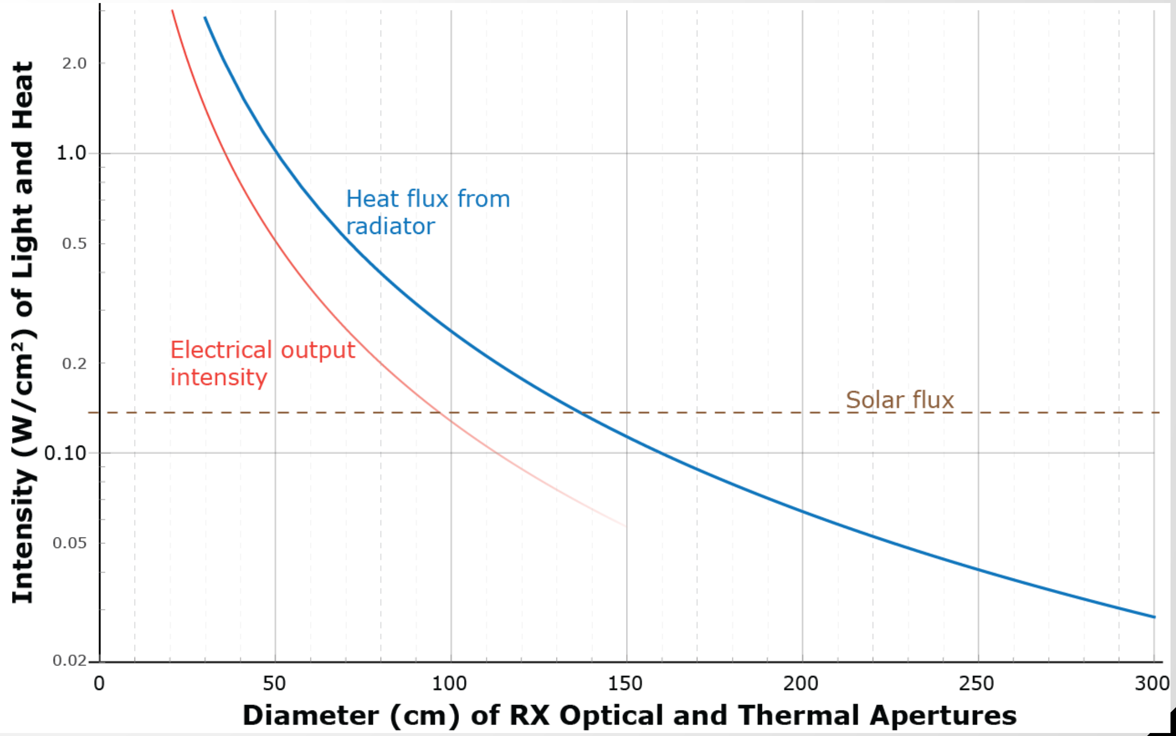


Image provided courtesy of Blue Origin

Thermal Management

- Intensity of radiative heat rejection is much lower than the “normal” (terrestrial) electrical and heat output from compact receivers
  - Implies either the use of (large) heat spreaders, or a larger beam and receiver, to reduce the heat intensity.



