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J. Kare, J. Early, W. Krupke, R. Beach

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New Technology and Lunar Power Option for Power Beaming Propulsion

Jordan Kare**, James Early*, William Krupke, Ray Beach*

***Kare Technical Consulting, *Lawrence Livermore National Laboratory*

Abstract. Orbit raising missions (LEO to GEO or beyond) are the only missions with enough current traffic to be seriously considered for near-term power beaming propulsion. Even these missions cannot justify the development expenditures required to deploy the required new laser, optical and propulsion technologies or the programmatic risks. To be deployed, the laser and optics technologies must be spin-offs of other funded programs. The manned lunar base nighttime power requirements may justify a major power beaming program with 2MW lasers and large optical systems. New laser and optical technologies may now make this mission plausible. If deployed these systems could be diverted for power beaming propulsion applications. Propulsion options include a thermal system with an Isp near 1000 sec., a new optical coupled thermal system with an Isp over 2000 sec. photovoltaic-ion propulsion systems with an Isp near 3000 sec., and a possible

INTRODUCTION

Orbit raising missions (LEO to GEO or beyond) are the only missions with enough current traffic to even be seriously considered for power beaming propulsion. Even these missions cannot justify the development expenditures required to deploy the required new laser, optical and propulsion technologies or the programmatic risks. To be deployed, the laser and optics technologies must be spin-offs of other funded programs. The manned lunar base nighttime power requirements may justify a major power beaming program with 2MW lasers and large optical systems. New laser and optical technologies may now make this mission plausible. If deployed these systems could be diverted for power beaming propulsion applications. Propulsion options include a thermal system with an Isp near 1000 sec., a photovoltaic-ion propulsion systems with an Isp near 3000 sec., and a possible new optical coupled thermal system with an Isp over 2000 sec.

NASA Mission Needs

Lunar and planetary exploration, both human and robotic, requires electrical power. A significant human presence on the Moon and widespread exploration will require many times the power levels of current space activities.

The most difficult power problem facing human lunar exploration is lunar base power. The two-week lunar night provides a difficult problem for energy storage systems. This problem and possible solutions are extensively discussed in, the literature (e.g., the *Lunar Base Handbook* [[i]]). Lunar base power requirements vary depending on mission assumptions, but range from ~50 kWe for a minimal permanent base to in excess of 1 MWe for substantial in-situ resource utilization . Options based on solar power plus energy storage are extremely mass-intensive. A minimal base (50 kW daytime power, 35 kW night power) is estimated to require ~11,000 kg for regenerative fuel cell storage for a polar site, and ~17,000 kg for an equatorial site [[ii]]. Nuclear reactors can be lower in mass (e.g., ~15,000 kg for 550 MWe [[iii]]) but will require an expensive program to develop and qualify. In addition, nuclear reactors are complex, expensive to develop, and challenging to set up and maintain. They may also be blocked by non-technical concerns.

Laser power beaming has been shown to be a superior technology for high-power (300 kW) lunar bases [[iv]] and was the subject of a small NASA development effort in the early 1990's [[v]], but the then-available technologies and mission priorities did not lead to a compelling case for further development.

For lunar rovers nuclear reactor power is impractical, and solar power will lead to energy-limited operations and curtailed nighttime activities, and thus inefficient use of expensive lunar installations. Power requirements for rovers are assumed to range from a few hundred watts for robotic explorers to ~100 kW for multi-person vehicles; exploitation of lunar resources may need even higher-power vehicles.

POWER BEAMING CONCEPT

NASA needs to include developing a practical non-nuclear option for supplying power for space exploration via laser power beaming. The primary focus will be on supplying lunar base and lunar rover power from Earth-based lasers, but the technologies are applicable to other missions, including powering Mars exploration using lasers based in Mars orbit. The use of laser power beaming will allow NASA to provide an energy rich environment for its surface exploration efforts.

