12-HOUR HOVER: FLIGHT DEMONSTRATION OF A LASER-POWERED QUADROCOPTER

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Laser power beaming enables unlimited flight endurance and in-flight recharging of electric UAVs. We report here on a recent record-breaking flight demonstration in which an Ascending Technologies Pelican quadrocopter, remained continuously aloft for over 12 hours, powered by a 1,000-watt laser diode array. The Pelican was automatically acquired and tracked by the laser system, and used feedback from the laser tracking system plus onboard attitude control sensors and software to maintain position over the laser autonomously. The demonstration also met several additional milestones on the path to deployed laser powered UAVs, including in-flight recharging of the Pelican's battery, and "Class I" eye-safe operation for all ground-level personnel.

INTRODUCTION

One of the main limitations of Unmanned Aerial Vehicles (UAVs) is poor endurance. VTOL (Vertical Take-Off and Landing) vehicles such as helicopters face even greater endurance challenges due to their inherently less efficient nature as compared to fixed wing aircraft.

LaserMotive has developed a wireless power system which transfers power via laser. This system was first demonstrated in November 2009, when LaserMotive was the only team to meet (and in fact, double) the minimum requirements of the NASA-sponsored Power Beaming Centennial Challenge. Capabilities demonstrated by LaserMotive at that event include beaming power out to a range of 1 kilometer, and receiving more than 1,000 W of power out of the receiver.

In 2010, LaserMotive partnered with Ascending Technologies of Germany to demonstrate wireless laser power on a rotary wing UAV by flying the vehicle for dramatically longer than would be possible with battery power alone.

WIRELESS POWER VIA LASER

How Laser Power Beaming Works

Laser power beaming (LPB) uses electricity from a common source, such as the electrical grid or a portable generator, and converts it into light via a laser. This laser beam is then shaped with a

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set of optics, and directed via a gimbaled mirror (also called the beam director) to a remote photovoltaic receiver. The PV receiver converts the light back into electricity to be used to charge a battery, run a motor, or do other work.

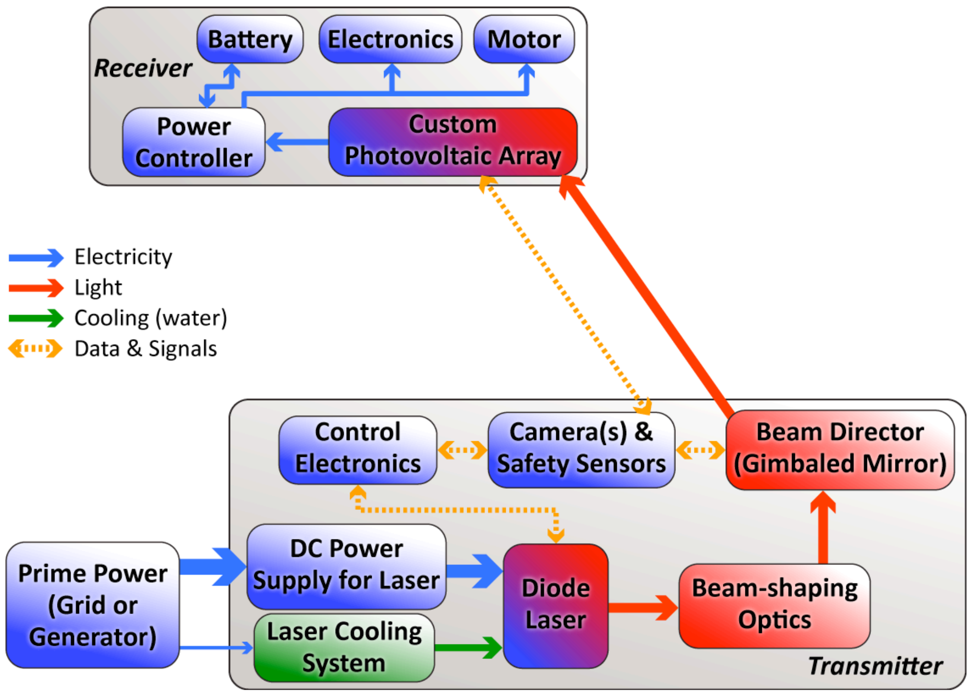

Figure 1. Schematic diagram of a laser power beaming system, showing the flow and conversion of power through the system.

