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Non-coherent LED Arrays as Ground Beacons for Small Satellite Optical Communications Systems

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ABSTRACT

Free space optical communication systems typically require receiving telescopes on the ground to be a co-located, high power, unmodulated laser transmitter to serve as a beacon for locating the ground station. Unfortunately, these lasers may be costly and subject to regulations on optical power and frequency of use, which would not apply to a non-coherent light source. A directed LED optical beacon for use with free-space laser communication downlink systems is designed, constructed, and tested. The beacon, consisting of an array of 80 green LEDs, produced 15.9 Watts of optical power at a peak wavelength of 528 nanometres with a beamwidth of 8.12 degrees FWHM. The beacon was tested at the Wallace Astrophysical Observatory in Westford, Massachusetts. On-orbit imaging was accomplished by an on-orbit Cubesat in collaboration with the Aerospace Corporation using a camera with a silicon CMOS detector and a 7.9 mm optical aperture. The LED beacon is easily identified in a series of 5 images taken by the CubeSat, demonstrating the viability of the use of a non-coherent LED arrays as optical communication uplink beacons.

INTRODUCTION

Space-to-ground optical communications have the potential to revolutionize small spacecraft communications by offering high data rates, superior power efficiency to conventional RF systems, and minimal regulatory overhead.[1] [2] Unfortunately, efficient optical communication requires the transmitted laser beam to be precisely pointed (within less than half a degree of error) at the receiving telescope.[1] To accomplish this precise pointing, an optical uplink beacon is often used to assist the spacecraft in locating the ground station and directing the transmitted free-space laser beam to the receiving telescope.

Most optical ground stations use a relatively high-power laser as an uplink beacon. The Optical Payload for Lasercom Science (OPALS), for example used a 976 nm, 10 W uplink beacon.[3] [4] A 10 W, 1550 nm uplink beacon is planned for use with the Optical Communication and Sensor Demonstration (OCSD).[5] [6]

Unfortunately, high-power outdoor coherent light sources are subject to regulatory restrictions in the United States and operators must coordinate with and obtain approval from the Federal Aviation Administration (FAA) and the Department of Defense's Laser Clearinghouse (LCH) in the case that the mission is DoD funded (although most laser operators co-ordinate with the LCH nonetheless).[7]

A possible alternative is to use an LED array as a beacon. Compared to a laser, which produces monochromatic light, an LED array would produce a narrow spectrum of light with a typical FWHM of tens of nanometres.[8] Due to the incoherent nature of the light produced by the LEDs, an LED array-based beacon would not be subject to coordination with the FAA or LCH. As a result, an LED array may be cheaper to implement and easier to operate than existing laser-based beacons.

To the author's knowledge, the use of a noncoherent LED array to provide pointing knowledge to small spacecraft in orbit has never been attempted or successfully demonstrated before. The closest existing products to what would be required for an optical communications beacon are architectural spotlights used for decorative illumination of structures. These spotlights produce beamwidths as narrow as 5 degrees FWHM with electrical power consumption around 280 Watts.[9] Unfortunately, these spotlights are not designed to track a target and their weight (roughly 75 pounds) make them too heavy to use with amateur telescope mounts. Instead of using an architectural spotlight, this approach involves a low-cost LED array that would be more suitable for the task.

BEACON DESIGN

LED and Optics Selection

With regard to focusing optics, multiple options were examined, including the use of parabolic mirrors versus using integrated lens assemblies which sit on top of the LEDs. After ordering an 8 inch by 6 inch reflector mirror of the type that might be used to construct such an array, it became apparent that the parabolic reflector mirror approach would not be viable due to the weight of the mirrors themselves and the weight of the support structure needed to hold the LEDs at the focal point of each mirror. As a result, the decision was made to use an integrated lens assembly.

Several brands and models of commercially available LEDs were examined for suitability for use in the LED beacon. After much consideration, green Cree XP-E2 LEDs were selected for use. These LED's have a single diode on each chip with a rated maximum power of 3 Watts.[8] The primary motivator in this decision was the availability of lenses which are either not available or are relatively costly for chip arrays of 10 or 100 diodes.

