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Ground and Flight Tests of a Laser Propelled Vehicle

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Abstract

A laser propelled Lightcraft vehicle has been successfully flown in a series of experiments conducted at the High Energy Laser Systems Test Facility (HELSTF), White Sands Missile Range (WSMR), NM. The flight tests, conducted under a joint USAF/NASA flight demonstration program, used 14-cm (5.5 in.) diameter, 50 to 60 gm (1.8 to 2.1 oz.) vehicles designed to fly on the 10 kW Pulsed Laser Vulnerability Test System (PLVTS) pulsed carbon dioxide laser (1 kJ per pulse, 30 μs pulse width at 10 Hz). The axisymmetric Lightcraft vehicles were propelled by airbreathing, pulsed-detonation engines with an infinite fuel specific impulse. Impulse coupling coefficients were measured with ballistic pendulums as well as a piezoelectric load cell and fell in the range of 10 to 14.3 dyne•s/J. Horizontal wire-guided flights up to 398 ft (121.3 m), using a laser beam pointing and tracking guidance system, have demonstrated up to 2.3 g's acceleration measured by a photo-optic array. Spin-stabilized free-flights with active tracking/beam control have been accomplished to altitudes of 14 feet (4.27 m).

Introduction

In the USA, beamed energy propulsion was first promoted by Kantrowitz.[1] His early analysis dealt with laser heated rockets, and assumed a specific impulse of 1,000 sec. The analysis indicated that gigawatt lasers were required to launch sizeable vehicles (1 ton to orbit) at an average acceleration of 10 g's. A principal advantage of the laser propulsion launch system was the capability to rapidly launch many relatively small payloads. Such a system could launch observation or communications relay microsatellites to quickly respond to new requirements or to temporarily replace critical, malfunctioning systems.

Background

The Lightcraft Technology Demonstrator (LTD)[2] is a laser propelled trans-atmospheric vehicle concept developed by Prof. Leik Myrabo of Rensselaer Polytechnic Institute (RPI) for Lawrence Livermore National Laboratory and the SDIO Laser Propulsion Program in the late 1980's.[3] This new launch system was envisioned to employ a 100 MW-class ground-based laser to transmit power directly to the Lightcraft in flight. An advanced combined-cycle engine would propel a 120 kg (265 lb) dry mass, 1.4 m (4.59 ft) diameter LTD, with a mass fraction of 0.5, to orbit. The LTD vehicle would then become an autonomous sensor satellite capable of delivering precise, high quality information typical of today's large orbital platforms.[2]

The dominant motivation behind this study was to provide an example of how laser propulsion could reduce, by an order-of-magnitude or more, the production and launch costs of sensor satellites. The study concluded that a vehicle production cost of $1,000/kg was realizable, and that launch costs must be limited to less than

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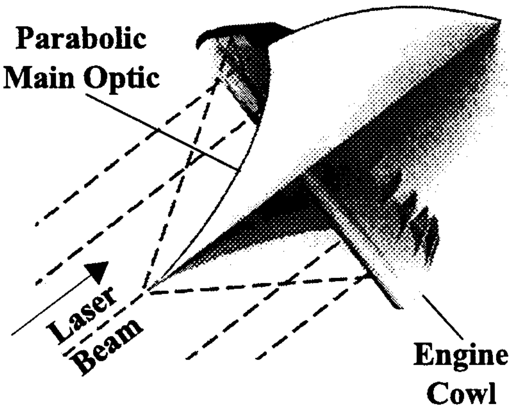


Fig. 1 Schematic of Lightcraft engine.

$100/kg for laser propulsion to play a significant role in the future of space transportation. Today our expectations for the use of laser propulsion technology are slightly less ambitious. We envision the launching of 1 to 10 kg (2.2 to 22 lb) Lightcraft vehicles at $1,000/kg using existing high power lasers, and $100/kg as a realizable goal within the foreseeable future.