Figure 1 above schematically shows the flow of power from input to output. The system can be viewed as a kind of extension cord, with electrical power going in at one end, and electrical power coming out at the other end.

History of Laser Power Beaming

The concept behind wireless electromagnetic power transmission (aka "power beaming") is not new. In fact, rudimentary tests demonstrating the transmission of electrical energy without wires were conducted approximately 100 years ago by Nikola Tesla[*], a Serbian scientist whose patents and theoretical work form the basis of the modern alternating current electrical systems and the modern AC motor.

The first person to integrate all the elements of power beaming into workable system was William C. Brown, one of the pioneers of microwave energy for wireless power transmission. Brown published his first paper on the topic in 1961, and in 1964 demonstrated a model helicopter powered by wireless microwave beam[†].

Since then, the concept has been looked at repeatedly, with both microwaves and lasers proposed as the energy transmitters. In the 1980s, researchers began looking at power beaming both

[*] http://www.teslasociety.com/biography.htm
[†] http://www.ieeeghn.org/wiki/index.php/William_C._Brown

for space-to-space energy transmission and for space propulsion. In the 1980s, a multinational group of researchers conducted tests using microwaves to power model aircraft, although the energy loss as the beam spread over long distances would be impractical for large applications. Inherent limitations on aperture size as well as possible radio frequency interference (RFI) issues have prevented widespread adoption of microwave power beaming.

Until recently the high cost and low efficiency of lasers suitable for power beaming have been barriers to the practical application of the technology. However, with recent advances, laser diodes are becoming powerful, efficient, and inexpensive enough to make the commercial development of laser power beaming feasible. In 2007, the Pentagon released a study recommending the development of space-based power systems using laser power beaming as one option for transmission[*]. In that study, the Pentagon found that, if placed correctly, space power systems could provide enough solar energy in a single year equal to all known oil reserves on Earth, provide power for global U.S. military operations and deliver energy to disaster areas and developing nations.

Several small-scale demonstrations of laser power beaming have been done[†] but only within the past few years have there been serious efforts to build complete laser power beaming systems, specifically to meet the requirements of the NASA Centennial Challenge for Power Beaming[‡]. Our team, LaserMotive, was the only entrant to meet the minimum requirements, and in fact doubled the performance requirements for the Level 1 prize in 2009.

Application to UAVs

Unmanned aerial vehicles are seeing widespread military use, and civilian applications are growing as well. Many of the situations in which UAVs are used can benefit greatly from greater endurance.

Laser power beaming can be used to power any type of UAV, including conventional winged aircraft, helicopter-type platforms, or LTA vehicles, subject only to the need for a reasonable downward- or side-facing surface for the laser receiver. Smaller systems could use lightly-modified versions of existing battery-powered UAV designs, with fractional-HP to ~20 HP (15 kW) motors; in many cases, existing airframes can be retrofitted with laser receivers (and smaller batteries). Larger UAV classes, currently fuel-powered, would need more substantial modifications or new designs, but there is no inherent obstacle to supplying up to several hundred kW to a suitable airframe.

Laser power links enable two types of operation. One is near-continual powering of the UAV, which would therefore need only a very small energy storage device on-board. The other is intermittent recharging when the UAV returns to a designated area within view of the transmitter base station; in this case the UAV still needs substantial on-board energy storage.

