

LASER-PROPELLED LIGHTSAILS AND LIGHTCRAFT LATEST RESEARCH DEVELOPMENTS

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Abstract:

This paper summarizes the latest developments over the past two years, on the author's laser-propelled Lightsails and Lightcraft research. Reviewed first are the Rensselaer Lightsail experiments performed in December '99 (pendulum-deflection tests), and subsequently in December '00 (wire-guided vertical flight tests) – using the LHMEL 150 kW infrared laser at Wright Patterson AFB, OH. The Jet Propulsion Laboratory and NASA sponsored this laser Lightsail research. The '99 Lightsail tests were the first known demonstrations of laser photonic thrust on a real laser sail material: i.e., a molybdenum-coated carbon microtruss fabric made by ESLI. The subsequent Dec.'00 Lightsail vertical levitation tests might possibly be the first laser photonic flights at >1 G, a claim that must first be confirmed by computer-based motion analysis, now underway, with results expected by Sept. 2001. Next, the paper reviews the author's 2 October 2000 world record flight to 71-meters altitude, of a 50-gram laser-propelled rocket Lightcraft at White Sands Missile Range (WSMR), NM. The spin-stabilized, free flight test program was sponsored by an independent foundation dedicated to promoting low cost access to space. In all, four 12.2-cm diameter, aluminum Lightcraft were propelled into the New Mexico skies – to record altitudes - by a 10-Kw pulsed carbon dioxide laser called PLVTS, located at the High Energy Systems Test Facility.

Phase I Laser Lightsail Tests (December 1999)

Laser-boosted light sail experiments were carried out located at Wright Patterson Air Force Base on 13-20 Dec. 1999 with the 150 kW LHMEL II carbon dioxide continuous wave (CW) laser, in a 2.13-m x 2.74-m chamber evacuated to 36-44 microTorr (Refs.1 & 2). The 5-cm diameter laser sail discs were made from an ultralight carbon microtruss fabric that was molybdenum sputter-coated on one side to improve reflectivity at the 10.6 um laser wavelength. Four sails with three different types of materials (areal densities of 6.6, 27 and 28 g/sq.m.) were tested on a magnetically suspended pendulum, designed specifically to measure the pendulum deflection vs. incident laser power. The three heavier pendulum sails had masses of 83.7, 87.3, and 88 milligrams, an overall length of 18 cm, and centers-of-

gravity at 11.5, 11.7, and 11.9 cm (respectively) below the steel support wire.

The pendulum sail specimens were hung from a 5-work station carousel that was mounted onto a vertical one-inch aluminum support shaft. This shaft penetrated the lower wall of the tank (i.e., by means of a "vacuum feed-through," installed previously), and could be rotated, so that a number of sail specimens could be positioned (in sequence) at the laser target area and tested, without having to re-pressurize and then re-evacuate the tank. A 0.508-mm diameter, 31.8-mm long steel wire (or "needle") with a mass of 55.7 milligrams was used to hang each pendulum shaft between two strong rare-earth permanent magnets. Normally, only one end of this steel "needle" is attracted into a concave, conical sapphire-bearing surface. Because of the very low magnetic bearing friction, a disturbed pendulum can require as long as 40 minutes to "settle" in the vacuum.

A HeNe alignment laser was used to measure pendulum deflection, by reflecting the beam off a 0.6-cm silica mirror (mass of 30 milligrams) attached to the pivot point (i.e., positioned over the steel needle) of each magnetically suspended pendulum. A vertical strip of graph paper was positioned inside the vacuum tank, to intercept a reflected HeNe laser beam (i.e., bounced off the mirror on the pendulum shaft), in full view of one VHS camera, to record the motion of the reflected HeNe beam. The HeNe system was calibrated for pendulum deflections up to 20-degrees maximum, at 2.5-deg. increments. An array of four VHS camcorders, one Beta SP camera, and two high-speed 16-mm film cameras (recording at 200 frames per second) were employed to document the pendulum motion. Note that the first time any laser sail is irradiated (i.e., during which the sail "out-gasses" or "cures"), the pendulum deflection is highly erratic, and cannot be recorded as "real" data; in contrast, the second irradiation is exceedingly well behaved.

