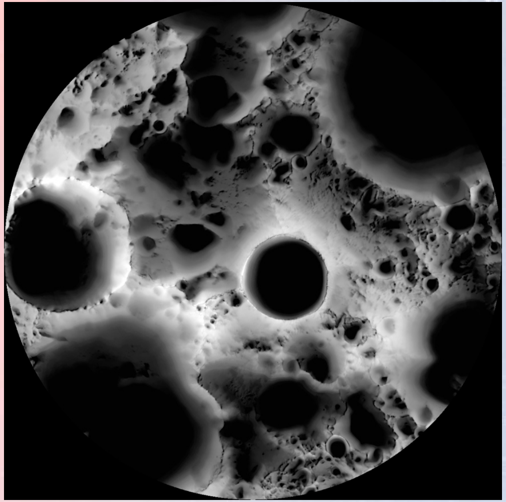
Power Transmission
for Difficult-to-Reach and Mobile Lunar Applications



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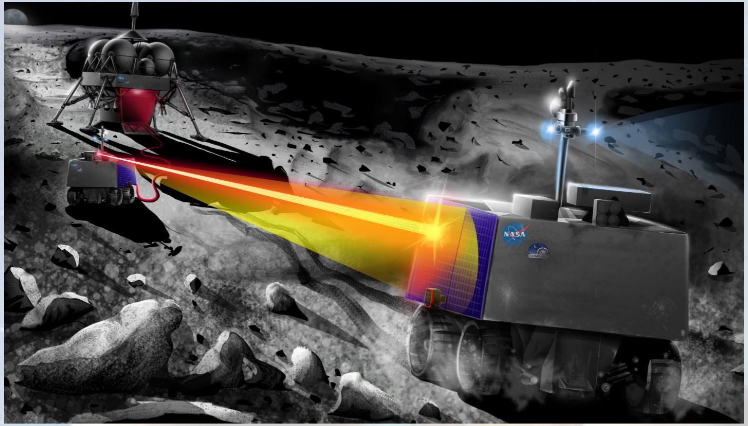
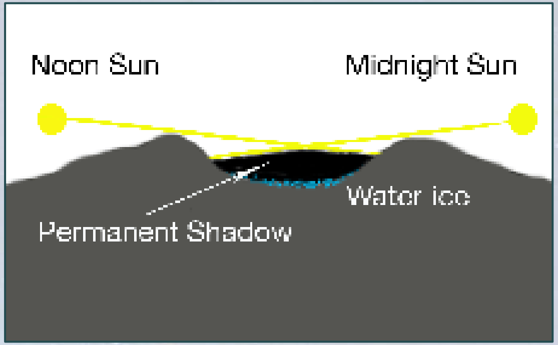


Lunar Polar Exploration

The poles of the moon have permanently shadowed craters that are known to hold frozen volatiles such as water ice.

- ➢ These are of great interest for both science and for resource utilization
- ➢ Identified as a high priority targets for future NASA exploration.
- ➢ South polar region is baseline landing site for NASA Artemis human exploration

