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Initial Demonstration of an Uplink LED Beacon to a Low Earth Orbiting CubeSat

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Abstract

In this study, an uplink light-emitting diode (LED) beacon that can enable a CubeSat to locate a laser communication ground station was designed, constructed, and tested, and detection of the beacon from low Earth orbit (LEO) with a CMOS camera on the AeroCube-5 CubeSat was demonstrated. The LED beacon described is an alternative to the near-infrared laser beacons commonly used in laser communication systems, and has the potential to be cheaper, easier to point, and to require less regulatory coordination than a laser beacon, while performing the same function. An optical design is detailed, consisting of an array of 80 green LEDs with a center wavelength of 528 nm, producing 15.9 watts of free-space optical power, focused to a beamwidth of 8.12 degrees full-width-half-max (FWHM). A link budget is presented that shows the beacon is detectable by a CubeSat-mounted camera with a 7.9 mm diameter aperture and a silicon CMOS detector. A prototype beacon comprised of an LED array, focusing optics, thermal control, and tracking mechanisms was designed and constructed, and laboratory measurements of the beam profile and optical power of the prototype beacon using an optical power meter are presented herein. A field test is also described, in which the beacon was deployed at Wallace Astrophysical Observatory in the early morning of May 15, 2017 and imaged with a camera on AeroCube-5. The array is successfully identified in a sequence of five images taken by the CubeSat, demonstrating the viability of LED uplink beacons with CubeSat imagers.

1. Introduction

Advances in electronics and low-cost launch services have led to a surge in the use of nanosatellites, spacecraft with masses under 10 kilograms that often use off-the-shelf components and "hitch rides" on launches of larger satellites. Nanosatellites have been deployed extensively by research institutions and are increasingly being used in industry for imaging and communication. These spacecraft are resource- constrained because of their limited size, weight, and power (SWaP). This makes it difficult to achieve high-rate downlinks with radio communication without requiring a large aperture ground station.

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CubeSats are also typically cost-constrained, and complex and expensive communications solutions may not be within the budget of many CubeSat programs (Clements et al., 2016). One way to address these limitations is to supplement radio communication with laser communication (lasercom), in which data is transmitted with narrow-beamwidth lasers. These systems can achieve higher data rates than radio systems for comparable power consumption, assuming that the pointing, acquisition and tracking of the ground and space terminals can be established and maintained (Kingsbury, 2015; Janson et al., 2016).

Satellites using lasercom require precise knowledge of the ground station location to successfully point the downlink laser, and often use uplink beacons to acquire this knowledge. The pointing accuracy of the satellite must be at least the beamwidth of the laser, typically 0.05–0.35 degrees for CubeSat-sized systems, and as low as $3.4 \cdot 10^{-3}$ degrees for larger systems (Clements et al., 2016; Janson et al., 2016; Perlot et al., 2007). Commonly, the satellite locates the ground station by detecting a laser uplink beacon, a laser and tracking mechanism near the receiver on the ground (Kingsbury, 2015). The laser beacon is configured to point at (track) the satellite through a pass, and the satellite detects this signal. The satellite uses the beacon centroid to improve its pointing estimate. A beacon was used with the Optical Payload for Lasercom Science (OPALS) (Perlot et al., 2007), and is planned for use on CubeSat lasercom systems including the Nanosatellite Optical Downlink Experiment (NODE) (Clements et al., 2016) and the Optical Communication and Sensor Demonstration (OCSD) (Janson et al., 2016).

Uplink laser beacons are subject to regulatory restrictions in the United States and require coordination with and approval by the Federal Aviation Administration (FAA) and, in many cases, by the Department of Defense's Laser Clearinghouse (LCH). Outdoor operation of lasers requires a letter of non-objection from the FAA to certify that the laser does not pose a risk to aircraft. To ease acquisition of this letter, laser beacons generally operate in near-infrared wavelengths so that they do not pose a distraction risk to pilots. Though not always required, most laser operators also coordinate with the LCH to ensure that their systems do not pose a risk to satellites (Lafon et al., 2017).

In place of laser beacons, a bright LED light deployed at night has been proposed as an alternative method for lasercom ground beacons. Incoherent LED sources emit light over a range of wavelengths; the spectrum of colored LEDs is generally approximately Gaussian with a full-width-half-max (FWHM) spectral bandwidth in the tens of nanometers (Cree, 2017). In contrast with lasers, LED light sources are not subject to coordination with the FAA or LCH.

LED beacons also have the potential to be lower in cost and easier to operate than laser beacons. Wide beamwidth LEDs mean the beacon can withstand pointing errors of several degrees while still keeping the target satellite in the half-power beamwidth. This pointing requirement can be satisfied using low-cost telescope mounts as the tracking mechanism. LEDs cost \$1–\$2 each, and the total component cost of the LED array built in this project was \$650. The Celestron Advanced VX mount used for tracking cost \$900, for a total beacon cost of only \$1,550. The looser pointing requirements, lower cost, and lighter regulatory requirements make LED beacons an attractive alternative to infrared laser beacons.

An LED uplink beacon for signaling a low Earth orbit (LEO) CubeSat has not previously been demonstrated, to the best of the authors' knowledge. The closest existing products are commercial LED spotlights designed for architectural applications. Such spotlights have the desired optical properties; they can produce beam-widths as narrow as 5 degrees, and consume electrical power up to 280 watts (Philips, 2008). However, these spotlights are not able to track a spacecraft without a motorized mount, are too heavy to be mounted on commercially available telescope mounts, and cost several thousand dollars apiece. It was decided instead to custom design a low-cost LED array capable of tracking a satellite.