While the concept of powering a Lunar base from Earth was explored a decade ago, two new technologies have emerged that make this concept technically feasible and much more economical:

- Diode Pumped Alkali Lasers (DPALs). DPALs are a new class of gas lasers with ideal properties for driving Si or GaAs photovoltaics. They are potentially inexpensive compared to alternative lasers, and scaleable to megawatt power levels. They are also efficient enough, and potentially compact and robust enough, to be based in space as well as on Earth.
- Ultralight space optics, particularly diffractive optics. Large thin-film diffractive optics developed and demonstrated (up to 5 m diameter) at LLNL can provide diffraction-limited performance with an areal mass of <0.5 kg/m^2, and, while usable for broadband imaging, are ideally suited to laser beam handling. Single

non-folding optics up to 20 m in diameter can be rolled up and launched in a Delta IV payload shroud, and require no space assembly.

Combining these two technologies with advances in large telescopes, adaptive optics, and other fields leads to the system illustrated in Figure 1. The laser beam is launched from a simple, non-steerable 5-m ground telescope to a geostationary relay satellite. The emergence of operational adaptive optic telescopes in the last decade now makes power beaming through the atmosphere clearly feasible. An LLNL team has been responsible for these systems in the two operational, large scientific telescopes that have laser guide star coupled adaptive optics; the 3m Lick observatory and the 10m Keck telescope. The adaptive optic system required for this mission will not be much more demanding than the current Keck system.