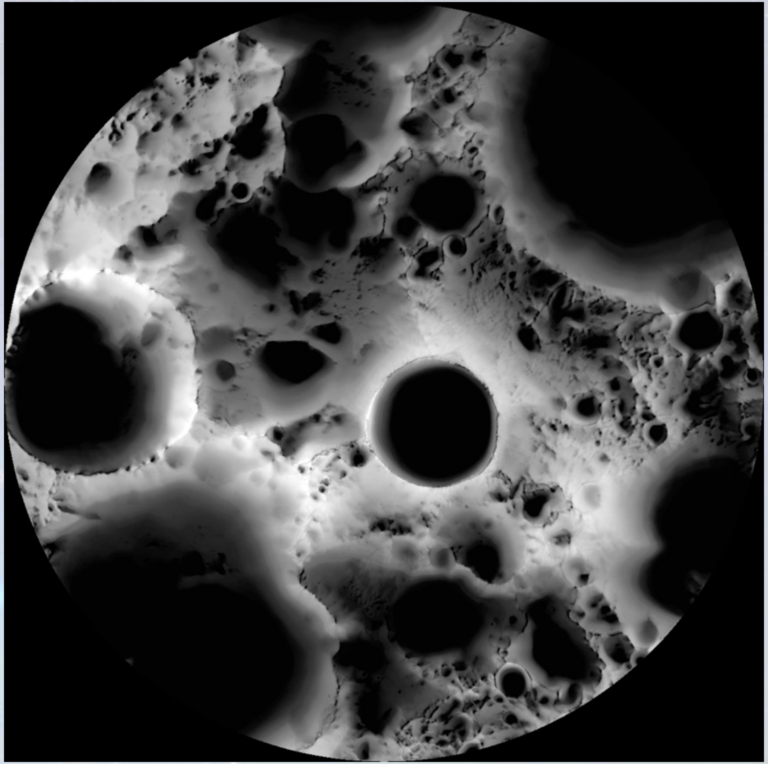


Schematic cross section of polar crater showing position of sun at noon and midnight.

At the lunar poles, the Sun rises no more than 1.6° above the horizon (the angle of the moon's axial tilt). Therefore, relatively shallow craters can have permanently shadowed floors
(NASA image)

Lunar Polar Exploration

- **But electrical power is a challenge for design of rovers for lunar polar operations.**
- The interior of polar craters, with a complete absence of sunlight, means conventional solar power systems cannot operate.
- This have been identified as a significant technology challenge for NASA's future exploration.



Illumination map of Lunar south pole showing regions of permanent shadow. Shackleton crater is visible just off center.

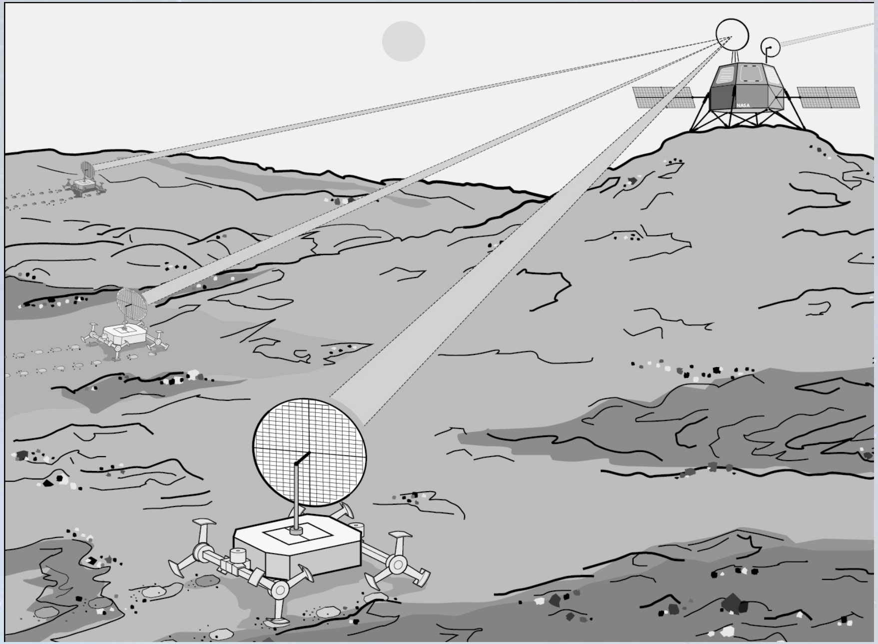
Power Beaming

Possible Beaming approaches:

- Microwave
- Laser
- Millimeter Wave

A **beamed power** system could be used to send power directly to a rover

- Power source at the illuminated rim of such a crater
- Collector on rover converts the beamed energy to electrical power



Sketch of the possible use of a base station on a crater rim beaming power to multiple rovers exploring the permanently shadowed craters of the moon.

