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World Record Flights of Beam-Riding Rocket Lightcraft: Demonstration of "Disruptive" Propulsion Technology

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WORLD RECORD FLIGHTS OF BEAM-RIDING ROCKET LIGHTCRAFT: DEMONSTRATION OF "DISRUPTIVE" PROPULSION TECHNOLOGY

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Abstract

On 2 October 2000, a 12.2-cm diameter, 50.6-gram laser-boosted rocket Lightcraft flew to a new altitude record of 71-meters (233-ft) at White Sands Missile Range (WSMR) in New Mexico. The PLVTS 10-kW pulsed carbon dioxide laser, located on the High Energy Laser Systems Test Facility (HELSTF) powered the record flight, as well as six others - two of which reached 48.4-m (159-ft) and 56-m (184-ft). These were the first outdoor vertical, spin-stabilized flights of laser Lightcraft to be performed with assigned launch windows secured from NORAD, with the cooperation of WSMR range control - to avoid illuminating LEO satellites and/or low flying aircraft. Besides nearly doubling the previous altitude record of 39 meters (128-ft) set on 9 July '99, the Model #200 Lightcraft simultaneously demonstrated the longest laser-powered free-flight, and the greatest 'air time' (i.e., launch-to-landing/recovery). With a modest investment of under a million dollars, a string of ever-increasing Lightcraft altitude records have been set over the past four years - since the first flight on 23 April 1997. This embryonic, propulsion concept embodies "disruptive technology" that promises to radically transform our ideas about global flight transportation and space launch systems, over the next 15 to 25 years.

INTRODUCTION

Lightcraft Technologies, Inc. (LTI) is launching a revolution in low-cost space access, promoting the use of beamed energy transmitted from remote power-plants, to propel vehicles around the planet in 45 minutes on suborbital trajectories, or right into orbit – without staging. LTI intends to develop and manufacture such unmanned and manned aerospacecraft designed to ride "Highways of Light." Simply expressed, LTI believes that only beamed energy propulsion holds the promise of radically reducing the cost of space access by 100X in the next 5-10 years, and ultimately by 1000X within 15-25 years. The establishment of an energy beam highway to space will simultaneously increase the reliability and safety of manned suborbital and orbital flights to incredibly high levels, at least equal to airline operations today, or better.

Highways of Light

This vision of the future depends upon significant investments into an energy-beaming infrastructure (laser and microwave) that large numbers of inexpensive Lightcraft can ride. Today's expendable, and partially-reuseable launch systems with their on-board power plants can be considered "infrastructure poor," in comparison. For the near-term nano-satellite launch application (i.e., 1-10 kg payloads), the technology and affordability of 1-10 megawatt-class commercial power-beaming lasers is certainly close at hand. In contrast, the several hundred-megawatt to one billion watt energy-beamers of the future, needed for manned Lightcraft (e.g., payloads of 100-1000 kg), are a bit of a stretch today. We must learn how to build these powerful laser and/or microwave sources, economically. At present, they are only within financial reach of national governments, and perhaps some very large multi-national corporations.

However, once fully mature "Highways of Light" are eventually in place, the global transport system will be unbelievably inexpensive and safe for us to ride. Laser and/or microwave sources on hundreds of orbiting solar power stations, linked in a space power "grid," will transmit completely "green" energy for Earth's flight transportation needs (Refs. 1-3).

A large fleet of small Lightcraft (e.g., 3 to 12 passengers), flying sub-orbital trajectories might eventually replace conventional jumbojets and high speed civil transports. Lightcraft could

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give highly personalized service, that would be hard to beat - 'called' to a local neighborhood 'Lightport' like we call for a cab today. Such vehicles could transport passengers half way around the globe in 45 minutes, at hypersonic speeds, where most of the flight is outside the atmosphere.

This is the ambitious LTI company vision: To ultimately enable affordable orbital, and suborbital flights around the planet, for a space-faring society.

LTI Company Overview

Lightcraft Technologies was incorporated for the sole purpose of developing beamed energy propulsion into a commercial reality. LTI defines a Lightcraft as any flight platform, airborne vehicle, or spacecraft designed for propulsion by a beam of light – be it microwave or laser. The author and Dean Ing, were the first to coin the word "Lightcraft" in their 1985 book *The Future of Flight* (Ref. 4)

Lightcraft Technologies, Inc. is an emerging technology based business, developing innovative *advanced flight propulsion and power* applications of long-term significance for industry and society. Presently, LTI is forming strategic partnerships with others in the energy/utility, transportation, and aerospace industries to accelerate the application of such innovative technologies in the first five years of the 21st Century. LTI is seeking discourse with other like-minded entrepreneurs, financiers, marketers, and institutions with vision - to identify the people who will likely play key roles in this technological drama as it unfolds over the next few years and decades.

"DISRUPTIVE" TECHNOLOGY

Air and space transportation systems undergo remarkable transformations when massive quantities of "weightless" electromagnetic power can be beamed directly to a vehicle in flight. This qualifies as "disruptive" technology at its best. Principally, the craft becomes unburdened from having to lift the energy source for its propulsion system. Compared with the limited energetics of chemical fuels (i.e., kilojoules per kilogram) used by today's turbomachines and rockets, beamed energy can pack in a 10- to 100-fold increase in the same "fuel" tank. Such has been the goal of HEDM (high energy density materials) research for the past decade, but thus far, none have appeared. Beamed-energy translates into striking reductions in the propellant fuel fraction and structural weight for Lightcraft, as opposed to more conventional flight platforms - in both suborbital and orbital launch applications. Ultra-energetic flight trajectories are altogether feasible with Lightcraft technology.

Competitive Energetic Sources?

Three other "on-board" super energetic sources have been proposed for future trans-atmospheric aerospacecraft: a) nuclear fission, b) fusion (once someone figures out how to do it), and c) antimatter. However these energetic sources produce high levels of ionizing radiation, and will likely require a 100 metric ton radiation shield for manned operations. The potential for catastrophic accidents with these sources is ever present, and clearly, a tank of antimatter is a virtual bomb waiting to go off. Although an existing technology, nuclear rockets would spew fission products into the atmosphere, trailing an exhaust cloud of radioactive "fallout" all the way to orbit. Not exactly "green" propulsion.

