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# Review Of Laser Lightcraft Propulsion System (Preprint)

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**Abstract.** Laser-powered "Lightcraft" systems that deliver nano-satellites to LEO have been studied for the Air Force Research Laboratory (AFRL). The study was built on the extensive Lightcraft laser propulsion technology already developed by theoretical and experimental work by the AFRL's Propulsion Directorate at Edwards AFB, CA. Here we review the history and engineering-physics of the laser Lightcraft system and its propulsive performance. We will also review the effectiveness and cost of a Lightcraft vehicle powered by a high-energy laser beam. One result of this study is the significant influence of laser wavelength on the power lost during laser beam propagation through Earth's atmosphere and in space. It was discovered that energy and power losses in the laser beam are extremely sensitive to wavelength for Earth-To-Orbit missions, and this significantly affects the amount of mass that can be placed into orbit for a given maximum amount of radiated power from a ground-based laser.

**Keywords:** Lasers, Lightcraft, Laser propulsion, Reusable launch vehicles, Laser propagation
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## INTRODUCTION

Laser propulsion is a new and exceptional method for reaching space. By launching spacecraft on a beam of electromagnetic radiation, researchers will have developed the first new method of achieving orbit since the late 1950's. In this concept, a remote or ground-based energy source, such as a ground- or space-based laser beam generator, transmits power to a spacecraft via a beam of electromagnetic radiation.[1-8] The spacecraft collects the beam energy and uses it to power the propulsion system. This concept has the advantage of using the ambient air as the working fluid in the atmosphere and carrying propellant only for use outside the atmosphere, leaving the energy source for heating the propellant on the ground. This results in a tremendous weight reduction and improved performance benefit for the spacecraft because a large propellant mass and heavy energy source are not carried on-board.

The laser-propelled vehicle, called "Lightcraft" because it flies on a beam of laser light, is designed to harness the energy of a laser beam and convert it into propulsive thrust. In the earliest laser-propelled rocket designs, beamed energy from a ground-based laser (with near-visible wavelengths) is absorbed by a heat exchanger on-board a rocket, and is transferred to a working fluid. The heated fluid (hydrogen, ammonia, etc.) then produces thrust by expansion through a nozzle as in a conventional chemical rocket. An alternative to this scheme is to use the beamed-energy to ablate an on-board solid propellant (such as Delrin) to generate thrust. However, a more recent incarnation of this concept is for the Lightcraft to operate in two propulsion modes: airbreathing (detonation wave) and rocket ablation (deflagration). The Lightcraft operates in air breathing mode up to Mach 5 and 30 km altitude, and in laser thermal rocket mode (using liquid, gaseous, or Delrin ablation propellant) in space.[7,8,9-16]

In the two-mode propulsion concept, a forebody aeroshell acts as an external compression surface for the airbreathing engine inlet. Affixed to the bottom of the craft is a parabolic-shaped afterbody mirror, which serves as a primary receptive optic for the laser beam and as an external plug nozzle expansion surface. The primary thrust structure is the centrally located annular shroud, which provides air through the inlet and also acts as a ring-shaped energy "absorption/propulsion" chamber for plasma formation. The air inlet is closed when the Lightcraft operates in the rocket mode.

The Lightcraft is very lightweight and uses its shape to facilitate vertical flight. The craft has the appearance of a fat acorn when viewed from the side. The lower portion of the craft is a very highly polished metal mirror, whereby the lower point of the acorn-shape is the midpoint of a stretched-out parabolic mirror. The Lightcraft receives kiloJoule pulses from a ground-based infrared laser at a rate of 25 times per second. The axisymmetric, off-axis parabolic collection mirror facilitates flight by concentrating the pulsed laser light into an annular focus. The laser beam's pulse interacts with the mirror, spreading out and focusing into an annular area inside the circumference of the craft. The intensity of the 18 microsecond pulsed laser is sufficiently high that atmospheric breakdown occurs in the annular area causing inlet air to momentarily burst into a highly luminous plasma (10,000 - 30,000 K), thereby producing a superheated plasma shock wave (with instantaneous pressures reaching tens of atmospheres) that generates thrust in the direction of the laser beam. A lip around the craft's circumference, akin to a plug nozzle directs the expansion of the plasma, creating downward thrust expansion. Multiple laser pulses and an atmospheric refresh of breakdown air generate the flight. This airbreathing pulsed-detonation engine concept owes its origins to the German V-1 "Buzz Bomb" of WW II that ran on aviation fuel.

