

CubeSat LED Transmitter for Optical Communication Downlink

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ABSTRACT

The CubeSat radio frequency (RF) spectrum licensing step has always been long and therefore stressful to developers. With more satellites entering orbit, spectral congestion in the available RF frequency bands has become a problem. An optical-only solution eliminates this problem and provides a path for a lower power and higher throughput data link. The risks of weather outages drive a solution that requires enough geographically diverse optical ground locations that a clear line-of-sight is always available. The Aerospace Corporation, with funding from NASA, has developed a CubeSat light emitting diode (LED) transmitter and an inexpensive commercial portable optical telescope to demonstrate an efficient, low-cost solution for low-data rate space-to-ground links. An LED was chosen over a laser because it is simpler, has a lower cost, has fewer safety considerations, and is more robust. It has a significantly wider beamwidth than a laser, which makes the link extremely tolerant of satellite pointing errors, but it will still be providing data rates equivalent to S-band radios.

The LED transmitter weighs 86 grams, has a 70 cm diameter circular footprint, and a height of 2.3 cm. It is comprised of two independent LED channels, both at 617 nm. The first channel is a beacon with a modulation rate of 10 Kbps and a beamwidth of 120 degrees. The second channel is a comm beam with a data rate of 1 Mbps and a beamwidth of 2.5 degrees. The optical ground terminal (OGT) is based on a commercial 28 cm diameter F/2.2 telescope that is pointed by a commercial motorized mount on a portable tripod. A stellar alignment calibration is performed at the chosen location site and commanded remotely to track an object using a two-line element (TLE) input. The ground terminal's ability to track a low-earth orbit (LEO) satellite was initially demonstrated with the International Space Station. The LED transmitter was environmentally tested to TRL 6 and is ready for a flight demonstration and may be funded by NASA's R5 CubeSat program.

INTRODUCTION

An all-optical communication path between a satellite and an earth-bound telescope is attractive. With more satellites entering orbit, spectral congestion in the available RF^{oo} frequency bands has become a problem. An optical-only solution eliminates this problem and provides a path for a lower power and higher throughput data link. Current lasercom solutions are expensive subsystems for a small satellite both in subsystem cost and in the increased satellite performance to utilize it. Furthermore, the OGT is not a common or low-cost element and due to weather, an "every day" optical downlink requires several OGT in different locations. Purchased-service OGT networks do not currently exist.

Most of the cost and complexity of the existing optical communication solutions for spacecraft is due to factors that enable their high performance. Existing through-space optical communication systems rely on lasers with a very narrow beamwidth to achieve very high data rates. Simple CubeSat lasercom downlinks without an uplink beacon have been demonstrated at 200 Mbps¹. To accommodate these data rates, the ground-based detector has a very small active area, limiting the ground terminal to a very small field of view, typically around 1 milliradian. The errors in the TLE and the mount model are large in comparison to the field of view and therefore scanning is required to acquire the satellite. Because the ground-based telescope has a narrow field-of-view, it is necessary that it is carefully anchored to the earth at a

facility that must be constructed for this purpose, which is a significant investment.

Very good engineering has been applied to reduce the size of optical terminals for the space segment. The OSIRIS4CubeSat LCT (1/3U size, 395 grams)² and the Clyde Space CubeCAT (1U volume, 1.2 kg)³ are two examples of a bi-directional lasercom terminal small enough for a CubeSat. The ground segment diversity and cost are impeding missions that would use these terminals. Perhaps noting this, MIT demonstrated and patented a portable optical ground solution based on an amateur commercial telescope.^{4,5} This reduces cost and facilitates geographic diversity. However, both the space and ground segments mentioned retain the complexity in managing a narrow optical beam on the downlink.

Therefore, there is room in the satellite optical communication domain for a solution at S-band data rates that can be realized for a lower cost. To explore this optical communication performance space, NASA, in partnership with The Aerospace Corporation (Aerospace) has created the Compact Optical Method for Long-range, Inexpensive Network Communication (COMLINC) project. Its goal is a low-cost, all-optical solution for uplink and downlink to replace RF modems. This paper will discuss the development of a COMLINC transmitter that will achieve 1 Mbps optical data transfer. Also, presented will be a description of and test data from the COMLINC OGT that has been constructed to receive that signal. A COMLINC LED transmitter has been built and tested to TRL6. Due to a limited optical link budget, its data rate has been limited to 100 Kbps. It will fly on a NASA R5 CubeSat mission slated for July 2026.

Precursor

Blinker was a combined GPS receiver and LED transmitter experiment that flew in 2022-2024 on The Aerospace Corporation Slingshot satellite. It was one of many payloads integrated onto a 12U Blue Canyon satellite bus that was launched July 2022 into a 500 km x 45 deg orbit and reentered in September 2024.⁶ Blinker was named because of the LEDs it blinked for the purpose of satellite identification.⁷ The LEDs were banks of three Inolux IN-C33CTLR (617 nm) and IN-C33CTLG (525 nm) devices (Figure 1). Each bank was monochromatic, independent, and three diodes comprising a bank were necessary for sufficient brightness. Each bank was driven with 0.7A of current and each produced the same radiant power but at different efficiencies: the green bank required 7.8 W and the red 6.0 W. The divergence of the light from both red and green LEDs was 120 degrees full-width, half-maximum.

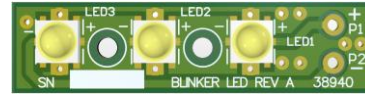


Figure 1: A Blinker LED bank assembly

The Blinker LEDs were observed by The Sapienza Space Systems and Space Surveillance Laboratory (S5Lab) in Italy several times throughout 2023.⁸ Figure 2 is video stills from the Sept 15, 2023 collect. Blinker repeatedly alternated between the color banks as such: 1.25 second ON Green, 1.25 seconds OFF, 1.25 seconds on RED, 1.25 seconds OFF. The stars in the image are the streaks, and the LEDs on the Slingshot satellite, which is being tracked open loop, are the dot in the red circle. Notably, the green LED (left) appears brighter than the red (right) despite the same radiant power output from each color.