An LED uplink beacon for signaling a CubeSat in LEO is demonstrated for the first time in this work. The high-level architecture for an LED uplink beacon is presented in Section 2. Based on the architecture a prototype beacon (named the "Beaver Signal,'' after MIT's mascot) was designed and built. The LEDs, lenses, and detector are described in Section 3, and a link budget for the Beaver Signal-to-AeroCube-5 link is presented. The mechanical, electrical, thermal and tracking elements of the Beaver Signal are detailed in Section 4. Section 5 presents laboratory measurements of the FWHM and optical power of the prototype. A field test of the Beaver Signal was carried out by imaging the beacon from Low Earth Orbit with the AeroCube-5 CubeSat. The test is described in Section 6, and the collected images are presented. The beacon is unambiguously identified in the sequence of images, demonstrating the viability of an LED uplink beacon.

2. Approach

The aim of an LED beacon is to be unambiguously detected and localized at night by a satellite. To accomplish this, an array of high-power LEDs is used to produce a signal. Each LED has a lens attached with adhesive that focuses the light produced from the initial wide angle to a narrower beamwidth. The array is mounted on a structure and supplied power, and that structure is mounted to a motorized telescope mount capable of tracking the satellite as it passes above the ground station location.

During nighttime laser communication operations, the beacon is deployed near the laser communication ground terminal. As the satellite passes overhead it takes a series of images of the approximate location of the test site. The satellite processes the collected images and calculates the pointing error between the downlink laser's pointing and the actual ground station location. The pointing of the downlink laser is adjusted, and when lock is acquired, the satellite transmits data down to the ground station. This concept of operations is illustrated in Figure 1.

3. Optical Design and Photometry

The goal of the beacon is to produce as many photons per square meter as possible at the receiver's location in orbit. To accomplish this, the optical elements of the beacon are designed to maximize the optical power produced and minimize the beamwidth of the transmitted beam. High power LEDs and focusing lenses were selected based on a survey of commercial options. The properties of the receiving camera, the AeroCube-5 narrow field-of-view (NFOV) camera, were analyzed. A link budget of the transmission from the prototype array to the AeroCube-5 NFOV camera is presented below, validating that AeroCube-5 can detect the prototype LED beacon.

3.1. LED and Optic Selection

Based on a survey of commercial LEDs, green Cree XP-E2 LEDs were selected for use in the beacon array. Chips with arrays of 10 and 100 LEDs exist and were considered for use. However, there are few commercial lenses for these LEDs, and achieving narrow beamwidths would have required a custom optical design. Instead, 1 watt high-powered LEDs were used. There are a large number of commercial vendors of LEDs, including LumiLEDs, Luminus Devices, Osram Semiconductors, Cree Inc., and numerous others. The Cree XP-E2 line of LEDs was selected because of its high flux output and high efficiency. However, the array could conceivably have used other high-power LEDs, such as the LumiLEDs Rebel or Osram Golden Dragon product lines.

Colored LEDs were selected to enable the beacon to be distinguished using spectral information. LEDs with peak wavelengths from 450–550 nm were considered; the quantum efficiency of CMOS detectors peaks around 500 nm. For the current study, 528 nm green LEDs were selected, because many detectors used in satellite imaging use Bayer filters, including the AeroCube 5 NFOV camera (ON Semiconductor, 2017). A Bayer filter is a color filter on each pixel of a detector. This type of filter has two green filter pixels for every blue or red pixel, meaning that the detector is more sensitive to green light than red or blue.

A lens is mounted to each LED, narrowing the beam from 130° to 7.5° FWHM and improving the transmission gain. The 7.5° FWHM lens produced by Lumileds was chosen because it is a narrow angle lens compatible with the Cree XP-E2 LED. A 7.5 degree