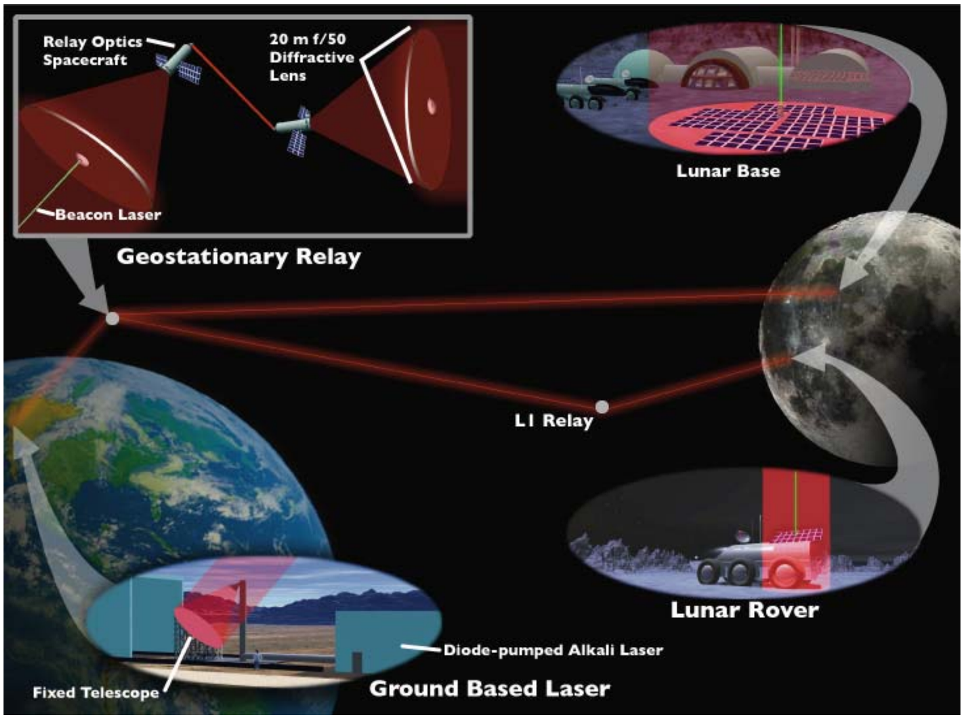

FIGURE 1. Lunar power beaming architecture

The geostationary relay is key to making the architecture economical. With a geostationary relay, a single ground station can transmit power to the lunar surface 24 hours a day, 365 days a year, except for brief (~70 minute) gaps when the Earth blocks the GEO-moon link. As few as two ground stations are sufficient to provide useful system availability. In previous direct Earth-moon beaming architectures, one ground station could only supply power for 6-8 hours/day, requiring 6-10 ground stations scattered around the world for continuous availability; these ground sites also needed very large (>10 m) ground telescopes with advanced adaptive optics. With a GEO relay, ground telescopes can use low-cost fixed mirrors, as in the Hobby-Eberly telescope. Large relay optics also reduce the beam divergence and thus the spot size at the moon compared to earlier concepts, reducing the required receiver area and the minimum practical system power; at 795 nm, a 20-meter GEO transmitter can focus 80% of its beam into a 30-m receiver.

For lunar rover applications, even 30m may be impractically large. A second relay located at the Earth-moon L1 point, 57,000 km from the moon, can provide much smaller focal spots, as well as better tracking of moving vehicles.

The major subsystems will be the laser, the ground optical system, the space relay primary optics, the space relay secondary optics satellites, and the receivers. The following sections discuss the details of these major subsystems.

Optimum Laser Characteristics For Photovoltaics

If the goal is to provide electric power , the wavelength and duty cycle must be compatible with efficient photovoltaic receivers. Figure 2 [vi] shows the wavelength dependence of PV conversion efficiency for several semiconductor materials. For a silicon PV cell, the peak conversion efficiency is ~40% at a wavelength of ~900 nm, and drops to ~20% at ~500 nm. However, after radiation damage in the space environment, silicon PV cells have decreased efficiency and the peak efficiency shifts to shorter wavelengths. Thus, the optimum operating wavelength of a laser power beaming source for a silicon PV cell receiver shifts from ~900 nm to ~770 nm after space exposure. GaAs PV cells have a excitation threshold of ~910 nm, rising to a peak conversion efficiency of ~60% at ~850 nm, and droping to half-peak conversion efficiency at ~300 nm. Thus, for GaAs PV cells, the optimum source wavelength is ~850 nm, but~800 nm will not result in a significantly lower efficiency.

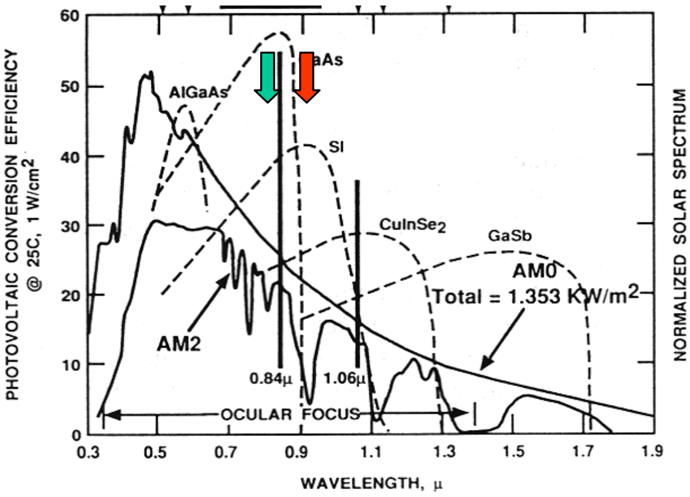

FIGURE 2. Spectral response of photovoltaic cells Colored arrows designate the operating wavelengths of rubidium (green), and cesium (red) DPALs

The preferred waveform for a power beaming laser is continuous wave (CW). PV cells produces useful electric power approximately proportional to the intensity, while resistance losses are proportional to the intensity squared. When illuminated by a pulsed source with a high peak to average intensity, the fractional resistive loss increases , lowering the cell conversion efficiency. The decrease in efficiency depends on the peak-to-average power ratio, the characteristic time duration of the pulses, and the internal response time of the cell photoelectrons.[vii] Simulations of Si and GaAs photovoltaic cell responses to pulsed waveforms have been carried out [viii] and correlated with measurements of cell performance under pulsed illumination. These studies show that: 1) cell performance degrades significantly for sources generating long pulses (>25 nsec) at low duty factors (<0.001) and 2) cell performance may degrade incrementally for sources generating short pulses (<100 psec) at high duty factor (>0.1).