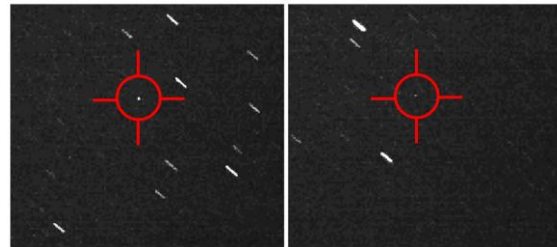


Figure 2: Video stills of Blinker: (Left) green diode bank is ON and (right) red diode bank is ON

The S5Lab CCD camera captured the Blinker LED light with a 0.4-meter diameter telescope with a CCD camera and no filters. The intensity of the camera pixels is plotted in Figure 3, and it is overlaid with a plot of the current supplied by the Blinker 5V switch powering the LED drivers. It is known that the green LED requires more electrical input power for the same radiant output power, so the higher currents correspond to light emission from the green LED bank. Both the S5Lab CCD camera data and the Blinker current telemetry have time stamps that correlate them.

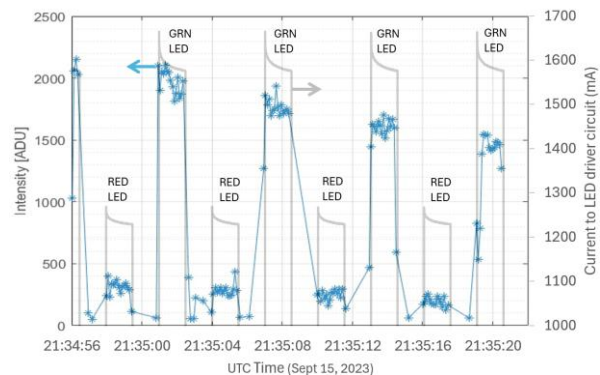


Figure 3: Raw counts from the CCD camera (blue) and time-correlated Blinker telemetry (gray)

The CCD camera arbitrary data units (ADU) in Figure 3 were calibrated with stars, and the apparent magnitude of the Blinker red and green LEDs are plotted in Figure 4. This is a useful comparison of the visibility of the COMLINC transmitter relative to other celestial objects. However, it is the radiant power that will inform the link budget.

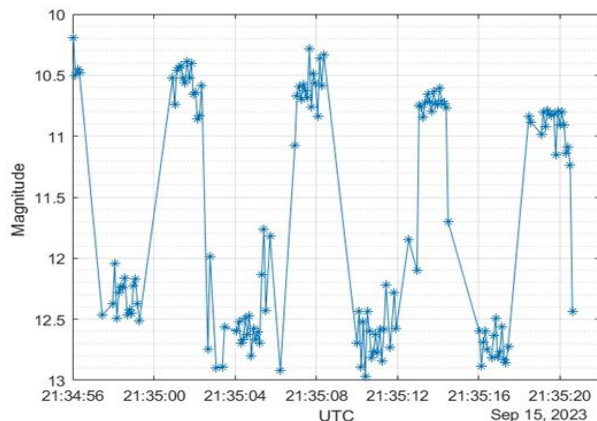


Figure 4: The conversion by S5Lab to an apparent stellar magnitude

The successful observation of such a small optical power inspired confidence in the idea of collimating the LED power to achieve an optical communications link. It was expected that the intensities would be closer in value and it has not yet been determined why they are not. The red LED was chosen for the first COMLINC demonstration because of its higher efficiency. However, changing the LED color is simple if they are from the same LED product family.

The Blinker demonstration on Slingshot provided more value than just a direct comparison of two colors through the atmosphere. In nine months, albeit with a modest effort, less than half-a-dozen successful collections occurred but there were two-dozen attempts. Reviewing this success rate, several operational realities became evident, and these are listed in Table 1. Understanding them and making changes will be a step towards realizing simple and reliable optical space-to-ground communication. Items 1 and 2 are factors controlled by nature and are solved with geographic diversity. Item 3a is improved by automation and item 4 is fixed by a standing rule on the satellite to attempt every optical ground station overpass. Item 3b, maintenance, if planned would be scheduled around the communication pass schedule but it may be unplanned due to a part failure.

Table 1. Operational realities made evident by Blinker observation attempts

1	The transit had to occur with the satellite in eclipse.
2	The transit had to occur when the weather was favorable over the S5Lab facility.
3	The transit had to occur when both Slingshot and S5Lab were available, where availability can be further broken down:
	a) operational times too late in the early morning were undesirable for the collection team
	b) sometimes the ground receiver was not available due to maintenance;
	c) sometimes the satellite was in safe mode and was offline until the fault was cleared.
4	There was on average a 1-day delay between when the satellite command schedule for and LED observation event was uploaded, and another 1-day delay before telemetry was downloaded to confirm that the satellite was pointed correctly and that the LED fired via timestamped LED drive current history.

TRANSMITTER DESIGN

The COMLINC transmitter has two separate LED circuits. They are for different purposes. The first is a spot beam. (Figure 5, left). It is a single LED with a large collimating optic. It will collect and collimate as much of the incoherent light as possible into the narrowest beamwidth. It will be the “high speed” data channel. The second is a beacon beam (Figure 5, right). The beacon has the same radiant intensity as one LED bank on Slingshot. It consists of three LEDs in series, each with a 120° beamwidth so that if the satellite is not pointing, the light will cover the hemisphere. It is a “low speed” data channel.

