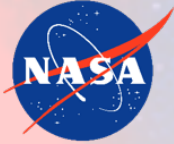


Lunar Polar Exploration with Beamed Powered Rovers

Geoffrey A. Landis

NASA Glenn Research Center, Cleveland, OH, 44135

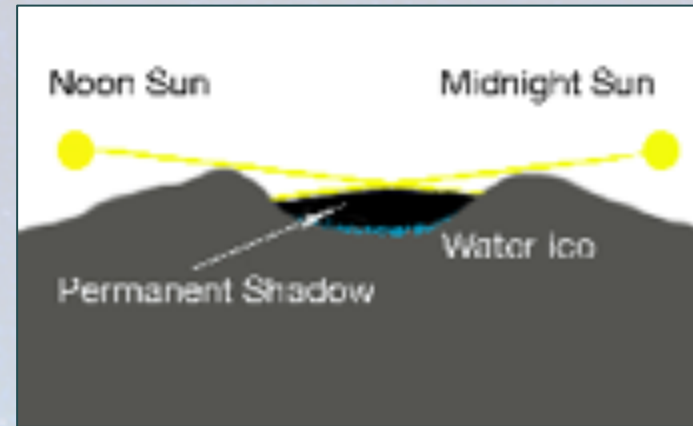
Conference on Advanced Power Systems for Deep Space Exploration,
Pasadena CA, Oct. 27-29 2020.



Lunar Polar Exploration

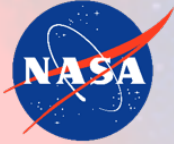
The poles of the moon have permanently shadowed craters that are known to hold frozen volatiles such as water ice.

- 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



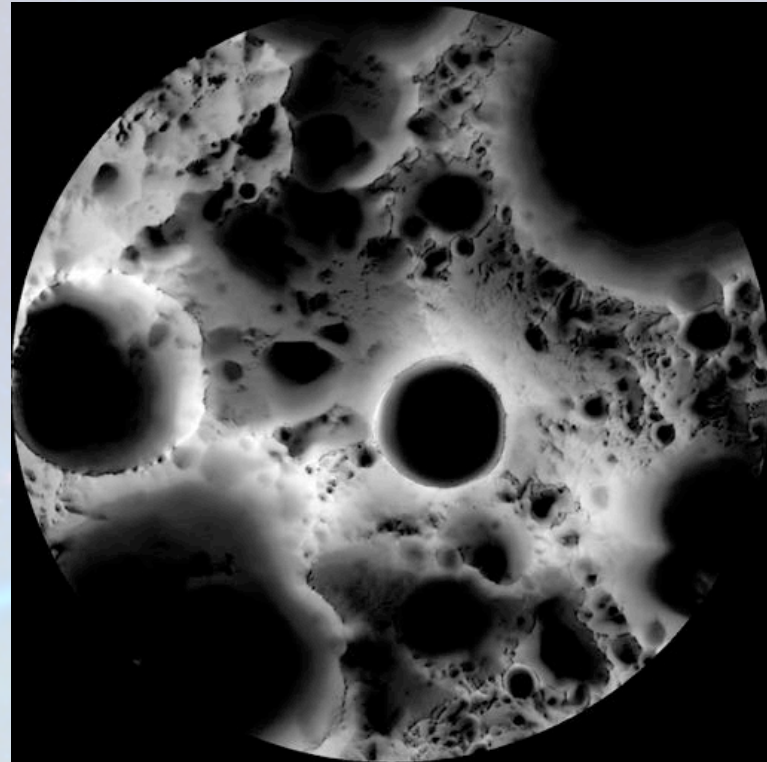
Schematic cross section of polar crater showing position of sun at noon and midnight.

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)

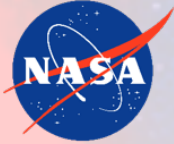


Lunar Polar Exploration

- **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.