Lightcraft Engines & Power Plants

Two distinct categories of Beamed Energy Propulsion (BEP) technology are in evidence for Lightcraft engines: 1) simple laser-thermal or microwave thermal engines, and, 2) more complex laser-electric, or microwave-electric engines. The 'BEP-thermal' engines must only absorb the beamed electromagnetic power directly into the working propellant. Clearly, the more sophisticated 'BEP-electric' engines must first convert the captured beam power into electricity, before the magnetohydrodynamic engines can use it. The latter category of "BEP-electric" engines holds the greatest promise for evolving hyper-energetic manned Lightcraft in the next 15-20 years. Most beamed-energy propulsion systems will likely exploit the atmosphere for momentum exchange to improve engine efficiency radically beyond that of today's chemical rockets. The matrix of feasible engine/optics/vehicle configurations is near infinite (e.g., see Ref. 5), but to pull off a new Lightcraft design successfully will require the close integration of widely different engineering disciplines. Lightcraft engine design is a formidable exercise in interdisciplinary design.

But what about the difficulty of designing the requisite power-beaming technology, taking for example, high power lasers? It is easy to understand why commercial ground-based or space-based lasers would be designed around completely different engineering design requirements than that of military directed-energy weapons. The latter (i.e., laser weapons) face severe restrictions upon the overall package dimensions, arrangement of components, and total mass. Military missions drive the design to a compact and powerful variety of open-cycle chemical laser, and short run times (typically ~100 seconds or less, as limited by the allowable weight for consumables). In sharp contrast, the engineering design constraints for a commercial power-beaming laser (or microwave) power plant are: high reliability, affordable cost, easy maintenance, and long service lifetime (e.g., 10-years or more). As such, cost is the major driver, second only to reliability.

MICROSATELLITE LAUNCHER

A realistic five-year objective for LTI is to launch the first kilogram-class commercial micro-satellite with a megawatt ground-based infrared electric laser. Note that the traditional figure-of-merit invoked for laser propulsion is 1-kg of payload to LEO per megawatt of laser power. Even sooner, suborbital flights to the edge of space (i.e., "sounding rocket' type trajectories) may present interesting commercial opportunities for 100 gram payloads and a 100 kilowatt-class laser: a) space radiation hardness testing of small, but critical electronic components of future large satellites, and b) short term zero-G testing.

Potential Applications

LTI envisions a host of innovative applications for a microsatellite laser launch services enterprise, including: a) high resolution imaging and mapping (Earth resources inventories, real estate mapping, state and local tax parcels); b) global positioning system; c) astronomical telescope using the 1-meter diameter Lightcraft rear optic (amateur and professional use); c) secure communications and relay platform (cellular phones); e) delivering lightweight replacement electronic components (small, but urgently needed payloads) to the International Space Station; and, d) threat detection and tracking (military).

By exploiting the economies of large scale mass-production, kilogram-class micro-satellites should cost no more than the price of a new automobile. -And to accelerate them into orbit will cost no more than a few hundred dollars worth of electricity to run the megawatt closed-cycle electric laser.

Launch Laser Design

High power electric infrared laser technology in the USA was pushed rapidly into maturity throughout the 1970's, benefiting in part from the "Star Wars" program. By 1980, SDI's attention had shifted to shorter wavelength lasers, even though Russia continued to improve their own CO_2 lasers. Today infrared electric laser technology is sufficiently developed to be seriously considered for commercial laser launch applications of small payloads. Pulsed, electric discharge carbon dioxide lasers exhibit electric-to-laser conversion (i.e., "wall plug") efficiencies of 20% to 30%, with very good operational reliability. They employ benign gases such as CO_2, He, and N_2, which are normally re-circulated in closed-cycle flow systems. On the rare occasion that a leak occurs anywhere, there are no dangerous, noxious gases to worry about.

As mentioned above, DOD long ago abandoned megawatt-class infrared electric laser technology in favor of more energetic, short-wavelength alternatives – specifically designed for military weapon systems. Such systems had to be small, compact and as lightweight as possible –to stuff into a large jet transport, or space platform. For the past 15-20 years, the military has shown little real interest in resurrecting its high-power infrared laser technology - largely because of the low lethality (i.e., inferior target "coupling"), and necessity of large transmitter apertures. Neither feature presents a problem for the commercial laser launch application, because: 1) there is no desire to damage the target (i.e., the Lightcraft), and, 2) the laser stays on the ground and has no critical dimensional or weight restrictions. Note that very large 10-meter diameter telescopes, a necessary ingredient for infrared laser launch, have been built for as little as $10-$11 million -- using hexagonal segmented optic technology (e.g., university astronomical observatories).

Table 1
Lightcraft Vertical Free-Flight Records

Altitude (feet)	Date	Lightcraft Model #	Miscellaneous Details
1.0	23 Apr. '97	early #100	Non-spinning; truncated optic; conical forebody & shroud.
6.5	26 Aug. '97	early #150	First gyro-stabilized flight, inside lab; flat-plate forebody.
14.	1 Oct. '97	early #150	Inside lab; flat-plate forebody.
50.	5 Nov. '97	#200	First outdoor record flight.
73.	4 Dec.' 97	#200	Last record flight by a 14.7-cm Lightcraft
91.	18 Apr. '98	#200-3/4	First record flight by an 11-cm Lightcraft.
99.	22 Apr. '98	#200-3/4	Last airbreathing engine record flight.
127.	9 July '99	#200-3/4SAR	First ablative rocket record flight; 23rd WSMR test.
233.	2 Oct. '99	#200-5/6SAR	LTI flights sponsored by non-government grant.

LASER LIGHTCRAFT FLIGHT HISTORY

Perhaps the simplest 'yardstick' for measuring the progress of laser Lightcraft technology is the sequence of altitude records set along the way (see Table 1), starting with the first 1-foot vertical free-flight on 23 April 1997. The information contained in Table 1 has been quite thoroughly disclosed in numerous television documentaries, newspapers and magazines produced over the past six years. Additional details have been revealed in several technical papers (e.g., see Refs. 6-16). The design of the author's best-flying, spin-stabilized, beam-riding Lightcraft is revealed in Refs. 10,13, &15. Designated Model #200, it has claimed all the altitude records of 50-ft and beyond, accomplished through a sequence of subtle improvements in the design of the Lightcraft, laser, telescope, launcher and launch procedures.