Narrow spectrum colored LEDs were selected over broad spectrum or white LEDs to enable the beacon to be distinguished using spectral information. A range of LEDs with peak emission wavelengths from 450 nm to 550 nm were considered, given that the quantum efficiency of CMOS detectors peaks around 500 nm. 528 nm green LEDs ultimately were selected, because out of the commercially wavelengths available, 528 nm is closest to the peak effective passband of the the Bayer filter used on many small satellite imagers.[10]

To direct the light from the LED towards the satellite, a lens manufactured by Ledil with a 7.5 degree nominal FWHM was selected due to its compatibility with the Cree XP-E2 LEDs.[11] The 7.5 degree FWHM results in a 90 km -3dB illumination area at 700 km altitude, which is more than sufficient to account for pointing error in the tracking mount and uncertainty in ground knowledge of the orbit of the satellite.

Receiving Optics and Detector

For the purpose of field testing, the MIT team reached out to collaborators at the Aerospace Corporation, a leader in development and operation of research CubeSats, to engage 1.5U CubeSat that was launched in 2013.[12] The CubeSat (AeroCube-5) carries an imager with a 7.9 mm diameter optical aperture, a 15.8 mm focal length, and an On-Semiconductor MT9D131 detector. The imager was not intended for Earth imaging, but nighttime imaging has been demonstrated in previous work.[12]

Link Budget

An optical link budget analysis was performed to verify that the beacon would be visible from orbit by the CubeSat. A preliminary link budget was used to size the beacon, and was updated once the optical properties of the prototype beacon were measured and the NFOV camera were available. The final link budget for the experiment as performed is shown in Table 1. Both the optical transmit power and beamwidth shown in the link budget reflect the value experimentally measured for the complete LED array. The free-space path loss is calculated assuming a path length of 620 km which is consistent with what might be expected for a CubeSat in LEO during a high elevation point in an over pass. Atmospheric attenuation is estimated at 4.5 dB, and pointing losses of 3 dB are assumed if the errors in the tracking mount are less than the Half Width Half Max of the optical beam.[13] The receiver gain is calculated based on the geometric gain of the 7.9 mm diameter aperture lens.[14] On the basis of these measurements and assumptions, received optical power at the image sensor was calculated to be -133.41 dBW.

In determining if the LED would be visible from LEO, the figure of merit is the SNR of the brightest pixel. The SNR is the ratio of the number of signal electrons in a particular pixel on the image sensor to the number of noise electrons in the same 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). To calculate the number of noise electrons, three sources of noise must be accounted for: 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 x 10^{-3} $W/m^2/sr/nm$ is used, based on data from satellite images taken of the outskirts of Amsterdam at night.[15] Read noise and dark noise were both taken from the datasheet for the MT9D131 image sensor.[10] Based on these parameters, the link budget yielded an SNR of 12.88 dB under fairly conservative assumptions, and so the LED beacon should be detectable by the on-orbit CubeSat.

Electrical Design

Electrically, the beacon consists of 80 high power LEDs spread across 20 metal core PCBs organized in two banks of 10 PCBs each. In addition to the four LEDs, each PCB also has a 2 Ohm current-limiting resistor. Each bank of PCBs is powered off a seperate channel of a DC benchtop power supply operating at 28.9 Volts and drawing 3.09 Amps per channel, for a total electrical power consumption of 178.6 Watts.

Mechanical Design

All 20 PCBs are mounted to a 21 inch by 12 inch by ⅛ thick aluminum sheet. The PCBs were arranged in a 4 by 5 grid and secured to the aluminum sheet with 4-40 machine screws and nuts. A Vixen V-style dovetail bar was used to secure the array to the tracking mount and was attached to the aluminum backplane with right angle brackets and 80/20 aluminum bar.