Power Beaming: approaches

Possible Beaming approaches:

- Microwave
- Laser
- Millimeter Wave

- Microwave beaming has the highest end-to-end power transfer efficiency, but the longer wavelength requires larger systems (transmitting and receiving antenna diameters)
- Laser power beaming has lower conversion efficiency, but allows smaller systems
  - Wavelength for optical beaming are factor of ~10^4 shorter than microwaves. Thus optics are smaller, and hence systems are much more compact.
- Millimeter wave beaming is at a lower state of technology development; intermediate between microwave and laser wavelengths.

Power Beaming: Microwave

Microwave systems have been proposed for power beaming since early 1970s, when Glaser proposed satellite solar power stations

- Typical frequencies proposed: 2.45 GHz to 5.8 GHz
  - wavelength 5 cm (5.8 GHz) to 12 cm (2.45 GHz)
- Well developed beam technology
  - Often proposed: magnetron tubes (used in microwave ovens)
  - These are cheap and efficient
- High conversion efficiency
  - 85-95% DC to RF efficiency is easy to do
- Receiver technology less well developed but well understood
  - Record rectenna efficiency is 91.4%[1]
  - 80% is more typical (can be less under non-ideal conditions)

[1] A. Bar-Cohen, et al., *Department of Defense Power Beaming Roundtable*, August 2015

Power Beaming: Laser

Laser systems have narrow beam width, and can beam power to photovoltaic cells

- Typical wavelengths: 500 to 1100 nm
- Conversion efficiency for laser transmitters:
  - Best laser efficiency is 50-60%
  - Higher beam quality lasers tend to have lower efficiency
  - Depends on wavelength
- Receiver technology: photovoltaic cells
  - Efficiency about 50% if cell is matched to laser
  - Cell will also convert solar light (but at lower efficiency)
  - Well developed technology

Power Beaming: Millimeter wave

mm wave systems are similar to microwave, but with shorter wavelength

Not typically proposed for terrestrial power beaming because it does not have good path length through clouds or humid air

- Typical frequencies: 90 GHz and up (W Band)[1]
  - Wavelength 3.3 mm and less
  - Short wavelengths allow narrower beam for the same transmitter size
- Beam technology is less well developed
  - But technology is improving rapidly: being developed for 5G telecom
- Receiver technology less well developed
  - Demonstrated efficiency 35% [2]
  - But room for improvement: very little past work on mm-wave rectennas

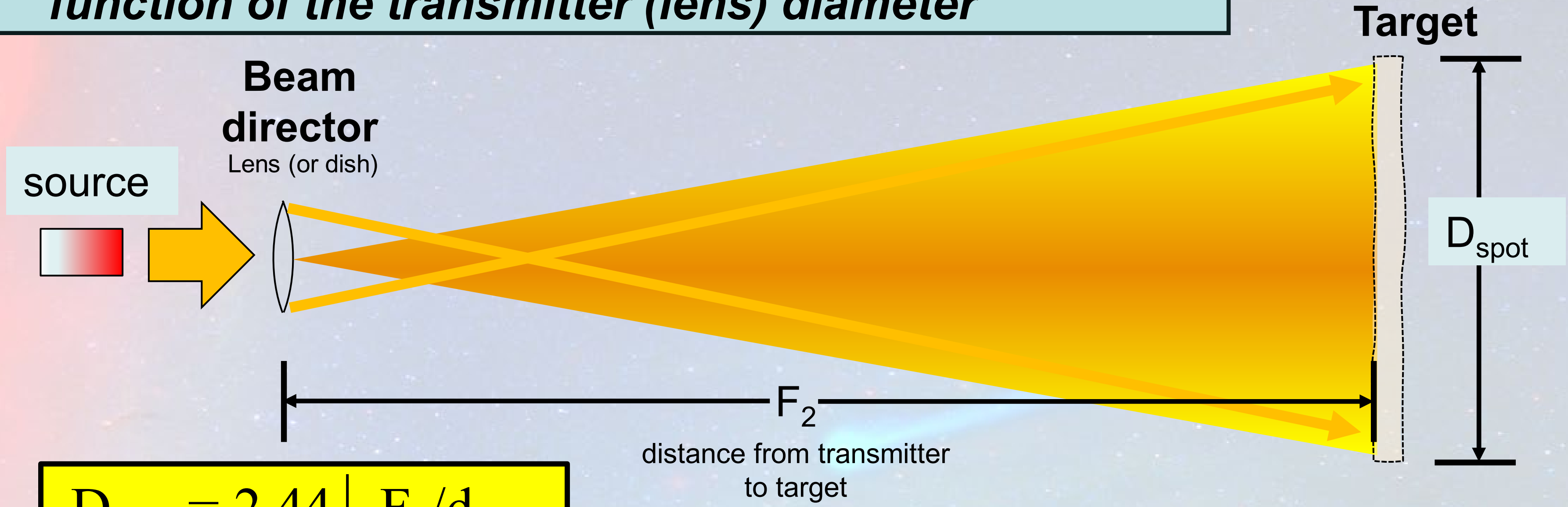
References:

[1] H. Kazemi et al., "Millimeter wave wireless power transmission-technologies and applications." 2019 IEEE Wireless Power Transfer Conference.

[2] A. Bar-Cohen, et al., *Department of Defense Power Beaming Roundtable*, August 2015

Diffraction-limited spot size

- In the diffraction limit, the size of the beam on target is a ***function of the transmitter (lens) diameter***



Target

Beam director

Lens (or dish)

source

D_{spot}

F_2

distance from transmitter to target

$$D_{spot} = 2.44\,\lambda\,F_2/d_{lens}$$

d_{lens} is the diameter of beam director, F_2 the source to receiver distance, and λ the wavelength.
Here spot diameter is defined as the first zero of the diffraction pattern (= 84% beam energy.)

Comparison of diffraction-limited minimum spot size

Spot size is diffraction-limited minimum.
Larger spot sizes can be achieved

50 cm beam director

Beam	λ	Spot size at 500 m	Spot size at 1 km	Spot size at 5 km
Microwave @5 GHz	6 cm	14 m	29 m	140 m
mm Wave @ 95 GHz	3.2 mm	0.780 m	1.6 m	7.8 m
Laser at 1 µm	1 µm	0.0024 m	0.0048 m	0.024 m

For a 50-cm beam director

- microwave beam spread is larger than reasonable rover even at short (500m) distances
- Mm wave beam spread may be reasonable at the shortest distances, but diverge to large areas at distances of several km
- Laser spot sizes are small at even km distances

NASA image

A 50-cm
equivalen

Comparison of diffraction-limited minimum spot size

Spot size is diffraction-limited minimum.
Larger spot sizes can be achieved

50 cm beam director

Beam	λ
Microwave @5 GHz	6 cm
mm Wave @ 95 GHz	3.2 mm
Laser at 1 µm	1 µm

For a 2.5 m beam director

- microwave beam spread is large but not completely unreasonable at ~500 m distance, but too large over km scale distances
- Mm wave beam spread is reasonable up to several km
- Laser spot sizes is small at all distances

2.5 m beam director

Beam	λ	Spot size at 500 m	Spot size at 1 km	Spot size at 5 km
Microwave @5 GHz	6 cm	2.9 m	5.4 m	29 m
mm Wave @ 95 GHz	3.2 mm	0.16 m	0.31 m	1.6 m
Laser at 1 µm	1 µm	0.0005 m	0.0048 m	0.0005 m

US DOT image

A 2.5-m beam director is roughly the size of a small satellite uplink dish

Different technologies for different applications

Microwave Power beaming
  - Large systems, where sizes are large and efficiency is important
  - Short distances, where beam spread is less important
- **Laser Power beaming**
  - Small systems, where size is an important parameter
  - Long distances, where beam spread is an issue
- **Millimeter Wave power beaming**
  - Possible compromise between size and efficiency
  - (but needs technology development)

Space Technology Research Grants program

Lunar Surface Technology Research (LuSTR) Opportunities 2020

Topic 3 - Flexible Power Distribution for Difficult to Reach and Mobile Applications

The goal of this topic is to promote the development of wireless energy transmission technologies to enable exploration in Lunar environments where conventional means of power generation, storage, and distribution are impractical. The objective is to provide simultaneous power beaming of approximately 100 W to multiple, distal (kilometers) assets operating in the lunar environment.

