

Laser Power Beaming for Lunar Polar Exploration

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Advances in laser technology now makes it reasonable to use a laser to beam power directly from a power source at the illuminated rim of the crater to a photovoltaic laser receiver on a rover exploring inside the permanently shadowed region. To move this technology from the conceptual design to a system that can be implemented for exploration, it will have to be demonstrated, both with ground- and space-based prototype systems. A conceptual design was done of a possible flight demonstration of laser power beaming. The design envisioned the demonstration as an addition to a proposed flight demonstration of the Kilowatt space reactor, on a proposed lunar lander.

I. Introduction

Systems to provide electrical power are a challenge for lunar polar operations. Specifically, exploration of the ice-bearing permanently-shadowed craters near the lunar poles, in which the complete absence of sunlight means conventional solar power systems cannot operate, have been identified as a significant technology challenge for NASA's future exploration (for example, in STMD Strategic Thrust D, "Sustainable power in extreme lunar surface environments".)

Enright and Enright and Carroll [1] and others [2-5] have proposed powering a rover in such conditions has been to utilize a laser to beam power directly from a power source (either a solar array or a nuclear reactor) at the illuminated rim of such a crater to a photovoltaic laser receiver that converts the optical energy to electrical power to recharge a rover exploring inside the permanently shadowed region.

Recent advances in laser technology now make this approach seem to be feasible. However, the gap to be addressed between needs and capability is that while such systems have been previously proposed, a demonstration of power transfer at high enough power to operate a rover has never been done, and this will be critical before any such system can be used on the moon. To move this technology from the conceptual design to a system that can be implemented for exploration, it will have to be demonstrated, both with ground- and space-based prototype systems. The project goal is to develop and demonstrate this capability: surface to surface laser-power beaming, at a level capable of powering a lunar rover.

Laser power beaming has been proposed before, including significant work done at NASA during the 1990s [6-9], culminating with a centennial challenge resulting in a demonstration of an optical power transmission system capable of beaming power over ~km scale distances [10], but there has not previously been a compelling need for the capability. The current NASA objective of developing technologies for lunar polar exploration provides the need, and the evolution of higher-power and more efficient lasers provides the opportunity. This will put together several disparate technologies: the recent development of high-efficiency fiber lasers, along with solar cells capable of operating at the laser wavelength.

Optical power beaming using a laser power can be compared to using microwaves, which has also been proposed for long-distance beaming of power. The wavelength used for optical beaming, a factor of about $\sim 10^4$ shorter than microwaves, makes the spot size correspondingly larger, and hence systems for optical beaming are much more compact. On the other hand, generation of microwaves using vacuum tubes can be done at efficiencies of 85% or higher, considerably more energy efficient than lasers, which typically have electrical-to-light efficiency of 50% at best. Likewise, the conversion of the beam to electrical power at the receiver is higher for microwave systems, again about 80% conversion efficiency under ideal conditions (the record conversion efficiency, by Brown, is 90.6% [11]). This compares to efficiencies on the order of 50% for the photovoltaic converters [12]. In the real world, both of these conversion efficiencies will be lower.

A peripheral advantage of laser power receivers is that the same photovoltaic panel that converts laser radiation

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into energy will also convert solar energy. Thus, when rover moves into an illuminated area, the laser receiver will function as a solar array.

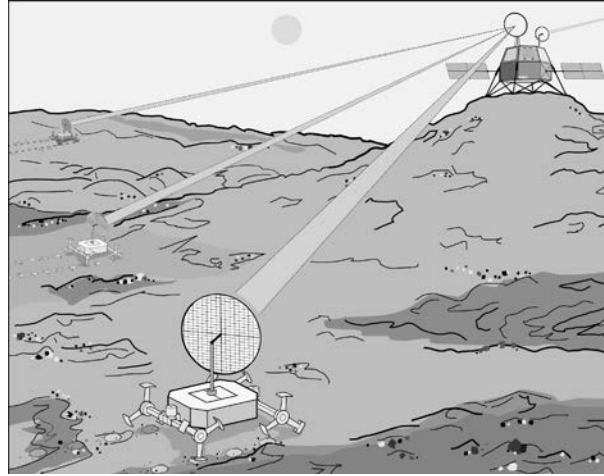


Figure 1: a sketch of the possible use of a base station on a crater rim beaming power to multiple rovers exploring the permanently shadowed craters of the moon.