The LTD concept, as illustrated in Fig. 1, was, and is today, a microsatellite in which the laser propulsion engine and satellite hardware are intimately shared.[2] The forebody aeroshell acts as an external compression surface (i.e. the airbreathing engine inlet). The afterbody has a dual function as a primary receptive optic (parabolic mirror) for the laser beam and as an external expansion surface (plug nozzle) during the rocket mode. The primary thrust structure is the annular cowl. The cowl serves as both inlet and impulsive thrust surface during the airbreathing mode. In the rocket mode, the annular inlet is closed, and the afterbody and cowl combine to form the rocket thrust chamber. The three primary structures (forebody, cowl, and afterbody) are interconnected by a perimeter support frame to which all internal subsystems are attached. Once in orbit, the single-stage-to-orbit (SSTO) LTD vehicle becomes an autonomous sensor satellite capable of delivering precise, high quality information typical of today's large orbital platforms.[2]

Laser Heated Rocket Investigations

Most previous experimental and analytical research into laser propelled vehicles has been concerned almost exclusively with laser heated rockets. The basic principle of a laser heated rocket is to use a remote, high energy laser to heat gaseous or solid propellant to very high temperatures. The high temperature rocket fuel then expands through a nozzle, producing thrust, cf. Fig. 2. The fuel for the laser heated rocket is typically a low molecular weight gas, in order to obtain the high specific impulse. Some designs use a solid fuel deposited on the base of the vehicle, which typically achieves a higher thrust.

An experimental investigation of a solid propellant laser heat rocket, reported in Ref. 4, was performed with a single pulse of a 60 J CO_2 laser. The laser pulse width was 100 μs, and was focused onto the solid propellant by a parabolic mirror which also

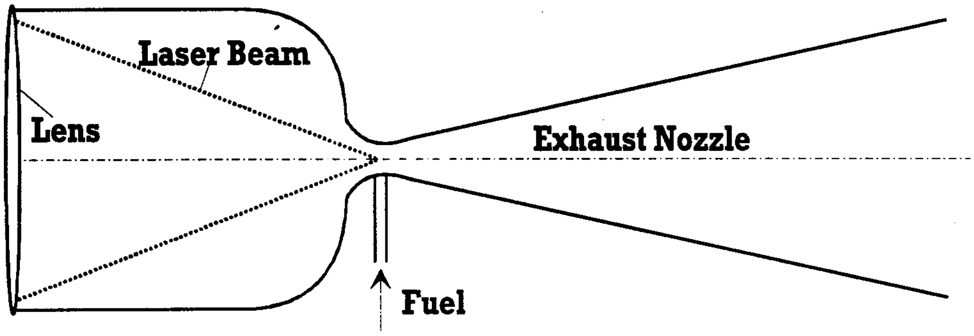


Fig. 2 Typical laser heated rocket configuration.

served as the engine's nozzle. The impulse obtained by the expansion of the solid propellant was measured using a ballistic pendulum. Specific impulses up to 500 sec were obtained with graphite fuel. Coupling coefficients, the ratio of impulse to the energy delivered to the engine, were reported to be between 2 and 92 dyne•s/J, depending on the type of solid propellant. Coupling coefficients for laser breakdown of ambient air were reported in the range of 6 to 30 dyne•s/J. These results were observed to depend on the laser beam flux being delivered to the polished aluminum primary optic. This dependence of the coupling on the incident beam area was attributed to oxide formation on the optic and low optical quality of the parabolic mirror.

A second experiment, with a 11 J, 3 μs CO_2 laser powering a conical nozzle helium fueled rocked obtained a specific impulse of 900 sec and a coupling coefficient of 17 dyne•s/J over two laser pulses.[5] Supporting analyses of laser propelled rockets[6] indicated that a megajoule laser operating at 350 pulses per second (350 MW average power) could accelerate a one ton rocket at 10 g's in a vacuum.

Laser Airbreather Experiments

A laser airbreathing thruster has the advantage that no fuel is carried onboard. Instead, a ground based, high energy laser is focused by onboard optics and used to heat air flowing through the engine inlet. Pulse detonation wave laser engines using atmospheric air as the working fluid have infinite fuel specific impulse. Some onboard propellent is necessary for orbital missions, since the air breathing engine must transition to rocket mode when the atmospheric density becomes too low to sustain meaningful thrust.