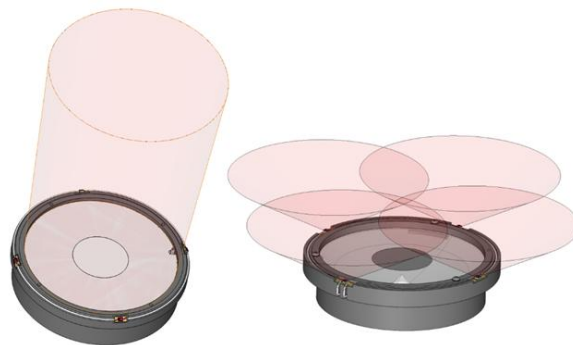


Figure 5: COMLINC optical modes: spot beam (left), and beacon (right)

The spot beam and the beacon can transmit data, and both have an adjustable baud rate. The spot beam modulation speeds range from 0.1 Mbps to 10 Mbps. The

beacon modulation range is from 0.1 Kbps to 10 Kbps. Drive circuits were designed to cover these ranges and thereby provide flexibility to the mission operators who could change the downlink baud rate at any time in the mission to reflect the realities of the link budget parameters.

The digital control of the COMLINC transmitter resides in a field programmable gate array (FPGA). Its function is to receive data from the satellite, encode it, and modulate the selected LED drive circuit. For link characterization, the FPGA can generate a pseudo-random bit sequence (PRBS). It passes through satellite I/O so that both the beacon and spot beams can be strobed at very slow rates like how Blinker was operated.

The physical structure of the COMLINC transmitter requires effective heat management of the LEDs, simple assembly, small size, and convenient mounting options. Figure 6 illustrates two ways to mount a COMLINC onto a 1U CubeSat, as a space-limited example. In the left figure the COMLINC is flush to the exterior of the satellite with screws from inside the satellite picking up the flange to secure it and heat sinking to the panel. In the right figure, the exterior bottom of COMLINC is mounted against the satellite panel with screws also coming from the inside and heating sinking also occurring through this interface. The right figure requires that the CubeSat can access what is called the “Tuna Can” volume within a dispenser, which is typically 8 cm in diameter and 4 cm deep.

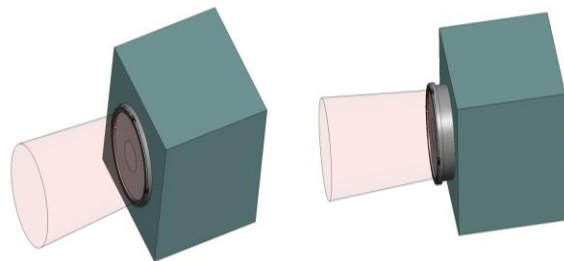


Figure 6: COMLINC on a 1U CubeSat: (left) recessed and (right) within the “Tuna Can” volume

LED Driver

The COMLINC transmitter uses direct modulation of the drive current, or On/Off keying (OOK), to an electro-optical device to send optical data. A drive circuit (Figure 7) was designed around three primary components: a high-speed GaN laser driver functioning as a low-side switch for rapid on/off control, a current sensor that monitors current, and a DC-DC converter that regulates current output based on sensor feedback to maintain the desired optical brightness.

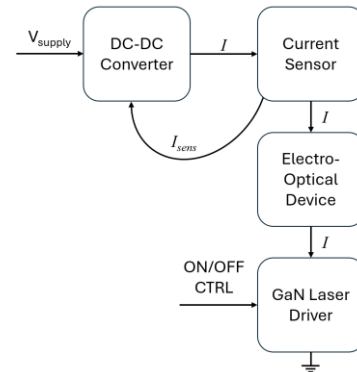


Figure 7: LED modulation circuit block diagram

The COMLINC electro-optical device is driven at a maximum data rate of 10 Mbps. Two device technologies were tried. The primary choice was a 7 W, multimode, pigtailed diode laser, QSP-1064-7. Its size and power were desirable, and it is packaged with a fiber pigtail that can be spliced to a pigtailed fixed divergence collimator. Figure 8 is the result of a 10 Mbps PRBS applied to it through the drive circuit. The blue waveform is the commanded input, the red waveform is the current drive input to the diode, which reflects its impedance. The diode laser was biased, and modulation did not drop below its threshold. The yellow waveform is the resulting OSRAM BPX 61 silicon PIN photodiode response to the diode laser light output. This diode laser has a transfer function between the current into it and the light out that prevents the clarity of “1” and “0” and is therefore not suitable for data transmission.

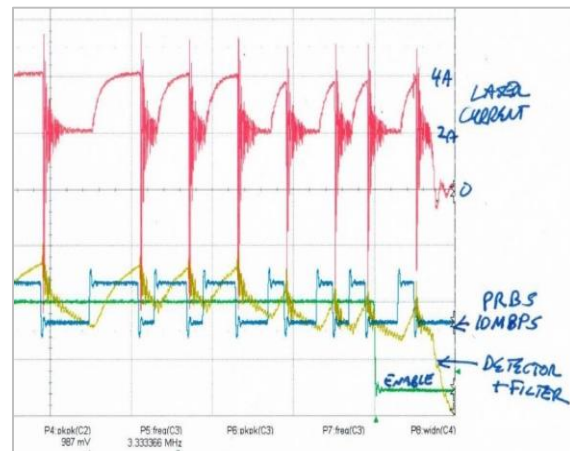


Figure 8: Diode laser modulation at 10 Mbps

The same 10 Mbps PRBS is applied to an LED, and the result is very different. In Figure 9, the blue waveform is the commanded input, the red waveform is the current drive input to the LED. The LED modulation is from 0 A for a “0” to 0.5 A for a “1.” The yellow waveform is the resulting silicon PIN photodiode response to the LED light output, and this is usable. For this reason and

because LEDs are available that output more than 1 Watt of radiant power, this electro-optical device technology was selected as a source and proceeded to the next problem of collimating the incoherent LED light.