An elliptical-shaped laser beam with dimensions of 4.52-cm tall by 5-cm wide was targeted just 1.9-mm above the centroid of each 5-cm diameter sail - such that the pendulum could deflect up to 12.2-degrees without "spilling" significant amounts of laser power. The laser beam is a rounded 'top hat' shape, with the center

intensity roughly 25-30 % higher than that at the edges of the beam. Laser power was slowly increased from 8-kW to 17.6 kW during these experiments. Pendulum deflection vs. laser power was found to be bounded between reasonable "photon thrust" limits (i.e., 6.67 N/GW for a perfect reflector, and 3.33 N/GW for an absorbing laser sail), up to a laser power of 12.5 kW - for the 27-28 g/sq.m. sail materials. For the ten best tests, measured photonic thrust fell in the range of 3.0 to 13.8 dynes; however, the three 'high power' tests (13 to 13.8-kW) exceeded the performance of a perfectly reflecting sail (i.e., 6.67 N/GW) by as much as 50%. The latter indicates that significant sublimation or ablation of the sail material was in evidence for these high power tests.

Note that successful quasi-steady pendulum deflections were accomplished only by first ramping up the laser power over a 2-second interval, followed by a 1-second constant power at the desired level. For each of 28 tests, the data acquisition system recorded the laser power and pyrometer readings with a sample rate of 500 Hz.

Sail temperature was monitored with a Thermogage SI 4670 optical pyrometer to determine when the ultralight, radiatively cooled surface exceeded 2500 to 2600 K. The pyrometer, which has a response time of 5 milliseconds, was mounted 163-cm from the 'target' and aligned to read the temperature across a 1.9-cm diameter (slightly out of focus) spot centered on the upper half of the circular sail; it monitored the sail's front face only. The most reliable temperature readings were attained from preliminary tests when the entire sail was briefly irradiated for only 0.2 seconds (i.e., too brief to cause significant sail deflections). The 6.6 g/sq.m. sail (Pendulum #1) registered a temperature of 2098-K at an incident laser power of 10.5-kW. The 27 g/sq.m. sails (Pendulums #4 & #5) reached 2306 -K at 7.9-kW, 2496-K at 10.5-kW, 2680-2711-K at 15.6-kW, and beyond 2823-K at 20-kW. (The 20-kW test could possibly have reached 2900-K or more, but the data acquisition system saturated at 2823-K, and did not record the highest sail temperature.) Finally, the 28 g/sq.m. sail (Pendulum #6) with its additional high reflectivity layer, seemed to run slightly cooler, giving 2269-K at 8.0-kW, ~2447-K at 10.5-kW, and 2546-K at 13.9-kW.

From studying the above data set that relates pendulum deflection to laser power and Lightsail temperature, one concludes that significant sublimation or ablation effects begin to contaminate the purely photonic thrust data when sail temperatures climb into the regime of 2500 to 2600-K.

Phase II Laser Lightsail Tests (December '00)

The Phase II, JPL/NASA-sponsored laser-boosted light sail experiments were carried out on 4-8 December 2000, again with the 150 kW LHMEI II carbon dioxide CW laser at Wright Patterson Air Force Base. For these tests, the 2.74-m long, 2.13-m diameter vacuum chamber was evacuated to 18-32 microTorr (Ref. 3). The principal objective of the Phase II tests was to propel 5-cm diameter laser sails (five specimens in all) vertically up a 0.9-meter long, 0.762-mm diameter molybdenum wire, thereby demonstrating greater than 1-G acceleration. Runs #22 and/or #23 (on 8 Dec. 2000) might indeed be the very first >1G flights of a laser-boosted light sail; motion analyses of the recorded flight footage (taken by 5 video cameras and one high speed 16-mm color camera) is presently underway - to confirm this tentative claim.

A very sharp, highly polished, copper 'plumb-bob' was used to weight-down the bottom of the vertical molybdenum wire used in these tests. The plumb-bob cross-sectional diameter is small (about 1/8th-inch diameter) in comparison to the 5-cm sail diameter, so that the plumb-bob throws a negligible portion of the incident laser power out of the beam (i.e., only 0.4 %). In contrast, note that the LHMEI II beam power is only measured with an accuracy of +/- 5%. The 10.6 um laser beam was nearly collimated, and focused to a diameter that is just slightly larger than the sails. This causes roughly 20.4% of the incident beam power to 'spill' around the sail's perimeter at the launch point; when the sail reaches 40.6-cm altitude, 22.4% is spilled; at 81.3-cm altitude, 30.6% is spilled. Note that the elliptical laser beam was measured (by "burn" patterns into Plexiglass) to be 6.2-cm by 5.8-cm at the top of the wire; hence, the sail diameter for future tests might perhaps be increased to 6.3-cm to eliminate the undesirable "edge effects" associated with beam spillage. Five vertical guide wires were suspended from the same remotely -rotated carousel unit used in the Dec. '99 tests, modified to include 13-cm graphite 'beam stops' at the top of each wire - to absorb and dissipate any spilled laser power.