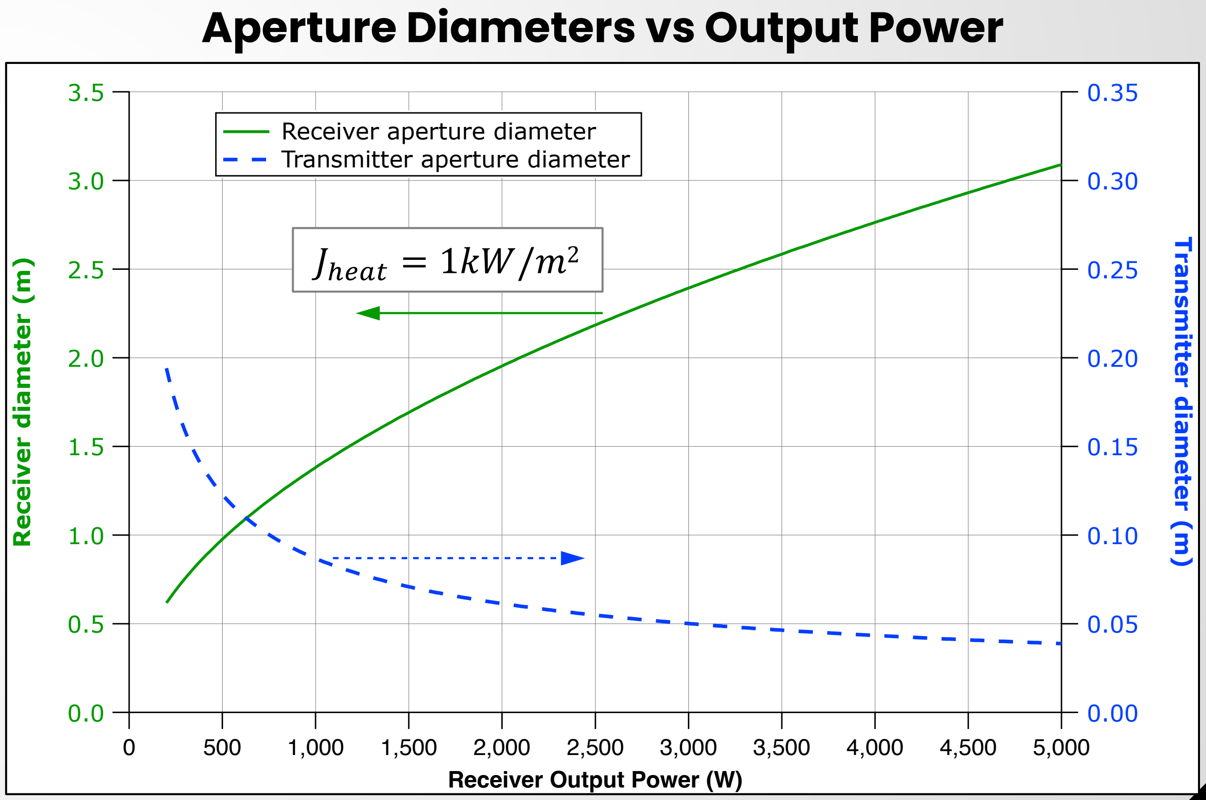


Aperture Sizes: Ground-to-Ground

- Beam quality and range determine RX & TX aperture minimum diameter trade-offs
- RX aperture can be 5x-50x as big as the TX aperture
  - Assumptions for graphs:
    - RX optical aperture determined by heat radiator size
    - 20km
    - M^2~8 (BPP=3 mm*mrad)