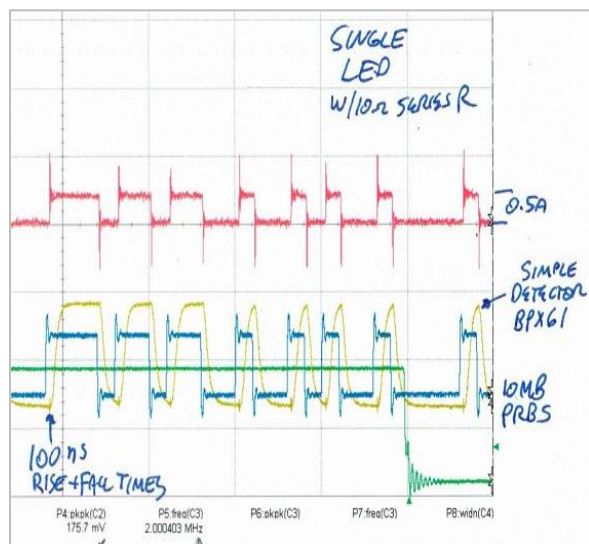


Figure 9: LED modulation at 10 Mbps

Spot Beam Optic

The COMLINC spot beam is a single high-power LED focused to achieve the best collimation. The lens diameter limits the amount of collimation. To bound its size, it was decided that COMLINC would be compatible with a 1U CubeSat and fit onto a 100 x 100 mm face. First, a survey of commercial lenses was done. To collimate the LED light to the smallest angle, a “narrow beam” lens is required. The 60 mm diameter Carclo 10158 commercial lens was selected. Carclo has used it to collimate LEDs from many manufacturers and posted the results.⁹ To check that result, the OSRAM LED with the Carclo lens was modeled. After that, a more efficient custom lens was created.

LEDs are difficult to collimate because they output incoherent light from an “extended source.” Incoherent light departs the emitting surface in all directions, drastically reducing the collection efficiency of a lens. The extended emission source increases the divergence angle because there is not a single focal point. Notably, in contrast, diode lasers have emitter areas that are 1000 times smaller than LEDs and the light that is emitted has much less divergence which makes the collimating lens smaller and more efficient. For this reason, modulating a diode laser was attempted first.

When selecting an LED, the emitter area was traded with LED current density. Collimating a small active area is more effective than a larger one. However, to get more

light from an LED, a larger emitter area is better. An LED with an emitting area of 0.75 mm x 0.75 mm was considered, but the 1 mm emitter OSRAM KR CSLNM1.23 was chosen because it could be driven with more current and therefore provide more light, even when collimated with less efficiency. It is expected that future LEDs will have even more brightness and power density, with the market driven by consumer items like landscape lighting, automobile headlights, and controlled environment agriculture.

The Carclo 10158 lens with the OSRAM LED was modeled. The model assumed 1 W of light output, with a finite Lambertian light profile, from a 1 mm x 1 mm emitter that was then collected and collimated by the lens. As shown in Figure 10, many rays from the LED escape collimation, which reduces the lens efficiency. In Figure 11, the estimated irradiance peak is 153 $\mu\text{W}/\text{cm}^2$ at a range of 10 meters and the one-half full maximum beamwidth, shown in Figure 12, is 2.5 degrees.

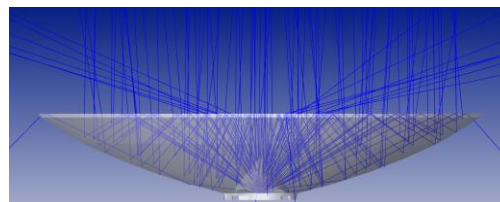


Figure 10: Carclo 10158 raytrace

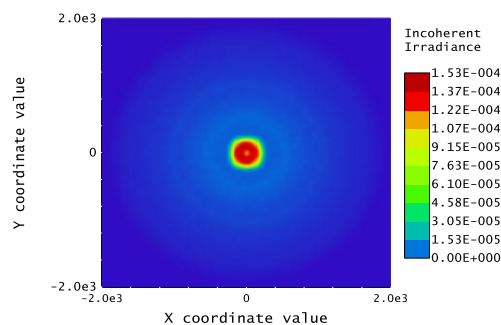


Figure 11: Carclo 10158 irradiance (W/cm^2)

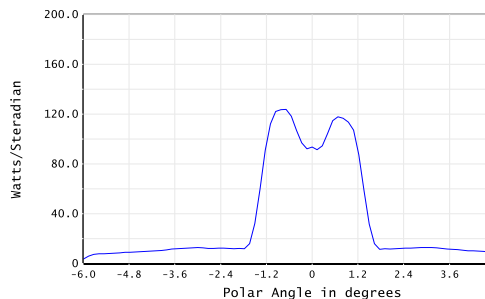


Figure 12: Carclo 10158 radiant intensity

Additionally, two custom lenses were designed for the 1 mm x 1 mm OSRAM emitter. The “Pentico 60,” named after its designer, Clark Pentico, is a 60 mm diameter catadioptric lens. It has better performance than the Carclo 10158, however, it is thicker and therefore heavier. The source modeling assumptions were the same. The rays from the LED collimate better (Figure 13) and the estimated irradiance peak is $600 \mu\text{W}/\text{cm}^2$ at a range of 10 meters (Figure 14) and the beamwidth is 1.6 degrees full-width half-maximum (Figure 15). The custom lens 60 mm diameter was chosen to allow the COMLINC transmitter to fit into the “Tuna Can.” However, if more brightness is needed, that requirement may be dropped. For that eventuality, the Pentico 90, a 90 mm diameter catadioptric lens was designed. Graphics of its performance are not shown here but its specifications are listed in tables forthcoming.