For the purpose of our study, we envision a Lightcraft Earth-to-orbit (ETO) transportation system that operates according to the following scenario. The airbreathing engine mode develops quasi-steady thrust by pulsing at a variable rate that depends on the Mach number and altitude flown along the flight trajectory to orbit. Once the Lightcraft reaches very high altitude and climbs above the atmosphere, it begins to operate in the thermal rocket mode using on-board propellant to convert and expand the laser energy for propulsion. The Lightcraft is spin-stabilized and can be launched vertically upward or on a slant upward trajectory, hover in mid-air, and undergo powered descent and landing. The ground-based laser beam generator system consists of the following: 1) power supply; 2) high-power (MW-class) laser beam generator/transmitter using novel beam optics; and 3) automated tracking, hand-off and safety systems.

## LIGHTCRAFT TECHNOLOGY DEMONSTRATION PROGRAM

The Lightcraft project originally grew out of the Lightcraft Technology Demonstration Program funded by the SDIO Laser Propulsion Program in the late 1980's. In the 1990's a joint program involving the NASA-Marshall Space Flight Center and the Propulsion Sciences and Advanced Concepts Division of the AFRL Propulsion Directorate developed and tested an experiment to determine the feasibility of using high-power pulsed lasers to launch a spacecraft into orbit. Successful tests at the White Sands Missile Range (WSMR) High Energy Laser Systems Test Facility (HELSTF) demonstrated the first passively controlled vertical free flight of an object that was propelled by the U.S. Army's 10 kW Pulsed Laser Vulnerability Test System (PLVTS) infrared $CO_2$ laser. Laser boost capability was demonstrated at the HELSTF with a Lightcraft reaching 43 m vertically in 2-second gyroscopically stabilized free flights, which was followed by horizontal guide-wire flights of 121.9 m lasting 10 - 20 seconds. A subsequent series of test flights achieved an altitude of 38.7 m.

This achievement can be compared to the first successful flights of Robert Goddard's liquid propellant chemical rocket, which attained a height of 12.5 m after a 2.5 second burn in March 1926. In sharp contrast with Goddard's rockets, there is absolutely no fuel on board the prototype Lightcraft, which has a diameter of 10 cm, mass of 20 - 40 g, and is machined from a solid block of 6061-T6 aluminum. Five different Lightcraft designs have been flight-tested using the pointing and tracking system on the PLVTS laser. Current Lightcraft designs are limited to about 60 g mass and 15 cm in diameter by the PLVTS laser. A MW-class laser will be necessary for a kilo-class Lightcraft to reach orbit and components for these lasers exist, which would demonstrate the feasibility of this technology for low cost access to space.

## SUMMARY OF TECHNICAL PERFORMANCE AND BENEFITS

We outline below the propulsion performance features of the Lightcraft launch system:

- The system is single-stage-to-orbit and completely reusable.
- Almost no on-board propellant is required (the reaction mass is free air), except for the small internal amount of propellant needed for final ascent to orbit and orbital maneuvering.
- Vehicle specific impulse ($I_{sp}$) is essentially infinite ($\approx$ *several* $\times 10^3$ seconds in rocket mode).
- Payload mass fractions are $\approx$ 50 - 95%.
- These systems are simple, reliable, safe, environmentally clean, and could have a very high all azimuth on-demand launch rate.
- Reduces space launch costs by two to three orders of magnitude below today's levels: estimated launch costs are \$20 - 200/kg of payload.
- The feasibility and physics principles have been proven by the AFRL's Lightcraft Concept Demonstration Program.[11,16-25]