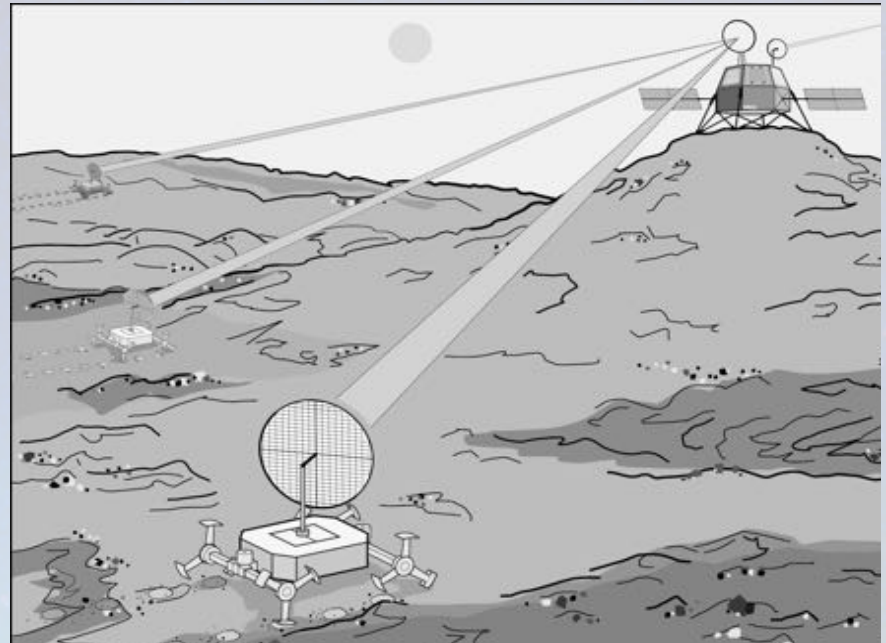
Illumination map of Lunar south pole showing regions of permanent shadow. Shackleton crater is visible just off center.



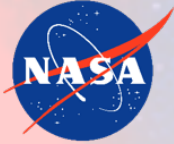
Laser Power Beaming

It has been proposed that a laser could beam power directly from a power source at the illuminated rim of such a crater to a photovoltaic receiver that converts the optical energy to electrical power on a rover exploring inside the permanently shadowed region

- Correctly chosen photovoltaic cells can convert monochromatic (laser) light into electricity at efficiency $>50\%$.
- Recent advances in laser technology now make this approach seem to be feasible.



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.

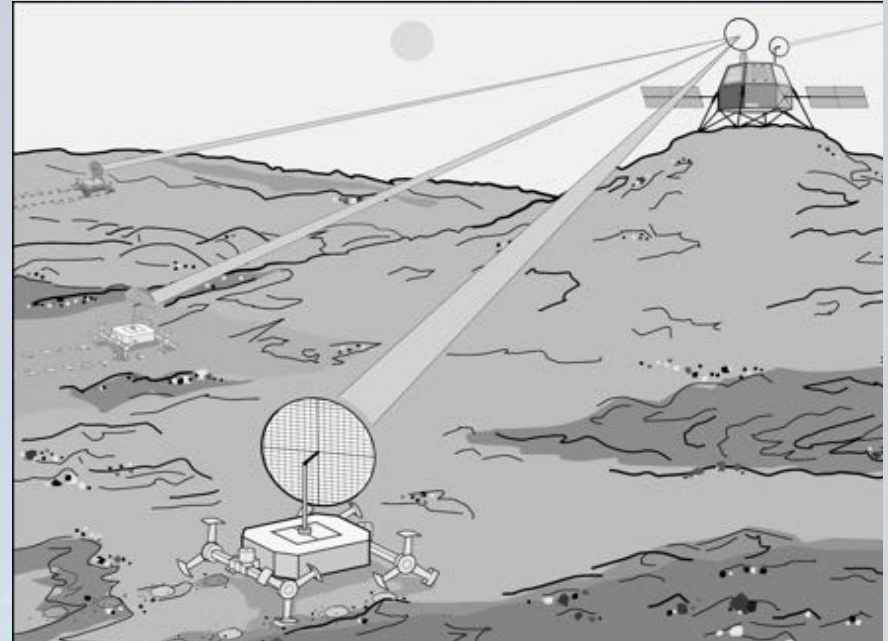


Why Lasers?

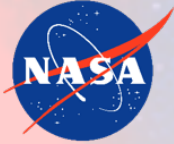
Power beaming has been proposed using both laser and microwave sources.