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[*] http://www.nss.org/settlement/ssp/library/final-sbsp-interim-assessment-release-01.pdf

[†] The earliest true laser power beaming demonstration we are aware of was done by one of the authors (Kare) in 1996, using an 808 nm laser diode array. Range (~10 m) and efficiency were low, but enough power was transmitted (3 watts) to run a small motor. In 2003, a small electric airplane was flown on laser power by Burdine and Bushman of NASA: http://www.nasa.gov/centers/dryden/news/FactSheets/FS-087-DFRC.html

[‡] NASA Power Beaming Competition. http://www.spaceward.org/elevator2010-pb and http://www.nasa.gov/offices/oct/early_stage_innovation/centennial_challenges/beaming_tether/index.html

MOTIVATION

Small electric multi-rotor helicopters have been seeing marked advances in performance and control in recent years. One of the main obstacles to their wider adoption and use is their short endurance as compared to fixed wing vehicles. For example, common small fixed wing UAVs with similar power consumption rates can generally fly for 2 hours or more, whereas the rotary wing UAVs are limited to roughly 25 minutes at most.

Ascending Technologies of Germany sells a number of multi-blade rotary wing systems, including quadrotor helicopters (aka "quadrocopter") which are used by research institutions around the world as well as for industrial inspection. At the AUVSI Unmanned Systems 2010 conference in August 2010, we met the Ascending Technologies (aka "AscTec") team and both companies expressed mutual interest to demonstrate extended endurance laser-powered flight with their technologies.

We chose to do the demonstration flight indoors in order to minimize the effort to prepare for the demo. Because both systems had been operated independently outdoors numerous times, it was felt that holding the flight indoors would not detract from the accomplishment. The Future of Flight Aviation Center at Paine Field in Mukilteo, WA, expressed interest in hosting the demonstration. The facility had a 60 foot high ceiling, which was adequate to attain a required minimum distance between the laser and the receiver. In order to minimize impact on the Future of Flight's normal daytime operations, we decided to do the laser-powered flight overnight.

INTEGRATION OF FLIGHT VEHICLE AND POWER RECEIVER

The entire project, from first meeting at AUVSI Unmanned Systems 2010 to the final 12.5 hour laser-powered flight, lasted only two months. A photovoltaic receiver design was iterated while the Pelican flight vehicle was shipped to the LaserMotive facilities in Kent, WA. The final hardware was integrated and then tested in our shop.

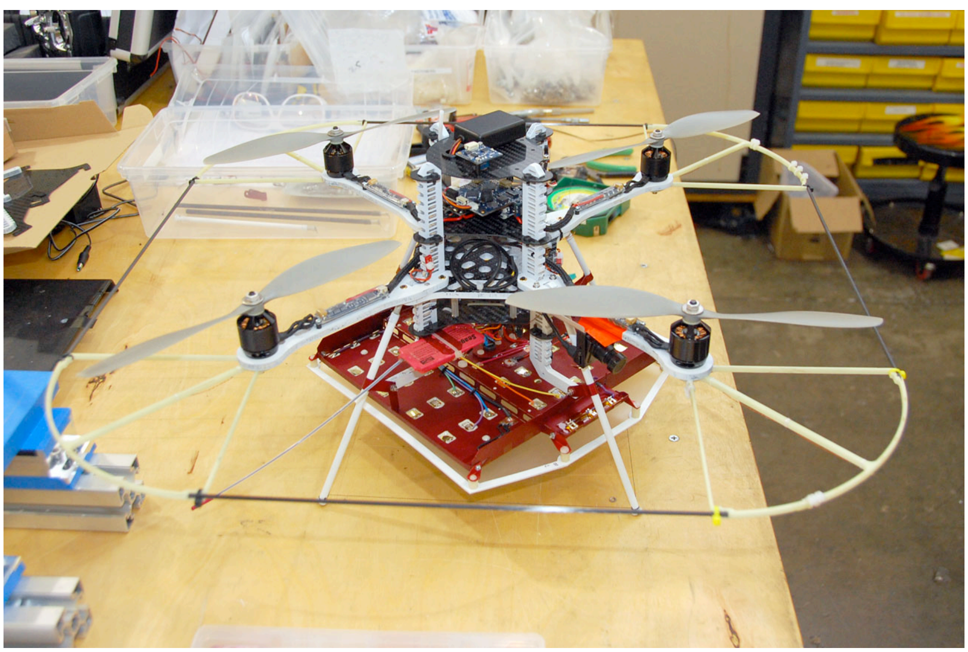

Figure 2. The Pelican with photovoltaic receiver mounted to the underside.