$$d_{TX} = \frac{4\,L\,BPP}{d_{RX}}$$

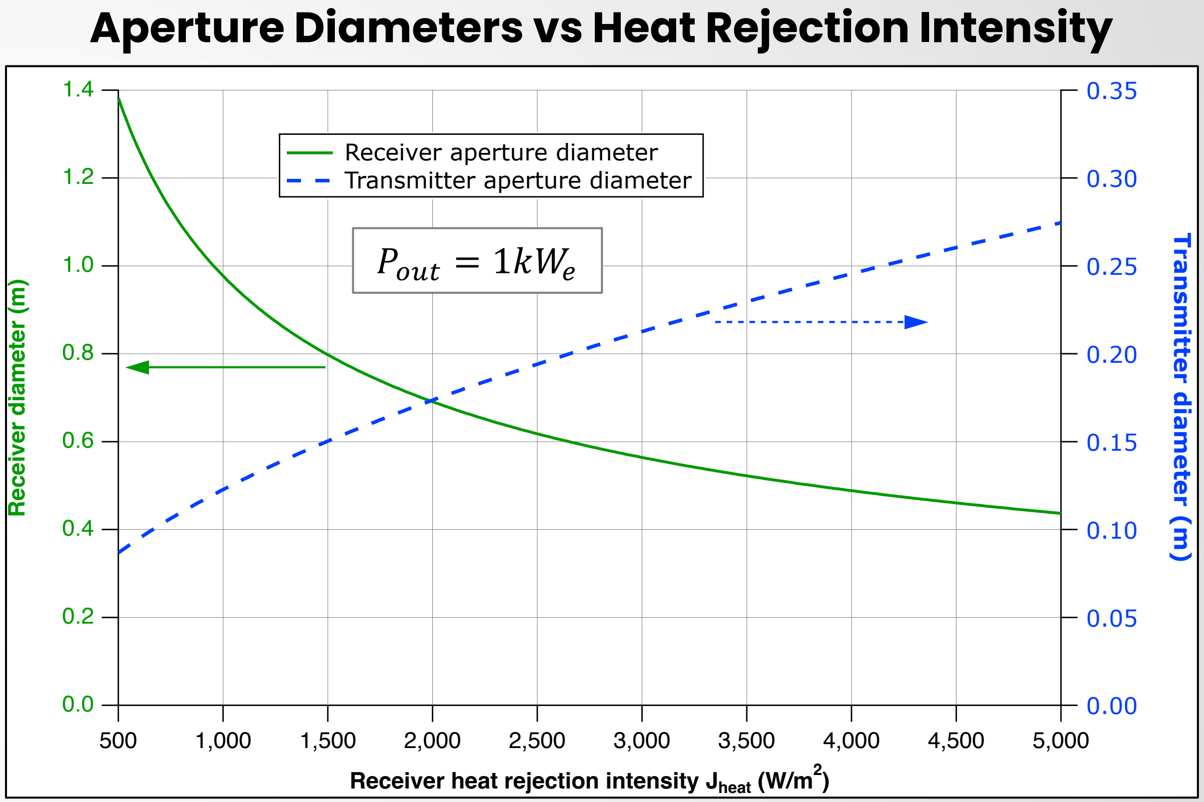
$$d_{RX} = 2\sqrt{P_{out}\left(\frac{1}{\eta_{RX}} - 1\right)/\pi J_{heat}}$$



PowerLight Technologies Proprietary

Aperture Sizes: Ground-to-Ground

- If average heat rejection intensity can be increased, then receiver can be much smaller