- Wavelength for optical beaming is factor of $\sim 10^4$ 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 $\sim 50\%$ electrical-to-light efficiency
- Both systems have possible applications in space.
- At small power levels (e.g., small lunar rovers), the size of laser systems is desirable

- Another 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.

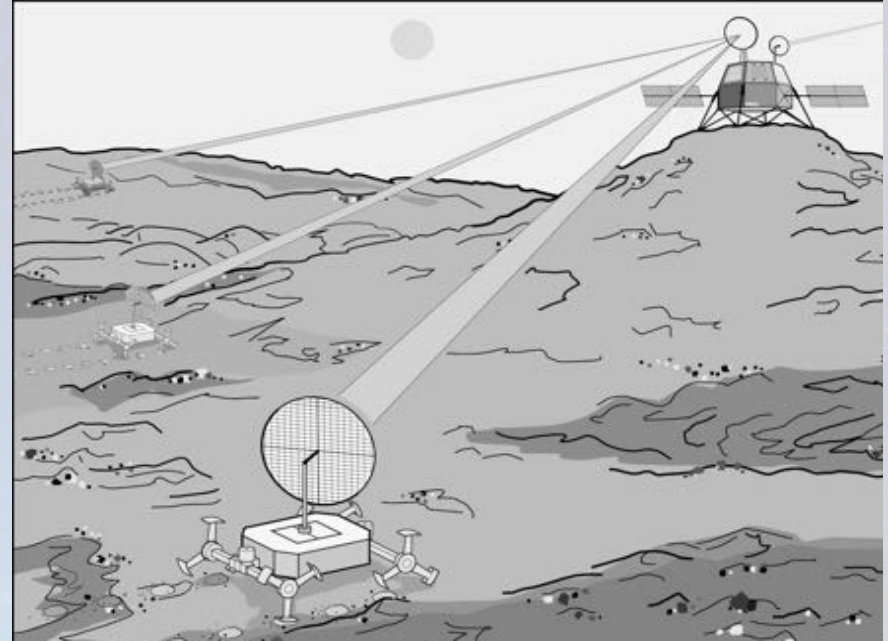


Sketch of the possible use of a base station on a crater rim beaming power to multiple rovers exploring the permanently shadowed craters of the moon.

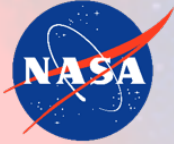


Demonstration needed

- While such systems have been proposed, a demonstration of power transfer at high enough power to operate a rover will be critical before such a system can be used on the moon.
- Project goal is to develop and demonstrate this capability: surface to surface laser-power beaming, at a level capable of powering a lunar rover.



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.



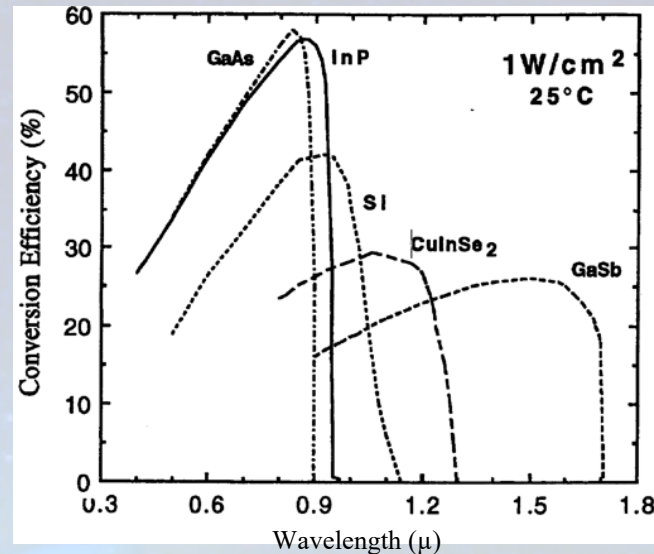
Choice of laser and receiver

Laser power is converted to electricity by photovoltaic cell.

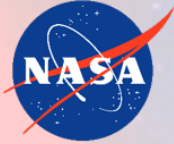
For maximum conversion efficiency, the cell needs energy bandgap slightly lower than the photon energy

$$E = hc/\lambda$$

- 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 and receiver

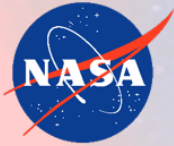
The laser choice is required to optimize the following criteria:

- 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



Choice of laser receiver: GaAs at 810 nm

- GaAs solar cells have the highest reported efficiency for converting laser illumination to electricity
- Efficiency of up to 60% has been reported*
 - *but not for free space transmission
- Commercially available devices with efficiency of 53% at $\lambda=810$ nm.