Areas of interest include:

1. Analysis and definition of system parameters and CONOPS for candidate mission scenarios and expected capabilities using up to 1 kilowatt prime power at the source.
2. Development of technologies that could lead to near-term lunar surface demonstration missions;
3. High-efficiency component-level developments that maximize overall system performance across a range of operating parameters with up to 100 Watts of delivered power across km distances; and
4. Pointing accuracy improvements for mobile and stationary operations;

The intent is a notional systems-level development plan for integration with existing technologies to create a fieldable lunar technology demonstration system.

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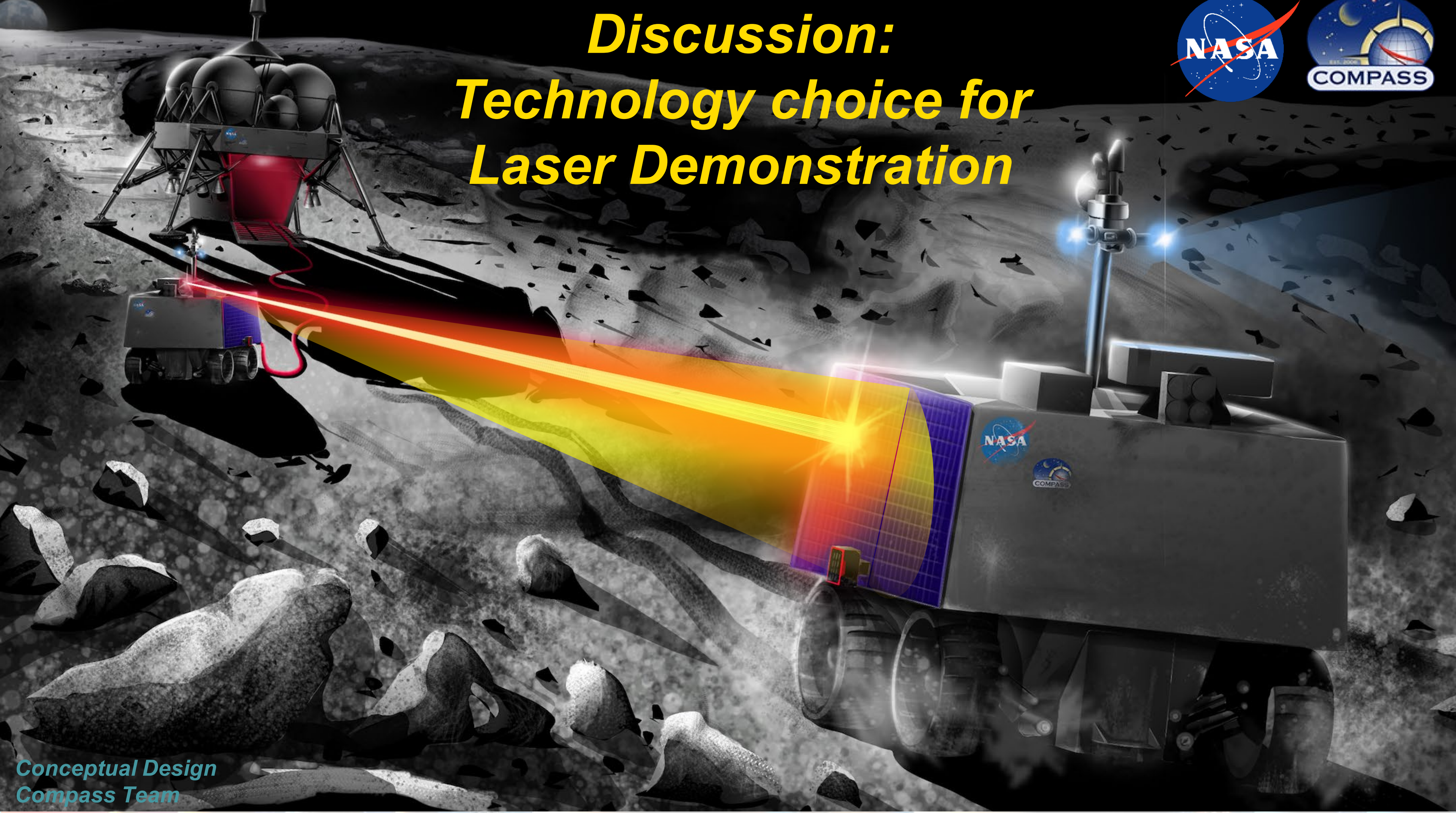
Solicitation issued July 2020
University teams submitted proposals September 2020
Awards to be announced March 2021