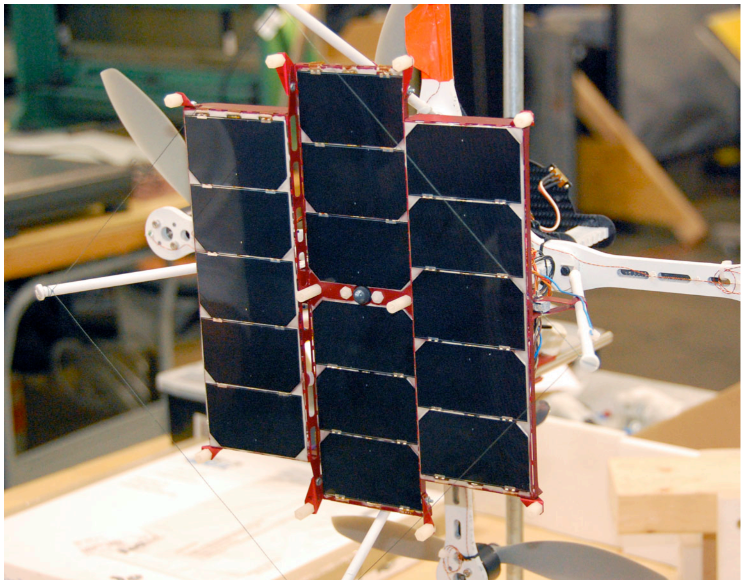

Figure 3. The laser receiving side of the PV array.

Figure 2 and Figure 3 above show the Pelican vehicle and the photovoltaic receiver mounted on it. The dual-junction gallium arsenide photovoltaic cells were made by Spectrolab, and have a nominal output voltage up to 2.1 volts, and around 1.7V at the maximum power point (MPP). The cells were mounted (using thermally conductive, electrically insulating adhesive) on anodized sheet aluminum shaped in a custom design. The 16 cells were arranged as two strings of eight cells, to produce nominally 13.6V at MPP. This design was chosen to provide a slightly higher voltage than the batteries for the Pelican were rated at, enabling charging in all charge states.

The PV array, including structure and wiring, weighed just over 240 grams, and produced as much as 190 watts during illumination tests, resulting in a specific power of ~790 W/kg. For comparison, when powered by the larger 4,500 mA-hr battery, the battery specific power is ~500 W/kg. While the smaller flight battery operated at a higher specific power, it was not a battery that would normally be used to fly the vehicle without a laser receiver as the main power source.

The final weight of the entire flight system was just over 1.1 kilograms.

Vehicle Control

The Pelican on-board control system is normally able to automatically maintain a set position using a combination of IMU and GPS data. The indoor location blocked GPS signals, so a pseudo-GPS signal was instead created by wirelessly sending information from the automatic laser tracking system to the Pelican. Details will be available in a forthcoming paper by Achtelik, Stumpf, Gurdan and Doth of Ascending Technologies, accepted for IROS 2011*.