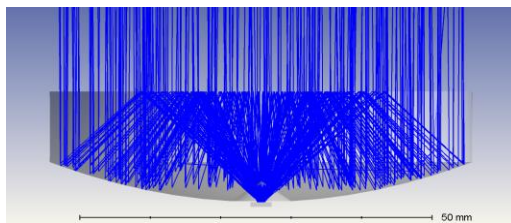


Figure 13: Pentico 60 raytrace

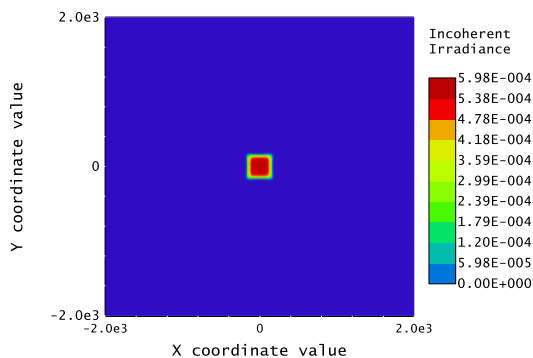


Figure 14: Pentico 60 irradiance (W/cm^2)

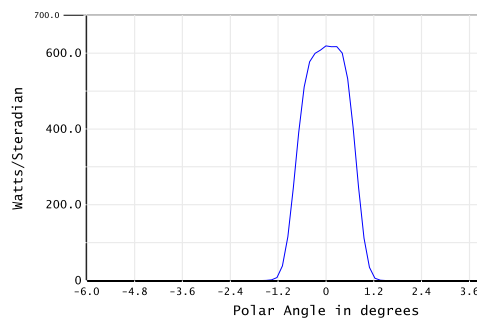


Figure 15: Pentico 60 radiant intensity

Table 1 is a summary of the three lenses considered for the COMLINC transmitter. The Pentico 60 is predicted to be five times more effective than the Carclo 10158. However, as will be presented in the measurement section, the improvement was only by a factor of two. The reason for this was not immediately apparent and it will be investigated in the next phase of the project. Notably, the Pentico 60 cost is 20 times more than the Carclo and its weight is 3 times greater. A gain in performance of a factor of five though is too important to ignore, so it will be investigated.

Table 1. Spot beam collimating lens performance predictions

Lens	LED light captured in 1.5 degrees full width	LED peak radiant intensity
	Percent	W/sr
Carclo 10158	8	120
Pentico 60	28.5	600
Pentico 90	64.1	1600

Link Budget

Aerospace has a history with laser communication from CubeSats, starting with the NASA-sponsored OCSD mission.¹ The OCSD laser transmitter is a very capable device, with 1 milliradian of beam divergence and 2 W of power after the lens. The wavelength is 1064 nm. Since the OCSD mission, Aerospace has added laser transmitters to most of its AeroCube satellites and is building an automated optical ground station network to support them.

A performance comparison between laser and LED transmitters is evident in the link budgets (Tables 2 and 3). The laser communication budget has significant data rate and link margin. It uses a 40 cm telescope in its ground segment. The detector used is a 0.1 mm avalanche photo diode (APD) to meet the high data rates. There is a significant pointing loss term because the beam is narrow and furthermore the ground telescope field of view is small because of the size of the detector and focal length of the telescope. There are a few uncertainties in this link budget because it has been demonstrated for several years.

Table 2. Optical link budget for a typical Aerospace AeroCube lasercom link

System Params (AeroCube)			Link Parameters		
Parameter	Value	Units	Parameter	Value	Units
λ	1064	nm			
Tx power	2	W	Tx power	33	dBm
$\theta_{div} (2 \times 1/e^2)$	1.7	mrاد	Pointing loss	-3	dB
Range	750	km	Atm loss	-1	dB
Rx aperture	0.4	m	Rx loss	-2	dB
Detector sensitivity	220	ph/bit	Power at detector	-40	dBm
BER 1×10^{-3}				1323	ph/bit
Baud rate	400	Mbps	Margin	7.8	dB

Table 3. Optical link budget for a COMLINC LED transmitter using a Carclo 10158 lens

System Params (Carclo 10158)			Link Parameters		
Parameter	Value	Units	Parameter	Value	Units
λ	615	nm			
Tx radiant intensity	97	W/sr	Tx radiant intensity	20	dBW/sr
			Pointing loss	0	dB
Range	600	km	Atm loss	-2	dB
Rx aperture	0.28	m	Rx loss	-1	dB
			sr_{Rx} at range	-128	dBsr
Detector sensitivity	6	pW	Power at detector	-81	dBm
BER 1×10^{-3}	186	ph/bit		258	ph/bit
Baud rate	0.1	Mbps	Margin	1.4	dB

The COMLINC optical link budget margin is minimal, mostly because of its broad beam and the low efficiency with which the lens captures the broad light pattern. In addition, program management decisions specific to the first flight test have further reduced the margin. For example, 3 dB of margin is lost by selecting the off-the-shelf Carclo 10158 collimating lens instead of a custom Pentico 60 lens. The Carclo configuration was required to meet a volume constraint imposed by the host R5 CubeSat vehicle. Another 3 dB of margin is lost by receiving with the 28 cm portable COMLINC ground telescope instead of 40 cm telescope in a fixed facility at Aerospace. This decision supports a demonstration of the portable, low-cost optical downlink ground station.

To compensate for a 6 dB link margin loss due to programmatic decisions, COMLINC will reduce its capability from the goal specifications. First, the data rate is reduced from 1 Mbps to 100 Kbps to gain back 10 dB. Second, the spacecraft must point with ± 0.5 -degree accuracy. Because the LED power does not change over this angle, this effectively adds 3 dB, which is the typical full-width half-maximum pointing loss entry in the link budget. Third, the maximum range must be reduced to 600 km. A common rideshare orbit is 500 km circular altitude. So, there will be occasions when the satellite is within range. Future missions will improve the link budget to extend range and increase the data rate.

Key link budget parameters are listed in table 4 and link margin increase or decrease of the COMLINC compared to The Aerospace Corporation AeroCube lasercom are shown in the far-right column. The terms with the largest magnitude are understandably the data rate and divergence. However, it was surprising to see the magnitude of difference in the collimating lens efficiency. The output of the lasercom optical fiber into a collimation optic is much narrower and the lens efficiency is high. Alternatively, the LED light is a Lambertian distribution with significant optical power at extreme angles of incidence on the collimating lens. The catadioptric lens design is necessary for any reasonable light collection efficiency. Also, a larger lens diameter and thickness help: the Pentico 60 and Pentico 90 custom lenses improve the lens efficiency from 8% to 28% and 69%, respectively.