Table 1

Parameter	Value	Units	Notes/Source
Peak Wavelength	528	nm	For Cree XP-E2 green LED
Optical Transmit Power	12.01	dBW	Measured as 15.9 W
Transmit Gain	29.01	dB	Measured as 9.12 deg FWHM
Free Space Path Loss	-263.37	dB	620 km path length
Atmospheric Loss	-4.5	dB	Assuming 20 deg elevation [10]
Pointing Loss	-3	dB	Assumed
RX Gain	93.44	dB	7.9 mm aperture
RX Loss	-3	dB	Assumed
Received Power	-133.41	dBW	Sum of gains and losses
Detector QE	0.215		For MT9D131 sensor
Exposure Time	0.2	s	Assumed (similar to other AeroCube-5 images)
BPFF	0.147		For Edmund optics lens
Background Radiance	0.0015	W/m^2/sr/nm	
Dark current	60	e-/s/pix	For MT9D131 sensor
Read Noise (RMS)	22	e-/s/pix	For MT9D131 sensor
Signal	690	e-	Signal on brightest pixel
Noise	35	e-	Sum of shot noise, dark noise, and read noise
SNR	12.88	dB	

Thermal Design

The high power LEDs in in the array produce a substantial amount of waste heat (over 1.25 Watts each) which must be sinked away and dissipated if the LEDs are to have a reasonable useful life. To this end, several design features of the array were specifically chosen to maximize heat dissipation. The PCBs that the LEDs are mounted on were manufactured on an aluminum substrate instead of an FR4 substrate to maximize heat conduction away from the LEDs. Additionally, thermal paste was used at the junction between the PCBs and the aluminum backplane. Finally, aluminum heat sinks were added to the backside of the aluminum plate to assist in convective cooling of the completed array. Thermal performance of the array was verified quantitatively after 10 minutes of continuous operation when the PCBs and aluminum plate were found to be warm to the touch but not hot.

Tracking Mount

To minimize costs, a COTS telescope mount was used to track the CubeSat during field testing. To avoid excessive pointing losses, the mount must be able to automatically track (or be modified to automatically track) a LEO object with less than 4.06 degrees of error (half of the FWHM of the optical beam as implemented).

The Celestron Advanced VX (AVX) was used for this purpose as its tracking abilities met the pointing error requirement, and one was available to borrow from another department. The software functionality needed to track a LEO object based on its TLE is not built in to the AVX mount so a program called Satellite Tracker, developed by John Eccles, was used to control the mount.[16] Pointing accuracies of 0.25 degrees have been demonstrated using this software package on a different Celestron mount, which is more than sufficient for this application.[17]

GROUND TESTING

Methodology

Prior to field tests with the on-orbit CubeSat, the LED array was characterized at the MIT Lincoln Laboratory optical test range. Irradiance measurements were made at various angles off-axis from the optical beam and these measurements were used to calculate FWHM and total optical power. During these tests, the LED array was mounted on a rotating stage and the Newport 2936-R power meter and Newport 918D-SL-OD1R photodetector were placed 30 metres from the array. The stages was rotated over the range from roughly -10 degrees to 10 degrees in increments of 0.5 degrees. Two trials with the same setup were completed.

Results

The beam profiles resulting from both trials of photometric measurements of the LED array are shown in Figure 1. Fitting a Gaussian curve to the data in MATLAB yields a FWHM of 8.16 degrees for trial 1 and 8.09 degrees for trial 2, the average of which is 8.12 degrees, the value assumed for the remainder of this paper.

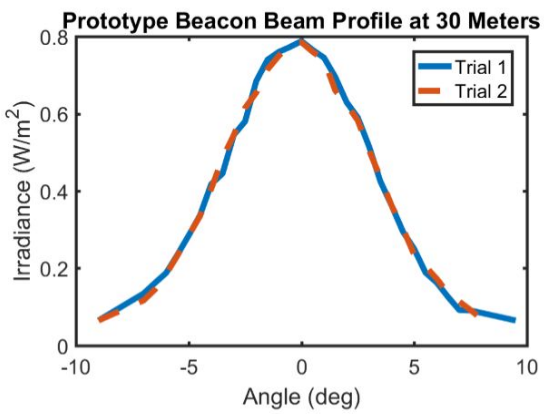

Figure 1: A graph of the beam profile measured for the LED arra beacon showing trials one and two separately.