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* http://www.iros2011.org/

LASER TRANSMITTER AND TRACKING

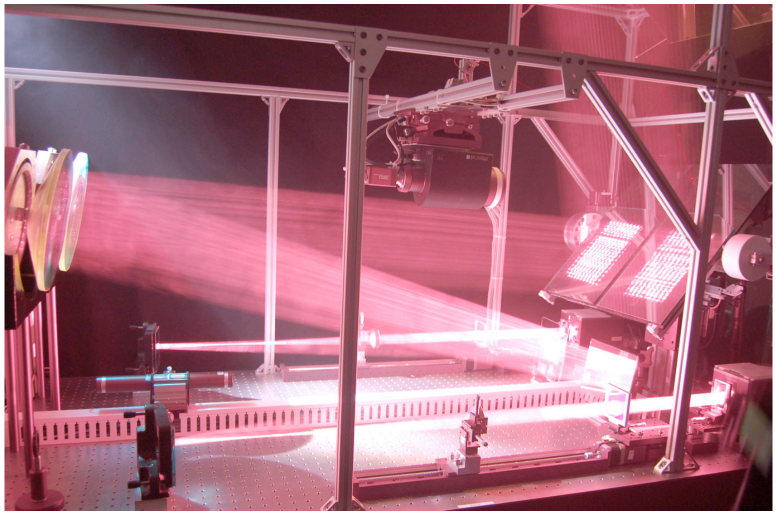

Figure 4. Dual 2.25 kW laser transmitter.

The laser transmitter used was an upgraded version, shown in Figure 4 above, of the trailer-mounted 4.5 kW laser system used for the 2009 NASA competition*. The transmitter uses two parallel beam trains, each with a 2.25 kW laser diode array assembly. Since the laser power required for the quadrocopter flight was only approximately 600 watts, only one of the two diode laser assemblies was powered, at slightly less than half its normal operating current. The transmitter beam size was nominally 15 x 15 cm.

The laser beam was steered to track the vehicle using a video camera-based machine vision tracking system (running on National Instruments Vision and Motion Platforms on a Real Time Industrial Controller), and an LED beacon mounted on the vehicle. The tracking and beam-steering systems were designed to track vehicles up to 1 km from the laser with an accuracy of a few cm, so for the relatively short range of this demonstration, the pointing errors were of order 1 mm over the entire +/- 15 degree pointing range of the transmitter.

Laser Safety

The receiver array absorbed nearly all incident laser light, and was designed to scatter any light not absorbed over a wide angle. We checked the reflectivity of the exposed Pelican structure ensure that there would be no intense "glints" from any surface. The museum hall used for the test had a diffusing white ceiling, and the specific test location was selected to minimize any possible glints from light fixtures, etc. Prior to the test, we had determined that with our laser beam properties, the maximum probable reflection even in case of a vehicle or beam-steering problem would be below the ANSI Z136 standard for maximum permissible exposure (MPE) of roughly 1.6 mW/cm^2 (at the laser wavelength of 810 nm) for distances more than 15 meters from the transmitter. Within the 15 meter perimeter we required laser safety goggles for all personnel.

Once on site, we used an optical power meter to check the scattered light flux, and an infrared viewer to look for "hot spots" due to reflective glints around the building interior from the ceiling and fixtures. We repeated these measurements after the beginning of the test flight. All meas-

* http://lasermotive.com/team/

urements indicated that the reflected/scattered laser flux was two or more orders of magnitude below the MPE everywhere outside the 15 meter perimeter, and was in fact substantially below the MPE even for an observer standing next to the transmitter trailer, directly under the vehicle.

Managing reflections, as demonstrated in this flight, enables safe operations for all personnel on the ground without needing eye safety goggles. The next step for LaserMotive is to demonstrate an automatic laser safety system which will turn off the laser beam to prevent direct exposure to anything in the air on a path towards the beam.