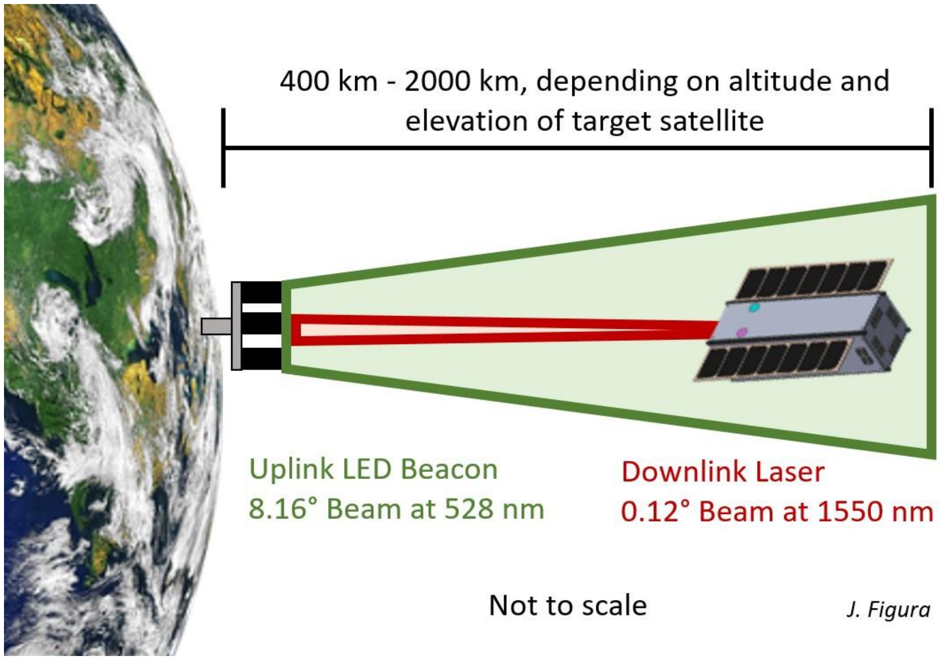


Figure 1. The concept of operations of the LED beacon, illustrating its use as part of a satellite laser communication system. The LED beacon's beam is shown in green and the downlink laser in red, coincident with each other.

beam produces a spot that is 90 km in diameter at 700 km altitude, more than enough to cover any uncertainty in the beacon tracking mechanism or spacecraft's orbit. As with LEDs, a number of other commercial options exist for the lens which would have worked just as well.

3.2. Receiving Optics and Detector

The prototype was tested with the NFOV camera on AeroCube-5, a 1.5U CubeSat that was developed by the Aerospace Corporation and launched in 2013 (Pack and Hardy, 2016). AeroCube-5 carries a camera with a 7.9 mm diameter aperture and a focal length of 15.8 mm, and an On-Semiconductor MT9D131 detector. The camera was intended as a reference for calibration of the attitude control system, not for Earth imaging. Nevertheless, nighttime imaging with the camera has been demonstrated in previous work (Pack and Hardy, 2016). AeroCube-5 was at an altitude of approximately 520 km at the time of the experiment. The beacon is demonstrated with this camera, but it theoretically can be used with any detector that is sensitive to light at 528 nm.

3.3. Optical Link Budget

An optical link budget was created to validate that the Beaver Signal is detectable by AeroCube-5. A preliminary link budget was developed to size the beacon, and was updated once the optical properties of the prototype beacon were measured and the AeroCube-5 NFOV camera was selected. The completed link budget for the experimental scenario is shown in Table 1.

The optical power in free space produced by the beacon was measured directly, as discussed in Section 5, so the value presented includes the transmit optical loss. The geometric transmission gain is calculated from the measured beam FWHM (Dolinar et al., 2012) of 8.12 degrees, rather than the lens specification of 7.5 degrees (Section 5). The free-space path loss is calculated based on a 620 km path length, corresponding to link distance at the beginning of the pass during the

Table 1. Optical Link Budget

Parameter	Value	Notes
Peak Wavelength	528 nm	For Cree XP-E2 green LEDs
Free Space Optical Power	12.01 dBW	Measured in ground testing, 15.9W
Transmit Gain	29.01 dB	For 8.12° FWHM
Free Space Path Loss	−263.37 dB	620 km path length
Atmospheric Loss	−4.5 dB	For transmission at 20° elevation (Nguyen, 2015)
Pointing Loss	−3 dB	Assumed
RX Gain	93.44 dB	7.9 mm optical aperture
RX Loss	−3 dB	Assumed
Received Power	−133.41 dBW	Sum of gains and losses
Detector QE	0.215	For 528 nm, weighted average of each color pixel for MT9D131
Exposure Time	0.2 s	Assumed, comparable to other AeroCube-5 nighttime images
BPFF	0.147	For an Edmund optics lens
Background Radiance	1.5 10^{-3}W/m^2/sr/nm	
Dark Current	60 e$^-$/s/pix	On-Semiconductor MT9D131
Read Noise (RMS)	22 e$^-$/pix	On-Semiconductor MT9D131
Signal	690 e$^-$	Signal on brightest pixel
Noise	35 e$^-$	Shot noise, dark noise, and read noise on brightest pixel
SNR	**12.88 dB**	

field test. Atmospheric attenuation is estimated at 4.5 dB (Nguyen, 2015), and a 3 dB pointing loss is assumed. Both of these values are conservative. The receiver gain is calculated from the geometric gain of the 7.9 mm diameter aperture (Dolinar et al., 2012). From these values, the power received at the imager aperture is calculated by summing the system gains and losses.

The figure of merit for the beacon-CubeSat link used here is the SNR of the brightest pixel. The number of signal electrons is calculated by multiplying the incident power by the exposure time, detector quantum efficiency (QE), and the brightest pixel flux fraction (BPFF). The exposure time on AeroCube-5 is determined by an auotexposure feature, and cannot be manually set; here, it is assumed to be 0.2 seconds, based on prior experience with nighttime imaging with this camera (Pack and Hardy, 2016). The QE used is the weighted average of the QEs of the blue, green, and red pixels on the MT9D131 detector at 528 nm. The BPFF used here is for the point-spread function of a 25.4 mm Edmunds optics lens (Nguyen, 2015). There are three sources of noise: shot noise from the signal and background irradiance, read noise, and dark noise. Background visible irradiance is very low at night, especially in regions away from artificial lights. A conservative upper bound of 1.5 10^{-3}W/m^2/sr/nm is used, taken from satellite images of the outskirts of Amsterdam at night (Kyba et al., 2015). The SNR is calculated by taking the ratio of the signal electrons on the brightest pixel to the shot noise, dark noise, and read noise on one pixel added in quadrature.