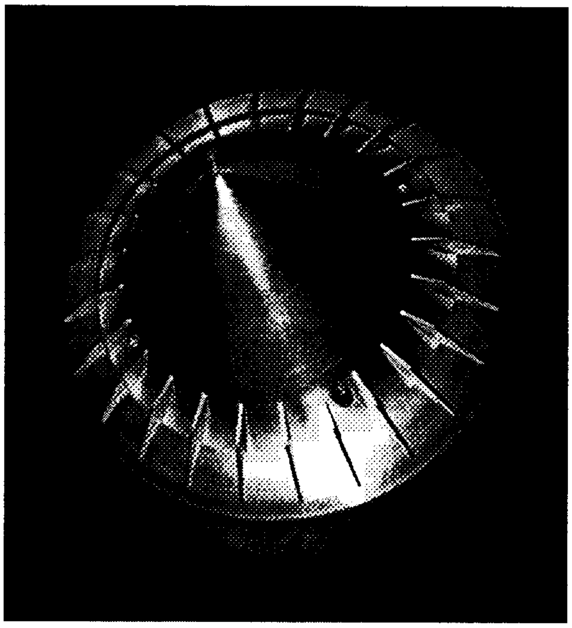
Ageev, et. al.[7] presented computed and experimental results for an air breathing, laser propelled engine. The experiments were conducted with a low energy (5 J/pulse), pulsed CO_2 laser to determine the optimum nozzle angle and length. The experimental configuration was similar to the laser rocket depicted in Fig. 2, with a parabolic nozzle but ambient air as the working fluid. Peak coupling coefficients of up to 50 dyne•s/J were reported for these static tests. Computations with an inflow of air from a simulated inlet resulted in higher performance.

The high energy, pulsed 1 μm PHAROS III neodymium-glass laser at the Naval Research Laboratory (NRL) was used to investigate the impulse imparted to a flat plate by laser induced air breakdown.[8] The impulse was measured using a velocitmeter coil and a pendulum suspended from the test cell ceiling. The test cell was at atmospheric pressure. Single laser pulses from 48 to 350 J were brought to a line focus at the target surface by a spherical lens. The pulse width varied from 5 to 30 ns. Coupling coefficients of 7.5 to 13.2 dyne•s/J were obtained on steel and aluminum flat plates. The coupling coefficient increased to a maximum of 17.8 dyne•s/J when a 0.5 Tesla magnet was inserted at the target surface. The experiment was designed around a segment of a full scale Lightcraft engine.

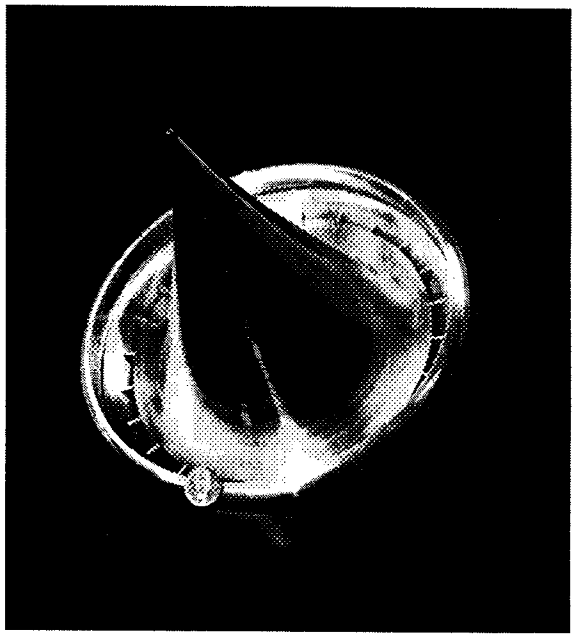
None of these previous experimental investigations of laser propelled rockets or air breathing engines obtained actual flight test data. The objective of the current Lightcraft Technology Demonstration program is to conduct, before the end of calendar year 1998, a flight demonstration to a significant altitude. This will be accomplished by launching a specially designed, ultralight Lightcraft to an altitude of about 0.6 and 1.0 km (1,970 to 3,280 ft) using an existing laser at the HELSTF located at WSMR. The first brief free-flight of a Lightcraft occurred during the tests of 21-24 April, 1997.

Experimental Apparatus

The current nominal 14-cm (5.5 in.) diameter, 50-gm (1.8 oz) vehicles, cf. Fig. 3, are designed to fly on the 10 kilowatt average power level available from the PLVTS pulsed carbon dioxide laser (1 kJ pulses at 10 Hz, 30 μs pulse duration). The axisymmetric vehicles are propelled by airbreathing pulsed detonation engines (PDE) with an infinite fuel specific impulse.



Lightcraft Nose



Rear Parabolic Optic

Fig. 3 Photographs of Lightcraft flight test vehicles (model configuration E).

Lightcraft Engine

The Lightcraft engine consists of a parabolic base which serves as a plug nozzle and also as the main optic, cf. Figs. 1 and 3. The vehicle is axisymmetric, with an annular cowl which encompasses the focus of the parabolic optic.

Several variations on the basic Lightcraft design were examined during the course of the test program. These variations included open and closed inlets, inlets with reed valves, and different optic and cowl configurations. The different vehicle configurations are summarized in Table 1.