The Model #200 engine contours were designed to provide an autonomous, 'beam-riding' function that causes the exhaust flow to automatically vector in flight -thereby pulling the vehicle back into the center of the laser beam during flight. This critical "beam-riding" feature is the principal ingredient made all these record-breaking flights feasible in the first place. The 99-ft flight on 22 August 1998 was the last altitude record to be demonstrated with an airbreathing, pulsed detonation engine (PDE) which has a propellant specific impulse of infinity - because no propellant is carried on-board. The 9 July 1999 record flights were the first to employ an ablative rocket propellant. The 127-ft record flight occurred at the 23rd and last WSMR test for which the author functioned as Principal Investigator of the USAF/NASA (i.e., government-sponsored) Laser Lightcraft Program.

LTI's record flights on 2 October 1999 were sponsored under a non-government grant (see details below). This was the author's 24th laser propulsion test at WSMR.

Origin of Laser Lightcraft Concept

The author has personally evolved the current and most successful #200-series Lightcraft engine over a 4-year period involving 23 laser propulsion tests at WSMR - starting from his original design study for the Lightcraft Technology Demonstrator (LTD). This LTD concept (see Ref. 17) was developed at Rensselear Polytechnic Institute (RPI) in 1989 under contract to the Lawrence Livermore National Laboratory and the (now defunct) Strategic Defense Initiative Organization, for the Laser Propulsion Program of the SDIO. The study was carried with the participation of numerous RPI graduate and undergraduate students. The full-sized 100 kilogram, 1.4-m diameter LTD spacecraft was designed for the micro-satellite sensor & communications roles -- to be boosted into low Earth orbit by a powerful, 100-MW ground-based laser. The initial, atmospheric portion of the laser-propelled flight employed an airbreathing PDE engine mode, followed by a rocket mode (using onboard liquid hydrogen) when the air became too thin (about Mach 5 and 30-km altitude).

But the laser Lightcraft work at RPI really began several years before the LTD study (e.g., see Refs. 18-19). All told, the author has collaborated with nearly one thousand RPI students over the decade from 1985 to 1995, in developing beamed-energy propulsion technology. This RPI research was funded under mostly NASA and USAF research contracts totaling just over $1M, and ultimately evolved laser Lightcraft technology to a critical threshold level where success with building real engines was eminent. This is fairly complicated propulsion technology, and it took a large team of creative young minds to move it forward. The author couldn't possibly claim all the credit, and owes a great deal to his RPI student collaborators. Without this preparation, the prospects for success in the subsequent "hardware" phase (funded under the USAF/NASA Laser Lightcraft Program) would have been slim indeed.

Transformation into Hardware

The design and construction of the first Lightcraft engine and test equipment began at RPI in 1995 with a $45K contract from the Phillips Laboratory (commonly known as the Rocket Lab) at Edwards AFB. One year later, the author was invited to join the Rocket Lab in what became a 3-yr IPA Fellowship (i.e., sabbatical from RPI, from 1 Sept. '96 through 31 Aug. '99) - to transform his 1989 LTD Lightcraft concept into hardware reality.

Throughout those 4 years of collaboration with the Rocket Lab (which later merged into AFRL), the author effectively served as principal investigator for this Laser Lightcraft program. To be entirely factual, the author personally designed every piece of Lightcraft test hardware, flightweight and laboratory engines, test stands, launch stands, and auxiliary equipment during this 4-year period. The author also supervised the fabrication of this equipment by the RPI Central Machine Shop, and wrote/conceived all but two of the 23 WSMR test plans. A former RPI Ph.D. student (Don Messitt) of the author, assembled the computer-based data acquisition and schlieren photography systems; several other RPI undergraduate and graduate students were also involved in the 4-year R&D activity.

The author has unquestionably created all the laser Lightcraft hardware emerging during this 4-year period at AFRL, and is recognized as the sole inventor on a recent USAF patent application covering this invention. The application was submitted to US Patent Office on 27 April 2001. Although the author's substantial contributions to what now is called the AFRL Lightcraft Technology Demonstration (LTD) Program remain un-acknowledged in Ref. 13 (i.e., quite 'conspicuous by absence'), C.W. Larson in Ref. 14 did refer to the invention as the "Myrabo Laser Lightcraft" or "MLL." However, in the most recent AFRL paper (see Ref. 16), no mention is made of the author's contributions to 'launching' the LTD Program. Note Refs. 13 & 16 are "officially released" publications of the AFRL Propulsion Directorate, Edwards AFB, CA.

In summary, it took a combined USAF/NASA investment of just under $1M over the four-year period to advance the Lightcraft technology program. Half of this was personally solicited (and secured) from the NASA Marshall Space Flight Center, to grow it into a joint program. Note also that only 10% of the $1M was spent for RPI Central Machine Shop services and the purchase (through RPI) of essential test equipment/ instrumentation for that 4-year period.

Transition to Solid Ablative Rockets

The LTD's airbreathing engine mode had a predicted theoretical impulse Coupling Coefficient (CC) performance of 580 newtons (thrust) per megawatt (laser power) at the launch altitude of 3-km, but required a laser pulse width of 0.3 microseconds. This pulse width is 50 to 100 times shorter than the 18 to 30 μsec pulses available from the PLVTS laser. At the 18 us pulse width, the #200-3/4 airbreathing engine had experimentally demonstrated (in the laboratory) a peak performance of only 160 N/MW, which is a factor of 3.6X less than that predicted for the LTD. Since PLVTS cannot be converted to such short pulse widths, other solutions to improving the thrust performance of the #200-3/4 engine had to be identified. Furthermore, attempts at powered flight times longer than 4 seconds with this aluminum engine were abruptly terminated - when the "absorption chamber" (i.e., the shroud) melted and came apart.

To circumvent both problems (i.e., for the short term), the author adapted the #200-series Lightcraft engine to use solid ablative rocket propellants that absorbed the infrared energy volumetrically (i.e., in depth). This solution came out of conversations with Dennis Reilly and Claude Phipps; both scientists had had experimentally confirmed that laser impulse enhancements were indeed available from such solids. Reilly suggested Delrin, and it indeed worked very well. The ablative rocket approach revealed a dramatic increase in thrust for the basic model #200-series Lightcraft engine (i.e., linked to PLVTS), at the expense of having to carry propellant (see below for more details). Otherwise, the 99-ft. record flight of 22 August 1998 might still be standing today.