The link budget shows that the beacon has a brightest-pixel SNR of 12.88 dB at the beginning of the pass under conservative assumptions, and so should be easily detectable by AeroCube-5. The transmission distance decreases through the pass, so SNR is equal to or greater than 12.88 dB throughout.

4. Beacon Design

The various elements of the Beaver Signal are designed to support the operation of the array of 80 LEDs: an aluminum backplane provides the structure, printed circuit boards and wiring supply power to the array, heat sinks provide thermal control, and a motorized telescope mount tracks the target object. Details of the electrical, mechanical, thermal, and tracking design are given in this section. The completed Beaver Signal, deployed indoors, is shown in Figure 2.

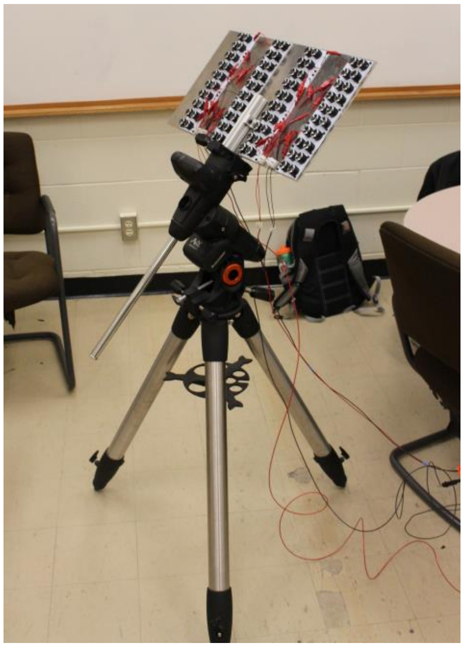


Figure 2. A photograph of the Beaver Signal, the prototype beacon. The LED array is mounted on top of the Celestron AVX motorized telescope mount, with the power supply out of the picture to the right. The array measures 58.4 cm by 30.5 cm, and the entire assembly stands 1.4 meters tall.

4.1. Electrical Design

The 80 LEDs in the Beaver Signal are surface-mounted on 20 aluminum-core PCBs, four per PCB. Additionally, each PCB has a 2-ohm current-limiting resistor. Leads are soldered to two exposed pads, and quick-release connectors are attached to each lead to connect between boards. Each board is connected to a second board in series, and five pairs of two boards are connected in parallel to each of the two channels of the power supply.

A circuit diagram of a PCB and the layout and wiring of the 20 PCBs on the backplane is shown in Figure 3. Each half of the beacon is a separate circuit, supplied by a separate DC power supply. This electrical layout was chosen to allow the power supply to drive the LEDs at as close to the maximum of the power supply as possible.

Power is supplied to the LEDs by a variable voltage DC power supply. The voltage of the power supply can be adjusted, allowing control of the brightness. The power supply used has two channels, each supplying a maximum 32 volts and about 3 amps, and half of the LED array is powered from each channel. During operation, the power supply shows a draw of 28.9 volts and 3.09 amps for each half, indicating that the power supply is operating at its current limit when driving the beacon. The beacon consumes a total of 178.6 watts of electrical power. Of this, 15.3 watts are dissipated by the current limiting resistors, and 163.3 watts are consumed by the LEDs. The current through each LED is 618 milliamps, keeping the circuit well within the maximum specification of 1 A.

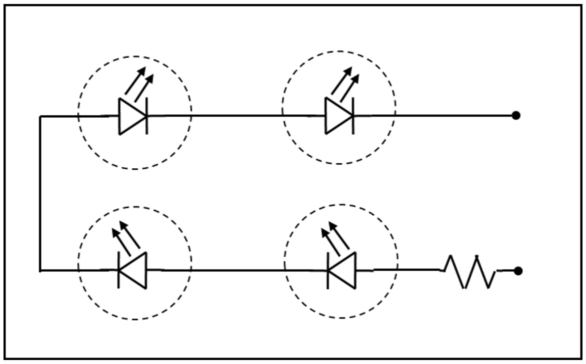
4.2. Mechanical Design

The PCBs are mounted to an aluminum backplane. The backplane is a 21 inch by 12 inch by 1/8 inch sheet of aluminum. The PCBs are arranged in a 4 by 5 grid and mounted to the backplane with 4-40 screws and nuts through holes in the backplane. The backplane provides a stiff structure to hold the LED PCBs.

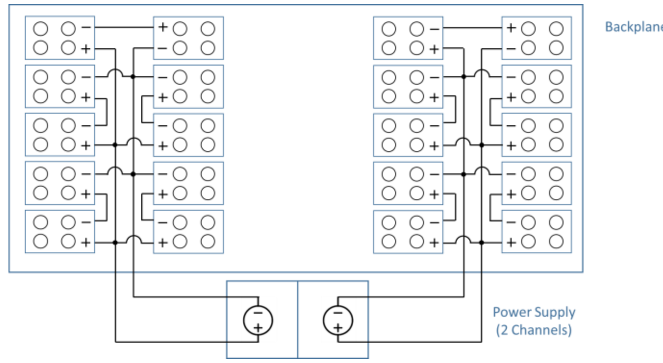
A dovetail bar is used to attach the backplane to the telescope mount. The dovetail bar attaches to two pieces of 80/20 aluminum, which, in turn, attach to the backplane with four right-angle brackets. The dovetail bar is a Vixen V style dovetail bar, the style used by the Celestron AVX telescope mount.