Choice of laser: 810 nm

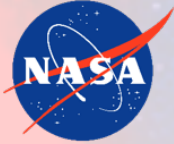
Semiconductor bar lasers are available including 810nm.

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



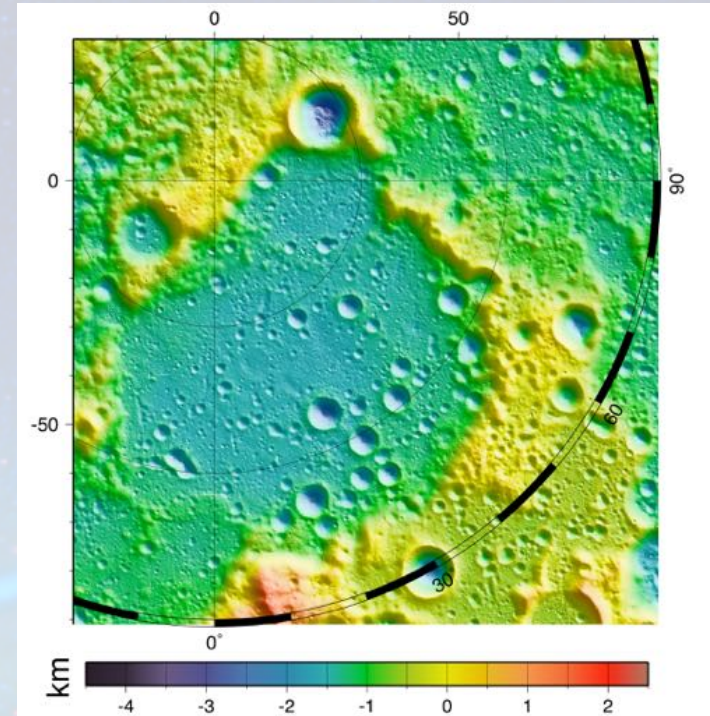
Example of high-efficiency semiconductor bar laser

- 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 shorter (hundreds of meters) or demonstration-level system to show the feasibility, this would be practical.



Demonstration mission

- Conceptual design done of a flight demonstration of laser power beaming.
- Designed as addition to a proposed flight demonstration of the Kilopower space reactor on a proposed lunar lander.
- The mission target was Peary crater, in the moon's northern polar region.
- 100 watt demonstration goal.