The total optical output power of the array was calculated using the the equation for the irradiance of a Gaussian beam from a point source (equation 1).

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

In this equation, I(r,z) is the irradiance measured at radial distance (r) from the axis of the beam axial distance (z) from the focus of the beam, P is the total emitted power of the point source, and w(z) is the area of the beam at axial distance z. Based on the measurement of I(r,z) on axis at a distance of 30 metres, the power of the beam was calculated to be 15.9 Watts.

Discussion

The measured FWHM beam width of 8.12 degrees and beam optical power of 15.9 Watts are within expectations for the LED design. The measured 8.12 degree beam width compares closely to the 7.5 degree beam width that would be expected based on the datasheet for the Ledil lens assembly.[11] This discrepancy may be in part due to treating the array as a point source despite only being 30 metres away from the light source.

The measured beam optical power of 15.9 Watts is slightly lower than might have been hoped for given the 178.6 Watt electrical power consumption of the LED array, and yields an overall electric power to optical power efficiency of slightly under 10 percent. It should be noted that the power consumption does include losses in the current limiting resistors and that with a more sophisticated constant current LED driver circuit, the overall system efficiency could be increased.

FIELD TESTING

Methodology

To demonstrate the viability of the LED array, the prototype was deployed at Wallace Astrophysical Observatory in Westford, Massachusetts on May 16, 2017. At roughly 0300 hours, the orbiting CubeSat passed over head and collected images of eastern Massachusetts.

In preparation for the overpass, the AVX mount was first aligned with the use of a 6-inch telescope using the two-star alignment procedure. The telescope was then removed and the LED beacon was installed. The Satellite Tracker software package running on a laptop computer was given the TLE for the AeroCube-5 CubeSat as computed based on a series of GPS fixes taken in the preceding days. At the beginning of the pass the LED array was powered on an began tracking the CubeSat when the satellite was approximately 10 degrees above the horizon.

During the 7 minute pass, the LED array was cycled on and off with a period of about 20 seconds and a duty cycle of 50 percent, which is twice the maximum repetition rate of the imager onboard the CubeSat. During this time, several images were taken with an elevation angle of 54 degrees for the first image, rising to 78 degrees for the final image in the series.

An image of the operational LED array during the pass can be seen in figure 2.

Figure 2: The operational LED array beacon at Wallace Astrophysical Observatory on the morning of May 16, 2017

Results

A source of green light was clearly visible in several images taken by the orbiting CubeSat. Of the series of 5 usable images downlinked by the CubeSat, images 1, 3, and 5 in the series show a green spot at the location of the Wallace Astrophysical Observatory. Two of the received images (cropped to show just the Boston metropolitan area) are shown as Figure 3(a) and Figure 3(b). In Figure 3(a), the test site is highlighted by the green square. The nearby cities of Boston and Worcester are also highlighted to assist in geolocating the image. In the area of the test site, there is no visible light, either green or otherwise. In Figure 3(b), taken roughly 10 seconds later, a green spot is present at the test site. Figure 4 is cropped specifically to the area of the test site to make the color of the spot clearer.

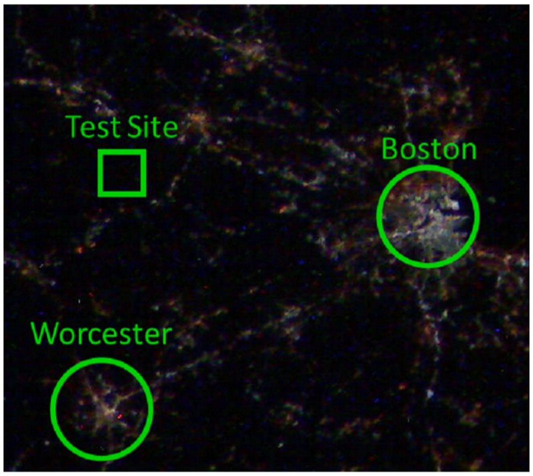

Figure 3(a): Image from AeroCube-5 showing the cities of Boston and Worcester (circled) and the test site (in a square). In this image, the beacon is off.