FLIGHT RESULTS

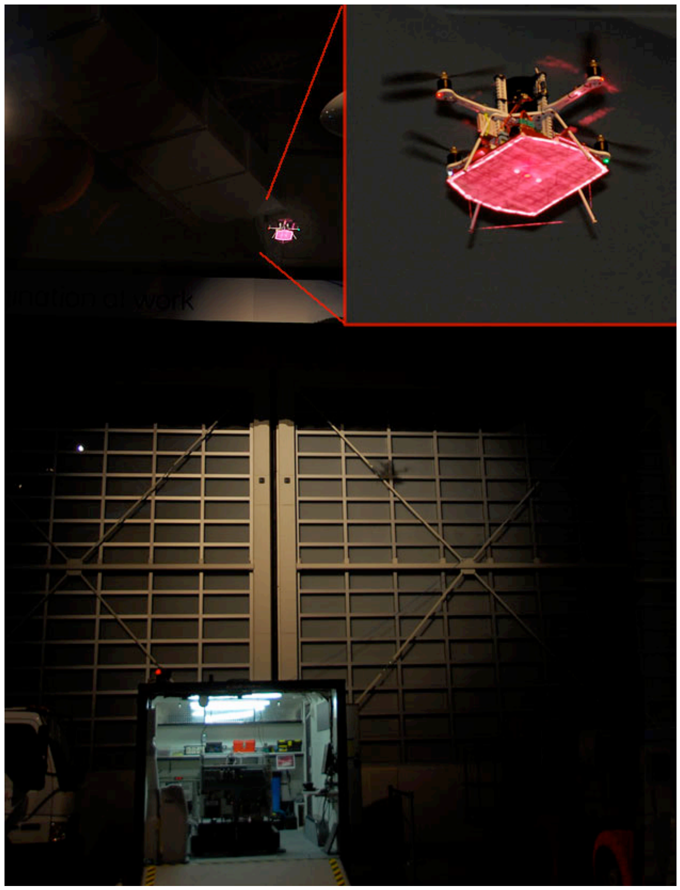

Figure 5. Laser transmitter in the trailer on the ground. Laser receiver-equipped Pelican quadrocopter flying above it (also in inset).

The demonstration flight took place at the Future of Flight Aviation Center in Mukilteo, WA overnight on October 27-28, 2010. Figure 5 above shows the flight setup, with the trailer-mounted laser transmitter at the bottom, and the illuminated Pelican with receiver near the top, and inset. The flight started at 7:37pm local time on October 27th, and ended as scheduled shortly after 8am local time on October 28th in front of a crowd of roughly 40 invited spectators.

Electrical Power

The on-board battery was rated at 1,100 mA-hr, which was expected to fly the Pelican for approximately 5 minutes.

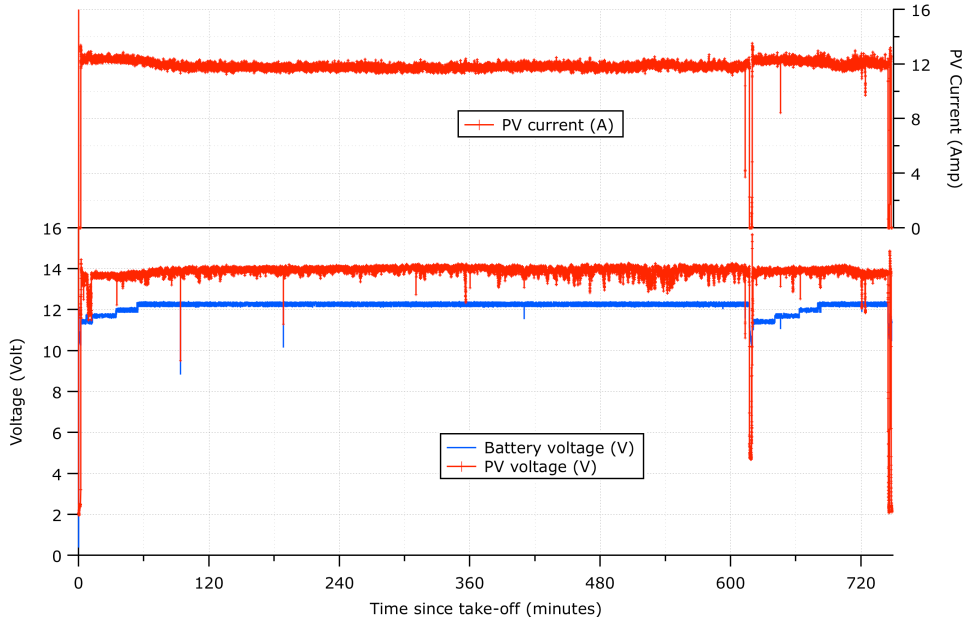

Figure 6. Voltages and currents throughout the entire ~12.5 hour flight.