Several well-developed lasers have been considered as potential sources for power beaming applications, including Nd:YAG (1064 nm), frequency-doubled Nd:YAG (532 nm), copper vapor (510 nm), Ti:S (690-1100 nm) and AlGaAs laser diode arrays (~810 nm). Of these, the Nd:YAG based lasers have ineffective wavelengths for matching practical photovoltaic cells. The copper vapor not only have a poor wavelength match, but also operates with a pulse duration (~40 nsec) and duty factor (~10^{-4}) that would significantly degrade photovoltaic conversion efficiency. The Ti:S laser is tunable from ~690 nm to ~1000 nm and well matches the response curves of both GaAs and Si. However, the Ti:S laser cannot be directly pumped with high performance semiconductor laser diode pumps, and to date there has been no attempt to scale the output power of the Ti:S laser above 100 watts. The concept of directly using high power AlGaAs laser diode arrays operating at a wavelength near 810 nm has been suggested, but attempts to scale diode array power while achieving near-diffraction-limited beam quality has been elusive.

The rf-linac-driven free-electron-laser (FEL) has been most aggressively assessed for power beaming applications. The rf-linac-based FEL typically produces low peak power pulses with pulse durations in the psec range, with operating duty factors up to 10^{-1}. Tests of both Si and AlGaAs PV cells with this type of waveform indicate little degradation in conversion efficiency. Under development for two decades, the pace of FEL development has been relatively slow (compared to the characteristic development time of solid state and gas lasers) because FELs generally require a significant investment in facility infrastructure even for low power exploratory experimentation.

Thus among the potential lasers considered for power beaming the DPAL laser is unique in having ideal wavelengths and waveforms as well as having a fluid laser medium that allow scaling to very high powers.

Diode Pumped Alkali Laser (DPAL)

Used as pump sources for solid state materials (doped glasses or crystals), diode laser arrays have enabled diode-pumped solid state lasers (DPSSLs) that possess greatly improved characteristics (efficiency, power, brightness, size, and weight) compared to earlier lamp-pumped SSLs. As a result, DPSSLs have become the workhorse of near-infrared lasers and have found many commercial, medical, industrial, and military applications. However, in pushing beyond kilowatt power levels, DPSSLs encounter severe deleterious thermo-optical phenomena inherent to solid state gain media: thermally-induced focusing, stress-birefringence, and mechanical rupture. A gaseous gain medium can have much more favorable thermo-optical characteristics, but until recently, no practical means of pumping a gaseous medium with diode arrays existed; other pumping approaches (electric discharges, e-beams, gas-dynamic systems) could produce high power, but with disadvantages such as low efficiency or high operating cost.

Krupke [ix] recently proposed a combination of optical and gas conditions that would allow lasers based on alkali vapor atomsto be efficiently pumped by laser diode arrays, and coined the term Diode-Pumped Alkali Laser (DPAL). Computer models and subsequent code validation experiments have confirmed that DPALs can efficiently convert the broadband (1-3 nm), low-brightness (M^2 ~1000) output of commercial laser diode pump arrays into high-quality narrow-line laser output.

The neutral alkali vapor atoms (Li, Na, K, Rb, and Cs) manifest the same low-lying electronic structure. The Rb atom energy levels are shown in Fig. 3. The spectroscopic properties of the allowed resonance transitions (the D_1 and D_2 transitions, respectively) of the alkali atoms have been extensively studied. [x] The collisional effects of all of the rare-gases and selected molecular gases on the population kinetics of ${}^2P_{1/2,3/2}$ excited alkali atoms, including spectral broadening of the D-transitions, collisional mixing rates of excited ${}^2P_{1/2,3/2}$ alkali atoms, and inelastic quenching rates have also been reported in the literature. [xi]