Each Lightcraft vehicle shape was machined from solid aluminum blocks using a CNC lathe. No additional polishing or coating was applied to the optical surfaces. The different optic and forebody configurations were constructed as interchangeable parts, and the assembled vehicles were statically balanced prior to flight.

The Lightcraft was positioned on a thin steel wire for horizontal (Fig. 4) and vertical wire guided flight tests. Steel roller bearings and nylon sliding bearings were used to reduce friction between the vehicle and the wire. Steel sliding bearings were used on the vertical free flight experiments to facilitate rapid separation from the short launch support rod.

PLVTS Laser

The PLVTS was used to provide the laser light for the Lightcraft ground and flight tests. PLVTS is a closed cycle CO_2 laser located at the HELSTF at WSMR,

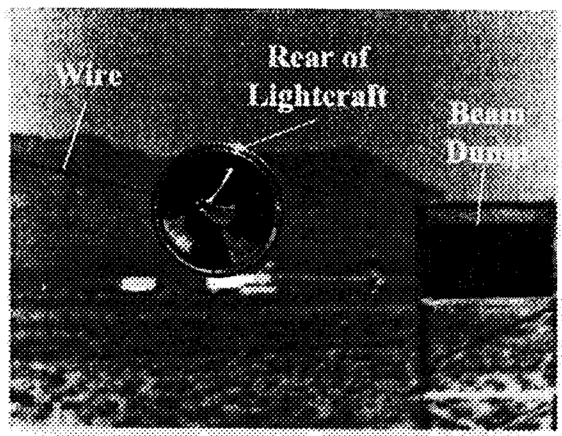


Fig. 4 Horizontal wire configuration with beam dump 398 ft. down range.

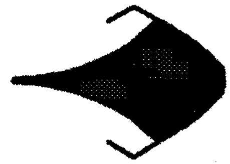
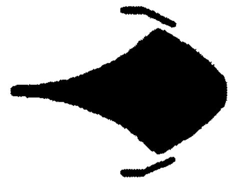
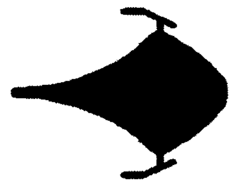
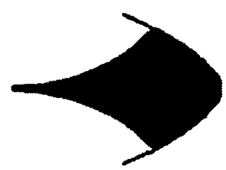
Vehicle Label	Description	Vehicle Shape
A	Final flight configuration. Closed inlet and reverse-curved nozzle. Parabolic optic and rounded nose.	
E	Original baseline, open inlet. Same optic and nose as configuration A.	
E-C	Same as configuration E but closed inlet.	
P	Closed inlet with cowl tangent to forebody contour.	

Table 1 Different vehicle configurations for laser propulsion testing.

New Mexico. The PLVTS laser is an AVCO-built HPPL-300 laser.[9]

PLVTS delivered pulsed laser energy at levels up to 852 J/pulse, as measured at the Lightcraft vehicle location. The pulse repetition rate was from single pulse to 10 Hz, with a pulse width of 30 μs. The beam was delivered to the target by turning flats, including an actuated mirror which was used for active pointing and tracking of the Lightcraft vehicle in flight.

The PLVTS laser produced a 10 cm (3.94 in) square laser beam profile. An imprint of the beam on thermal paper is presented as Fig. 5. This beam pattern was obtained at the initial vehicle position (on the launch pad). The beam profile changed appreciably with range due to diffraction effects. The square beam profile was nonuniform, with the energy distribution changing slightly from pulse to pulse.

The average pulse energy was measured during each thrust stand experiment, and following each flight test series. During the thrust stand experiments, a high energy beamsplitter was positioned in the optical path immediately prior to the engine's primary optic, cf. Fig. 6. A small

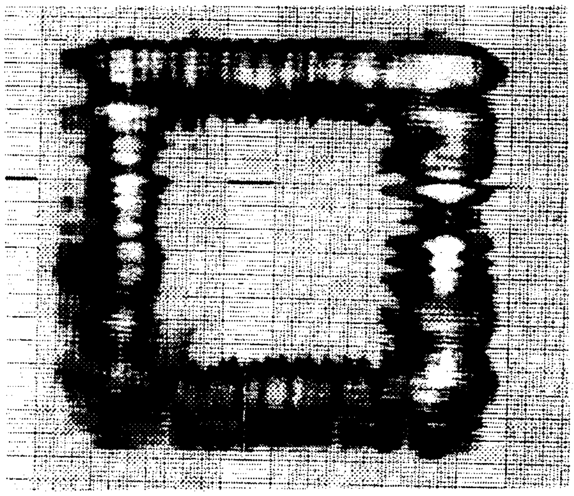


Fig. 5 PLVTS beam profile imprinted on thermal paper at low pulse energy.

custom Labview programs.