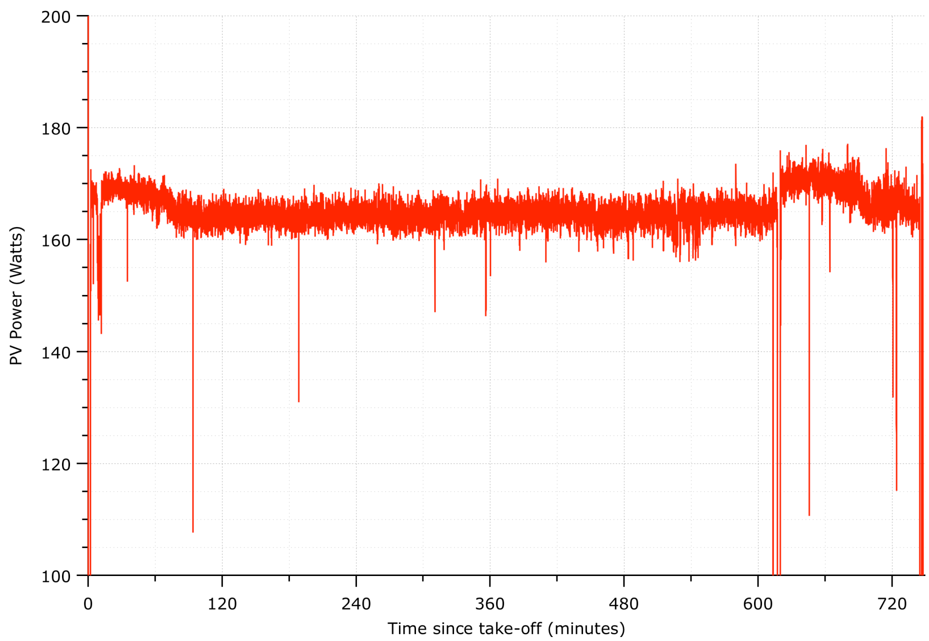

Figure 7. Power from the photovoltaic array for the entire flight.

Figure 6 shows the voltages measured at both the battery and the photovoltaic receiver, and the current out of the PV receiver, for the entire duration of the flight (just under 750 minutes). Ignoring minor outliers, it is clear that the system operated very steadily for almost the entire flight.

Nominal required power to hover the total mass was just below 140 W, based on previous measurements by AscTec. Due to the PV array blocking some of the airflow, required power for hover was higher. As seen in Figure 7 above, the measured PV output power (calculated by multiplying PV voltage by the PV current) was steady around 165 W, except when charging the battery when it was rose to 170 W.