4.3. Thermal Design

The Beaver Signal is designed to conduct heat away from the LEDs and radiate it, to keep the LEDs below their maximum operational temperature. The LEDs produce approximately 1.7 watts of waste heat each when running at full power, and that waste heat must be removed. Aluminum-core PCBs were used to conduct heat away from the power electronics, in place



a) A diagram of the LED PCB.



b) A diagram of the full array of 20 PCBs. Mechanical components are shown in blue.

Figure 3.

of more common FR4-core PCBs. Thermal paste between the PCBs and the backplane provided a thermal path from the PCBs to the backplane. Finally, aluminum heat sinks were mounted with thermal adhesive to the backplane, behind each column of PCBs. The thermal path runs from the LEDS through the PCBs, backplane, and heat sinks to the environment. The effectiveness of the thermal design was verified by running the beacon for ten minutes at the test current. At that point, the LEDs and boards were warm to the touch, but not hot. The LEDs have a maximum operating temperature of 150º Celsius, so the LEDs stayed well below their maximum temperature during an operational scenario.

4.4. Tracking

The beacon must be capable of tracking the target satellite to keep it within the beam through the entire pass. The Beaver Signal's beam has a FWHM of 8.12 degrees, so the tracking mechanism must be capable of pointing the beacon to within 4.06 degrees of the target satellite's predicted trajectory to keep the satellite within the half-power beamwidth. To accomplish this, the LED array is mounted to a motorized telescope mount driven by tracking software.

The Celestron Advanced VX (AVX) was selected for the prototype because it is a low-cost, motorized mount that meets the 4.06 degree pointing requirement. The AVX is a portable equatorial two-axis mount, stands 1.62 meters high, and is controlled by the NexStar+ hand controller.

The AVX mount does not have built-in capability to track an LEO object. Instead, the Beaver Signal uses a program called Satellite Tracker, developed by John Eccles, to control the mount (McNish and Teague, 2009). Pointing accuracies of 0.25 degrees have been demonstrated using Satellite Tracker and a NexStar+ hand controller on a different Celestron mount, which meets the 4.06 degree half-power beamwidth requirement (Koller et al., 2016). Satellite Tracker takes as inputs the latitude and longitude of the ground site and the two-line element (TLE) set of the target object's orbit. From these, the software calculates the path of the satellite across the sky during a pass, then directs the telescope mount to slew to a sequence of right ascension and declination targets, tracking the satellite. The combination of the AVX mount and Satellite Tracker enables the Beaver Signal to track the target LEO satellite through a pass.

Lastly, the mount must be aligned relative to the Earth before each use. The AVX has a built-in two-star alignment procedure that is performed during each deployment and before use. A six-inch Celestron telescope is used during the alignment procedure to precisely point the mount.

5. Ground Testing

5.1. Methodology

The Beaver Signal was measured in a laboratory to determine the beam FWHM and total power, the two most important optical properties. The prototype beacon was deployed in the optical test range of MIT Lincoln Laboratory, and irradiance measurements were taken with a photodetector at a range of angles from the beacon. These measurements characterize the amplitude profile of the beam, and the FWHM and total optical power were calculated from the measured profile. The FWHM and total optical power were compared to the hardware specifications, and both were within expectations for the lenses and LEDs being used.

In testing, the LED array was mounted on a rotational stage, and the photodetector was placed in the beam at a distance of 30 meters from the centerline of the backplane. The stage was rotated in increments of 0.5 degrees and the incident power was recorded at each angle relative to the beacon. Two trials were conducted; between trials, the photodetector was taken down, reset, and the distance to the beacon was re-measured. Measurements were taken with a Newport 2936-R power meter and a Newport 918D-SL-OD1R photodetector. A laser rangefinder was used to measure the distance between the beacon and the probe, and a cross-hair laser tool was used to align the probe with the axis of the beam.

5.2. Results

The Beaver Signal's measured amplitude as a function of angle off-axis is shown in Figure 4. The FWHM was calculated from these measurements by fitting a Gaussian to the collected data, using MATLAB. The first set of measurements had a FWHM of 8.16 degrees, and the second set, a FWHM of 8.09 degrees. Averaging the two values produces 8.12 degrees, which is the FWHM used in this work.

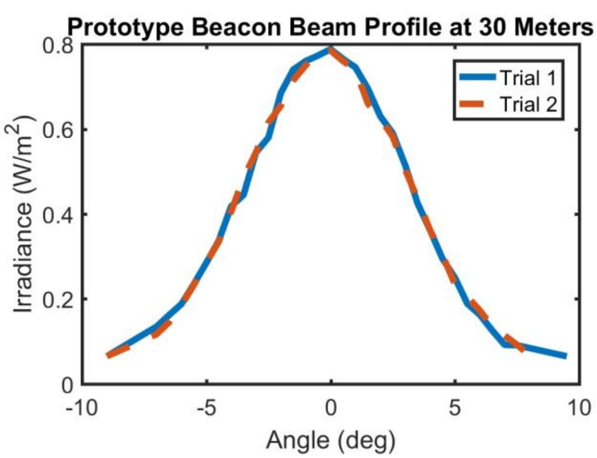


Figure 4. The irradiance profile of the prototype beacon's beam, measured from a distance of 30 meters.