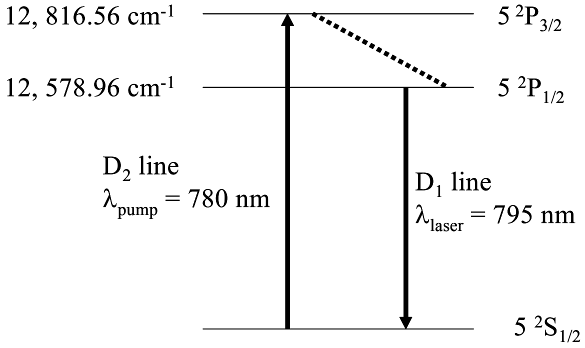

FIGURE 3 Energy level diagram of atomic Rb indicating pump and laser transitions.

In a DPAL, the D_2 transition is the pump transition, and the D_1 transition is the laser transition. Table 1 lists optical properties for rubidium and cesium alkali vapors. These alkalis are of particular interest because they can be pumped with mature laser diode arrays (AlGaAs and InGaInP) and are well matched to the peak responsivity of photovoltaic converters.

TABLE 1. DPAL wavelengths, energy gaps, and quantum defects

Alkali Atom	**λ_{pump} (nm)**	**λ_{laser} (nm)**	**${}^2P_{3/2}$-${}^2P_{1/2}$ Energy Gap (cm^{-1})**	**Quantum Defect**
Rb	780	795	237.5	0.019
Cs	852	895	554.1	0.047

Because of the small energy difference between the D_1 and D_2 transitions (~2% for Rb, ~5% for Cs), these atoms have the potential to be especially efficient laser species. By buffering the alkali vapor with a helium at moderate pressure, collisionally broaden D_2 transition widths give a high absorbed-fraction of pump radiation when used in an “end-pumped” laser geometry. With ethane rapid collisional transfer to the upper laser state [xii], one can anticipate *efficient diode-pumped* laser action on the first resonant D_1 transitions of the alkali atoms.

LLNL has achieved CW TEM_{00} laser action at 795 nm on the D_1 transition of rubidium, using a Ti:Sapphire pump laser as a surrogate for a diode pump. More recently, CW TEM_{00} laser action at 895 nm on the D_1 transition of cesium was demonstrated. The best performance was a slope photon conversion efficiency of 0.59 W/W, relative to the absorbed pump power. The end-pumped geometry in this laser demonstration was modeled using the methodology developed by Beach [xii] for CW end-pumped quasi-three-level lasers such as Yb:YAG. Excellent quantitative matching of experimental data with the LLNL model code was achieved using literature spectroscopic and kinetic data.

Earth Based Optics Subsystem

Earth-based transmitters can use well-established telescope technology. Using a geostationary beam relay allows the transmitters to aim at a nearly fixed point in the sky, and thus to use a fixed primary mirror, rather than requiring a one- or two-axis tracking mount. The cost advantage of a fixed telescope over a conventional one can be up to 10:1; the Hobby-Eberly 9.2 m telescope (fixed elevation, azimuth rotation) cost $13.5M, 15-20% of the cost of comparable standard telescopes. Primary mirror options include segmented mirrors (Hobby-Eberly) or lightweight monolithic mirrors, now routinely produced up to 8.4 m diameter.

Adaptive optics are needed to compensate for atmospheric turbulence, but are within the state of the art for astronomical telescopes. At the power levels and apertures of interest, we do not expect significant thermal blooming or nonlinear atmospheric transmission effects, although this must be verified. Potentially the adaptive optics can use a reference beacon orbiting one kilometer ahead of the GEO relay, eliminating the need for laser guide star technology. Use of large (>4m) optics operating at 0.8μm will probably require the use of three laser guide stars.

Diffractive Optic For The Space Relay Primary Optic

In addition to DPALs, the enabling technology for the proposed system is large (10 – 20 m), ultralight space optics. Such optics are required for high-performance GEO and L1 relays at reasonable cost. Diffractive optics, used as transmissive lenses, offer two major advantages for large, space-based optical elements; they have much looser optical tolerances than conventional reflectors, and they can be fielded as flat, flexible, thin-films, not stiff, precisely curved, structures.