Two different types of 5-cm diameter laser sail materials (i.e., the test specimens) were manufactured for these tests by ESLI. Each sail was equipped with a short carbon tube 'eyelet' at the center, to guide its flight up the molybdenum guide wire. The first three sails to be tested (specimens #4, #1 and #2) had masses of 33.9, 34.6, and 32.4 mg, respectively; these exotic sails were fabricated with a front surface layer of ultralight carbon foil, reinforced on the backside with the same carbon

microtruss fabric employed for the Dec. '99 tests. The carbon foil was sputter-coated with a very thin layer of molybdenum (on the exposed or 'front' side only), to improve the reflectivity at 10.6 μm laser radiation. The final two laser sails that were tested in Dec. '00 (specimens #3 and #8, with masses of 12.7 and 14.9 mg, respectively), employed just the carbon microtruss fabric alone, but again were sputter-coated on the "front face" with molybdenum.

ESLI reported areal densities in the range of 8.9 to 9.6 gm/sq.m. for the carbon foil sails, and about 6.3 to 7.3 gm/sq.m for the carbon microtruss sails that were manufactured in 1999. The newer, opaque carbon foil sails had a transmissivity of zero, whereas the mesh-like carbon microtruss sails transmitted 48% of the incident power through the moly-coated fabric. If the sails were perfect reflectors, the new carbon foil specimens could be expected to photonically levitate (i.e., assuming 6.67 N/GW) on an incident beam power of roughly 40 to 50-kW. However, since 20.4% is 'spilled' at the launch point, a minimum of 60 kW is needed for specimen #4 (and 63 kW for specimens #1 and #2). In contrast, the two carbon microtruss specimens #3 & #8 (again with 100% reflectivity) would lift off with an incident power of 39 or 46 kW. Including the spilled power, this translates to a total beam power requirement of 49 or 58 kW, respectively.

Two Thermogage optical pyrometers were employed to measure sail temperature, and this data was adjusted for an assumed 'average' emissivity of 0.25 for molybdenum. Note that the emissivity of molybdenum is known to be 0.20 at a temperature of 1500 K, 0.25 at 2000 K, and 0.30 at 2500 K. The germanium chip pyrometer unit (Model 8000-1A) has a spectral response of 1.45 μm (peak) and range of 755 to 3255 K. The silicon chip unit (Model 8000-1) has a spectral response of 0.90 μm (peak) and range of 1422 to 3700 K. Both pyrometers were positioned to observe the front (i.e., irradiated side) face of the sails (45-deg angle of incidence), at a distance of 112-cm from the launch point. (Note that in the Dec. '99 pendulum sail experiments, the recorded data from the silicon chip pyrometer assumed an emissivity of 0.999 (i.e., that of the calibration blackbody source). This Dec. '99 temperature data needs to be re-evaluated for an emissivity of 0.25, because the pyrometer was also positioned to read the sail's front surface temperature.

The '00 experiment took 4 days to set up, and all 27 tests were performed on December 8th. As with the Dec. '99 tests, each new sail was subjected to a 'curing' or 'conditioning' process just prior to the vertical flight

attempts. When first irradiated with the lowest power beam of 8-kW, with the shortest exposure time of 0.2 seconds, each sail was observed to jump vertically - usually a half-centimeter or more. On the second test, with the same laser power and duration, the sail would glow, but not move; at this time, the sail was assumed to be fully 'out-gassed' and ready for photonic flight tests.

The very first carbon foil sail to be tested was specimen #4; it was selected because it had the fewest front-surface foil imperfections of the three. The initial two tests at 8 kW demonstrated the expected result, so the laser power was increased first to 10 kW in Run 3, and then increased by 10 kW increments in subsequent tests. Upon reaching 70 kW in Run 10, the beam burned through the foil (i.e., an evaporation process), leaving a highly visibly crescent-shaped mark - which revealed a non-uniformity in the beam intensity profile. (Note that such large-scale damage to specimen #4 was observed after the 60 kW run, which heated the foil to nearly 3400 K.) Unfortunately, the carbon sail 'cemented' itself to the molybdenum guide-wire early in the testing process, and could not lift off during the 60 kW run. ESLI suspects that the high sail temperatures in these tests caused the molybdenum wire and the carbon within the eyelet, to fuse - probably forming moly-carbide in the process. Sail temperatures for specimen #4 ranged from about 1566 K at 8 kW, to as high as 3520 K at 70 kW when finally, the sail was severely damaged. No further testing of specimen #4 was attempted.