Next, the total optical power of the prototype beacon was calculated from the measurements under the simplifying assumption that the beam can be modeled as a Gaussian beam with a point source. The equation for the irradiance of a Gaussian beam with a point source is

$$I(r,z) = \frac{P}{\pi w(z)^2/2} e^{-2\frac{r^2}{w(z)^2}} \quad , \qquad (1)$$

where $I(r, z)$ is the irradiance of the beam, r is the radial distance from the center axis, z is the axial distance from the focus, P is the total power of the beam, and $w(z)$ is the $\frac{1}{e^2}$ radius of the beam at the axial distance z.

The total power of the beam, P, can be calculated using Equation 1 and the collected measurements. We measured $I(0, 30)$ at 0.77 W/m^2, and calculated that $w(30)$ is 3.61 m by finding the $\frac{1}{e^2}$ angle, then calculating the corresponding radius of the beam at 30 meters, assuming the beacon is a point source. Substituting these two values into Equation 1, it was calculated that the optical power of the beacon in free space is 15.9 W.

5.3. Discussion

The measured FWHM and optical power are within expectations for the hardware. The beam profile measurements used to estimate the beam divergence were conducted at a range of 30 m because this was the longest indoor range available. At this distance, a beacon with width 0.5 m has an angular width of just under 1 degree, and the point source approximation is not strictly accurate. As a result, the calculated beam profile is slightly wider than the actual beam profile. Indeed, the measured FWHM of 8.12 degrees is slightly larger than the 7.5 degree specification of the lens LEDs. This discrepancy is consistent with point source approximation error, or with the actual lens FWHM being wider than advertised, or random alignment errors when mounting the eighty lenses that would cause the beam to spread. Although the calculated beam divergence is likely an overestimate, it is used as a conservative value for the link budget estimate.

Based on the measured free space power and electrical power consumed by the LEDs, the Beaver Signal's electrical-to-optical efficiency is 9.7%. The total efficiency of the beacon can be described as

$$P_o = P_e \cdot \eta_{LED} \cdot \eta_{Th} \cdot \eta_{TX} \quad , \tag{2}$$

where P_o is the output optical power, P_e is the input electrical power, and η_{LED} is the ratio of the diode's output optical power to input electrical power at room temperature. η_{Th} is the thermal loss, the ratio of the optical output at the operating temperature to the output at 25 degrees, and η_{TX} is the transmission loss of the lens. The total electro-optical efficiency, $\frac{P_o}{P_e}$, is the product of the diode efficiency, the thermal efficiency, and the lens efficiency.

We can use the measured P_o and P_e along with assumptions for the other efficiencies to check whether the measured power is reasonable. During the test, the LEDs consumed 163.3 W of electrical power and produced 15.9 W of optical power. The published transmit efficiency of the lens is 0.85. The Beaver Signal runs quite hot, so the thermal efficiency of the LED at 150º C is used, 75% (ON Semiconductor, 2017). The LED electro-optical efficiency at room temperature is not given in the datasheet, but by using the above values in Equation 2, we calculate a wallplug efficiency of 15.3%. This is within the typical range of wall plug efficiencies for green LEDs, 15%–20% (Mukai et al., 1999). Therefore, the measured free-space power is consistent with typical green LEDs, given reasonable assumptions.

6. Field Testing

6.1. Methodology

The feasibility of an LED uplink beacon was demonstrated by imaging the prototype beacon at night from LEO with AeroCube-5. In the early morning of May 15, 2017, the Beaver Signal was deployed at Wallace Astrophysical Observatory in Westford, Massachusetts. At about 3:00 AM, AeroCube-5 passed overhead and took images of Boston and the surrounding area. In the collected images, the beacon is clearly identifiable, demonstrating the feasibility of an LED uplink beacon.

On the test date, the Beaver Signal was set up on the AVX mount adjacent to the observatory. First, the mount was aligned using a six-inch telescope and a two-star alignment procedure. The telescope was removed and the beacon was mounted to the AVX, then connected to the DC power supply. A laptop with Satellite Tracker was connected to the mount. An image of the Beaver Signal turned on during testing is shown below (Figure 5).

The orbit of AeroCube-5 had been determined in the days before the experiment with a series of GPS fixes on the satellite. From these, a final TLE was generated about 24 hours before the experiment. During the pass AeroCube-5 was above 20 degrees elevation for approximately seven minutes, starting around 7:00 UTC (3:00 AM EDT in Boston). At the time of the first image, the satellite was at an elevation angle of about 54 degrees relative to the beacon site, rising to about 78 degrees by the last image. With a satellite altitude of 520 km, these elevation angles correspond to ranges of 630 and 530 km at the beginning and end of the pass, respectively. The Beaver Signal was commanded to begin tracking the satellite just before 3:00 AM EDT, when the satellite reached 10 degrees elevation, and the beacon was turned on when the satellite cleared the tree line at approximately 20 degrees elevation. The test continued until the satellite's position fell beneath the tree line on the far side of the observatory, at which point the beacon was switched off. For this experiment, the NFOV camera on AeroCube-5 was commanded to take a series of images in its auto-exposure mode, with an exposure time of approximately 0.3 seconds. Successive images were taken at the maximum repetition rate, about every ten seconds. During the pass, the beam was modulated by switching the power supply such that the beacon was on for ten seconds and off for ten seconds. By cycling the beacon at twice the time between images, the beacon was expected to be clearly identifiable by comparing successive images. The images should quickly sample the

Figure 5. The beacon during testing at Wallace Astrophysical Observatory. The LED array is mounted on the AVX in the center of the frame. The power supply and computer controller are out of the frame to the bottom.

beacon's on/off state, such that the signal appears and disappears between images.

