Laser Power Beaming for Lunar Polar Exploration

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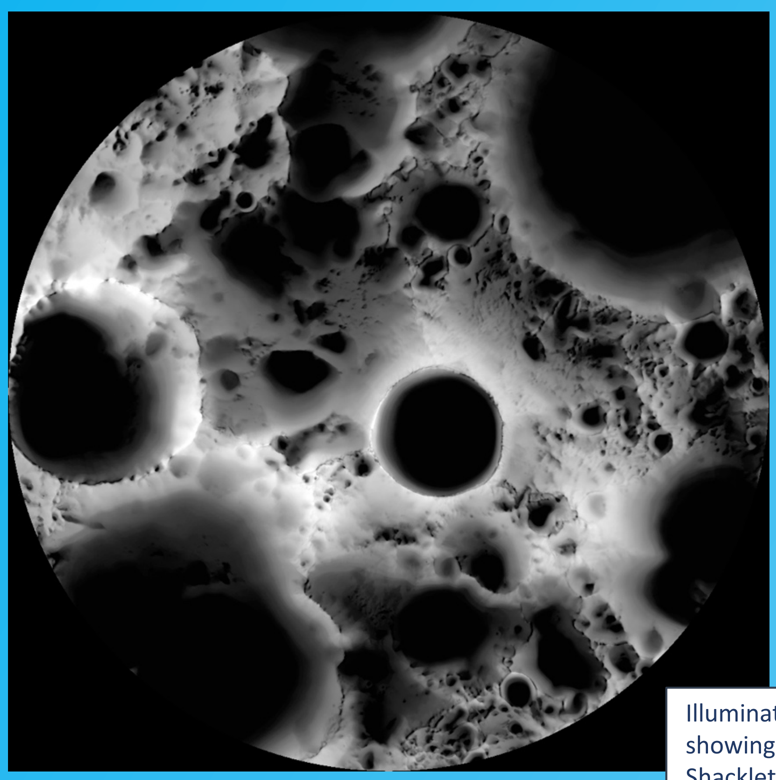
The poles of the moon have permanently shadowed craters that are known to hold frozen volatiles such as water ice.

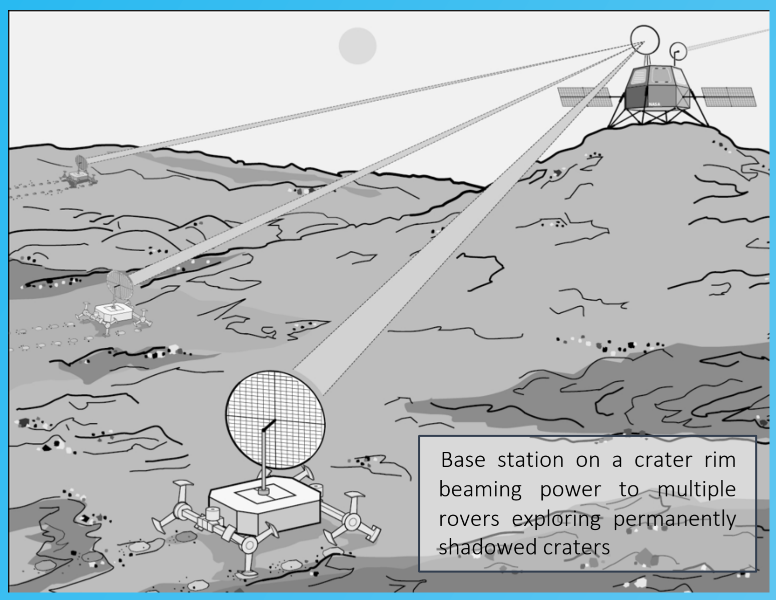
- These are of great interest for both science and for resource utilization
- Identified as a high priority targets for future NASA exploration.
- South polar region is baseline landing site for NASA Artemis human exploration

But electrical power is a challenge for design of rovers for lunar polar operations.