II. Conceptual Design

A. Choice of laser and receiver

The laser power beam is converted into energy using a photovoltaic array. For maximum conversion efficiency, the semiconductor chosen for the photovoltaic array has an energy bandgap E_g that is slightly lower than the photon energy of the laser,

$$E = hc/\lambda \quad (1)$$

For wavelengths shorter than this, the monochromatic conversion efficiency drops nearly proportional to wavelength; while for longer wavelengths, producing photons of energy less than the bandgap, the efficiency drops to zero [12,13].

This can be done either by selecting a photovoltaic cell material to match the laser chosen, or else selecting a laser wavelength to match the optimum conversion wavelength of the photovoltaic cell of choice.

The laser choice is required to optimize the following criteria:

1. wavelength matched to the photovoltaic cell
2. high electrical to optical conversion efficiency
3. high power
4. good beam quality

The highest conversion efficiency of photovoltaic cells converting laser illumination into electricity has been achieved to date with GaAs solar cells, with an energy bandgap $E_g=1.44$ eV. Efficiency of up to 60% [13] for conversion of monochromatic light at wavelength $\lambda=840$ nm has been reported (although only for a laser sent through a fiber optic, not for free space transmission, and a very small area cell). Commercially available devices are available with efficiency of 53% at $\lambda=810$ nm [14]. GaAs is a well-developed technology, and large-area arrays can be purchased.

Semiconductor bar lasers are available at a wide range of wavelengths in the near infrared, including the 810nm wavelength desired. Efficiencies of up to 67% have been achieved with semiconductor bar lasers [15], and commercially available bars are available with electrical to optical conversion efficiencies of over 55% at power levels of over 1 kW. Thus, these satisfy the first three conditions: wavelength matched to the cell, high efficiency, and high power. However, the beam quality is poor: in laser terms, the devices are not coherent (that is, the light emitted from one spot on the bar and light emitted from a different spot are not in phase). Quoting Jordin Kare, the beam from these laser is “a flashlight,” and not the coherent beam of a high-quality laser. The low beam quality means that the beam divergence will be set by imaging optics, rather than diffraction-limited beam spread, which means that the spot size, for a beam sent over a large distance, will be large.

However, with good design this distance can be hundreds of meters, and for a demonstration-level system to show the feasibility of laser power beaming, this would be practical.

Alternately, recently diode-pumped fiber lasers have realized efficiencies of up to 50% at a wavelength of about

1064 nm. 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, rather than vice versa.

There are two reasonable cell choices. It is possible to make a cell using a ternary or quaternary III-V alloy at a bandgap selected to match the laser, about 1.08 eV. This is very close to the material needed for the intermediate junction of next-generation multijunction solar cells, and hence there is considerable research expertise in materials of this composition. The best result to date is a conversion efficiency of 45.5% using $\text{In}_{0.24}\text{Ga}_{0.76}\text{As}$ material [16], but this result is on a very small area cell (0.0784 cm^2) with a high incident intensity, with lower efficiency, 31.5%, for a 1 square cm cell at lower intensity of 1.5 W [17]. Other authors report up to 37.87% at 538 mW/cm^2 incident power density at 1064 nm [18].