Discussion: Technology choice for Laser Demonstration



Conceptual Design
Compass Team

Laser beaming: Choice of laser & receiver

The choice of laser must optimize all four of the following criteria:

- Laser has high electrical to optical conversion efficiency
- Cell has high optical to electrical conversion efficiency
  - (requires laser wavelength selected to match the cell choice)
- High power possible
- High beam quality

Note that the previous discussion of beam spot size was for a diffraction-limited beam. This is only possible if the laser itself produces a beam at the diffraction-limited coherence. Low optical coherence will produce a larger beam spread

Laser choice: Beam Quality

- **Low coherence** light sources project can only focus to a spot size based on classical object/image optics
  - (but not less than diffraction limit)
- **High coherence** light sources can project a spot size as small as the diffraction limit

Laser choice: Efficiency

Two laser technologies have the required high efficiency at wavelengths compatible with photovoltaic receivers

- ➢ Diode laser bars have low coherence
  - ➢ Essentially a classical light source: light output is not in phase
- ➢ Diode-pumped lasers have high coherence
  - ➢ Light output is in phase

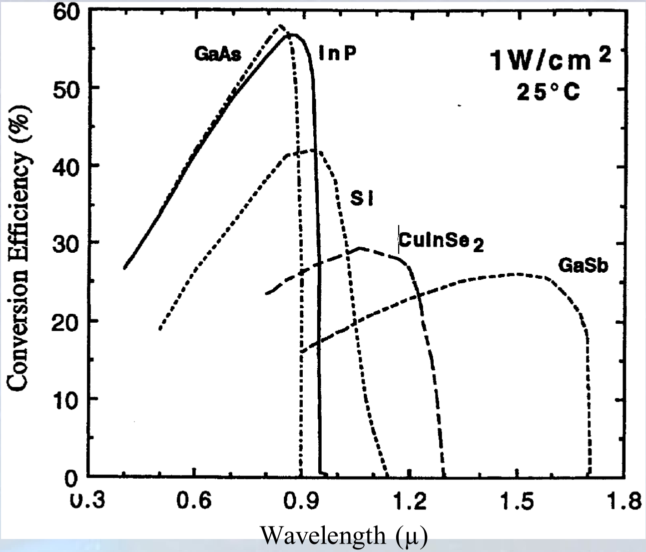
Choice of laser and receiver

Laser power is converted to electricity by photovoltaic cell.

For maximum conversion efficiency, the cell needs energy bandgap slightly lower than the photon energy

$$E = hc/\lambda$$

- For bandgap less than this, efficiency drops proportional to wavelength
- For bandgap higher than this, efficiency is zero
- Can either select a photovoltaic cell to match the laser, or select laser wavelength to match the photovoltaic cell of choice.



Typical cell output as a function of incident wavelength. Note that for all different photovoltaic materials, efficiency rises roughly linearly with wavelength up to peak, then drops to zero for wavelengths longer than the cutoff.

Choice of laser receiver: GaAs at 810 nm

- GaAs solar cells have the highest reported efficiency for converting laser illumination to electricity
- Well-developed technology, flown in space
- Efficiency of up to 60% has been reported*
  - *but this is for fiber transmission, not for free space
- **Commercially available devices** with efficiency of 53% at λ=810 nm.