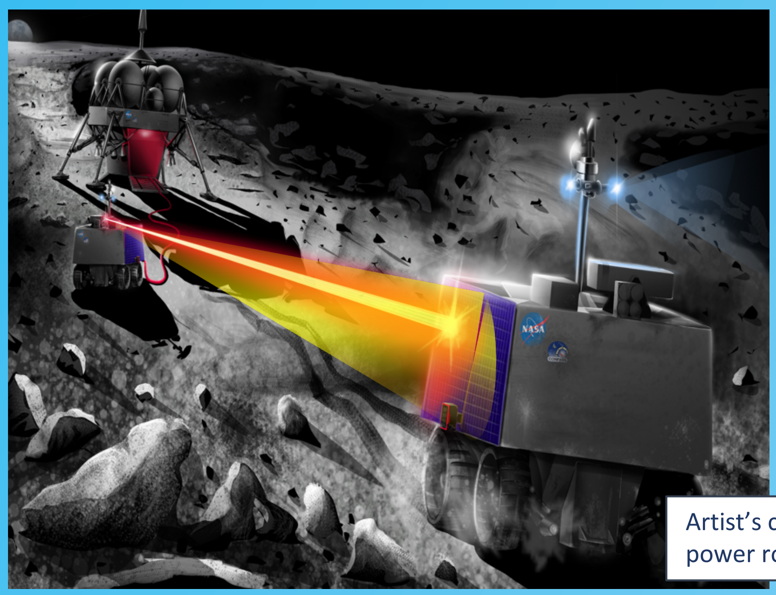
- The interior of polar craters, with a complete absence of sunlight, means conventional solar power systems cannot operate.
- This have been identified as a significant technology challenge for NASA's future exploration.



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



Base station on a crater rim beaming power to multiple rovers exploring permanently shadowed craters



Artist's conception of laser-beamed power rover demonstration

Power beaming has been proposed using both laser and microwave sources.

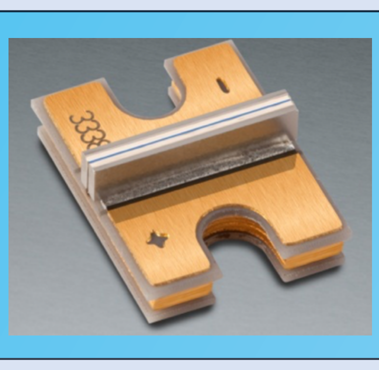
- Wavelength for optical beaming is factor of ~10^4 shorter than microwaves. Thus optics are smaller, and hence systems are much more compact.
- On the other hand, generation of microwaves can have efficiencies of 85% or higher, while the best lasers have ~50% electrical-to-light efficiency
- Both systems have possible applications in space.

A possible advantage of laser power receivers is that a photovoltaic panel to convert laser radiation will also convert sunlight.
When rover moves into an illuminated area, a laser receiver functions as a solar array.

Trade-off choices: available technology

Laser choice: 810 nm

Commercial semiconductor diode laser bars are available with electrical-to-optical efficiency over 55% at 810 nm, at power >1 kW.
Wavelength can be selected for a range of visible and near-IR



Example of high-efficiency semiconductor bar laser

Laser choice: 1060 nm

Diode-pumped fiber lasers available commercially have 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 is not variable, and hence the system must choose a photovoltaic cell to match the laser.

Laser receiver: 810 nm

- GaAs solar cells operating at 810 nm 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
- receivers with efficiency of 53% at λ=810 nm are Commercially available.

Laser receiver: 1060 nm

- Two reasonable cell choices.
  1. III-V ternary or quaternary alloy at a bandgap selected to match the laser, about 1.08 eV.
     - Reported efficiency for 1 cm^2 cells range from 31.5% to 37.87% at 538 mW/cm^2 incident power density at 1064 nm
     - Not a commercially available product
  2. Silicon cells.
     - Despite bandgap near optimum, Si has a low absorption constant at 1064 nm
     - hence conventional silicon cells have poor spectral response at this wavelength.
     - Advances in Si solar cell technology have pushed long wavelength response

For laser power beaming, the laser choice is required to optimize 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

Laser choice: Beam Quality

- Low coherence light sources project can 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