An alternate, however, is to use silicon cells. Unfortunately, despite a bandgap of 1.1 eV near the optimum value, silicon has a low absorption constant at 1064 nm, and hence conventional silicon cells have poor spectral response at this wavelength. However, advances in silicon solar cell technology have pushed the long wavelength response of Si, and the best cells now produce reasonable quantum efficiency even at this wavelength. The best silicon cells at 1064 nm wavelength are 39.4% efficient at 1064 nm at a reasonable intensity of 58 mW/cm^2 . This is similar to the efficiency produced by the InGaAs cells above, but large-area advanced silicon cells are being produced in high quantities for terrestrial use at (comparatively) low cost. Although the degradation of these cells when exposed to space radiation is expected to be high, the lunar surface is a comparatively low radiation environment, far from the Earth's radiation belts, and with a 2π mass shield provided by the body of the moon. It is likely that, with a reasonable coverglass to provide added shielding, the cells should hold up to the environment.

Based on these considerations, an initial mission baselining an 810 nm diode laser bar and GaAs receiving photovoltaics was analyzed as a conceptual design; and a test will be baselined to verify whether the 1064 nm diode-pumped fiber laser with high-efficiency Si cells could be used for a longer distance beaming.

B. A conceptual design was done of a Demonstration mission

A conceptual design was done of a possible flight demonstration of laser power beaming. The design envisioned the demonstration as an 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 hemisphere, with a 100 watt demonstration goal. For the flight demonstration, the laser transmitter was mounted on a small rover which was recharged by the Kilopower system, but capable of moving to a location where it is in line of sight of the receiving rover, *e.g.*, on a crater rim where it has a view into the permanently dark region to be explored.

The laser-beaming system is itself mounted on a small rover, as shown in figure 2. The rover is connected to the lander with the Kilopower reactor by a power cable. The reason to mount the laser on a small rover is twofold: first, it allows us the rover to position itself tens of meters away from the reactor, to reduce the neutron dose from the reactor. Second, however, it allows us to place the beam director in an optimum position, for example, at the rim of a crater, or other location where it can see the recipient rover. Figure 3 shows the laser and beam director.

The rover is shown in an artist's conception in figure 4. A 250 watt (beam power) laser diode bar transmits power at 808 nm, using a 10.5 cm diameter optical beam director. The beam is received by a GaAs photovoltaic array mounted on the receiving rover, where it is converted into electrical power at an assumed 50% optical to electrical efficiency. (The receiving rover, not shown, is essentially similar to the transmitting rover). For the flight demonstration, a distance of 50 meters of laser transmission is assumed. The design shows that a total laser mass of 7.8 kg would be capable of producing the beam needed, not including the thermal control system. The array on the receiving rover would also be capable of producing power in sunlight, although the solar efficiency is about half of the laser efficiency, and when the array is not illuminated by the laser, it is used for solar conversion.