Lightcraft systems have sufficient power density to operate as ETO launch systems. It requires a beam power of ~ 0.1 MW per kg of vehicle mass, while orbit-to-orbit propulsion requires a modest 0.1 - 10 MW of total beam power. The ground-based MW-class laser beam generator is state-of-the-art technology. The cost of generating electrical power for the ground-based laser beam generator/transmitter is ~ \$0.10/kWh, which translates to < \$2/kg of payload. An SDIO study[10,11] showed that all launch to orbit conditions for a Lightcraft could be satisfied by a single, high-power ground-based laser – with or without the aid of a low altitude laser relay mirror or space-based laser beam generator system. The majority of the system mass required to launch a 1-ton payload to orbit is left on the ground in the form of the beam generators and their electrical power sources. The dry spacecraft mass can be further reduced by two orders of magnitude, and thus the operating costs reduced by a factor of 10 (to ≈ \$2/kg of payload), if Buckytubes are used to construct the vehicle and its subsystems.

## Lightcraft Configuration

As shown in Figure 1, the Lightcraft configuration consists of: 1) a conically shaped “forebody” for lift and aerodynamic compression of ingested airflow (prior to its detonation by laser heating during atmospheric flight); 2) an annular “cowl” or “shroud” within which air detonation or propellant ablation (by intense laser heating) occurs; and 3) a parabola-shaped “afterbody” whose mirrored surface focuses beamed laser energy into regions of sufficient smallness for intense air or propellant heating to occur. And as shown in Figure 2, the vehicle is powered by laser airbreathing propulsion (by detonation of air) until hypersonic speed within the sensible atmosphere is reached; and then the vehicle is powered by laser rocket propulsion (by heating of propellant) during flight above the sensible atmosphere, until cut-off velocity for orbital flight is reached.

The low vehicle propellant fraction for laser powered Lightcraft (~ 0.5 of vehicle takeoff mass) resulted in vehicle takeoff masses that were approximately 45, 80, and 360 times less than those of conventional rockets for placing masses of 10, 5.0, and 1.0 kg into low Earth orbit (LEO). And preliminary life-cycle cost estimates made during the AFRL study indicated that transportation system costs for placing 10, 5.0, and 1.0 kg of mass into orbit using Lightcraft and ground-based lasers would be approximately 3, 5, and 15 times less than with conventional rockets.

One of the two most important findings from the AFRL study is the significant influence of Lightcraft drag on airbreathing laser propulsion performance, and the consequence of this on laser rocket propulsion performance during the latter phase of Lightcraft flight. As indicated in Figure 3, a significant reduction in both Lightcraft size and drag coefficient ($C_D$) – as compared to that of the initial government baseline design – was needed for acceptable airbreathing thrusting acceleration during atmospheric flight. Figure 3 shows that both size and drag coefficient reduction were accomplished in several steps – with both size and $C_D$ reduction accomplished during the first step, and further $C_D$ reduction (by increased forebody fineness ratio) during the second step.

It was also found that sufficient Lightcraft airbreathing thrust required thrust variation with altitude, somewhat comparable to that achievable by contemporary airbreathing propulsion systems – whose flight dynamic pressure ($q$) and thrust remain constant with increasing vehicle altitude and speed until constant $q$ can no longer be maintained. Here, acceptable airbreathing thrust minus drag performance was needed to reach maximum airbreathing speed (Mach 10) within acceptably short flight times and distances. And such short times and distances were required to ensure adequate receipt of beamed power by the Lightcraft out to the longest ranges associated with laser rocket propulsion flight; where beamed power would travel the longest distances through the atmosphere and space, and collected power would drop to lowest values.

