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Laser Power Transmission

Edmund J. Conway

Since their development, lasers have offered the potential of projecting large amounts of power onto a distant, small area. (Laser power was once measured in "gillettes," the thickness in number of razor blades it took to just stop the beam.) Initially, this characteristic seemed good for weapons (e.g., the laser rifle) and mining (thermal fracture or vaporization of rock). Actual applications later developed in the areas of cutting (anything from sheet metal to cloth), welding, scribing, and surgery.

One of the earliest proposals for the application of a high-powered laser in the civilian space program was made by Kantrowitz (1972). He proposed an Earth-to-orbit launch system in which a laser on the ground supplied thermal energy to a single species of rocket propellant (such as hydrogen). The removal of the oxidizer, no longer needed to release chemical energy for propulsion, reduced the lift-off weight of Earth-launched vehicles.

This and similar proposals on power and propulsion generated a great deal of speculation and study in the 1970s. These activities, although generally incomplete and sometimes contradictory, identified several themes:

- Lower cost power and propulsion is key to the development of near-Earth space.
- Solar- and nuclear-powered lasers have the characteristics for high payoff in space applications.
- Expensive transportation applications show high potential for cost reduction through the use of remote laser power.
- Economical power beaming in space requires multiple customers who cannot use available (solar photovoltaic) power sources.
- High laser conversion efficiency is a key power-beaming challenge.
- NASA laser power requirements are very different from those of DOD and DOE, but NASA can benefit from the breadth of basic research generated by the programs of other agencies.

A particularly complete study by Holloway and Garrett (1981) showed substantial payoff for both laser-thermal- and laser-electric-powered orbit transfer vehicles. A recent comparison by DeYoung and coworkers (1983) suggests that with a laser providing 100 kW or more of power for electric propulsion and for other onboard utility needs, spacecraft will be able to operate in low altitude, high drag orbits and will be much lighter and smaller.

From the studies, then, a general set of requirements are emerging for beaming power by laser to currently envisioned space missions. First, the laser must be capable of long-term continuous operation without significant maintenance or resupply. For this reason, solar- and nuclear-powered lasers are favored. Second, the laser must supply high average power, on the order of 100 kW or greater for applications studied so far. For this reason, continuous wave or rapidly pulsed lasers are required.

Since solar energy is the most available and reliable power source in space, recent research designed to explore the feasibility of laser power transmission between spacecraft in space has focused on solar-pumped lasers. Three general laser mechanisms have been identified:

- Photodissociation lasing driven directly by sunlight
- Photoexcitation lasing driven directly by sunlight
- Photoexcitation lasing driven by thermal radiation

Solar-Pumped Photodissociation Lasers

Several direct solar lasers based on photodissociation have been identified, including six organic iodide lasants that have been successfully solar pumped and emit at the iodine laser wavelength of 1.3 micrometers. (See figure 40 for a possible application of such a laser.) Another lasant, IBr, has been pumped with a flashlamp and lased at 2.7 μm with a pulsed power of hundreds of watts. One organic iodide, C_3F_7I, and IBr have been investigated intensively to characterize their operation. Several reports on experimental results and modeling have been published (Zapata and DeYoung 1983, Harries and Meador 1983, Weaver and Lee 1983, Wilson et al. 1984, DeYoung 1986). An important characteristic of the photodissociation lasers under consideration is that they spontaneously recombine to form the lasant molecule again. Both C_3F_7I and IBr do this to a high degree, permitting continuous operation without resupplying lasant, as is generally required for chemical lasers. In addition, C_3F_7I absorbs almost no visible light and thus remains so cool that it may require no thermal radiator except the pipe that recirculates the lasant. A variety of other lasants offering increased efficiency are under study.