During Runs 11-12, sail specimen #1 behaved as expected, but when the laser power was increased to 10 kW in Run 13, the carbon foil blew off the central area. The foil peeled away from the sail immediately after the beam was shut off, when the sail was cooling down. No further tests were performed with this specimen. It is useful to note that the temperature data from specimen #1 fell right in line with that of specimen #4. Prior to beginning the Dec. 8 tests, a detailed examination of both specimens #1 and #2 had revealed defects in the carbon foil near the eyelets. Hence it was not too surprising that when specimen #2 was first tested at 8 kW in Run 14, the carbon foil immediately blew off (again, mostly in the center region) - sending the sail up the wire. With only 8-kW of beam power available, the motion was surely caused by ablative thrust. The optical pyrometer gave such a low temperature reading for Run 14 that it was deemed unreliable, and therefore discarded.

Runs 15-27 were carried out with two carbon microtruss sails (i.e., having no carbon foils), designated by ESLI as specimen #3 (mass = 12.7 mg), and specimen #8 (14.9 mg). First to be tested was specimen #3, which

behaved as expected in the 8-kW curing cycle of Runs 15-16, but then appeared to fuse itself to the guide wire in Runs 17 to 21 — as laser power was ramped again from 10 kW to 40 kW. After the 30 kW Run 20, the sail shape changed slightly from that of a flat disc into more of a 'potato chip' geometry that presented a cylindrical surface (i.e., with the edges curled upward, with a radius of about 4.5 cm) to the laser beam. This new sail geometry was maintained for the remainder of the test. In Run 22, after the first 50 kW irradiation, specimen #3 appeared to break loose from the wire at the end of the test. During Run 23, specimen #3 was propelled up the wire in what might very well be the first successful, photonic flight at 1-G acceleration, for a 1-second laser duration. Since levitation was indeed anticipated for specimen #3 at total laser power levels beyond 49 kW, it is quite possible that the 50 kW flight in Run 22 may indeed be a historic first.

However, to ascertain what portion of the sail thrust could be attributed to photonic vs. ablative sources in this test, the following two studies are necessary: 1) a thorough motion analysis of the video and film footage of this flight, and, 2) an examination of the 1999 sail temperature data from the Dec. '99 pendulum tests, re-computed for the proper emissivity of 0.25. Note that the '99 pendulum tests identified 2600 K as the maximum sail temperature for purely photonic thrust (i.e., an insignificant ablation effects). However, this optical pyrometer data assumed an emissivity of 0.999 (i.e., with the silicon chip sensor - spectral response of 0.9 μm peak). In accounting for the much lower emissivity of 0.25 for the sail's front surface molybdenum coating, this Dec. '99 reading of 2600 K translates into a temperature of 3357 K (+/- 10 degrees). Note that the average temperature of the three 50 kW sail tests in Runs 21-23 was 3335 K, which is just under this limit. Additional flight tests in the future would of course conclusively resolve such discrepancies.

In Run 23 with specimen #3, the laser power was again set at 50 kW, but the laser exposure was increased to 2 seconds. In this flight, specimen #3 was rapidly propelled to the top of the wire and impacted the graphite beam stop -- whereupon the eyelet was punched out, producing a shower of sparks in the beam (probably uncoated carbon microtruss fragments, being rapidly heated). Once the beam was terminated, the sail fell back down wire, slipped over the copper plumb bob, and landed on the vacuum tank floor. The temperature data on specimen #3 revealed that the carbon microtruss fabric ran 100 to 200 K hotter than the carbon foil, for comparable laser power levels.

It is important to note that at 50 kW, specimen #3 was levitated while sustaining a temperature of 3270 to 3388 K, and yet exhibited little visible damage other than the missing carbon eyelet. At the conclusion of testing for specimen #3, no circular, highly visible 'burn' marks were observed in the carbon microtruss fabric (e.g., like specimen #4 suffered at 70 kW and 3520 K). Note also that specimen #4 survived 60 kW and 3398 K without significant damage. Evidently, with proper 'conditioning,' ESLI's laser sails can sustain temperatures up to nearly 3400 K for short durations, without catastrophic damage and/or degradation — even though molybdenum should melt at 2883 K.