A space-based diffractive lens consists of a series of shallow (~ 1 μm deep) sawtooth-shaped surface grooves on the surface of a thin-film. These grooves coherently focus the power-bearing laser beam, applying a digital set of λ-sized phase corrections rather than a single, multi-thousand-λ, phase change as conventional optics do. This small phase correction allows diffractive lenses to be thin (hence lightweight) and flat (since focusing comes from groove spacings, not the film's physical shape).

The diffractive lens's huge (~ 10,000-fold) tolerance improvements come, however, from the more prosaic reason that it is a transmissive rather than reflective element. The fundamental advantage of lenses over reflectors is that, when bending light through an angle of θ, the optical effect of figure errors is enhanced by a factor of $(1+\cos\theta)$ for reflection, but $(1-\cos\theta)$ for transmission. By employing optically-slow lenses, this $(1+\cos\theta)/(1-\cos\theta)$ advantage, which scales as $(4F/D)^2$, can become huge: 10,000 for an F/D = 25 lens. This raises optical tolerances from ~ 50 nanometers up to half a millimeter, a tremendous practical advantage when trying to field a large, lightweight aperture in space.

As diffractive lenses are flat films, they can be held taut and in shape by purely in-plane forces; either edge forces applied at the perimeter, or centrifugal force caused by slow spinning. This is in contrast to large reflectors, which, in addition to requiring ~ 10,000-fold greater out-of-plane precision, must be curved. Since curved shapes cannot be held taut by in-plane forces, reflectors require either intrinsic stiffness (with excessive mass/area), or precise, areally distributed, out-of-plane forces.

A final advantage to a flat diffractive lens is that it can be packaged (e.g., by folds or rolls) into a much more compact package than can a surface having 2-D curvature, such as a reflective optic.

In order to field a large diffractive lens in space, it must be fabricated from a thin, lightweight, space-suitable material. Two attractive options exist: inorganic sheets (typified by glass or silica) or polymer films. Inorganic sheets offer the advantages of space radiation resistance and that diffractive patterning can be performed with well-proven lithographic techniques. LLNL has used thin glass sheets (700 μm thick) to build and test a 5 meter diffractive lens (Fig.4); the lens contained 72 meter-sized panels, precisely aligned along their borders, and attached together in a foldable origami pattern so as to be compactly packagable for launch.

FIGURE 4. Five meter diffractive optic lens demonstrated at LLNL. Optic is made with 700 μm glass. To reach <<1 kg/m^2, a lens would have to be made from even thinner (~ 100 μm) panels, but such material is commercially available in meter-sized panels, and can be patterned and handled (we have wrapped 75 μm sheets around coke cans) with the same techniques.

Geostationary Relay Satellites

The GEO relay configuration illustrated in Figure 1 actually consists of four separate satellites: two primary optics spacecraft (one receiver and one transmitter) and two secondary "eyepiece" spacecraft at the primary optics' focal points. The large f-number and apertures of the diffractive primary optics in these telescopes gives a focal length of approximately one kilometer. The telescope optical trains must therefore be in separate spacecraft from the primary optics.

The primary optic spacecraft consists of the diffractive optic itself plus a small central hub structure that controls the orientation of the optic. The receiving telescope, aimed at a fixed position on the Earth's surface, must rotate through 360^o in 24 hours. There are several ways to accomplish this rotation and control. One option is to spin the optic to provide a flattening tension and to have a counter-rotating central hub to give a net zero angular momentum to the satellite. Then the combination can rotate with a 24 hour period to maintain the needed orientation. The central hub structure will also contain the spacecraft utilities and station keeping propulsion to deal with orbit perturbations, similar to standard geostationary satellites.