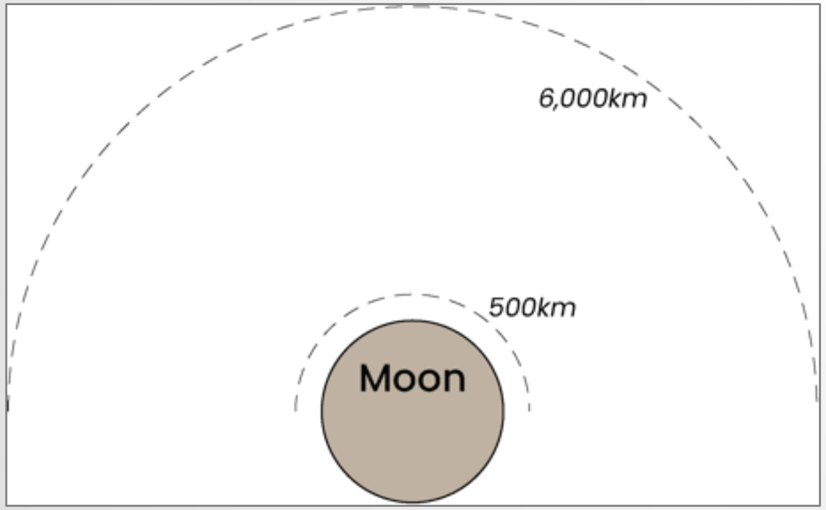


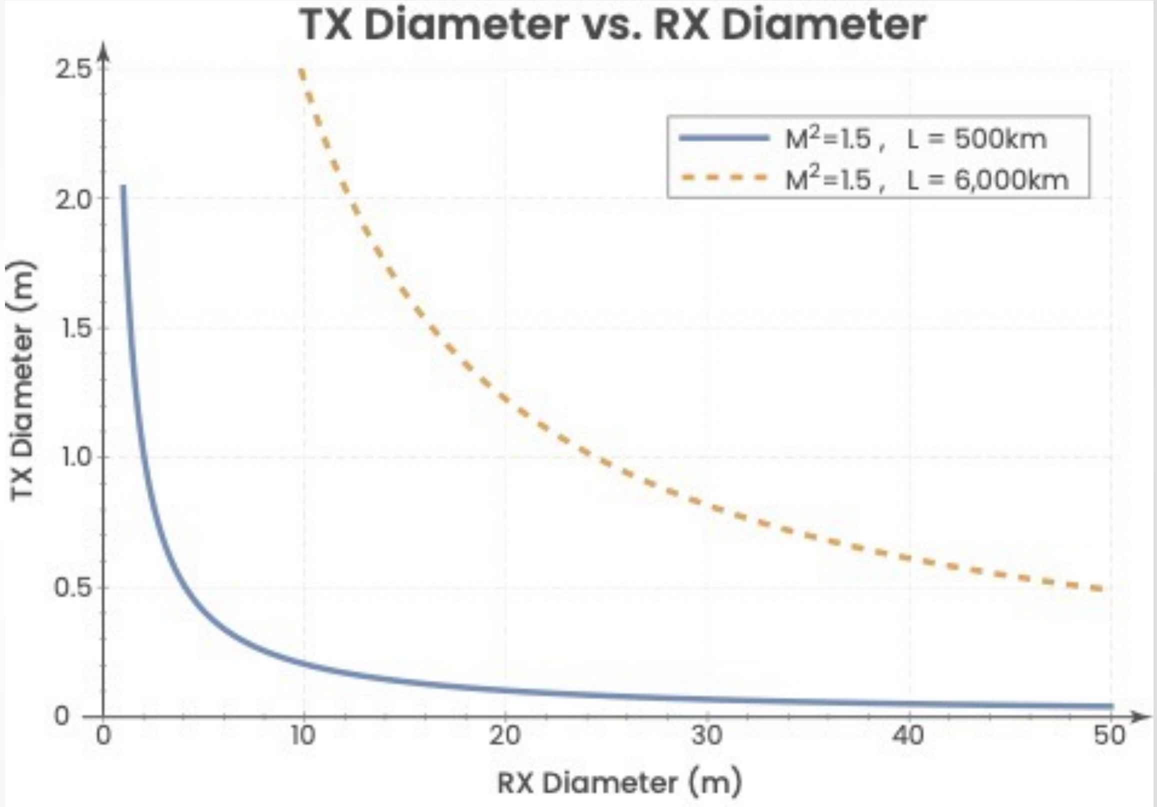
$$d_{TX} = \frac{4\,L\,BPP}{d_{RX}}$$

$$d_{RX} = 2\sqrt{P_{out}\left(\frac{1}{\eta_{RX}} - 1\right)/\pi J_{heat}}$$

Orbit to Ground Apertures

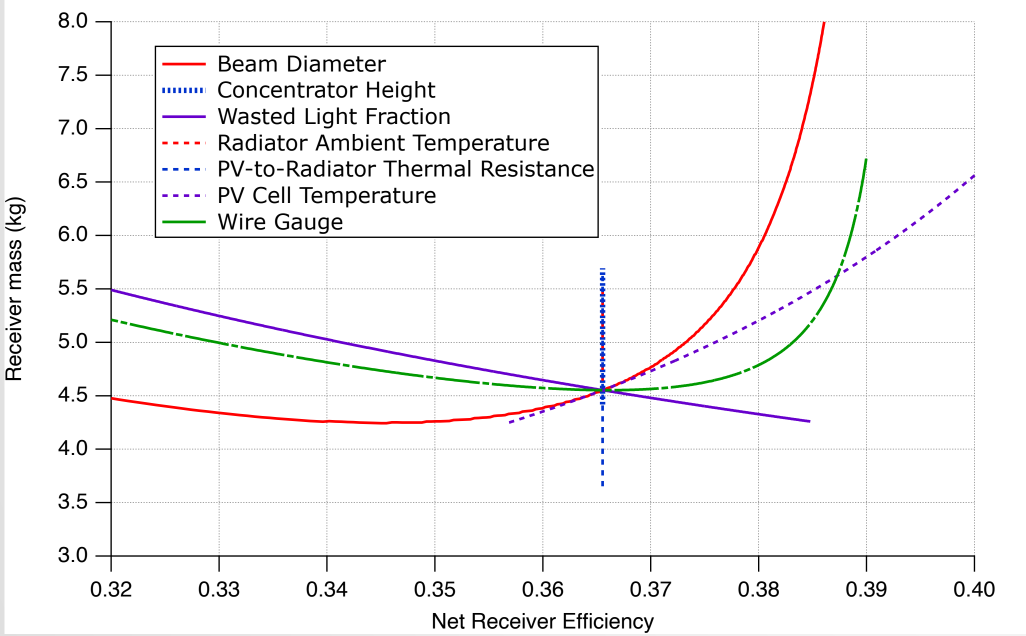
- Provide coverage through the lunar night, regardless of latitude
- Requires larger apertures in orbit and on the surface