July '99 Flights to 127-ft

As mentioned earlier, this was the 23rd and last WSMR laser propulsion test (under the USAF/NASA Laser Lightcraft Program), that the author effectively served in the capacity of principal investigator. The following provides more details on this 9 July 1999 test, the essentials of which were disclosed in Refs. 13 and 14.

In two consecutive launches on 9 July 1999, lasting ~3.5 seconds each, two different laser-propelled ablative rockets climbed rapidly to an altitude of 128-ft (39-m) and impacted a 4-ft x 8-ft plywood "beam-stop" suspended by a crane. These Lightcraft hit the beam-stop with a velocity sufficient to crush in their aluminum noses. The spin-stabilized, beam-riding rocket design was a logical derivative of an earlier airbreathing engine design that established the former free-flight altitude record of 99-ft on 22 August 1998. The new Lightcraft were designated model #200-3/4SAR, for which the 'SAR' stands for solid ablative rocket.

These 127-ft record flights (as usual) took place in New Mexico on the White Sands Missile Range (WSMR) at the High Energy Laser Systems Test Facility (HELSTF) – using the 10-kW pulsed infrared laser called PLVTS. This US Army laser is operated by the Directorate for Applied Test, Training and Simulation (DATTS). The historic videos of the record 127-ft flights were included in a National Geographic Television production (Explorer-Series) entitled "The Quest for Space" - which was first aired on 6 July 2000.

The two record-breaking rocket Lightcraft were made at RPI from 6061-T6 aluminum to a diameter of 11-cm (4.3 inches), and had launch masses of 26.3 and 29 grams. The second rocket to be flown carried slightly more ablative propellant aloft than the first. An especially important design feature of this engine was to pack the inert ablator in a place that would increase Lightcraft stability, rather than reduce it. By wrapping the plastic propellant in a thin band about the thrust chamber's perimeter, gyroscopic stability was indeed improved - at least until the propellant was all ablated. The rapidly evaporating plastic probably reduced the engine's operating temperature, thereby extending engine life.

Post flight inspection of the two rocket Lightcaft and their rear reflectors (i.e., thin aluminum mirrors) revealed that the first engine to fly, showed no signs of stress. However, the second engine's optic (on the heavier Lightcraft) had indeed sustained visible thermo-mechanical damage; it was somewhat warped, but still in one piece. Neither rear optic appeared to be contaminated (i.e., coated) by the ablated propellant; no obvious evidence of such condensation could be found on the mirrored surfaces. Also, when videos of the two flights were carefully reviewed, no indication of particulate-induced air breakdown could be observed in the beam transmission path.

Advantages of SAR-Lightcraft

For the earlier airbreathing-engine versions, peak air plasma temperatures can reach 20,000-K to 30,000-K, which is 3 to 5 times hotter than the sun's surface. Hence, run times with the 11-cm bare aluminum engines are severely limited to about 100 laser pulses, or less than 4 seconds of operation, before the chamber walls melted and blew apart. This of course abruptly ended the flight. In sharp contrast, the aluminum shroud on both ablative rocket flights survived well, sustaining minimal damage. This suggests that the craft could have flown well beyond the 127-ft plywood beam stop. Note that the PLVTS infrared laser was set up to deliver 18-us, 450 joule pulses at repetition rate of 26 to 28 pulses per second.

Not only does the ablative propellant increase vehicle gyroscopic stability (i.e., through its proper placement) and reduce engine temperatures, but it also more than doubles the thrust available from PLVTS. Whereas the pure airbreathing engine version developed only 0.36-lb (1.6 newtons) of time-averaged thrust, the ablative rocket gives better than 0.81-lbs (3.6 N) - on the same 10 kilowatts of laser power. At the 18 us pulse width, the #200-3/4 airbreathing engine has experimentally demonstrated (in the laboratory) a peak impulse Coupling Coefficient (CC) performance of only 160 to 170 N/MW. In contrast, the #200-3/4 SAR engine has exhibited 360 N/MW at low pulse energy of ~95 Joules, at which energy the airbreathing engine develops only 80 N/MW. This was the principal ingredient that enabled rocket-propelled Lightcraft to easily exceed the previous year's 99-ft record.

Finally, by packing this ring of ablative solid propellant into the annular focal region of the rear concentrating optic, the Lightcraft's propulsion system may also be transformed into a kind of rocket-based, combined-cycle (RBCC) engine - at least within the dense atmosphere at subsonic speeds. Under these conditions an auxiliary airbreathing process, wherein the local ambient air is expelled ahead of the hypervelocity ablating rocket exhaust, might augment the engine's thrust.

LTI RECORD FLIGHTS TO 233-FT

Early in the morning of 2 October 2000 on the High Energy Systems Test Facility (HELSTF), Lightcraft Technologies, Inc. (LTI) set a new altitude record of 233 feet (71 meters) for its 4.8 inch (12.2 cm) diameter laser boosted rocket -- in a flight lasting 12.7 seconds. Although most of the 8:35 am flight was spent hovering at 230+ ft., the Lightcraft sustained no real damage, and will fly again. Besides setting a new altitude record, the craft simultaneously demonstrated the longest ever laser-powered free-flight, and the greatest 'air time' (i.e., launch-to-landing/ recovery). The #200-series Lightcraft employed a plastic ablative propellant, and were spin-stabilized to at least 10,000 RPM just prior to launch.

LTI launched a total of seven vertical spin-stabilized, free-flights (see Table 2 below) between the hours of 8:30 am and 11:30 am, with three Lightcraft weighing about 1.8 ounces (i.e., 50-51 grams). Two lesser flights reached 159 ft and 184 ft (Runs #4 & #6), as shown below in Table 2.

Figure 1: Lightcraft and Launcher (WSMR, 2 Oct. '00)

All three Lightcraft were an improved version of the basic model #200-5/6SAR configuration. Table 3 gives the initial gross liftoff mass for the vehicles, and the flight Run #'s for each. The ablative rocket propellant ring added 4.12 grams to the initial launch mass, and it was not replaced with "fresh propellant" between flights. Note that Lightcraft #1 was flown thrice, and accumulated 71.6-ft + 159-ft + 184-ft - for a total of 415 feet of altitude in the process, with quite a lot of propellant still remaining. Clearly, with the proper telescope arrangement PLVTS could have boosted this #200-series craft to 500-ft, which indeed is now the objective for the next LTI flight test.