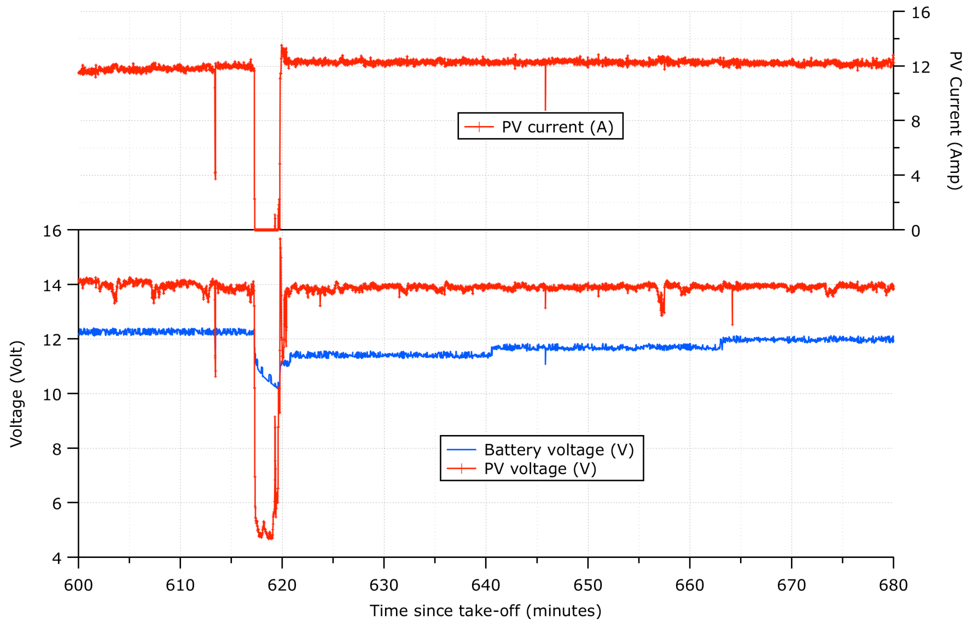

Figure 8. Voltages and current during and right after laser off event.

Just before the 10.3 hour mark (~615 minutes), there was a minor computer problem at the ground station, requiring a brief laser outage. The Pelican continued to fly on battery power alone, and laser power was restored within a few minutes. Figure 8 shows the result of the outage, as the current from the PV goes to zero and the battery voltage rapidly declines. Once power was restored, at roughly the 620 minute mark, the PV output current was modestly higher as some of the available power was used to recharge the on-board battery.

The temperature of the PV array remained steady around 63°C for most of the flight.

HIGHLIGHTS AND RECORDS

The flight* was the longest laser-powered flight on record at 12 hours, 26 minutes and 56.9 seconds, which represents a duration of 150 times the on-board battery lifetime. The flight set the following unofficial records:

- Longest hovering flight duration for an untethered electric vehicle: Limited only by the venue; the Ascending Technologies Pelican quadrocopter and the LaserMotive power system were both capable of continuing indefinitely.
- Endurance record for any VTOL aircraft in this weight class
- Longest beamed-energy-powered flight of any type

In addition, the flight marked the following key milestones towards operational laser-powered UAVs:

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* http://lasermotive.com/2010/11/12/video-of-laser-powered-quadrocopter-endurance-flight/ shows the entire 12.5 hour flight time-compressed into roughly 4 minutes.

- Repeated fully automatic acquisition of UAV by a laser tracking system
- In-flight battery recharging
- Automatic position hold in beam, with the laser tracking system controlling the UAV position
- "Class I" operation, meeting US and international laser exposure limits everywhere on the ground.

CONCLUSION

Laser power beaming is a fundamentally new method of delivering energy. It acts as a "wireless extension cord" to deliver power to end-users where it might otherwise be too expensive or impractical to run normal power lines. The demonstration flight of a laser-powered Pelican quadrocopter serves as proof that laser-powered UAV flight is practical. Further refinements will tailor the system for use in specific scenarios.

We believe that wireless power may be less than 18 months from deployment in a field system. Potential users can now start considering how they might incorporate this capability into existing or future conops. VTOL vehicles may now see wider use as their endurance can be extended indefinitely.

ACKNOWLEDGMENTS

We would like to thank everyone at Ascending Technologies, but especially Jan Stumpf and Michael Achtelik, for their support throughout our partnership. We would also like to thank Barry Smith and the staff of the Future of Flight Aviation Center for the use of their facility and their support during our testing. We would like to thank Owen Kindig of Ztoryteller for his creative methods for capturing the entire flight on video and showing the passage of time in the time-compressed video. Finally, we must thank everyone on the LaserMotive team for their tireless efforts to pull off this demonstration in a short time window.