Peary crater: topographic map based on laser altimetry from LRO

Lunar Kilopower Demonstration Mission



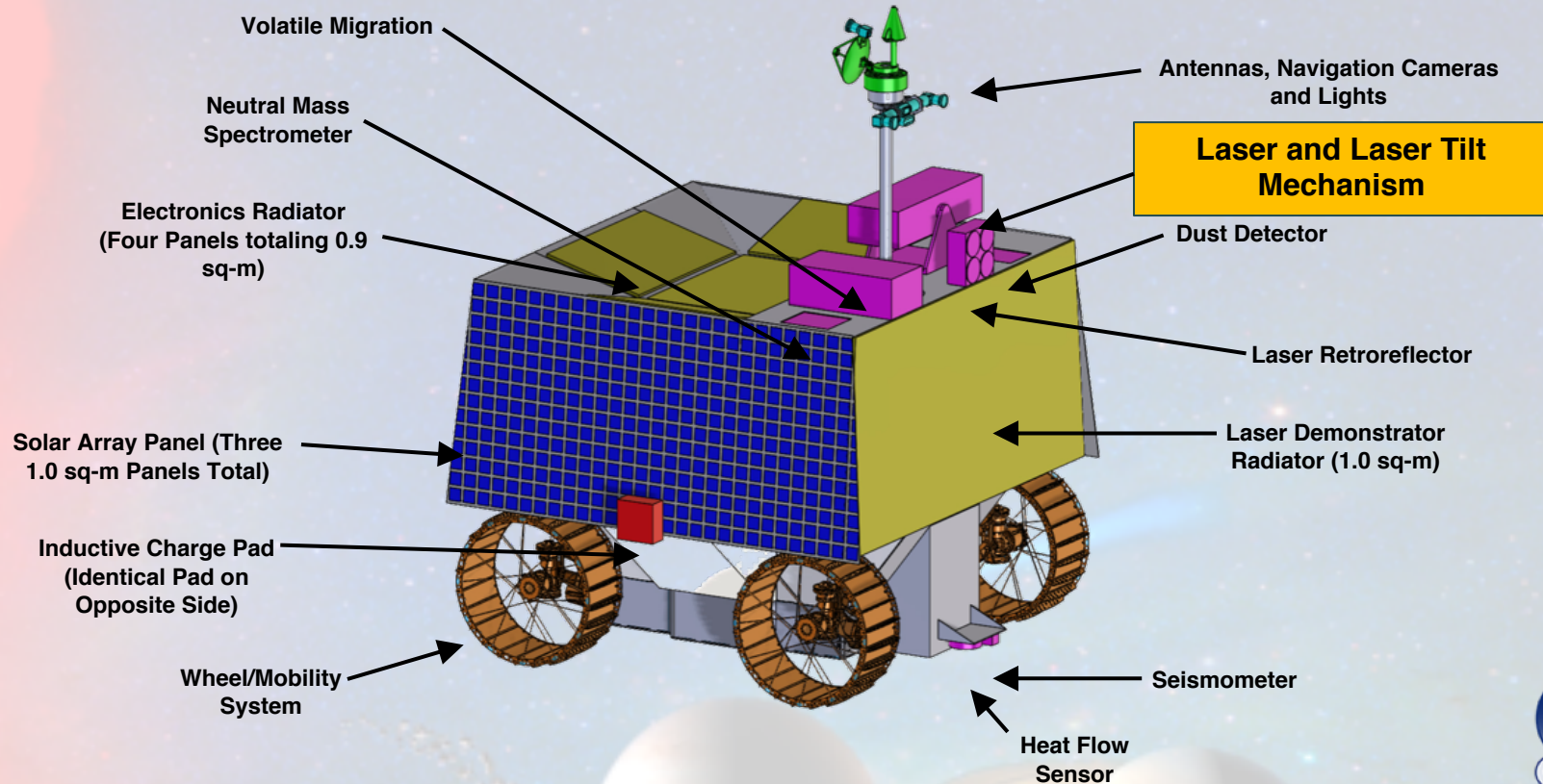
***Conceptual Design
Compass Team***



Demonstration mission: lander showing rover deployment



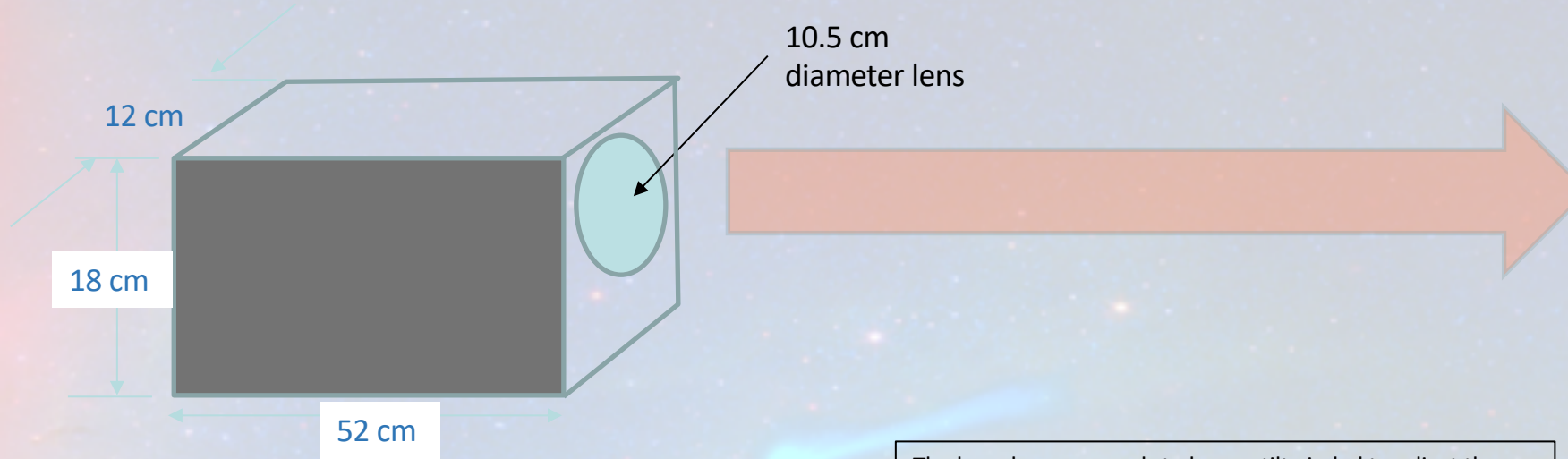
Lunar Kilopower Demo Service Rover External Components