The receiving eyepiece must be in an orbit that has a radius that is approximately one kilometer larger and always be slightly below (about 70m) the plane of the equator to point to a site such as New Mexico. This orbit can be maintained with a very low thrust electric propulsion system. The thrust requirement can be lowered but not totally eliminated by the use of a tether, but the propulsion weight reduction will probably not justify the additional complexity. The optical train in this satellite must collimate the laser beam at a size that does not create optical loading problems at this power level (0.5 – 1.0 m diameter) and send the beam to the second pair of satellites, the GEO transmitter telescope.

The GEO transmitter will be quite similar to the GEO receiver telescope. The main difference will be the orientation in the orbit. The direction of this telescope will take a lunar month to rotate through 360^o. The primary optic will remain in a geostationary orbit that trails the receiver optic by approximately a kilometer. The secondary spacecraft is in an orbit with the same semi-major axis and period but with a positional shift equal to the focal length. This orbit combination keeps the correct orientation during a 24 hour orbit and requires only a slow modification over the lunar month. The propulsion requirements for this satellite will be lower, but some propulsion will still be needed for orbit perturbations.

Lunar receivers

The lunar receiver for a manned base will simply be a PV array on the surface. For a 30m receiver the laser intensity will only be a factor of solar. Simple optical concentrators will be able to reduce the require area of photovoltaics and resulting system expense. The degree of concentration will be constrained by the temperature impact on conversion efficiency and by the radiative cooling system design.

This laser power beaming concept can also supply power to rovers. The rovers will have to have photovoltaic receivers to convert the laser beam to electrical power or to use direct thermal conversion for some applications. If the laser beam spot is larger than the receiver, then the receiver may be expandable to allow higher power levels when the rover is not in motion.

For lunar rovers the laser can be beamed directly from the GEO relay satellites or can be further relayed from a satellite located at the moon-Earth L1 point. Placing a relay satellite 57,000 km from the lunar surface at the L1 point provides much smaller and more intense laser beam spots on the surface. This option may be of particular interest if NASA pursues the concept of placing an assembly facility at the L1 location. A 20m launch telescope located at L1 would give a 6m spot on the lunar surface. The intensity in this small spot would be limited by the thermal limitations of the PV array, approximately 20 sols or 30kW/m^2. This intensity would provide 15kWe/m^2 to the rover.

Laser power beaming has the potential to provide a power rich environment for surface explorations. It overcomes the limitations of sunlight availability at high latitudes or at night. It also removes the strong range and power limitations associated with stored energy concepts.

POWER BEAMING FOR LEO-TO-GEO MISSION

For large laser facilities the capital costs typically dominate over operating costs. Under these circumstances desirable mission characteristics involve continuous operation or at least high duty factors. For applications to propulsion, short and rare events such as earth-to-LEO flights should be avoided. Potential longer durations but very rare flight profiles such as interplanetary missions also offer few attractions. The most attractive space power beaming propulsion opportunity appears to be the lifting of satellites from LEO to GEO. The current launch rate would provide over ten launches per year. If the flight duration is around one month, then a power beaming system could potentially have near continuous utilization.

The primary savings in raising satellites to GEO would be the lowering of the conventional launch costs by a reduction of payloads required to be lifted to LEO. In modern launch vehicles a high efficiency second stage (I_{sp}~450 sec) is used to insert the satellite into a geosynchronous transfer orbit (GTO). For a Delta IV vehicle the payload in GTO is about 0.57 of the payload capacity in LEO. A lower efficiency solid rocket (I_{sp}~290 sec) is used to circularize the orbit at apogee. As a result the payload weight in GEO will be less than thirty percent of the launch vehicle's capacity for LEO. A power beaming propulsion system would have a higher payload to LEO mass fraction.

Power beaming propulsion could be used either for the less demanding circularization task requiring a velocity change of approximately 2 km/sec or for both tasks requiring a total change of 5.2 km/sec. These velocity changes for slow, low acceleration systems are larger than these values for the fast impulse changes of conventional rockets. This difference is lowered if the power beaming propulsion is applied primarily near perigee and apogee.