The initial impulse measurements were conducted with a pendulum apparatus. This technique employed a velocimeter coil, which was used in previous work to determine the impulse imparted to a flat plate using the 1 μm PHAROS III laser at NRL.[8] The Lightcraft was suspended and suitably weighted before being subjected to a single pulse of energy from the PLVTS laser.

Later experiments used a piezoelectric force sensor. The sensor was mounted in a thrust stand in such a way as to measure the time dependent thrust from the laser engine, cf. Figs. 6 and 7. Different Lightcraft engine configurations were mounted to the thrust stand and subjected to

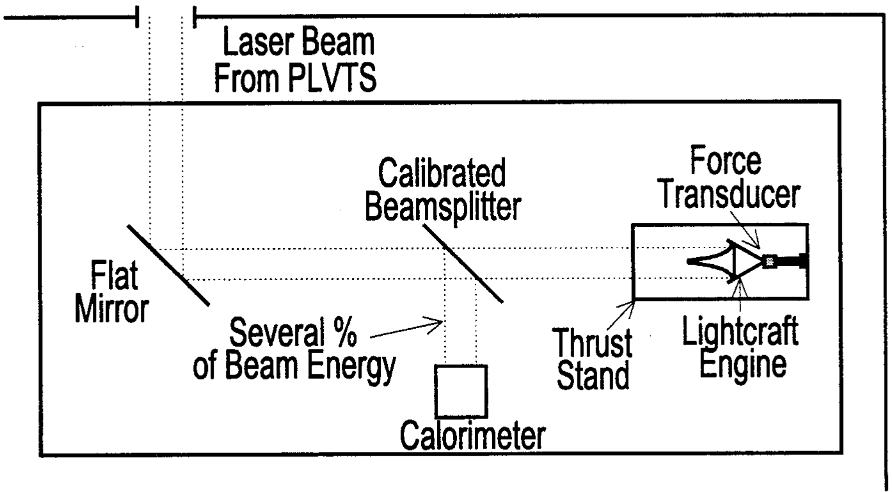


Fig. 6 Schematic diagram of optical setup for Lightcraft thrust measurements.

percentage of the incident laser beam was reflected off of this beam splitter into a calorimeter, which measured the average laser power over approximately 30 pulses (3 sec at the primary laser operating frequency of 10 Hz). The beam splitter was calibrated prior to each experiment.

Measurement Technique

A VXI mainframe with a Tektronix VX4244 16 channel digitizer and a VX4780 16 channel differential amplifier was employed to acquire the thrust and Lightcraft position data. The VXI was controlled by a laptop computer using

Fig. 7 Photograph of thrust stand apparatus.

repetitive pulses from the PLVTS laser at 10 Hz. The time average impulse was divided by the simultaneously measured time average laser pulse energy to obtain the coupling coefficient.

Results and Discussion

Initial laser propulsion experiments focused on measurement of thrust and short, wire guided horizontal flight tests in order to prove the Lightcraft concept. Lightcraft engine models were suspended from a pendulum and the induced current in an attached coil was used to determine the imparted impulse from a single laser pulse, as in Ref. 8. The average laser pulse energy was not measured simultaneously, but was determined at the end of the experiments. Coupling coefficients were between 10 and 20 dyne•s/J.

A piezoelectric force sensor was mounted to Lightcraft models and fixed to a thrust stand to determine the impulse imparted to the engine by the high energy laser. Initial results from the thrust stand were compared with the previous pendulum experiments and were found to be somewhat lower than the pendulum measurements. The pendulum experiments were not time averaged, and the simultaneous laser average pulse energy was obtained only for the thrust stand experiments.

The coupling coefficient was determined by performing multiple experiments at several different laser pulse energies. The measured impulse was plotted against the average laser pulse energy to obtain an average coupling coefficient. The engine performance was found to scale linearly with pulse energy, at average energies from 300 to 850 J. A typical result is plotted in Fig. 8.