Beamed Laser Demonstrator

- Beamed power laser experiment
- Laser placed on top Service Rover
 - 10cm beam director (Primary mirror reflector)
 - Laser package (includes secondary reflector mirror 0.5m beampath from primary)
- 500We input to laser (250 Wth waste heat - needs dedicated radiator)
- 250W beamed power to array on science rover (80% of beam hits 1m² array)
- 100We to science rover (at 50 m away from lander) 50% conversion efficiency
- Solar arrays for the experiment need to be single junction GaAs
 - will still operate with normal sunlight BUT at 20% efficiency

Laser and Beam director: dimensions



Schematic: not to scale

Total laser mass 7.8 kg, not including the thermal control system.

The laser beamer needs to have a tilt gimbal to adjust the aim point relative to the horizon. The CONOPS is that the rover will steer to the beam position, rather than the beam targeting the rover, and hence no azimuth gimbal is needed.



Laser power beaming experiment: specifications

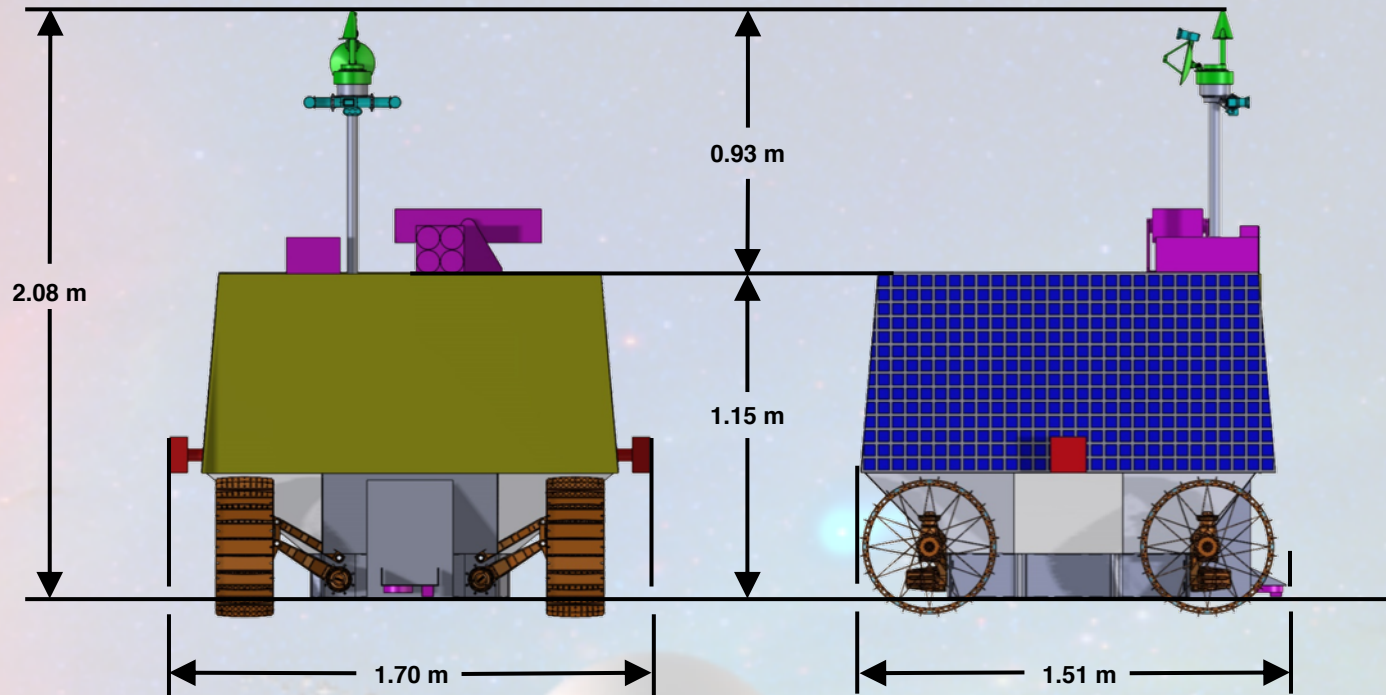
500 watts input power to laser
250 watts laser beam power
250 watts heat rejection required to keep laser temperature $<35^{\circ}\text{C}$