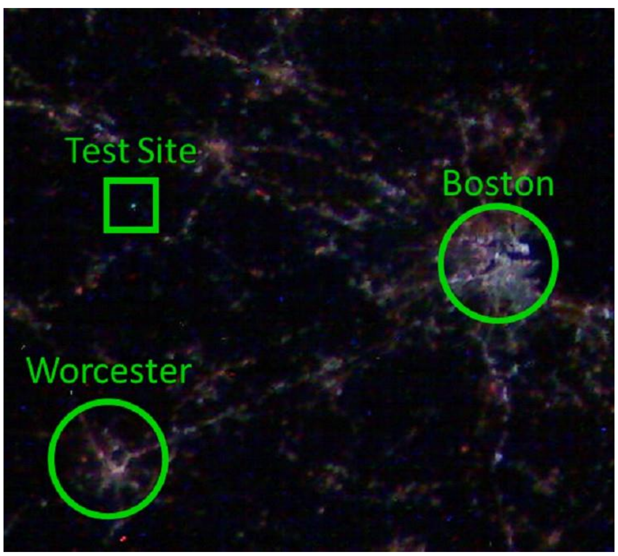
The images acquired by AeroCube-5 were taken using a point-and-stare mode (Pack and Hardy, 2016). In this mode, the satellite is continuously slewed, so as to keep the camera pointed at the target location on the ground. The point-and-stare mode is necessary because previous work with nighttime imaging has shown that the exposure time of the camera is sufficient to generate streaking if the camera simply pointed continuously in the nadir direction. The exposure time is not controllable and is set by an auto-exposure mode, and in previous nighttime imaging experiments, the exposure time has been a few tenths of a second.

6.2. Results

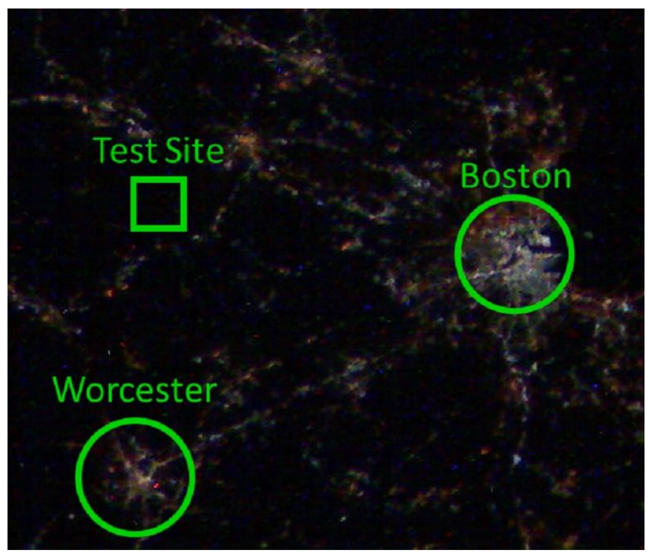
The beacon was successfully detected by AeroCube-5 during the field test. Five usable images were obtained during the pass over the Boston region, with approximately ten seconds between the time of capture of each. There is a green spot in the approximate location of the test site in the first, third, and fifth images; the spot does not appear in the second and fourth images. Thus, this green spot can be unambiguously identified as the beacon because it cycles with the power cycling of the beacon.

The AeroCube-5 images are shown in Figure 6, referred to as Images 1–5, in the order they were taken. The top picture shows the full 1600 by 1200 pixel frame of Image 1, with north indicated by the red arrow. The middle row shows Images 1 and 2, cropped to the Boston metropolitan area. Boston is the circled cluster of lights on the right side of the frame. Logan Airport can be identified as the bright white spot on the east side of the city, and Boston Harbor and the Charles River Basin are visible as dark patches near the city. Worcester, Massachusetts (MA) is circled in the bottom left of each image. Lowell and Lawrence, MA, are visible as the pair of cities in the top, to the left of center. The test location in Westford is boxed and labeled. In Image 1, the beacon is visible at the test site. In Image 2, the beacon is off and is not visible. Closeups of the testing location for every image are shown in the bottom row. A green/white region is visible in Images 1, 3 and 5, and not visible in Images 2 and 4. The closeup shows the full sequence, and that the beacon alternates between being visible and not visible.

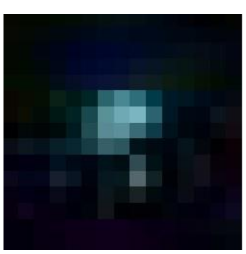
a) The full frame of the first image collected.



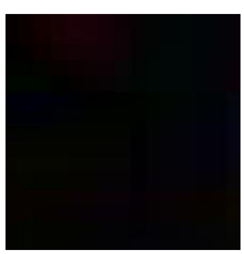
b) Image 1, cropped to the Boston metropolitan area. The beacon image is visible as the green spot at the testing location.