Choice of laser: 810 nm

Semiconductor bar lasers are available including 810nm.

- Commercially available bar lasers with electrical-to-optical efficiency over 55% available at power >1 kW.

Example of high-efficiency semiconductor bar laser

- But beam quality is poor
  - In laser terms, the beam is not coherent
  - Low beam quality means larger-than-diffraction-limited spot size.
- However, with good design this distance can be hundreds of meters
  - for hundreds of meter demonstration-level systems, this would be practical.

Choice of laser: fiber pumped laser at 1.06 µ

- Diode-pumped fiber lasers have a high single-mode coherence
- Commercially available at high power levels.
- realized efficiencies of up to 50% at a wavelength of about 1.06 µ.
  - Since this relies on a specific transition of Neodymium atomic levels, the wavelength choice is fixed, so here we must pick a photovoltaic cell to match the laser, instead of picking a laser to match the photovoltaic cell

[1] Clay McPheeters, *2020 Conf. on Advanced Power Systems for Deep Space Exploration*

Choice of cell for laser at 1.06 μ

Two reasonable cell choices

1. **III-V ternary (**or quaternary) at a bandgap selected to match the laser, about 1.08 eV.

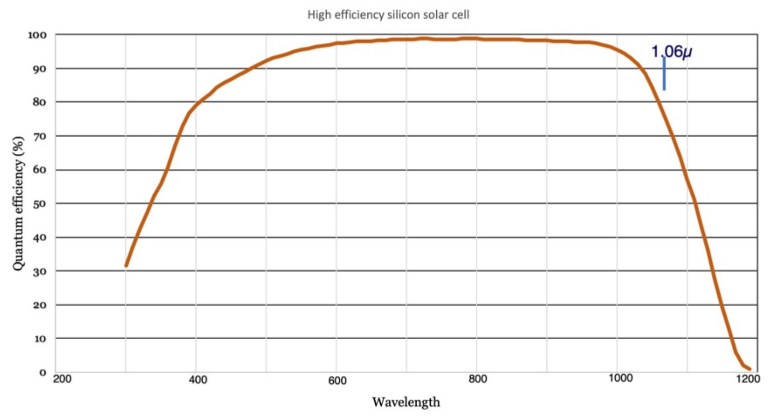
- This is an adaptation of the technology of multijunction cells currently used for space
- Reported efficiency for 1 cm^2 cells range from 37.87% at 538 mW/cm^2 power density at 1064 nm, up to (extrapolated) 47.5% efficiency at 1.5 W/cm^2 incident power[1]
  - These power densities are extremely high, and would require large heat sinks. Power density for beamed power systems is likely to be somewhat lower, and hence efficiency wlll be lower.
- Not a commercially available product

[1] Clay McPheeters, *2020 Conf. on Advanced Power Systems for Deep Space Exploration*

Laser and cell choice: 1.06 μ

2. **Silicon cells**.

- Despite bandgap near theoretical optimum, Si has a low absorption coefficient at 1.06μ
  - hence conventional silicon cells have poor spectral response at this wavelength.
- But advances in Si solar cell technology have pushed long wavelength response
- Another possibility is to let the cell operate at higher temperature. This will increase the long-wavelength response.



Example quantum efficiency of a high-efficiency Si cell, showing >80% QE at 1.06 micron wavelength

- Best silicon cells are 39.4% efficient at 1.06 μ.
- Advanced silicon cells are commercially produced in high quantities for terrestrial use.
- Radiation tolerance of these cells is expected to be low, but the lunar surface is a comparatively low radiation environment
  - If required, the coverglass thickness can be increased to decrease radiation dose

Conclusions

- Power beaming technologies are a plausible technology to power rovers exploring permanently shadowed lunar craters
- Microwave, mm-wave, and laser beams all have advocates
  - Different technologies may be optimal for different applications
- One plausible power transmission candidate is a diode-pumped fiber laser at 1.06 μ, using III-V ternary or a Si photovoltaic converter
- No showstoppers for use of this technology for a lunar demonstration
- but technology needs to be developed and demonstrated