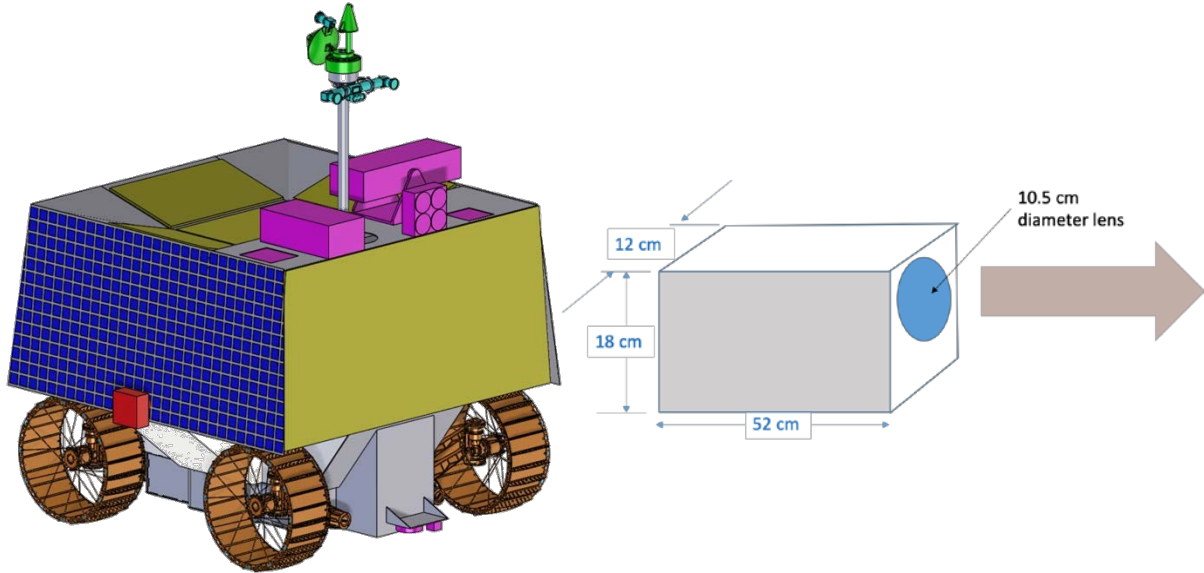


Figure 2 (left): Visualization of the power beaming experiment mounted on a rover. The elements relating to the power beaming experiment are shown in purple. In this image, the wheels are retracted for storage. Figure 3 (right): dimensions of the laser and beam director (not including gimbal elements for pointing).

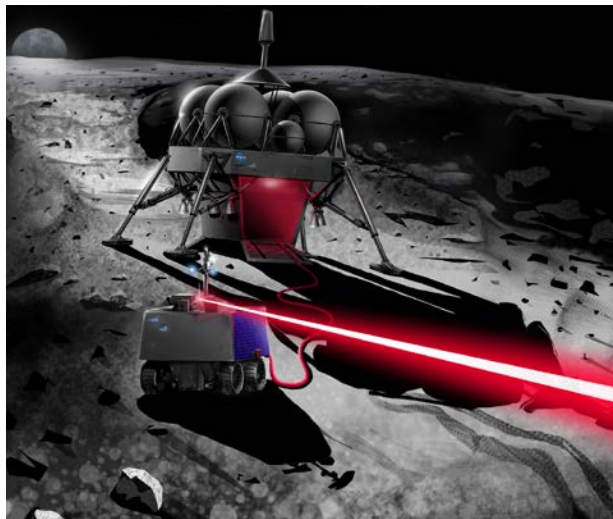


Figure 4: artist's conception of the rover beaming power

C. Increased range design and further work

The initial conceptual design was for a short distance demonstration. It would be valuable to do a demonstration of laser power beaming capable of longer distance point-to-point beaming on the moon. To do this will require a higher coherence than the diode laser bars in the initial analysis.

The next step to mature the technology would be to press forward toward a lunar flight demonstration. This would entail working with industry to make flight-ready versions of the components, addressing operation in the space environment, minimizing weight, and reducing the required power, as well as fitting the form factors needed for the CLPS flights.

In the future, this has the potential to enhance and enable future human exploration of the moon, since harvesting and utilizing the ice resources of these permanently-shadowed craters is envisioned to be a key value in the lunar

initiative. Demonstration of short-range power transmission on the lunar surface may also lead to other applications in space [20]. And as a technology for power transmission, it is expected that there may be significant potential commercial applications for other applications requiring power transmitted from remote sources.

III. Conclusion

While power transmission by laser has been proposed before, advances in laser technology are now reaching the point where the technology has reached a readiness level that it could be realistically implemented. Specifically, diode-pumped fiber lasers using the Erbium/Ytterbium system now can be purchased commercially at multi-kW power levels, with overall conversion efficiency of greater than 50%.

This development high-efficiency, high-power lasers has made the concept of laser power beaming feasible. For a near-term technology demonstration, GaAs photovoltaic cells can be used to receive power from a diode laser bar. For a longer-term solution, diode-pumped fiber lasers fills this technology need.

The diode-pumped fiber lasers have a wavelength of 1064 nm. Two technology choices exist for a photovoltaic converter for this wavelength, either an InGaAs photovoltaic cell, using technology developed for next-generation multi-junction space solar cells, or else a newly-developed high-quantum efficiency silicon cell, using technology developed for low cost, high-efficiency terrestrial arrays.

Acknowledgments

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