Table 4. Optical link budget parameter study

		AeroCube lasercom	Carclo 10158 COMLINC	dB
Data rate	Mbps	400	0.1	+36.0
TX power	W	2	1	-3.0
Wavelength	nm	1064	615	-3
Pointing error		-3	0	+3
Collimator efficiency		0.95	0.08	-10.7
Divergence	mrاد	1.7	41	-27.6
Tel. aperture	cm	40	28	-3.1

Ground Segment Optical Detector

The COMLINC detector requires excellent low light sensitivity. As has been discussed, collimating an LED is not efficient and the collimated beamwidth is at least 20 times wider than the usual lasercom. The loss of optical power is compensated for by a lower data rate,

less than 10 Mbps, and a more sensitive detector. Surveying optical communication uses, it was found that underwater free-space optical links exist.¹⁰ In that application, a photomultiplier tube (PMT) has been used for its superior sensitivity and large active area, relative to alternative detector technologies. The COMLINC LED optical communication link is equally challenged, and work done on this detection method is useful.

Two low light detectors were tested when developing the COMLINC link budget. The Hamamatsu H14951 PMT module and the Hamamatsu C14455 multi-channel charge plate (MCCP). The PMT is a current output and therefore a C9999 transimpedance creates a voltage without sacrificing bandwidth. The size of each is shown in Figure 16 next to a US quarter. The H14951 module may not be optimized for this application. Inside is a high voltage source so that only +5V is supplied to it, but it does not have a thermoelectric cooler (TEC) to reduce its dark current. The bandwidth is greater than 10 MHz and the small packaging is ideal. It has a detector area that is 8mm in diameter, which increases the field-of-view of the OGS. The C14455 is a different technology but a little more sensitive, probably helped by a TEC inside. It is larger, so it will block more of the telescope aperture. Unfortunately, its bandwidth is only 2 MHz, and the detector size is only 3 mm in diameter. In a later section, the two detectors are directly compared at 1 Mbps.



Figure 16: Two Hamamatsu detectors and a transimpedance amplifier

IMPLEMENTATION

Mechanical Packaging

The COMLINC transmitter structure is a single aluminum cup shape (Figure 17). The circuit board with the drive circuitry and spot LED sits on the floor of the cup and the collimating lens fits into the bore. The cup has a flange on which the three beacon LEDs are spaced

evenly, and it has six 2-56 tapped holes that can be used to mount the unit to the host. The mass of the cup is a heat sink for both the beacon LEDs and the spot LED.

The collimating lens fits the inner diameter of the structure with only 0.002" of clearance. When installing it and focusing it over the spot LED, there is no lateral adjustment. Therefore, the alignment error is a sum of these errors: LED to the PCB; PCB centered in the structure; concentricity of the outer diameter of lens and its focal point. These lateral position errors will reduce the performance of the collimating lens relative to the optical models. In the focus direction, three screws thread through the base of the structure and push the lens away from the spot LED. Then three screws thread from the flange towards the lens and secure it against those prior three. The lens is bonded in place with Scotch-Weld 2216 in six places evenly spaced. Those locations are not just on the surface but run down the piston surface of the lens via scallops in the housing. This allows the adhesive to engage the piston surface of the lens to stop lateral motion and to increase contact area.

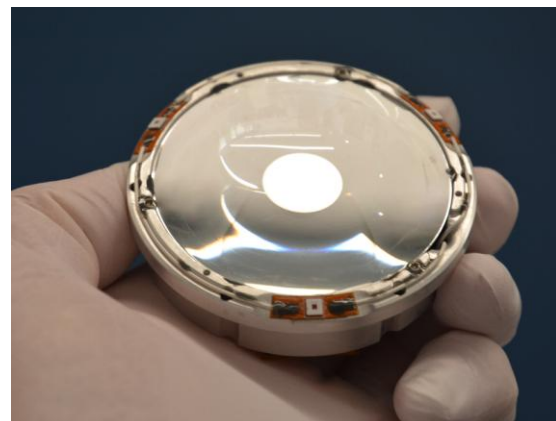


Figure 17: Outward face of the COMLINC transmitter assembly

The COMLINC electronics were broken into two parts for reasons of time and cost. The LED drive electronics for the spot beam and the beacon reside on a custom round-shaped printed wire board (PWB) that is constructed from FR4 material 0.060" thick. It mounts to the inside floor of the housing. The FR4 material and the thickness were a requirement of the PWB fabricator for low-cost and rapid delivery. The low-cost approach is a critical success criterion for this transmitter (and system at large). The thick FR4 does not support the design goal of a low resistance thermal path for the Spot LED to remove its heat. To solve this problem, a pocket was bored to within 0.010 inches of the top surface LED heat sink pad. A copper slug was bonded into the pocket and bonded in place with silver-filled epoxy. Figure 18 is the assembly curing in an oven. The screw just being used

as weight. This copper slug is bonded to the floor of the housing, completing a low-resistance thermal path.

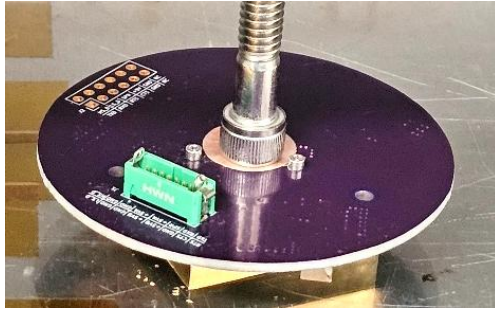


Figure 18: Driver PWB in oven to bond the copper slug into the counterbore

The second electronic circuit is the FPGA that formats digital data for optical transmission. For simplicity, the FPGA is implemented in a COTS module that can be easily procured and is immediately functional. It is appended to the custom drive circuit via a header through the structure (Figure 19). This was cost-effective and improved schedule, but it is mechanically awkward. Future work could implement the FPGA onto the driver circuit board and eliminate the external module, but it will wait until after a successful COMLINC demonstration.