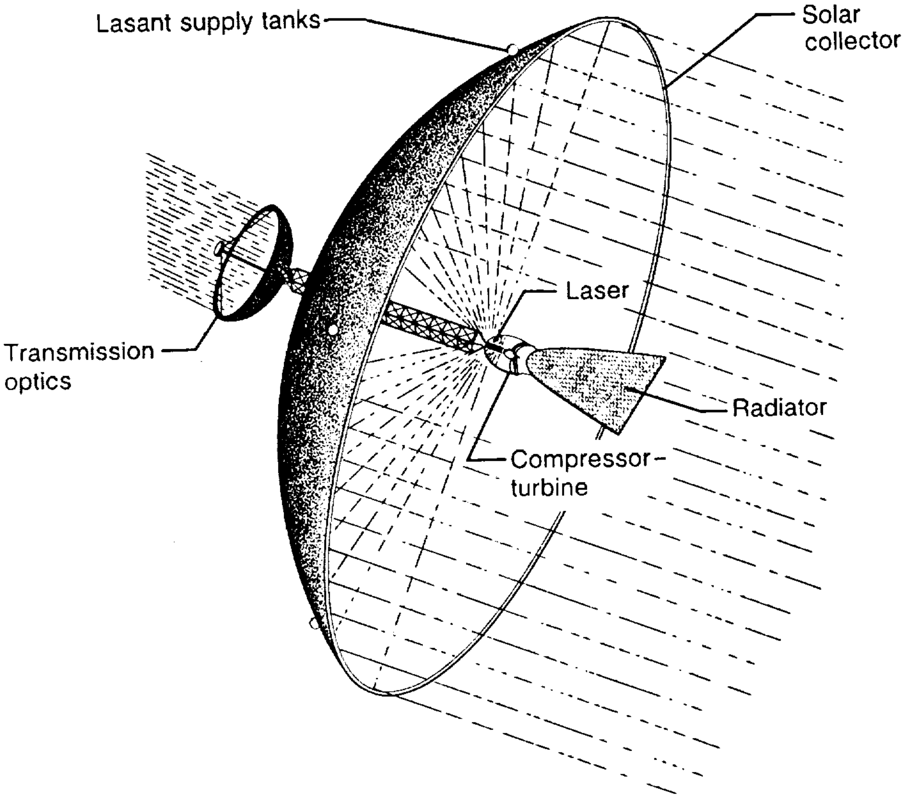


Figure 40

One-Megawatt Iodine Solar-Pumped Laser Power Station

This picture shows the elements of an orbiting laser power station. A nearly parabolic solar collector, with a radius of about 300 meters, captures sunlight and directs it, in a line focus, onto a 10-m-long laser, with an average concentration of several thousand solar constants. An organic iodide gas lasant flows through the laser, propelled by a turbine-compressor combination. The hot lasant is cooled and purified at the radiator. New lasant is added from the supply tanks to make up for the small amount of lasant lost in each pass through the laser. Power from the laser is spread and focused by a combination of transmission mirrors to provide a 1-m-diameter spot at distances up to more than 10 000 km.

Solar-Pumped Photoexcitation Lasers

Another group of direct solar-pumped lasers rely on the electronic-vibrational excitation produced by sunlight to power the laser action. Two systems are being actively studied. The first is a liquid neodymium (Nd) ion laser, which absorbs throughout the visible spectrum and emits in the near-infrared at 1.06 µm. This lasant has lased with flashlamp pumping and is currently being tried with solar pumping, since calculations indicate feasibility. A second candidate of this sort is a dye laser, which absorbs in the blue-green range and emits in the red, near 0.6 µm. These lasers offer good quantum efficiency and emission that is both of short wavelength and tunable. However, the lasers require extremely high excitation to overcome their high threshold for lasing, and the feasibility of achieving this with concentrated sunlight is still a question for further research.