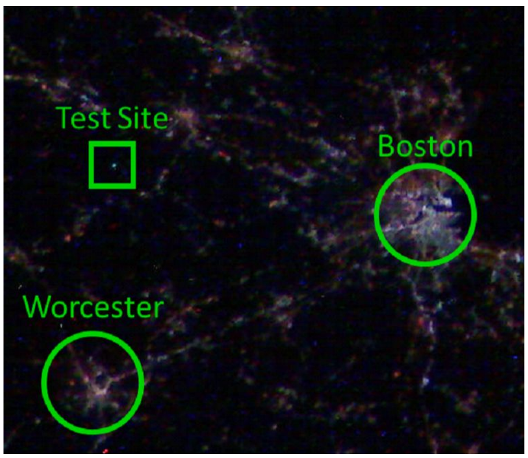

Figure 3(b): Image from AeroCube-5 showing the cities of Boston and Worcester (circled) and the test site (in a square). In this image, the beacon is on.

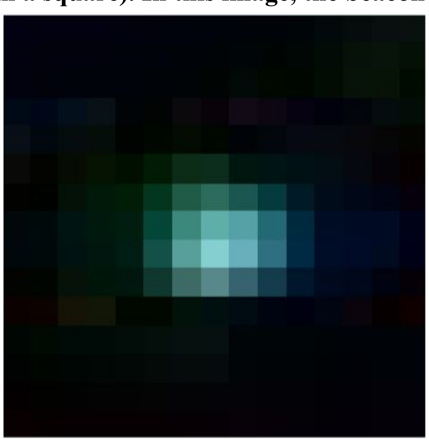

Figure 4: A cropped image of the test site from figure 3(b) showing the green color of the beacon

Discussion

The green spot evident at the test site in several of the images can be identified as the LED beacon with a fair degree of confidence. Positive identification of the light source seen at the test site is helped by the location of the spot (in a generally very dark area), the color of the spot (green consistent with the LEDs used in the beacon, and inconsistent with most other forms of artificial lighting), and the on-off period of the light source.

Unfortunately, little else other than its source can be determined about the green spot. The imager on the AeroCube-5 was not intended to make photometric measurements, and as a result the image can not be used to make a reasonable measurement of received optical power. The exposure time of the imager on the CubeSat is not the same for all images taken, and not recorded in any metadata associated with the image. Additionally, the CubeSat only downlinks a compressed JPEG image and not a raw Bitmap file, so even pixel to pixel comparisons against objects of relatively well known brightness will not yield the quantities of interest.

CONCLUSIONS AND FUTURE WORK

This project has demonstrated the viability of using a non-coherent LED array as a beacon to assist spacecraft in LEO in identifying a site on the ground, but much work remains before the beacon can be used in an operational optical communications system. There are several improvements that should be made the on-the-ground portion of this demonstration, as well as improvements to the on-orbit portion of the demonstration before the risk associated with using a an LED array as part of an optical communications pointing system can be retired completely.

With regard to the beacon itself, both the total beam power and efficiency can be improved with several design changes including the use of more efficient LEDs and the use a constant current circuit on each PCB instead of a current-limiting resistor. Additionally, it might be worthwhile to look into other wavelengths of LEDs. Blue LEDs are one possibility due to their generally higher efficiency compared to green LEDs

Another option is to switch to near-infrared light. Near-infrared can have acceptable quantum efficiencies even with low cost silicon image sensors while having the advantage of being invisible to the unaided human eyes, reducing the chance that operation of the beacon might distract pilots flying overhead. However, this does increase the risk to the builder and tester of the LED beacon array, of unintentional exposure to high optical power.