Table 2
Lightcraft Flight Details (2 October '00)

Flight (Run #)	Theodalite (degrees)	Maximum Altitude (meters / feet)	Time to Max Altitude (sec)	Time to 23-m (sec)	Time to 46-m (sec)
1	30	21.8-m (71.6-ft)	3.5	--	--
2	62	71.1-m (233-ft)	12.73	2.57	5.17
3	14	9.4-m (30.9-ft)	--	--	--
4	52	48.4-m (159-ft)	5.16	2.03	4.8
5	18	12.3-m (40.3-ft)	--	--	--
6	56	56.0-m (184-ft)	5.57	1.6	4.5
7	22	15.3-m (50.1-ft)	--	--	--

Table 3
Lightcraft Gross Liftoff Mass
(Recorded Before First Flight)

Lightcraft (vehicle #)	Launch Mass (grams)	Diameter (cm)	Flight #'s	Accumulated Altitude (meters / feet)
#1	49.02	12.2	Runs 1, 4, & 6	124-m (415-ft.)
#2	50.62	12.2	Run 2	71-m (233-ft.)
#3	51.05	12.2	Runs 3, 5, & 7	37-m (121-ft.)

Laser Problems

The record flights were (as usual) performed with the 10 kW pulsed carbon dioxide laser named "PLVTS" by the Directorate for Applied Training, Test and Simulation (DATTS). The beam profile at the launch pad is given below in Figure 2. Even though the laser was suffering from a grounding or arcing problem in the sustainer that caused it to run erratically, the time-average beam power was still adequate to propel the craft to record altitudes. (This laser problem was identified and fixed in the following day.) Note that vehicle #3 did not fly well, but it might be blamed on unlucky timing with a rough-running laser.

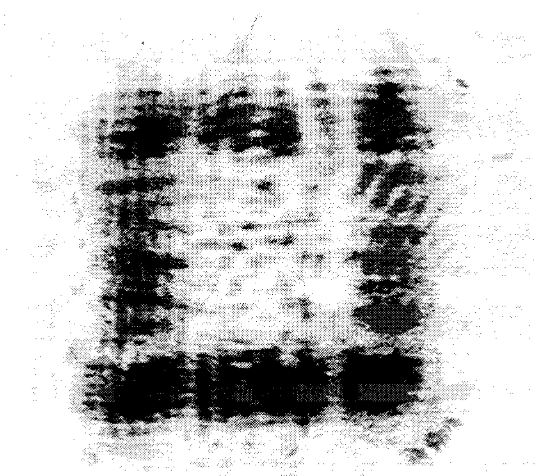

Figure 2: PLVTS beam profile at launch pad

NORAD Clearance

These were the first ever vertical, free-flight tests to be performed without a 4-ft X 8-ft plywood "beam-stop," suspended by a crane - to intercept stray laser energy that sometimes 'spills' around the vehicle in flight. The LTI flights were carried out with the cooperation of NORAD and WSMR range control to avoid the irradiation of both low Earth orbital satellites and low flying aircraft. Twelve launch "windows" varying from 2.56 to 41.25 minutes in length were secured from NORAD. With the 233 ft. flight on Oct. 2, LTI attained its objective of nearly doubling the previous altitude record of 128 ft. - set on July 9, 1999 (with a 11 cm #200-series Lightcraft) under prior joint USAF/NASA funding.

Post-Flight Inspection

One major concern with longer Lightcraft flights was that ablating rocket propellant might contaminate either: a) the engine's rear parabolic optic, or b) the laser beam's atmospheric propagation path. In the former, vaporized propellant that condenses and sticks to the rear optic, could eventually 'darken' the brightly polished aluminum surface, reducing its reflectivity. This may cause the thin metal reflector to overheat and warp, especially in the forward portion of the optic where high over-pressures are created from reflecting laser-induced detonations (e.g., see Refs. 10 & 15). However, these fears were unfounded.

Post flight inspection of the three Lightcraft's rear reflectors revealed no signs of either mechanical stress or contamination. Also when the videos of the seven flights were carefully reviewed, no indication of particulate-induced air breakdown could be observed. No attempt was made to measure laser transmission losses through the rocket's plume.

Computer-Based Motion Analysis

The results from a detailed computer-based motion analysis study of Flights #2, #4, and #6 are plotted in Figures 3 through 8. Note that the camera used to film these flights, was positioned with the DATTS "manlifter" base centered in the video frame, to indicate an altitude of 75 feet from the launch pad. Hence the maximum altitude recorded by the camera was 150 feet. Fortunately, theodalite readings were taken to identify the maximum altitude of each flight. Two other cameras were employed to record additional flight footage: a vertical "look-up" camera positioned roughly 1-foot from the launch pad, and a mobile hand held camcorder.

For Run #2 in Figs. 3 and 4, the Lightcraft accelerated over the first two seconds, thereafter maintaining a quasi-constant velocity of 27 ft/sec for the next 3.5 seconds. Most of the 12.73 second flight was spent hovering above 200 feet, before setting the new World's altitude record (at least for laser Lightcraft) of 233 feet. Figures 5 and 6 tell the story for Run #4; note that this craft reached a top velocity of 35 ft/sec on the way to a peak altitude of 159 feet. Run #6 reached the 140-ft point in 3.5 seconds, which was 1.5 seconds quicker than Run #2, and 1.0 second faster than Run #4. Note in Figure 8, that Run #6 attained a maximum velocity of 49 ft/sec on the way to a peak altitude of 184 feet. If the PLVTS laser had not been suffering that morning from an electrical grounding problem, no doubt all peak velocities would have been in this range, or higher.