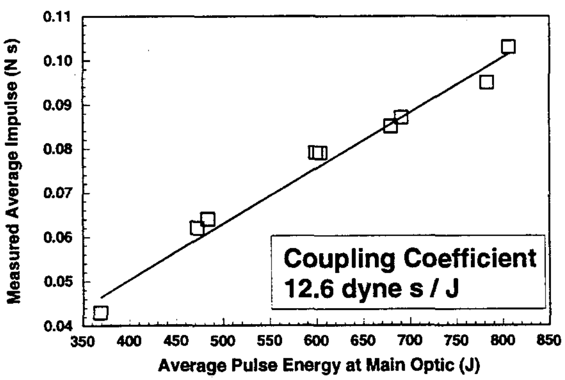
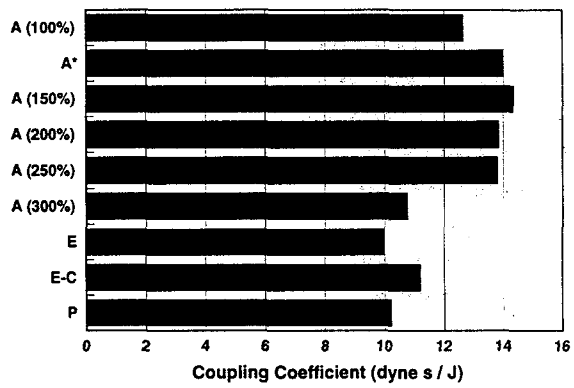


Fig. 8 Determination of coupling coefficient from impulse/energy plot.

Some of the thrust stand data is presented in Fig. 9 as a plot of the coupling coefficient for different vehicle geometries. The coupling coefficients, as determined from force sensor measurements, ranged from 10 to 14.3 dyne•s/J, depending on the engine configuration.

The effect of model scale was investigated by performing thrust stand measurements with engines from 100% to 300% scale. The coupling coefficients did not show any variation with engine size, except for the largest engine (300% scale), which was 20% lower than the value for the smaller engines.



* Changed Optic

Fig. 9 Measured coupling coefficients for several engine geometries.

A photo-optic array was employed to measure the flight path of the Lightcraft during wire-guided, indoor flight tests. A typical trajectory for an early vertical flight test is presented in Fig. 10. These early flight tests did not employ active steering of the laser beam. The motion of the Lightcraft vehicle caused the guide wire to whip, bringing the vehicle optics out of alignment

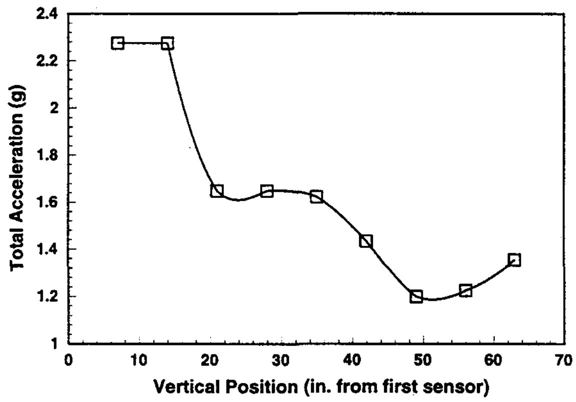


Fig. 10 Typical Lightcraft trajectory from indoor, vertical wire guided flights.

with the PLVTS laser. Average coupling coefficients computed from the initial portion of trajectory agreed well with the thrust stand measurements.

Figure 11 presents a photograph of the Lightcraft model during a single pulse laser propulsion experiment. Laser absorption by air in the annular engine created a plasma which is clearly visible in the photograph. The laser pulse energy was approximately 650 J with a pulse duration of 30 μs. With this engine geometry and pulse duration, most of the laser created plasma extended outside the engine.

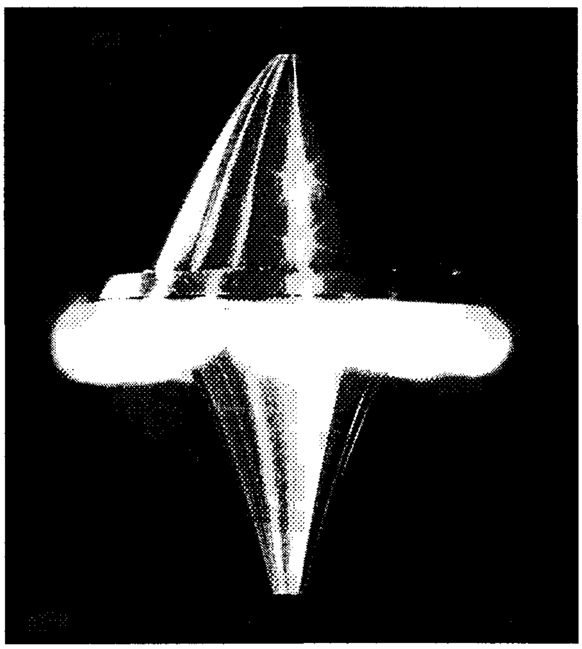


Fig. 11 Close-up photograph of plasma induced from a single laser pulse.