Future improvements to the receiving optical system include the use of a larger optical aperture to enable more light to be collected, an image sensor with a deterministic exposure time, and a way of taking more precise photometric measurements. Additionally, if possible, it might be ideal to incorporate a quadcell, beam-splitter, low power CW laser diode, and fine steering mirror onboard the CubeSat, which would enable the demonstration satellite to test not only acquiring the beacon, but also directing a free-space optical beam back to the ground in real time.

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REFERENCES

1. Emily Clements, Raichelle Aniceto, Derek Barnes, David Caplan, James Clark, Inigo del Portillo, Christian Haughwout, Maxim Khatsenko, Ryan Kingsbury, Myron Lee, Rachel Morgan, Jonathan Twichell, Kathleen Riesing, Hyosang Yoon, Caleb Ziegler, and Kerri Cahoy. Nanosatellite Optical Downlink Experiment: Design, Simulation, and Prototyping. SPIE Optical Engineering, 2016.

2. Ryan Kingsbury. Optical Communications for Small Satellites. PhD thesis, Massachusetts Institute of Technology, 2015.

3. N. Perlot, M. Knapek, D. Giggenbach, J. Horwath, M. Brechtelsbauer, Y. Takayama, and T. Jono. Results of the optical downlink experiment KIODO from OICETS satellite to optical ground station Oberpfaffenhofen (OGS-OP). In Lasers and Applications in Science and Engineering, volume 6457, pages 645704–645704–8, 2007.

4. Clements, E. et al. "Integration and Testing of the Nanosatellite Optical Downlink Experiment," USU CubeSat Summer Workshop 2017

5. Siegfried Janson, Richard Welle, Todd Rose, Darren Rowen, Brian Hardy, Richard Dolphus, Patrick Doyle, Addison Faler, David Chien, Andrew Chin, Geoffrey Maul, Chris Coffman, Stephen La Lumondiere, Nicolette Werner, and David Hinkley. The NASA Optical Communication and Sensor Demonstration Program: Initial Flight Results. 2016.

6. R. P. Welle et al., "CubeSat-scale laser communications," 31st Space Symposium., Colorado Springs (2015).

7. Robert Lafon, Janet Wu,and Bernie Edwards. Regulatory Considerations: Laser Safety and the Emerging Technology of Laser Communication. In Commercial Laser Communications Interoperability & Regulatory Workshop. GSFC, JPL, 2017.

8. Cree XLamp XP-E2 LEDs Product Family Data Sheet. Technical report, Cree, 2017.

9. ColorReach Powercore Gen2 Product Guide. Technical report, Philips, 2008.

10. MT9P031, 1/2.5-Inch 5 Mp CMOS Digital Image Sensor. Technical report, ON Semiconductor, 2017.

11. Ledil Leila Product Family Data Sheet. Updated 10/4/2014

12. Dee W. Pack and Brian S. Hardy. SSC16-WK-44 CubeSat Nighttime Lights. In 30th Annual AIAA/USU Conference on Small Satellites, 2016.

13. Tam Nguyen. Laser Beacon Tracking for Free-space Optical Communication on Small-Satellite Platforms in Low-Earth Orbit. PhD thesis, Massachusetts Institute of Technology, 2015.

14. Sam Dolinar, Bruce Moision, and Baris Erkmen. Fundamentals of Free-Space Optical Communication. In Keck Institute for Space Studies (KISS) Workshop on Quantum Communication, Sensing and Measurement in Space, 2012.

15. Christopher C.M. Kyba, Stefanie Garz, Helga Kuechly, Alejandro Sanchez de Miguel, Jaime Zamorano, Jurgen Fischer, and Franz Holker. High-resolution imagery of earth at night: New sources, opportunities and challenges. Remote Sensing, 7(1):1–23, 2015.

16. Larry McNish and Darwin Teague. Satellite Tracker User Manual Version 0.0.8. Technical report, 2009.

17. Scarlet Koller, Marissa Ruiz, and Prof Kerri Cahoy. Accurate Tracking of the International Space Station Using Low-Cost COTS Equipment. Technical report, Massachusetts Institute of Technology, 2016.