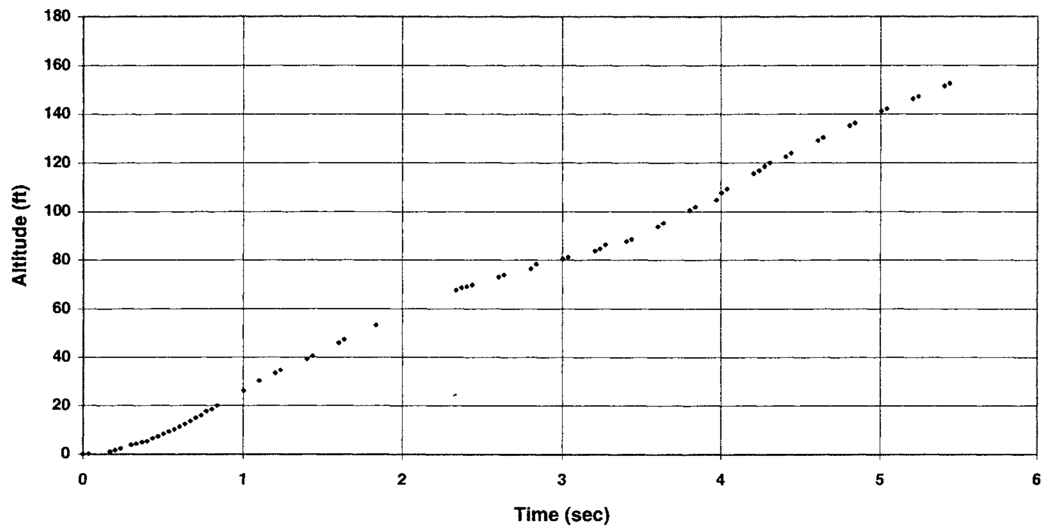

Fig. 3: Altitude vs. Time for Flight 2

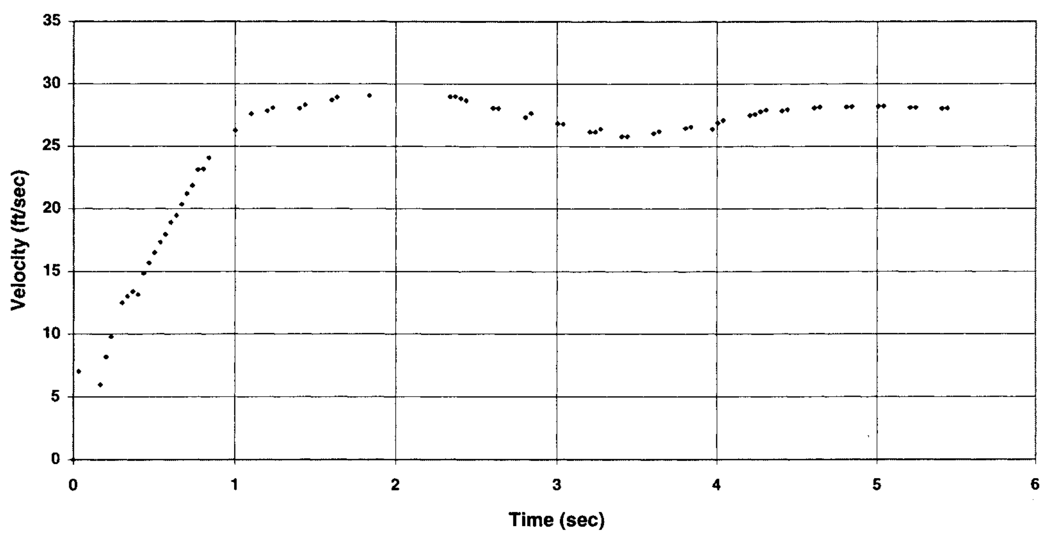

Fig. 4: Average Velocity vs. Time for Flight 2

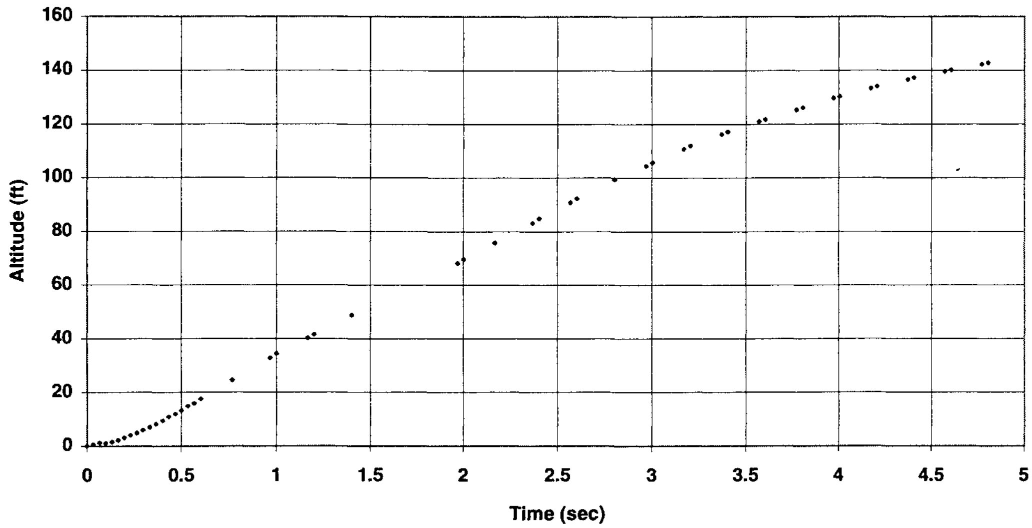

Fig. 5: Altitude vs. Time for Flight 4

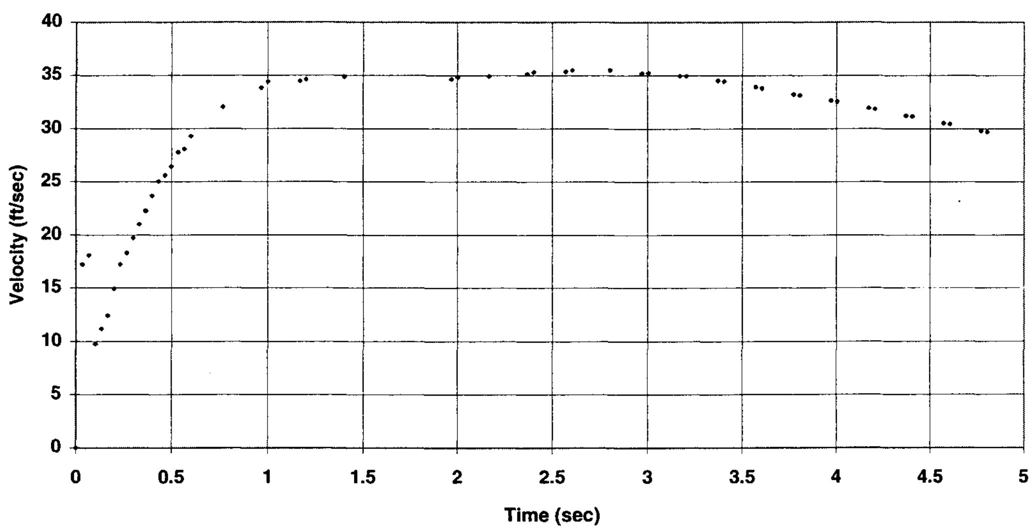

Fig. 6: Average Velocity vs. Time for Flight 4

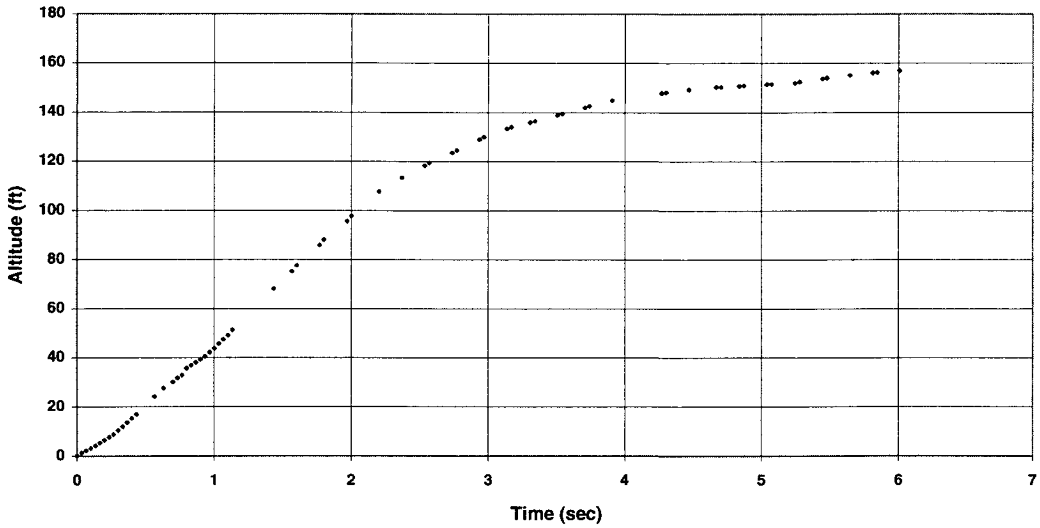

Fig. 7: Altitude vs. Time for Flight 6

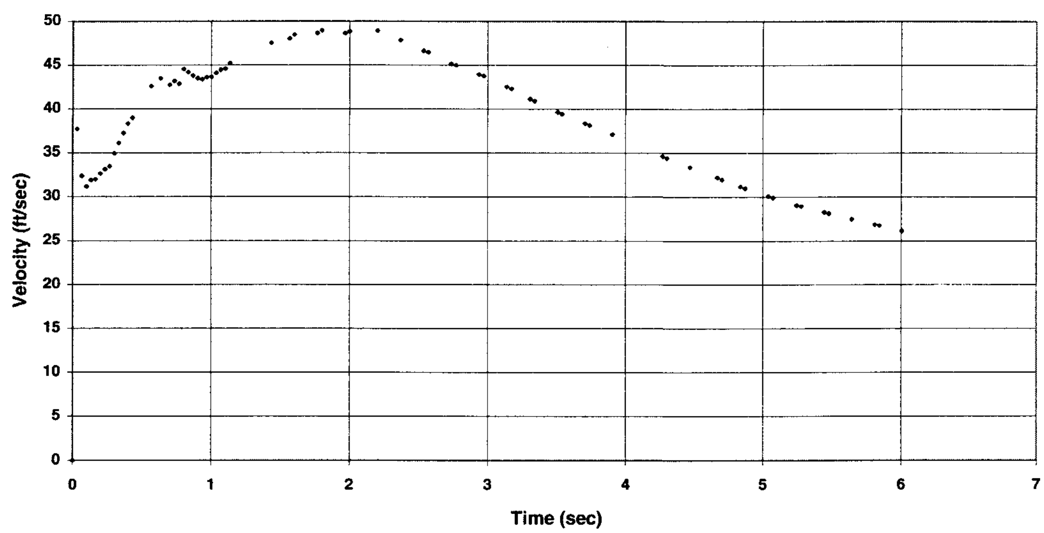

Fig. 8: Average Velocity vs. Time for Flight 6

FINDS Sponsorship

The 2 October 2000 record-breaking Lightcraft flights at WSMR were sponsored by the Foundation for International Non-governmental Development of Space (FINDS), a non-profit organization dedicated to promoting low cost access to space. With FINDS funding, laser launch technology has been decidedly moved out of the exclusive realm of government-sponsored research into the commercial launch arena. Lightcraft Technologies attributes its successful flights to proprietary improvements in the design of both the launch stand, and the #200-series Lightcraft itself. LTI has now set its sights squarely upon doubling its current altitude record, again—to attain altitudes of 500 ft. or beyond within the foreseeable future. Note that ten more doublings in altitude are necessary to reach the edge of space (e.g., 256-kft, or 78-km).

THE NEXT STEPS?