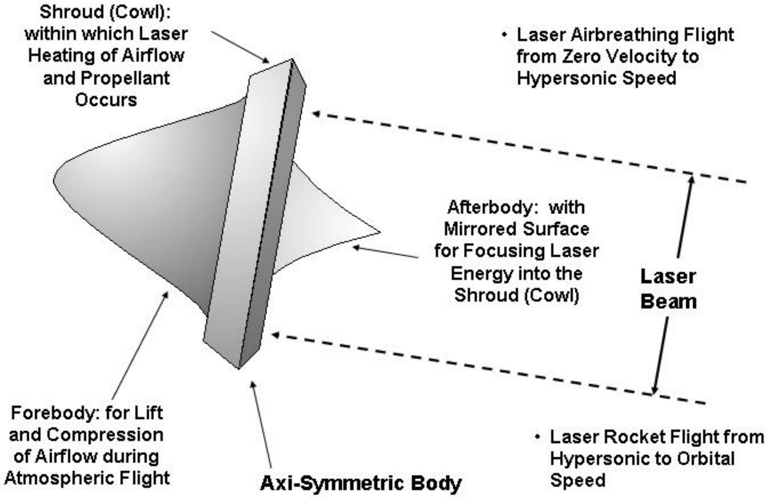

**FIGURE 1.** Lightcraft Concept.

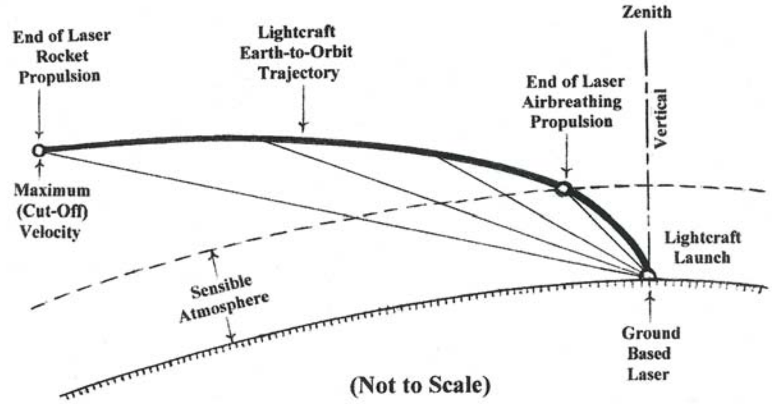

**FIGURE 2.** Lightcraft Trajectory and Associated Pointing Angles.

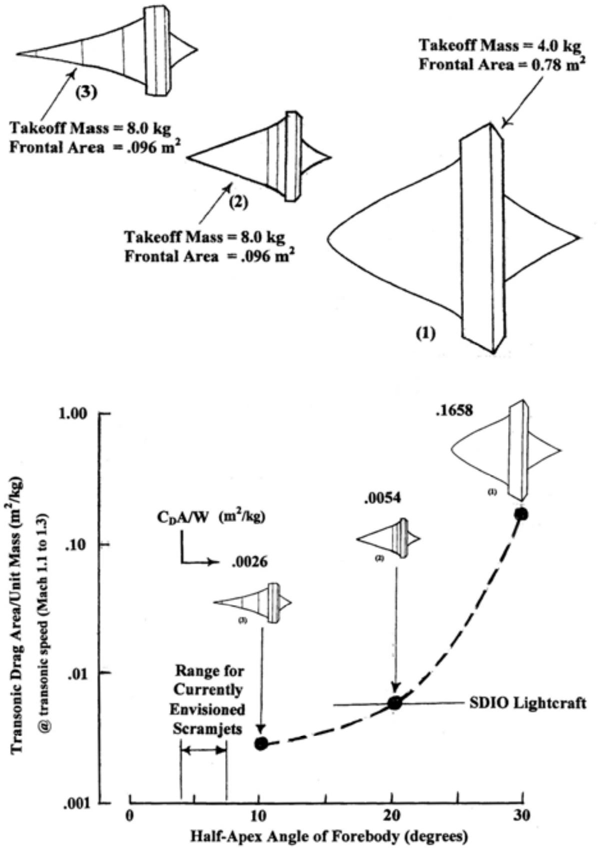

**FIGURE 3.** Lightcraft Vehicle Evolution (in 3 steps).

The AFRL study also determined that the ground-based laser selected ($\lambda$ = 1.62 μm, 10 MW radiated power, 10 m diameter aperture) would enable a Lightcraft takeoff mass of 8 kg and Lightcraft propellant mass of 4 kg. Therefore, this would allow approximately 4 kg of mass to be placed into orbit with the selected ground-based laser. And vehicle synthesis work determined that the remaining masses for the Lightcraft airframe, propulsion, and control systems would be 0.63 kg, 0.46 kg, and 0.45 kg, respectively, together with a 30 percent contingency (of 0.47 kg).