Recent Laser Lightcraft World Record Flights at WSMR

Early in the morning of 2 October 2000 at the High Energy Laser Systems Test Facility (HELSTF) in White Sands Missile Range (WSMR), NM, a new world's altitude record of 233 feet (71 meters) was set by a 4.8 inch (12.2 cm) diameter laser-boosted Lightcraft (Ref. 4). Although most of this 12.7-second flight at 8:35 am was spent hovering near 230+ ft., the aluminum Lightcraft sustained no damage, and will fly again. Besides setting the 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). A total of seven vertical flights were demonstrated that morning between the hours of 8:30 am and 11:30 am, with three Lightcraft weighing about 1.8 ounces (49 to 51 grams). In addition to the new record flight of 233 ft, two others reached 159 ft and 184 ft. The Lightcraft flight test program was conceived and carried out by the author and Lightcraft Technologies, Incorporated (LTI).

These flights were powered with the 10 kW pulsed carbon dioxide laser named "PLVTS" by the organization that owns it: the Directorate for Applied Training, Test and Simulation (DATTS). Even though the laser was running erratically, the time-average beam power was still adequate to propel the craft to record altitudes; the laser problem was isolated and fixed the following day.

They were the first ever vertical, free-flight tests to be performed without a 4 X 8 ft plywood "beam-stop," suspended by a crane. In all previous laser Lightcraft flights (carried out under NASA and USAF sponsorship), the black-painted plywood was positioned to intercept stray laser power that frequently 'spills' around the vehicle in flight. The LTI flights were carried out with

the cooperation of NORAD and the WSMR range control to avoid the irradiation of low Earth orbital satellites. 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 obtained its objective of nearly doubling the previous altitude record of 128 ft. -- set on July 9, 1999 with an 11-cm diameter craft of a similar design -- under prior joint NASA/USAF sponsorship. In both records, the Lightcraft employed a plastic ablative propellant, and were spin-stabilized to 10,000 RPM just prior to launch.

The 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 support, laser launch technology has been decidedly moved out of the exclusive realm of government-sponsored research into the commercial arena. The successful flights and new altitude record can be attributed to proprietary improvements in the design of the Lightcraft vehicle itself, as well as the launch system. LTI has now set its sights squarely upon doubling its current altitude record, again -- to attain altitudes of 500 ft. in the foreseeable future. Ten more doublings are necessary to reach the edge of space.

Summary and Conclusions

Significant progress has been made over the past two years on the development of laser-propelled Lightsails and Lightcraft. The first section of this paper reviewed the continuing RPI experiments on laser-boosted Lightsails, sponsored by the Jet Propulsion Laboratory and NASA. The December '99 and December '01 Lightsail tests were carried out at Wright Patterson Air Force Base in Ohio, using the 150 kW continuous-wave carbon dioxide laser called LHMEI II. The '99-'00 Lightsail tests were filmed with an array of video and high-speed 16-mm film cameras. The December '99 experiments employed 5-cm diameter, molybdenum-coated, carbon-microtruss fabric specimens, suspended as pendulums from low-friction magnetic bearings. Forces from 3 to 13.8 dynes were observed, with pendulum deflections reaching 12.2 degrees - for incident laser powers of up to 12.5 kW. These were the first known measurements of photonic forces on real laser Lightsail materials, demonstrating equivalent accelerations of up to 0.15 Gs.

The subsequent December '00 Lightsail tests at WPAFB were structured for vertical wire-guided flights

(i.e., > 1 G), with 5-cm carbon microtruss materials similar to that used in the Dec. '99 pendulum tests; in addition, a new variety of carbon-foil sail was also tested. In two consecutive flights, Lightsail specimen #3 was propelled to 30-cm and 90-cm altitude, with a 50-kW laser beam. The sail temperature data (generated by two optical pyrometers) indicated that the material probably reached the ablation-onset threshold at liftoff. However, at altitudes of 30-cm and beyond, the Lightsail fabric should have cooled below this threshold, into the purely photonic thrust regime. A computer based motion analysis study of the flight test video/film recordings is now underway to determine if these were indeed the first photonic levitation of a laser Lightsail, ever demonstrated. Energy Science Laboratories manufactured all these Lightsail specimens, in San Diego, CA.

Finally, a brief review is given of the 2 October 2000 world record flights to 71-meters (233-ft) altitude, of a laser-propelled rocket Lightcraft at White Sands Missile Range, NM. The author set the previous altitude record of 39-meters (128-ft) in July 1999, under NASA/USAF sponsorship. The tests were conducted by the author and Lightcraft Technologies, Inc., and were sponsored by an independent foundation dedicated to promoting low cost access to space. The Army's 10-Kw pulsed carbon dioxide laser (called PLVTS) propelled the spin-stabilized free flights, at the High Energy Systems Test Facility. The 50-gram, 12.2-cm diameter Lightcraft was significantly improved beyond the original Model #200 geometry that the author developed under prior NASA and USAF funding.

References

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