The feasibility of ambitious flight demonstrations for laser Lightcraft to extreme altitudes (e.g., 10 to 30 kilometers) in the near future, depends upon three key steps: 1) scaling the launch laser power to at least 100-150 kilowatts; 2) linking this laser to a 1.4 meter telescope; and finally, 3) scaling the #200-series Lightcraft design to diameter of 23-cm or more.

Launch Laser Technology

Several high power lasers of "Star Wars" vintage have been "mothballed" at HELSTF over the past decade: e.g., DRIVER, MALIBAR, and most recently, CORA. Also, stored in Test Cell 2 is a formidable pulsed electric power supply from the EMRLD excimer laser. This power supply is sufficient to drive a megawatt-class CO_2 laser. Several mammoth cylindrical pressure vessels are also available on site, for potential use in laser gas 'blow-down' experiments (a customary process in shaking out a new prototype 'laser head.'

In short, HELSTF has a large stockpile of high power laser parts on hand, sufficient to construct (or restore and/or upgrade) a 100-150 kW pulsed CO_2 electric laser. The laser upgrade project has been estimated to cost nearly $ 2.5 million and take 2 years to complete. Clearly, to be useful the new laser must also be linked with a large telescope (i.e., the transmitter) in order to project a collimated beam to high altitudes. Anticipating this need, NASA Marshall Space Flight Center has already transported a surplus 1.4 meter telescope to HELSTF in 1999, taken from a remote outpost in Australia. The telescope must still be converted for its new role as high power laser transmitter.