The AFRL study further indicated that small off-the-shelf chemical propulsion systems, with sufficient thrust, would be about a factor of 7 - 12 heavier than those needed to meet Lightcraft orbit circularization needs. However, such mass reductions were deemed possible with emerging micro-electromechanical systems (MEMS) technologies being developed under the National Nanotechnology Initiative. It was also found that the currently configured composite structure for the Lightcraft forebody must be reduced from 2-ply to 3-ply (with the same ply-thickness) to meet Lightcraft airframe mass requirements. Detailed estimates of guidance, control, and propulsion subsystem mass were not made because their requirements have not yet been defined. However, their very lightweight mass allocations appear achievable with MEMS technology.

Another important finding in the study was the significant influence of the ground-based laser wavelength on Lightcraft performance. Figure 2 illustrates the adverse beam propagation geometry associated with ETO laser propulsion by means of ground-based lasers. It is seen that beam propagation distances through the Earth's atmosphere are short during initial flight phases when the path length traveled by laser energy to the Lightcraft is least. But during latter flight phases (when the vehicle itself is above the sensible atmosphere) the beam propagation path within the atmosphere is much longer, and power losses due to atmospheric attenuation become ever greater with increasing range. And since power losses due to laser beam spreading – even in vacuo – also increase with increasing distance from the laser, power losses are greatest at the end of laser propulsion (when vehicle distance from the laser is greatest).

For a ground-based laser with given aperture diameter, adaptive optics, atmospheric conditions, and radiated power, the laser power collected by the Lightcraft was found to be extremely sensitive to laser wavelength ($\lambda$). Here, $\lambda$ determined the amount of radiated laser power lost through "thermal blooming," turbulence, and "extinction" during beam passage through the Earth's atmosphere in addition to the power lost from "diffraction" (beam spreading at longer ranges) during propagation through the vacuum of space. And since each loss mechanism was a function of $\lambda$, the investigators considered each loss mechanism in their estimation of lost power for the six different laser wavelengths associated with the six different ground-based laser candidates that were evaluated in the study.

Shown in Figure 4 (without dimensions) is the fraction of radiated laser power collected by the Lightcraft at maximum laser propulsion range (when necessary "cut-off' velocity for orbital flight is achieved) for the spectrum of wavelengths investigated. It is seen that a significant fraction of laser-radiated power is lost, even if there were no atmospheric transmission losses at all. And additional losses associated with beam propagation through the atmosphere are seen to result in power losses on the order of 75 - 99%. Figure 5 shows that significantly more power would be available at the end of laser airbreathing flight than at the end of laser rocket flight. This might benefit surface-to-air Lightcraft missions that would mainly entail airbreathing flight.

Figure 6 shows, for a given laser aperture diameter, adaptive optics, and atmospheric conditions, the decrease in laser power collected by the Lightcraft with increasing range from a 11.2 μm wavelength $CO_2$ laser. The decrease is shown for a vertical laser-pointing angle and for a final laser-pointing angle of 83° (from the vertical) that occurs at maximum laser propulsion range (about 500 km), where the Lightcraft reaches maximum speed.

Figure 7 shows the significant difference in the laser power collected by the Lightcraft during its laser propulsion phase of flight for the selected laser wavelength of 1.62 μm, and for the 11.2 μm $CO_2$ laser wavelength chosen for a government baseline Lightcraft. This comparison is for a Lightcraft trajectory determined from optimization work during the latter phases of the AFRL study. It was also for the highest radiated power (10 MW) and the largest laser aperture (10 m) that was deemed practical for Air Force operations and systems.

Unfortunately the demonstrated laser power levels for the attractive 1.62 μm wavelength, which suffered the least propagation losses, are relatively modest. This attractive laser wavelength is associated with solid state free electron lasers (FEL), whose maximum power levels are currently in the 10 kW range. Thus there is the need for a thousand-fold increase in FEL power to achieve the 10 MW power level desired for Lightcraft ETO propulsion.