Figures 12 and 13 are multiple exposure photographs of Lightcraft vehicles in free flight. These early flight test experiments were conducted inside Test Cell 3 at the HELSTF. These initial tests were operated indoors to reduce the costs associated with range safety concerns required for outdoor free flights. The laser propelled vehicle was launched 14 ft (4.27 m) to the ceiling of the test cell. Vehicle recovery was achieved by capturing the Lightcraft with a fishing net after laser pulsing was terminated.

The Lightcraft was spin stabilized for these free flight experiments. The vehicle was positioned on a short rod launch pad and spun up to more than 3,000 rpm using a high pressure nitrogen jet. The jet was removed several seconds before initiation of the first laser pulse. The

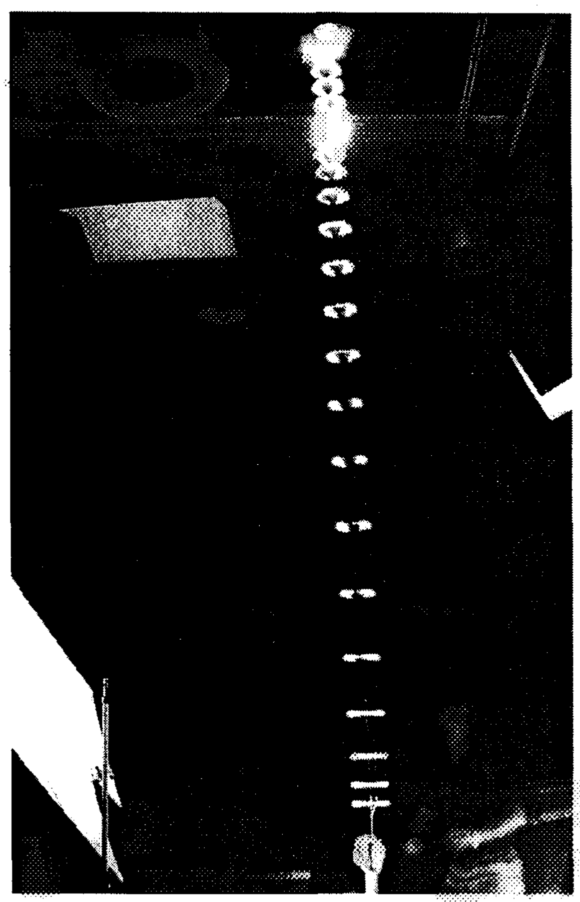


Fig. 12 Indoor Lightcraft free flight.

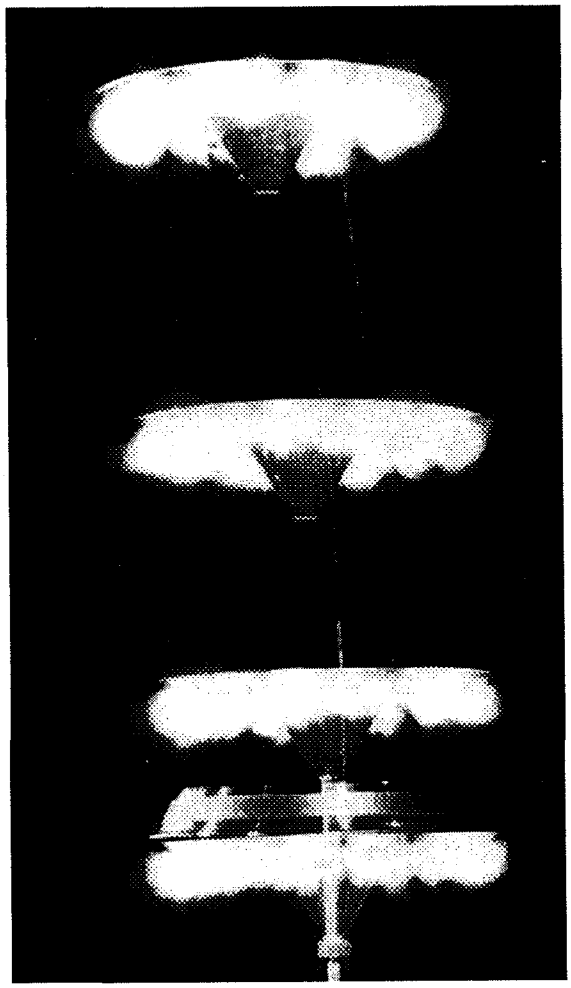


Fig. 13 Multiple exposure close up of Lightcraft launch to free flight.