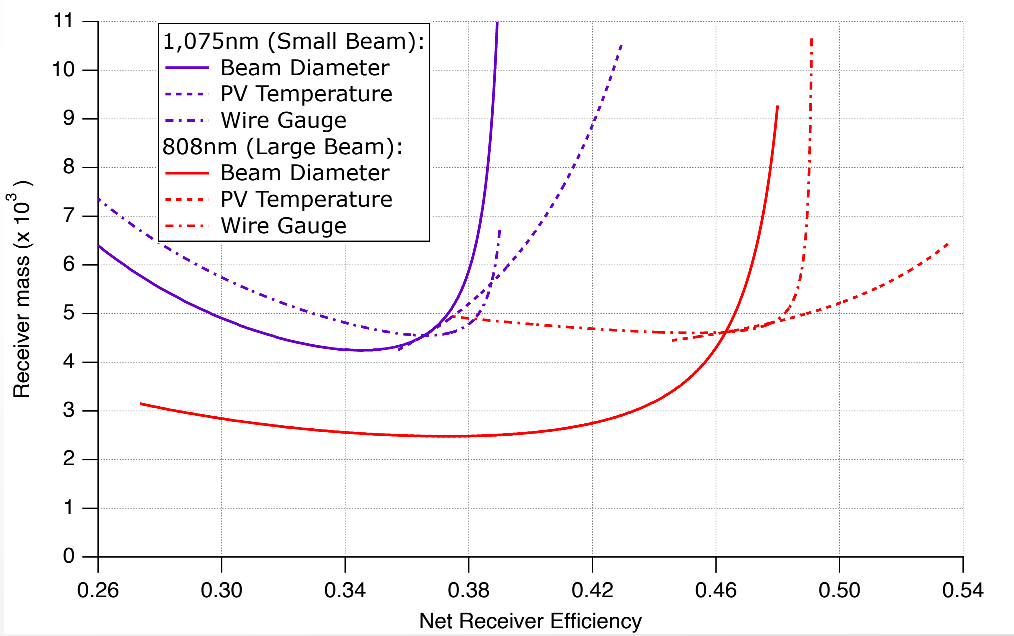




Other Parametric Dependencies

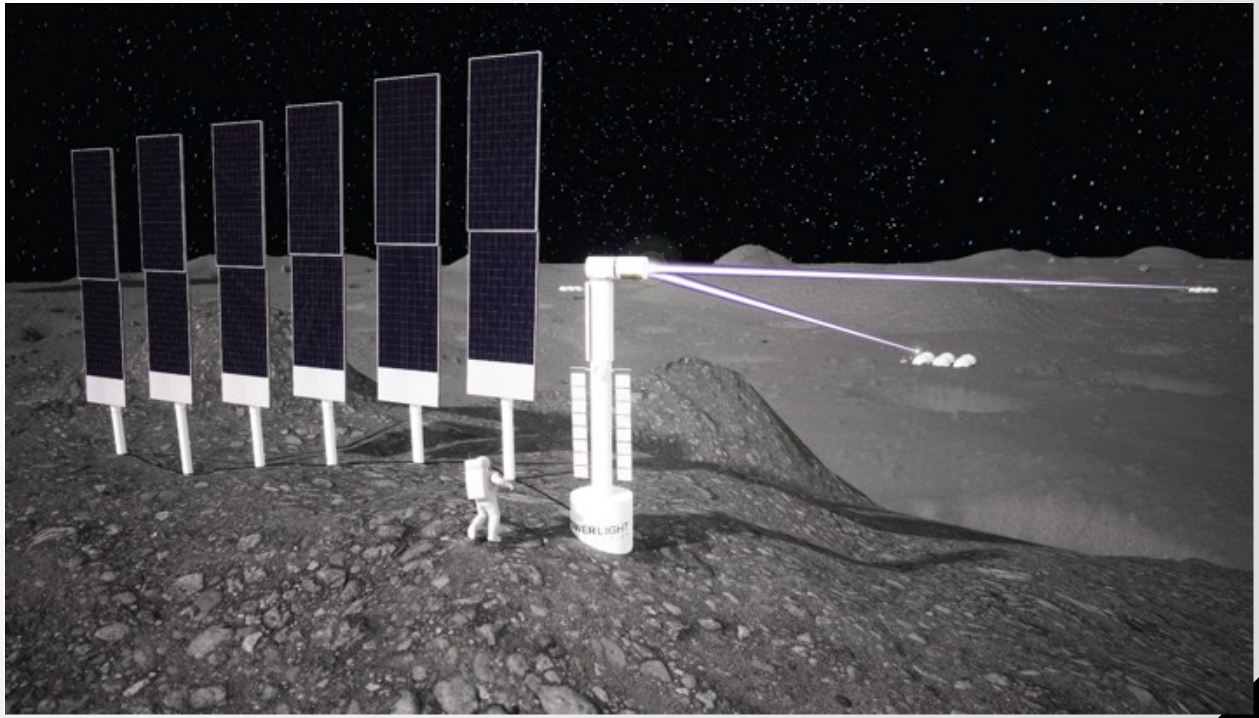
- See impacts on RX mass vs. efficiency when varying a single parameter:





Conclusion

- Laser power beaming on the Moon can solve many limitations of traditional methods of distributing power
  - Continuous power distribution over long distances to mobile devices
  - Provides adaptability to remote locations and flexibility for extended missions
- Biggest challenges are due to the limits of radiative heat rejection