Note that this new 100-kW or 150-kW CO_2 laser could later serve as the master-oscillator for a 1 or 2 megawatt power amplifier. This megawatt launch laser has been estimated to cost about $25M and take 3 years to construct. Hence, the 150-kW system has significant growth potential – leading directly to a 1-kg micro-satellite launch laser. At least two megawatt-class CO_2 electric lasers have been built during the 1970's in this country. These were the open-cycle "Thumper" laser, and very much smaller "flight-weight" system built for the Airborne Laser Laboratory, both constructed by the AVCO Everett Research Laboratory.

Capitalizing on this mature CO_2 electric laser technology should be a straight-forward engineering enterprise. No expensive cutting-edge "Star Wars"- R&D expenditure is needed, since that technology investment was made over two decades ago in the USA. Constructing a megawatt CO_2 electric laser could indeed be a conservative undertaking, with well-defined risks, incorporating the most up-to-date electronic control systems. Note that the original plans for a half-megawatt CO_2 electric laser still exist at a major aerospace company in the USA.

Scaling Lightcraft Technology

The July 1999 and October 2000 WSMR tests have conclusively proven that the requisite Lightcraft engine technology for flights to 'extreme altitudes' is certainly close at hand. What remains to be done is to scale the engine size to 23-cm (or larger) for a reasonable near-term objective of 10-km to 30-km altitudes. Note that two 23-cm Lightcraft have been constructed at RPI under the author's supervision, prior to September 1999. The first 23-cm complete Lightcraft was designed and built as a rotating wind tunnel model as the central focus of a graduate student thesis project by Andrew Panetta (supervised by the author). The rotating model was run in RPI's 4-ft X 6-ft subsonic wind tunnel, to obtain the aerodynamic performance data desired for future flight simulations (see Ref. 9).

The second 23-cm diameter Lightcraft engine to be fabricated at RPI was designed for laboratory experiments with and without ablative propellants. The engine was finally tested with solid ablative inserts in Test Cell 3 at HELSTF on 9-11 July 1999, with PLVTS. The performance data revealed coupling coefficients as high as 460 newtons per megawatt (N/MW) using laser pulse energies up to 667 joules with a 30-μsec pulse duration. Further increases in CC performance beyond 500 N/MW would seem to be feasible - with substantially higher laser pulse energies. Fully developed, the 23-cm laser propulsion engine could conceivably produce a thrust of at least 100 newtons (22.5 pounds) with a 150-kW infrared laser that delivers, say perhaps, 10 kJ pulses @ 150 Hz. For a projected 23-cm Lightcraft vehicle empty weight (i.e., no propellant or payload) of just 1.5 newtons (5.3 ounces), thrust/ weight ratio would be nearly 67. This scale of Lightcraft could certainly enable flights to the edge of space, but the discussion is academic until a 10X more powerful CO_2 electric discharge laser is built.

SO WHAT IS LTI UP TO?

LTI is pursuing the development of beamed energy propulsion technology on two simultaneous fronts: a) creating substantially improved Lightcraft engine and vehicle concepts, and b) encouraging the restoration and/or upgrades of infrared launch lasers at HELSTF. Clearly, without at least a 10-fold upgrade in beam power beyond the present 10-kilowatt carbon dioxide laser at WSMR, everyone's ability to set future Lightcraft altitude records will be severely curtailed. One thousand feet might be the best that PLVTS can do.

As mentioned above, LTI received a grant last year from a non-profit organization interested in promoting low cost access to space. Under this grant, LTI is developing a family of new laser propulsion engine geometries, integrated with vehicle concepts that are specifically tailored for laser launch applications. These innovative prototype engines will soon be fabricated and tested in the laboratory with available pulsed CO_2 lasers. Once compatible launch stands are constructed, these new laser Lightcraft designs will then be flight-tested outdoors.

LTI is seeking sponsors to explore major refinements of this revolutionary kind of laser propulsion engine, and vehicle, and to bring the system to a much higher performance level than has been demonstrated to date. Additional funds are needed for the construction of these new Lightcraft prototypes, to protect intellectual property, and to obtain engine performance data – from both in the laboratory and from outdoor flight-testing. Investors have the opportunity to get in at the ground floor, and promote a revolutionary "disruptive" launch technology that will ultimately reduce payload delivery costs to unheard of levels. Chemical rockets will not be able to compete for nanosat and microsat class of payloads, once laser launch technology becomes commercially available.

Accomplishing the laser-launch of microsatellites objective is simply a matter of will, and finances. The scientific knowledge and engineering expertise to pull this off is already here: e.g., the high power infrared electric lasers, high power laser optics, ceramic matrix composite materials, lightweight electronics, sophisticated guidance and control systems, and the like. The laser launch system has, among others, one notable asset: the most expensive part of the launcher (i.e., the laser and telescope), always remains on the ground, and is never subjected to the risks of launch. Produced in large quantities, microsat Lightcraft should be almost expendable, certainly reusable, and probably recoverable from any failed flight. After minor refurbishment, they could be launched again (and again) – until successfully delivered into orbit.

Lightcraft engine and vehicle development goals must certainly be anchored to, and interwoven with, their high power lasers. Anyone can put together an ambitious schedule for growing laser Lightcraft technology over the next five years or more – mapping vehicle diameter, payload mass, and propellant fraction against altitude objectives. And indeed, altitude is the most accurate measure of progress in beamed energy propulsion technology. –But without serious investment in more powerful launch lasers, the exercise is futile. Hence, LTI is committed to promoting the growth in launch laser power at WSMR – immediately to 150 kilowatts, then to one megawatt in the near future.

SUMMARY

We are facing a revolution in advanced propulsion and power technology - for future flight transportation systems. This technology can certainly be labeled as "disruptive," and it will ultimately touch each and every one of us within the next 15 to 25 years. In this future era, subsonic jumbojets and high-speed civil transports will be as obsolete as the first Wright Flyer biplane; our space shuttles will have been retired to the Space museums. What is this revolution? The answer: "Highways of Light." (www.lightcrafttechnologies.com)

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