launch rod extended only 1/2" (1.27 cm) past the vehicle, and the first laser pulse propelled the Lightcraft completely off of the launch pad, cf. Fig. 13.

Wire guided, horizontal flights tested the laser beam active target tracking system. A beam dump, consisting of a 4'x8' plywood sheet painted flat black, was positioned 398 ft (121.3 m) down range to contain the laser beam in the event that it was steered off of the Lightcraft's engine optics, cf. Fig. 4. The long run of steel wire sagged appreciably, and was perturbed by wind and by the motion of the Lightcraft. The laser beam active tracking system was able to keep the beam on the moving target throughout the nearly 400 ft of wire guided flight, cf. Figs. 4 and 14.

Conclusions and Future Work

A laser propelled Lightcraft vehicle has been successfully flown in a series of experiments conducted at the HELSTF, White Sands Missile Range WSMR, NM. The flight tests, conducted under a joint USAF/NASA flight demonstration program, used a 14-cm (5.5 in.) diameter, 50 to 60 gm (1.8 to 2.1 oz) vehicles designed to fly on the 10 kW average power PLVTS pulsed carbon dioxide laser (1 kJ pulses for 30 μs duration at 10 Hz). The axisymmetric Lightcraft vehicles were

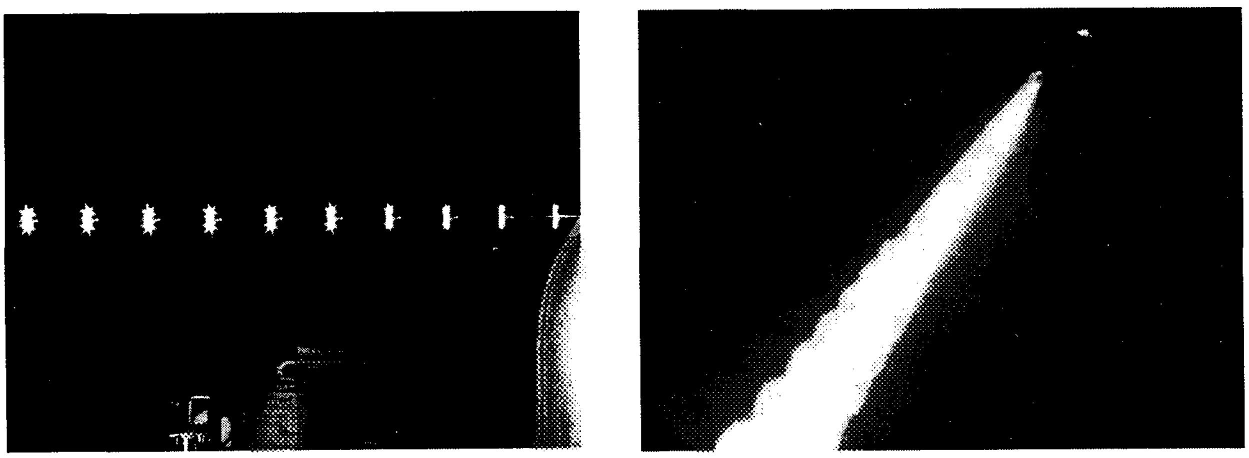


Fig. 14 Horizontal, wire guided night flight of Lightcraft outdoors, (a) side view near Lightcraft launch point, vehicle travels right to left; and (b) view from launch point to 400 ft. tower.

propelled by airbreathing, pulsed-detonation engines with an infinite fuel specific impulse. Impulse coupling coefficients were measured with ballistic pendulums as well as a piezoelectric load cell and fell in the range of 10 to 14.3 dyne•s/J. Horizontal wire-guided flights up to 398 ft (121.3 m), using a laser beam pointing and tracking guidance system, have demonstrated up to 2.3 g's acceleration measured by a photooptic array. Spin-stabilized free-flights with active tracking/beam control have been accomplished to altitudes of 14 feet (4.3 m).

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