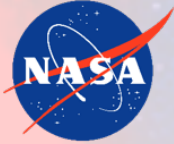
250 watt beam power:
assume 80% of beam hits receiver array (50 meter distance)
200 watts incident into receiver array at 50% conversion efficiency:
100 watts DC power to rover out of array

Laser is a high efficiency diode bar at 808 nm
Laser must be radiation shielded from reactor neutrons
1 cm square laser head
0.5 meter focal length to beam director
projects to 1 meter square at 50 meters (need 10 cm mirror for 10 degree divergence on slow axis)

5 minutes is the minimum requirement to declare success
1 hour is our nominal baseline experiment.

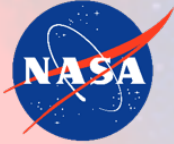
Lunar Kilopower Demo Service Rover Dimensions





Laser and cell choice: Next-generation system

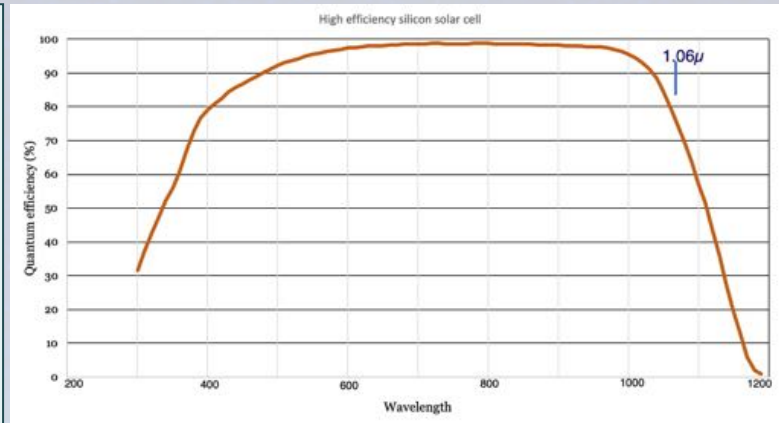
- Diode-pumped fiber lasers have realized efficiencies of up to 50% at a wavelength of about 1.06μ .
 - Since this relies on a specific transition of Neodymium atomic levels, the wavelength is not variable, and hence the system must choose a photovoltaic cell to match the laser.
- Two reasonable cell 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



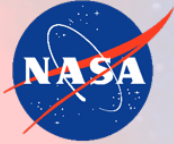
Laser and cell choice: Next-generation system

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



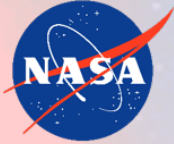
Example quantum efficiency of a high-efficiency Si cell, showing >80% QE at 1.06 micron wavelength



Laser and cell choice: Next-generation system

2. Silicon cells.

- Best silicon cells at 1064 nm wavelength are 39.4% efficient at 1064 nm.
 - Similar to the efficiency produced by the InGaAs cells above,
- Large-area advanced silicon cells are being commercially produced in high quantities for terrestrial use.
- Although radiation degradation of these cells is expected to be high, the lunar surface is a comparatively low radiation environment
 - the cells should hold up to the environment.
 - If required, the coverglass thickness can be increased to decrease radiation dose
- **Candidate selected for next-generation converter**



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 was analyzed using diode laser bars at 810 nm with GaAs photovoltaic converters
- Longer distance power transmission candidate is diode-pumped fiber laser at $1.06\ \mu$, using Si photovoltaic converter
- No showstoppers found for use of this technology for a lunar demonstration