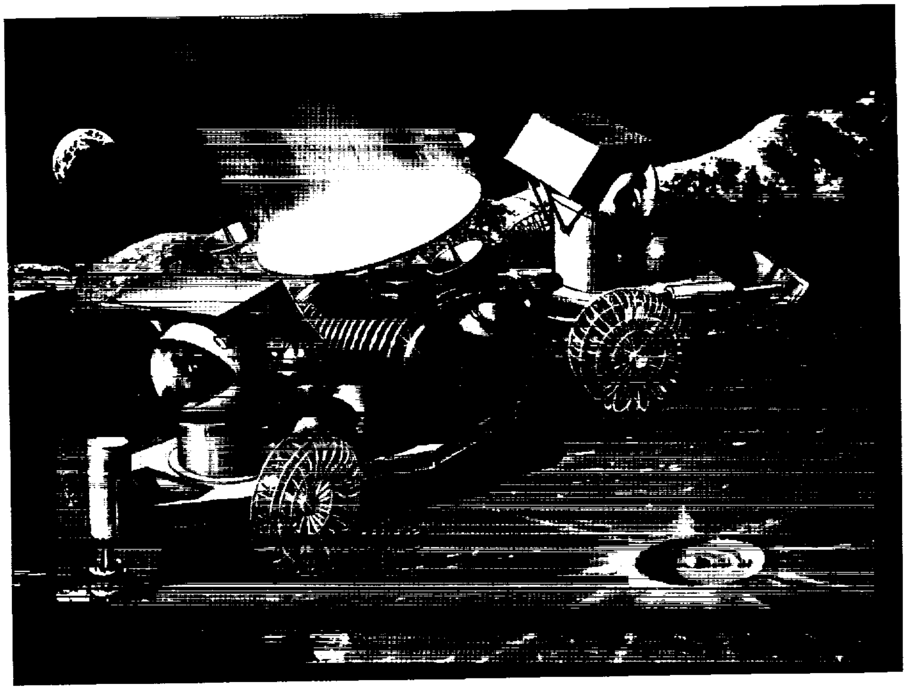
Laser Power to a Lunar Base

In this artist's concept, a large receiver is covered with photovoltaic converters tuned to the laser wavelength. Such a system could produce electric power with an efficiency near 50 percent.

Artist: Bobby E. Silverthorn

Indirect Photoexcitation Lasers

Photoexcitation lasers driven by thermal radiation produced by the Sun are termed indirect solar-pumped lasers. The lower pumping energy implies longer wavelength emission than with photodissociation lasers. Two lasers, the first blackbody-cavity-pumped laser (Insuik and Christiansen 1984) and a blackbody-pumped transfer laser (DeYoung and Higdon 1984), work on this principle. Molecules such as CO_2 and N_2O have lased with emission wavelengths between 9 µm and 11 µm. These lasers are inherently continuous wave and have generated powers approaching 1 watt in initial laboratory versions, with blackbody temperatures between 1000 K and 1500 K. While such lasers, powered by solar energy, may be used in space, they also offer great potential for converting to laser energy the thermal energy generated by chemical reactions, by nuclear power, by electrical power, or by other high-temperature sources.



Laser-Powered Lunar Prospecting Vehicle

This manned prospecting vehicle, far from the base camp, is receiving laser power for life support, electric propulsion across the lunar surface, and drilling. Since this power is available during lunar night as well as day, prospecting need not be shut down for 14 Earth days every month.
A mobile habitat module (not shown) accompanies the prospecting vehicle on its traverse.

Artist: Bobby E. Silverthorn

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Conclusions

Henry W. Brandhorst, Jr.

It is abundantly clear that energy is the key to utilization of space. In fact, bold programs are completely dependent upon and in effect hostage to the availability of energy. We believe that, for either the baseline scenario or the alternative scenario that makes use of lunar resources, there is sufficient time to develop the broad mix of power sources and associated technologies necessary for success.

A list of envisioned applicable technologies related to power and energy supply for space activities at various power demand levels is shown in table 6.

TABLE 6. *Applicable Power Technologies*

Power level	Technology	Application
1 - 100 kW	Photovoltaic	Lightweight arrays for satellites in GEO Space station in LEO On the lunar surface (day only) (hardware derived from space station)
	Radioisotope	Radioisotope thermoelectric generator (RTG) for lunar rover Dynamic isotope power system (DIPS) for martian rover
	Energy storage	Individual pressure vessel (IPV) nickel-hydrogen battery Hydrogen-oxygen regenerative fuel cell (RFC) Bipolar nickel-hydrogen battery Flywheel
100 kW - 1 MW	Photovoltaic	Solar electric propulsion for orbital transfer vehicle
	Solar dynamic	Space station in LEO On the lunar surface (day only) (hardware derived from space station)
	Direct solar heat	Mirrors and lenses for processing lunar and asteroidal materials
	Nuclear	SP-100 (safe, human-rated derivative) for lunar base
	Waste heat rejection	Liquid droplet radiator Belt radiator Rollup heat pipes
1 - 10 MW	Nuclear	Nuclear electric propulsion for orbital transfer vehicle or piloted spacecraft to Mars
	Waste heat rejection	Liquid droplet radiator Belt radiator Rollup heat pipes
	Power management	High-voltage transmission and distribution Laser power beaming

In general, stepwise development of a variety of sources is envisioned: First, an expanding LEO space station with power levels up to 10 MW powered by solar or nuclear sources. Then, lightweight photovoltaic systems for GEO and lunar surface operation. It is likely that lunar camps staffed only during the day could derive all their power (25-100 kW) from solar arrays. Lightweight electrochemical storage systems such as hydrogen-oxygen regenerative fuel cells would find use at GEO and, in concert with solar arrays, would power surface-roving vehicles and machines.