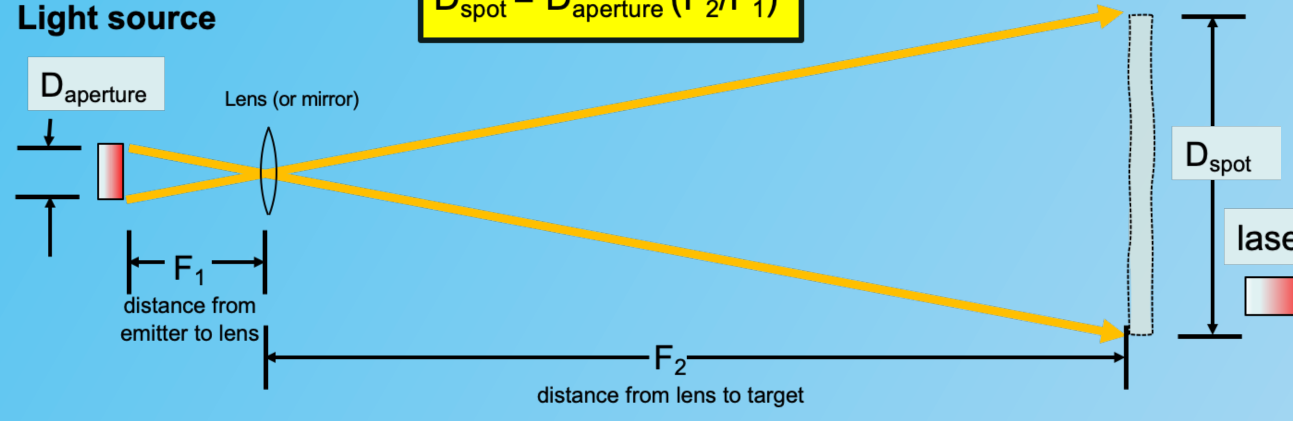
Two types of laser have the required high efficiency

- 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

Classical optics spot size

In classical (incoherent) optics, the size of the beam on target is a ***projected image of the emitting aperture***

$$D_{spot} = D_{aperture} (F_2/F_1)^*$$



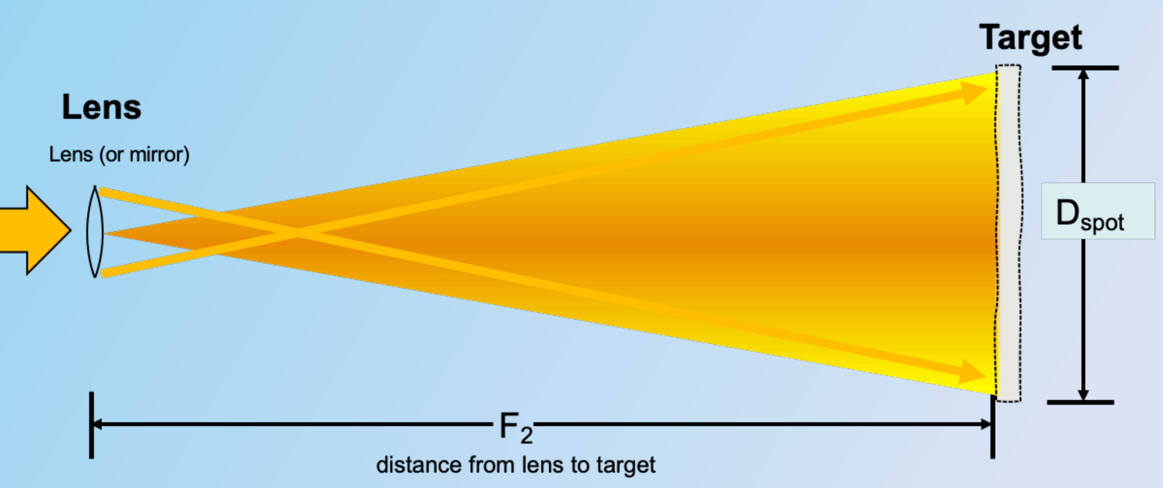
Example case:

$D_{aperture}$ = 1 mm
F_1(focal length) = 25 cm
F_2(distance to target) = 200 m
D_{spot} =800 $D_{aperture}$= 80 cm

Coherent source: Diffracted limited spot size

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

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



Example case:

d_{lens} = 20 cm
λ = 1 μ (10^{-6} m)
F_2(distance to target)=200 m
D_{spot} = 0.244 cm

Photovoltaic receiver choice

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
- either select a photovoltaic cell to match the laser, or select laser wavelength to match the cell choice.

Conclusions

- New laser technologies with high efficiency at high power has made feasible laser beaming for providing power to rovers exploring permanently shadowed lunar craters
- Near-term design: diode laser bars at 810 nm with GaAs photovoltaic converters
- Longer distance power transmission: diode-pumped fiber laser at 1.06 μ, using III-V or Si photovoltaic converter