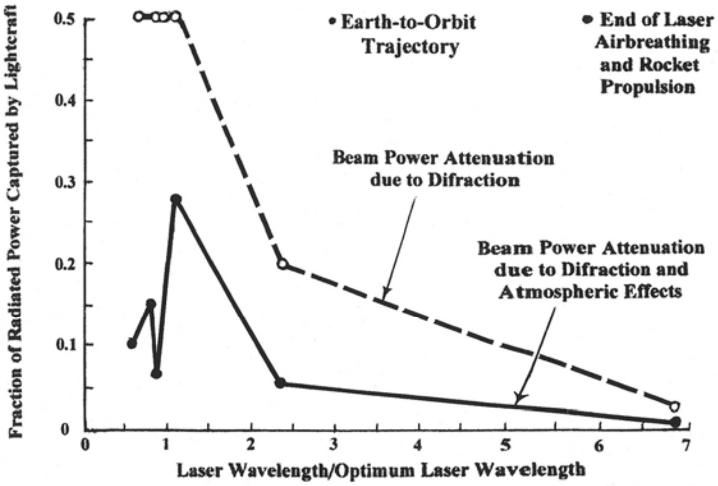

**FIGURE 4.** Attenuation Effects on Captured Laser Beam Power.

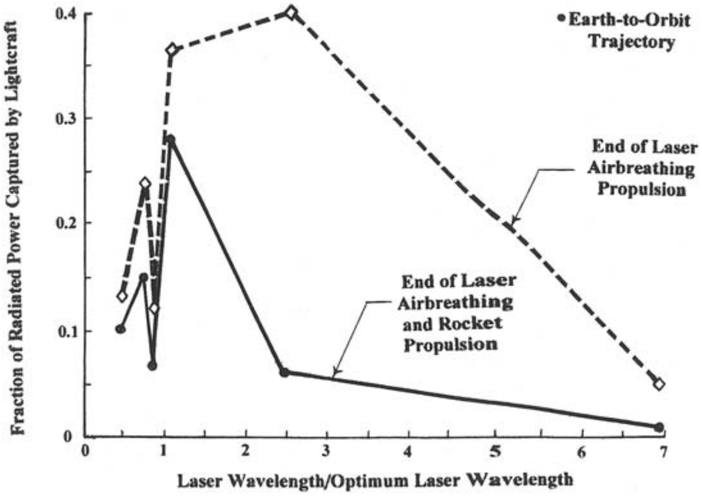

**FIGURE 5.** Influence of Trajectory and Laser Wavelength on Captured Power.

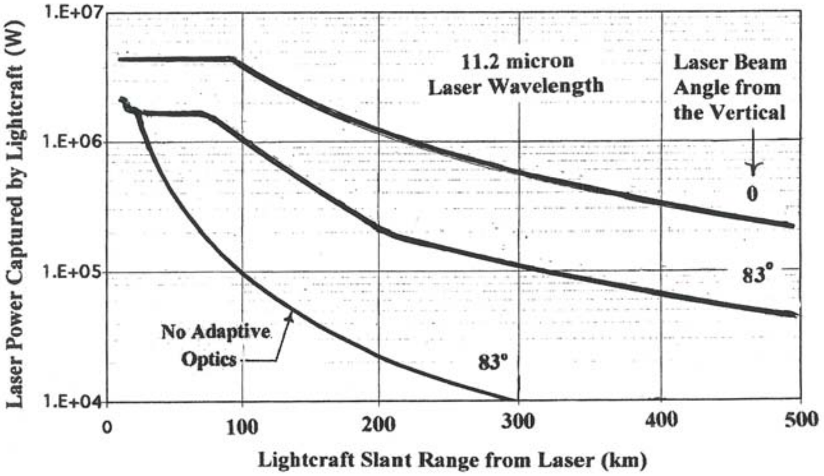

**FIGURE 6.** Captured Laser Power vs. Increasing Range from 11.2 μm $CO_2$ Laser.

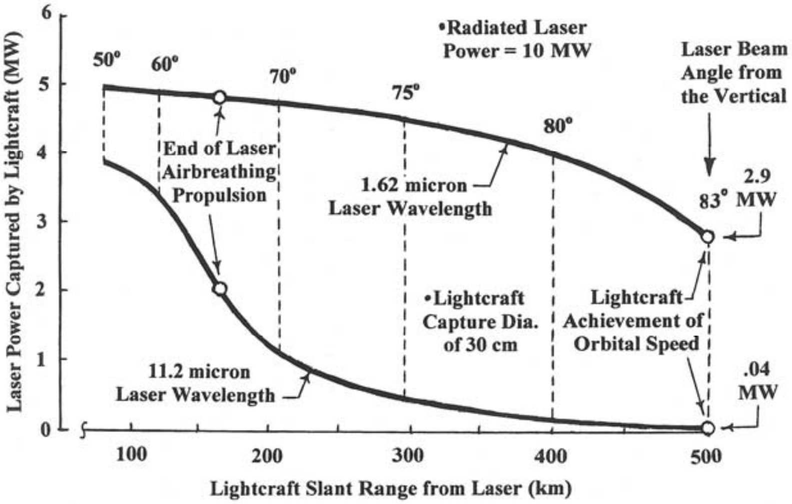

**FIGURE 7.** Influence of Lightcraft Range and Pointing Angles on Captured Power.

## Life-Cycle Cost of Lightcraft System

As might be expected, the AFRL study found that ground-based laser costs comprised the major portion of a Lightcraft ETO transportation system – with ground-based laser costs comprising about 80% of the total laser Lightcraft system life-cycle cost (LLC). The LCC of a laser Lightcraft ETO transportation system was estimated using Lightcraft vehicle and ground-based laser cost inputs from AFRL/PRSP together with programmatic cost inputs from another cost database. Table 1 shows the programmatic assumptions together with the system acquisition and operation costs for the various Lightcraft vehicle and ground-based laser system elements. Laser acquisition and operation costs were assumed to be shared with another user, and all operations costs are reduced to one-half those values estimated from historical data. Launch costs are seen to be extremely low (only about $75,000 per launch) with laser-associated costs comprising approximately 90% of the laser-powered Lightcraft ETO transportation system LCC.