When full-time staffing becomes appropriate, we believe that nuclear systems are the most likely source of power. Power levels in the 100-1000 kW range would be derived from lunar-modified SP-100-class designs, while powers in the 1-10 MW range would be derivatives of civil and military multimegawatt nuclear developments. These man-rated, safe nuclear systems would simply be used as power demands warranted.

Thus, for a lunar base, photovoltaic (or solar dynamic) systems would be used initially for daytime operation, SP-100-class systems would be used for full-time staffing at power levels to 1 MW (by replication or design), and these would be followed by multimegawatt systems for the 1-10 MW needs. Similar progress is envisioned for either scenario for GEO operations and asteroid and Mars exploration. Attention must also be paid to the impact of the lunar, asteroidal, or martian environment on parameters of the power system.

We consider it unlikely that use of nonterrestrial resources will affect power system development before 2010. It is rather the opposite: power systems will enable the development and use of nonterrestrial resources.

Significant advances in the areas of nuclear power development and beamed power transmission will be made by both the military and the civilian space program. Full advantage must be taken of such corollary developments.

It should be noted that development of the 1- to 10-MW class of nuclear (or even solar) power systems will have a profound influence on the state and direction of the electric propulsion programs. These power levels enable electrically propelled orbital transfer vehicles and interplanetary explorers to travel to the outermost fringes of the solar system with larger payloads and shorter trip times than chemical systems. In view of these potentialities, a strong emphasis on developing such propulsion systems is warranted.

Assuming that current programs in photovoltaics and in the SP-100 nuclear plant continue, the following are considered critical technological issues for further research and development. They are presented in order of priority. By piggybacking atop and augmenting existing programs, we can ensure timely development of the requisite systems.

1. SP-100-derivative nuclear power system capable of providing power to 1 MW in an environment safe for humans
2. Large-scale photovoltaic arrays; solar dynamic power conversion suitable for space, using collectors that concentrate sunlight
3. Solar furnaces and process heat applications suitable for processing space resources at high temperatures
4. Multimegawatt (1-10 MW) nuclear power-generating systems for electricity and heat
5. Thermal rejection systems to reject waste heat from the power conversion system, processing, and environmental conditioning (New concepts for efficient radiation are required; the use of lunar subsurface rejection should be investigated.)
6. High-voltage electric transmission and distribution of multimegawatt power
7. Thermal energy control and distribution for both manned and unmanned systems

8. Lightweight, rechargeable thermal and electrical storage
9. Machine design including human factors; robotics to substitute for humans in hostile environments
10. Laser technology for solar and infrared sources to beam power in space
11. Environmental interactions in space associated with energy sources, processing, and work in space; i.e., the impact of foreign materials and pollutants

A broadly based program aimed at developing solar and nuclear power systems to the multimegawatt level is of the highest priority. For brevity's sake, we have discussed only a few of the variety of long-range, innovative energy-related programs supported by NASA, DOD, DOE, and industry. To ensure a broadly based, innovative program, a portion (up to 5%) of the funds allocated for space power research should be devoted to areas that may permit radical advance and extremely high payoff, albeit at high risk.

Heavy Lift Launch Vehicle

An unmanned heavy lift launch vehicle derived from the Space Shuttle to lower the cost of transporting material to Earth orbit would make it feasible to transport to orbit elements of a lunar base or a manned spacecraft destined for Mars. Its first stage would be powered by two solid rocket boosters, shown here after separation. Its second stage would be powered by an engine cluster at the aft end of the fuel tank that forms the central portion of the vehicle. All this pushes the payload module located at the forward end. This payload module can carry payloads up to 30 feet (9.1 meters) in diameter and 60 feet (18.3 meters) in length and up to 5 times as heavy as those carried by the Shuttle orbiter.

Artist: Dennis Davidson


DAVIDSON
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