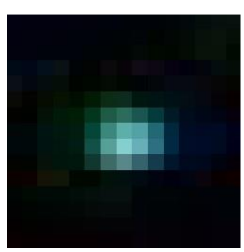
c) Image 2, cropped to the Boston metropolitan area. Here, the beacon is off and is not visible at the test location.



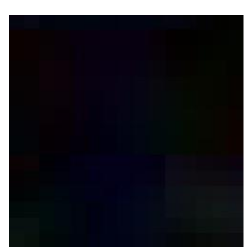
d) Test site in Image 1. Beacon is on.



e) Test site in Image 2.



f) Test site in Image 3.



g) Test site in Image 4.

h) Test site in Image 5.

Figure 6. A collection of images taken by AeroCube-5 during testing.

6.3. Discussion

This test qualitatively demonstrates two methods to identify an LED beacon in a nighttime image, with modulation and with color. As discussed, the beacon is definitively identified by its modulation. Additionally, the LED beacon can be identified by color; it appears green, while other artificial lights appear red or white. If an LED uplink beacon is implemented in a CubeSat laser communication system, either or both of these methods could be used by the flight computer to process the image and identify the ground site in real time.

As mentioned, the NFOV camera on AeroCube-5 was intended for calibration only, and has a number of limitations that prevent photometric analysis of the images. The camera only downlinks images in a compressed JPEG format that does not preserve raw image data. Exposure time is set by an autoexposure mode and is not downlinked, so the exposure time of the image is not known. Lastly, there is an uncertainty of about ten seconds in the timing of the image sequence that corresponds to a 75 km uncertainty in the location of the satellite along the orbit track.

7. Future Work

This work presents a proof-of-concept of an LED uplink beacon that could be used as part of a CubeSat laser communication system. Further work is necessary to incorporate an LED beacon into an operational system. There are several improvements to the beacon hardware and receiving detector that could be made, and some trades made during the development of the Beaver Signal should be reexamined for an operational system.

7.1. Improvements to the Beacon

The output optical power of the LED array could be increased in several ways. The DC power supply used in the Beaver Signal was the limiting electrical element. It ran at its current limit and drove the LEDs at only 3/5ths of their maximum current specification. A higher-current power supply could increase the optical output of the current beacon design, though at the cost of increased dissipation. More thermal control, such as larger radiators or active cooling, could reduce thermal loss by maintaining the beacon at a lower operational temperature. Finally, the number of LEDs on the beacon could be increased by increasing the size of the backplane or reducing the spacing between LEDs. Some combination of these changes could conceivably double or triple the number of LEDs on the beacon, while maintaining the same general design, though additional power and thermal control would be required.

Green LEDs were used for the prototype beacon because a CMOS detector with a Bayer filter has the highest quantum efficiency in green wavelengths, but a future beacon will likely use blue or near-infrared LEDs. Green LEDs suffer from the lowest wall-plug efficiencies of any visible LED, a phenomenon known as the “green gap” (Jiang et al., 2015). Future visible beacons should consider using blue LEDs, which have the highest electro-optical efficiencies of any color LED, as well as high quantum efficiency on silicon detectors with an appropriate filter. A second possibility is to substitute near-infrared LEDs for visible LEDs. While they suffer from reduced quantum efficiencies with CMOS detectors relative to visible light, near-infrared LEDS have the potential advantage of being invisible to the human eye. Invisible light eliminates the risk of distracting aircraft pilots and avoids the need to coordinate with the FAA, but is more dangerous in the near field because light that is not visible does not induce people to look away, nor trigger the pupil to contract. However, avoiding the need to coordinate with the FAA may be worth these costs.

7.2. CubeSat Receiver

The AeroCube-5 camera proved capable of detecting the beacon, but the field test was a mission of opportunity using a camera not specifically designed for this purpose. A dedicated LED beacon receiver could increase the signal received in several ways. The AeroCube camera aperture is very small, at only 7.9 mm diameter; by increasing the aperture diameter, the received signal can be increased substantially. Doubling the aperture to 15.8 mm increases the received power by a factor of four (6 dB) while keeping the aperture much smaller than the 10 cm side-length of a

CubeSat. AeroCube-5's camera also uses a Bayer filter, which allows the camera to detect and identify a range of visible wavelengths, but reduces the quantum efficiency for any individual wavelength. A dedicated beacon camera could instead use a monochrome detector combined with a bandpass filter centered at the beacon's wavelength. This combination would increase the quantum efficiency of the received signal, while still allowing the signal to be distinguished by its color.

Finally, the receiving CubeSat must be able to "point and stare" at the target location to integrate over an appreciable time. AeroCube-5 was able to do this with some level of accuracy, and a high-precision point-and-stare mode would likely already be a requirement on a CubeSat that employs lasercom.

8. Conclusion

This work demonstrates the utility of an LED beacon to enable a satellite to locate a laser communication ground station. An approach to building and operating an LED beacon is described, a prototype LED beacon was constructed, and the performance of the beacon was demonstrated with irradiance measurements and images collected from orbit with AeroCube-5. This project demonstrates the viability of a small, low-cost LED beacon that is detectable from orbit, and shows that the LED beacon can viably supplement or replace existing near-infrared laser beacons. The development of the Beaver Signal prototype serves as a first step towards developing an LED beacon that can be incorporated into a future CubeSat laser communication system.

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