**TABLE 1.** Laser Lightcraft Model Cost Summary.

| **Laser Lightcraft Model Cost Summary** | **Share Solid-State Laser Cut Ops Costs by 50%** | |
|---|---|---|
| Mission Model Length (Years) | 10 | |
| Launch Rate Per Year | 1,000 | |
| Payload Per Launch (kg) | 2.0 | |
| Mission Flight Time (s) | 221.52 | |
| Total Program Cost ($M) | 741.410 | |
| DDT & E / Acquisition Costs ($M) | 680.358 | 91.77% |
| Operations Costs ($M) | 61.053 | 8.23% |
| | | |
| Average Cost Per Flight ($) | 74,141 | |
| Average Cost Per kg (based on operations costs) ($) | 3,052 | |
| | | |
| DDT & E / Acquisition Costs ($M) | 680.358 | |
| Laser Lightcraft (LLC) Development Cost ($M) | 18.000 | 2.65% |
| Laser Lightcraft (LLC) Acquisition ($M) | 37.596 | 5.53% |
| 10 MW Ground-Based Laser Acquisition ($M) | 624.762 | 91.83% |
| Launch Site Facility Costs (Construction) ($M) | 5.000 | 0.73% |
| | | |
| Operations Costs, Annual ($M) | 6.105 | |
| Laser Annual Operations Cost ($M) | 3.750 | 61.42% |
| Laser Refurbishment, Annual ($M) | 0.750 | 12.28% |
| Laser Consumables, Annual ($M) | - | 0.00% |
| Energy Cost, Annual ($M) | 0.101 | 1.65% |
| Launch Site Facility Cost, Annual ($M) | 0.250 | 4.09% |
| USAF Sys Prgrm Office (SPO) Cost, Annual ($M) | 0.250 | 4.09% |
| NORAAD Coordination Cost, Annual ($M) | 0.500 | 8.19% |
| FAA Coordination Cost, Annual ($M) | 0.250 | 4.09% |
| Range (Safety, Tracking, Telemetry), Annual ($M) | 0.255 | 4.17% |