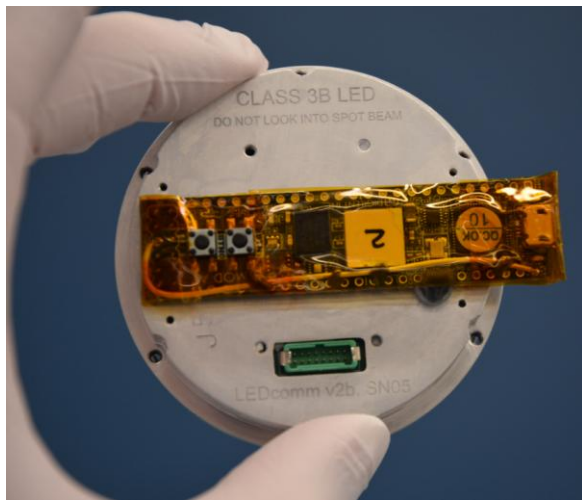


Figure 19: Inward face of the COMLINC transmitter assembly

Electrical Interface

A single harness (G125-FC11605L0-0150L) transfers spacecraft data, power, and I/O to the COMLINC transmitter (Table 5). The COMLINC beacon LEDs and a spot beam LED are controlled independently. They can be operated at the same time if the power and thermal budgets allow it. The drive circuits for the beacon and spot both can transmit data at different rates. They were

designed for an operating range so that the data rate can be selected to support link conditions. The beacon LEDs can transmit at 0.1-10 Kbps and the spot at 0.1-10 Mbps. But the link budget for this first mission will require the spot beam to transmit at its lowest rate of 0.1 Mbps.

Table 5. Wiring harness pinout between spacecraft and COMLINC

Pin	Name	Pin	Name
1	DATA_beacon	9	DATA_spot
2	GND	10	GND
3	GND	11	GND
4	+5V_beacon	12	+5V_spot
5	+5V_beacon	13	+5V_spot
6	GND	14	SPARE
7	UART_CTS	15	UART_RXD
8	UART_CTS	16	UART_TXD

Figure 20 is the ground operating configuration. A computer running a terminal emulator hosts command and packetizing software that formats data into 8-bit Universal Asynchronous Receiver-Transmitter (UART) frames and sends them to the COMLINC FPGA. The FPGA unpacks the data from the UART frames and repacks it into High-Level Data Link Control (HDLC) frames using 64b/66b line encoding. The FPGA then modulates the LED driver. Flow control signals indicate to the computer when to pause sending data to COMLINC. In the flight configuration, the satellite processor replaces the ground computer.



Figure 20: COMLINC transmitter ground operating configuration

The COMLINC transmitter has three optical transmitter modes to choose between, selected by I/O pin voltages. These are summarized in Table 6. Mode 1 is strobing the DATA pin with a computer. The COMLINC will flash along with the strobe signal. This is useful for very slow blinking that might be useful for the purpose of visual identification of the satellite. Mode 2 is the transmission of a preprogrammed PRBS. When the +5V_beacon is powered, the PRBS is transmitted from the beacon LEDs at a baud rate set by the flight computer within the

beacon baud rate allowable range. The same holds for the spot beam. This will be helpful in characterizing the link margin of this optical communication system. Mode 3 is data transfer. Data is transferred to the transmitter from a satellite source, and the COMLINC FPGA converts it to NRZ format and sends it immediately. For the space-to-earth link, the spot beam is used. However, in some future implementation, two satellites relatively close to each other can use the beacon in Mode 3 to transfer data between them, if each they also contain a receiver. The current implementation of COMLINC only has a receiver in the ground station on earth.

Table 6. COMLINC operating modes

Mode	To	First	Then
1	Blink	power +5V_x, [spot, beacon]	strobe DATA_x, [spot, beacon]
2	Send PRBS	power +5V_x, [spot, beacon]	hold UART_RTS pin low
3	Send data	power +5V_x, [spot, beacon]	send DATA_x, [spot, beacon]

Thermal Management

The LED temperature is a major performance factor in the COMLINC design. In this project, two solutions for LED thermal management were tried. For the spot beam, the LED is soldered to an FR4 PCB next to its low-impedance drive circuitry. A pocket was milled in the FR4 to get near the LED and a copper slug was bonded into the pocket to transfer heat from it to the COMLINC housing. The result, shown in Figure 21, is a 26.5°C difference between the 52.1°C LED emitter temperature and the 25.6°C housing. The LED manufacturer's curve for power loss due to temperature rise is shown in Figure 22. LED output power changes by 0.7% per degree Celsius change in the diode junction temperature. This equates to a power loss of 20%. The lab measurements of the spot beam power were taken with the emitter at 52.1°C and that performance is used in the link analysis.

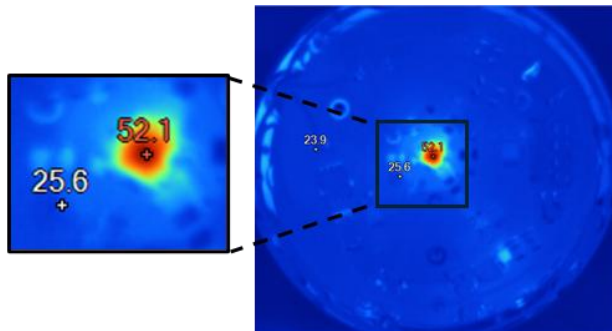


Figure 21: COMLINC spot beam LED temperature rise above the housing temperature

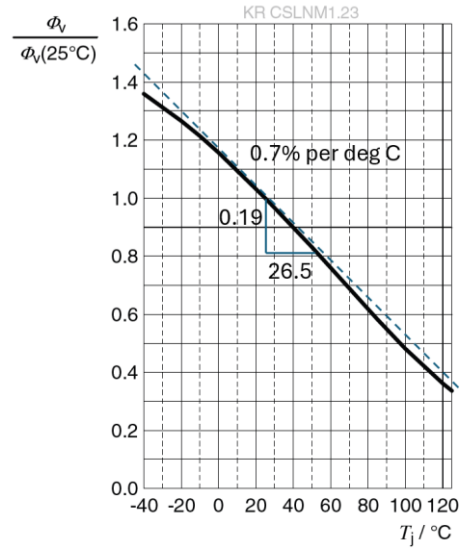


Figure 22: OSRAM KR CSLNM1.23 datasheet, relative luminous flux plot

The second approach to thermal management of the same OSRAM KR CSLNM1.23 LED was applied to the beacon LEDs. Three of them were dotted along the exterior rim of the housing and wired in series. See Figure 20 again for a clear picture of them installed. They were mounted on a two-layer Kapton flexible circuit. In addition to a very thin Kapton specification, a window of Kapton was removed on backside opposite the thermal pad and when silver filled epoxy is used to adhere the PCB to the housing, there is a minimal thermal path between it and the housing. The temperature differential between the LED emitter and the housing was 12°C for a 1 A current through the LED. This result gives confidence that the spot beam LED heat path can be significantly improved.