If a 2MW laser is used for the lunar base mission, then the power beaming propulsion capabilities are quite significant. With a conventional ion propulsion system with an Isp of 3000 sec., a Ga As array providing 700kWe would give 17 N for thrust (170 times DSP-1). This could transport around 10MT from LEO to GEO, but the flight times would be over two months. The mass in GEO would over 50% of the mass in LEO.

A thermal propulsion system (Fig.5) has the advantage of converting most of the beam power into usable thrust, but the Isp is limited to around 1000 sec by thermal limits of materials. The better use of energy partially offsets the lower Isp, giving a mass fraction delivered to GEO of approximately 50%. The primary advantage of thermal propulsion is higher thrusts and almost a factor of ten shorter flight times.

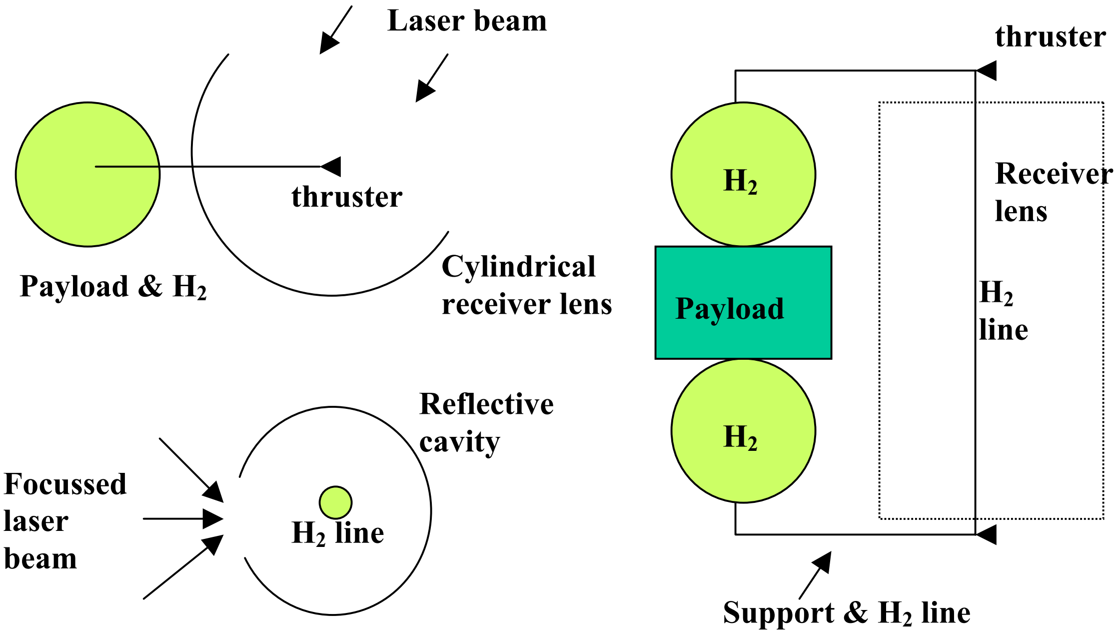

FIGURE 5 Power beaming thermal propulsion system

It may be possible with the DPAL laser to combine the power utilization efficiency of thermal propulsion with the mass efficiency of high Isp. If the hydrogen propellent is seeded with a very small fraction of the same alkali vapor used by the laser, then the laser light can be directly absorbed by the propellent without heating wall materials. This speculative propulsion concept deserves further investigation.

SUMMARY

The completion of a power beaming project will provide NASA with an important option for providing a power rich environment for future surface explorations on the moon and Mars. This concept is an enabling technology for non-nuclear manned surface operation during the lunar night. These benefits may be enough to obtain NASA support. A power beaming laser of order 100 kW appears adequate to address some of the current propulsion requirements. If such a system is built with MW capabilities, then power beaming propulsion will be a logical next step and may allow significant economic savings for orbit raising missions.

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