## Estimated Payload Cost for Lightcraft Launch Using 10 MW $CO_2$ Laser

The AFRL study used a proposed electron gun driven 10 MW $N_2/CO_2/H_2$ laser design to estimate the Lightcraft payload launch cost, which is described in what follows. Each power oscillator optics module transmitting a 2.5 MW beam of 10.6 $\mu$m wavelength photons generates $1.334 \times 10^{26}$ photons/s, and 15 kg/s of $CO_2$ mass flow represents $2.053 \times 10^{26}$ molecules/s of gas flow. These figures taken together mean that 1.54 $CO_2$ molecules are required to lase one photon. A 2.5 MW laser operating for 300 seconds of thrusting will allow us to send 5.25 kg of payload into LEO, and the total laser energy ($E_{\mathrm{laser}}$) output is 750 MJ. If the laser efficiency is 0.20, then we will need to use 12.5 MW of electrical power for 300 seconds (or 3,750 MJ of total energy), which, at a cost of \$0.10 per kWh (or \$0.0278 per MJ), gives a total cost of \$104 for the required electrical energy to launch the payload.

The kinetic energy ($K_{\mathrm{E}}$) of a Lightcraft in LEO is given by $K_{\mathrm{E}} = \eta\alpha\beta\gamma E_{\mathrm{laser}}$, where $\eta = 1$ (is the conversion efficiency of laser rocket propellant-thrust-jet $K_{\mathrm{E}}$ into vehicle

$K_E$, in which the propellant/laser is designed so that the rocket thrust-jet velocity is equal to the vehicle velocity throughout the mission, i.e., the laser rocket has variable $I_{sp} \approx 100$ s at beginning of mission to 1,000 s at end of mission), $\alpha\beta = 0.5$ ($\alpha$ is efficiency of laser energy absorption, $\beta$ is efficiency of conversion of propellant internal energy into thrust-jet $K_E$), $\gamma = 0.7$ (is the atmospheric transmission efficiency), and $E_{laser} = 750$ MJ. These numbers multiplied together give a vehicle $K_E = 262.5$ MJ in LEO. If the effective change in velocity ($\Delta v$) required to get to LEO is 10 km/s (8 km/s orbital velocity + 1 km/s for gravity + 1 km/s for drag loss), then 1 kg in LEO has 50 MJ of energy investment and a 5.25 kg payload in LEO has 262.5 MJ of energy investment.

The 60 kg/s mass flow requirement of the 3:1 $N_2/CO_2$ lasing gases means that a mass flow of 15 kg/s of $CO_2$ and 45 kg/s of $N_2$ is required. For the 300 s of thrust we will therefore need 4.5 tons of $CO_2$ and 13.5 tons of $N_2$ gases (we are neglecting the tiny amount of $H_2$) to launch a payload to LEO. Liquid $CO_2$ costs $100 per ton and liquid $N_2$ costs $154 per ton. The total lasing gas cost is therefore $450 for the liquid $CO_2$ and $2,079 for the liquid $N_2$. Adding these two gas fuel costs to the $104 cost of the required electrical energy gives a total of $2,633 to launch a 5.25 kg payload to LEO. This result represents a cost of $501 per kg of payload (or $228 per pound) launched to LEO, which is 44 times lower than the oft-quoted standard space launch industry cost of $10,000 per pound for conventional chemical propulsion rockets systems.

This cost figure needs to be slightly adjusted to account for other factors. If we use the $N_2/CO_2$ gases at a temperature of 217 K in the laser, then we will have to boil the liquid $CO_2$ and the liquid $N_2$ with additional heating of the gaseous $N_2$. Boiling 4.5 tons of liquid $CO_2$ at 217 K requires 1,175 MJ of energy, boiling 13.5 tons of liquid $N_2$ at 77 K requires 2,683 MJ of energy, and heating the 13.5 tons of gaseous $N_2$ from 77 K to 217 K requires 1,890 MJ of energy. Therefore, the additional energy required to prepare the laser gases is 5,748 MJ (= 1,175 MJ + 2,683 MJ + 1,890 MJ), which represents an additional electricity cost of $160. Adding this additional energy cost to the previous total of $2,633 gives a *final total cost* of $2,793 to launch a 5.25 kg payload to LEO. This new final result represents a cost of $532 per kg of payload (or $241 per pound) launched to LEO, which is 41 times lower than the space launch industry cost of $10,000 per pound for conventional chemical propulsion rockets. Note that these estimates excluded the annual operations costs shown in Table 1.

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