- In the lunar environment, the balance of cost, weight, and flexibility present unique opportunities for laser power beaming.



Power Beaming Book

- Power Beaming: History, Theory, and Practice
  - by Jaffe, Nugent, Strassner, & Szazynski
- Table of Contents:
  - Introduction
  - History
  - Fundamentals
  - Link Characterization
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POWER BEAMING

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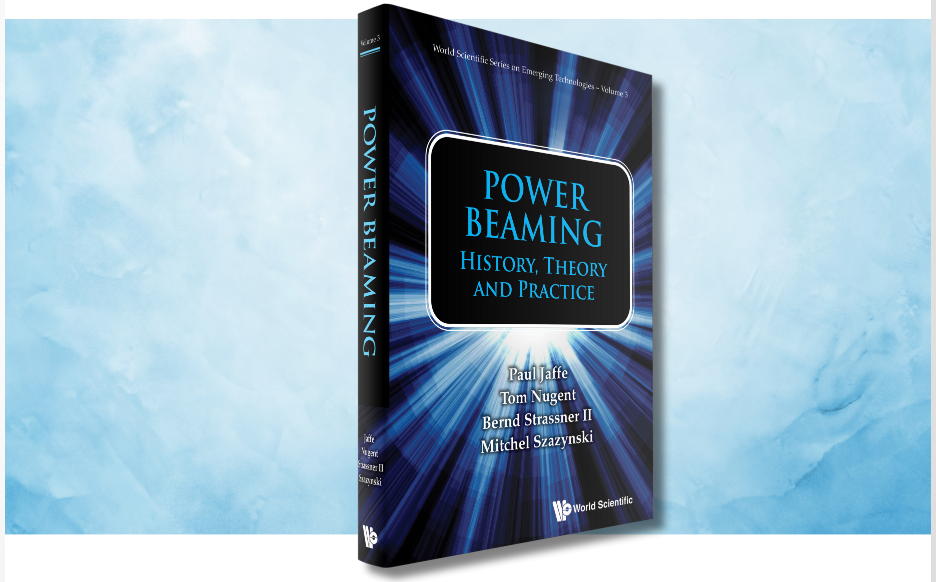

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