Spot Beam Lens

When configuring the COMLINC transmitter, two 60 mm diameter lenses can be used. The Carclo 10158 (Figure 23) is thinner and lighter than the Pentico 60 (Figure 24). The Pentico 90 has been fabricated but no housing has been made for it at this time. Table 7 is a summary of the physical parameters of the lenses.



Figure 23: Carclo 10158 lens



Figure 24: Pentico 60 custom lens

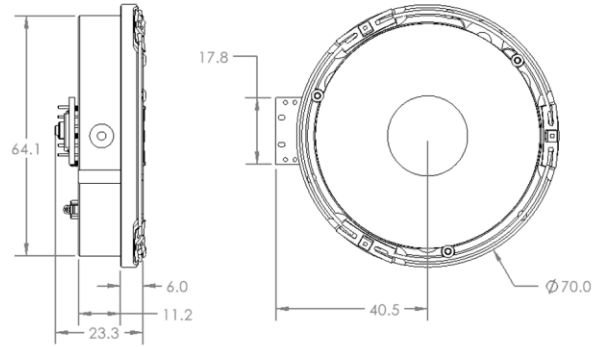


Figure 25: COMLINC transmitter with external FPGA (dimensions in mm)

Table 7. COMLINC collimating lens physical specs

Lens	Mass	Diameter	Thickness
	grams	mm	mm
Carclo 10158	15.8	60	11.5
Pentico 60	48.7	60	18
Pentico 90	82	90	18

Three copies of the Pentico 60 and two of the Pentico 90 lenses were machined from acrylic and coated for high reflectivity on the reflective surfaces and anti-reflection on the transmissive surfaces. The custom lenses were significantly more expensive because they were machined and not molded. They had a lead time of 6 months.

Completed Unit

The shape and outer dimensions of the Carclo 10158 model of the COMLINC transmitter is depicted and dimensioned in Figure 25. The spot beam is a single OSRAM KR CSLNM1.23 LED that is driven with 2A. It produces an intensity of 1.02 W into the collimating lens. Figure 26 is an image of it operating. The beacon consists of three unlensed OSRAM KR CSLNM1.23 LEDs bonded around the periphery and wired in series. They are driven by 1A of current, so each LED emits 0.566 W of radiant power at 617 nm. Figure 27 is an image of them operating. The LEDs are canted 30 degrees from the spot beam axis such that they provide 2π steradians of coverage. On axis, the radiant power of each LED adds to 0.85 W but 90 degrees from the spot axis the radiant intensity reduces to 0.28 W.

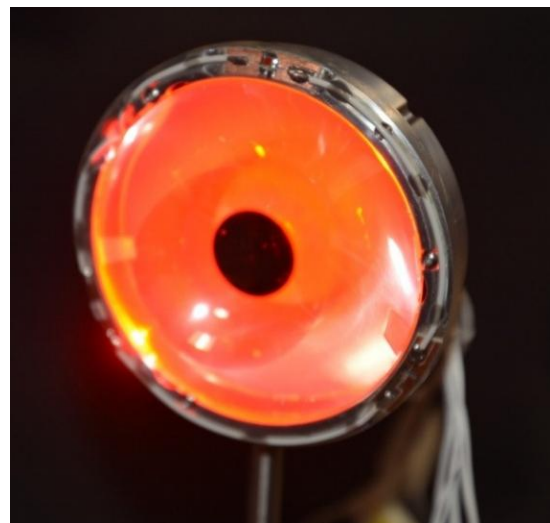


Figure 26: COMLINC spot beam operating

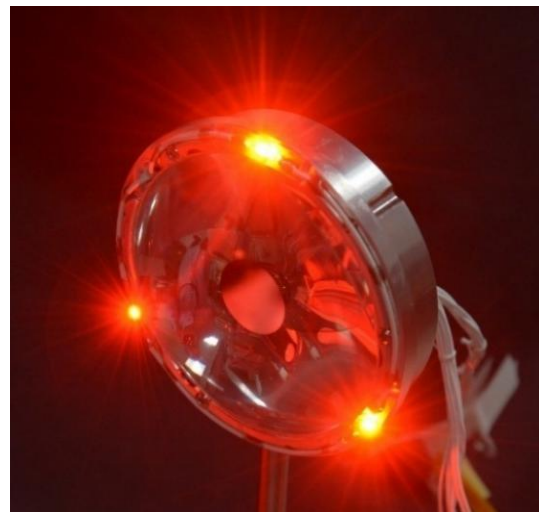


Figure 27: COMLINC beacon operating

There are currently three configurations for the COMLINC transmitter. The physical specifications for each assembly are listed in Table 8. Note that the Pentico 90 has not been assembled, and it is listed for completeness. Choosing one configuration over another depends on factors such as size, performance, and cost. The Pentico lenses are custom and therefore more expensive and heavier, but they have better performance.

The COMLINC transmitter electronics are common to all configurations. Table 9 is the spacecraft power requirement. Note that transmitting a PRBS is equivalent in power to sending data. The average power is half the peak because there are an equal number of “1” and “0” in an OOK data stream with 64b/66b line encoding. The heat generated by the beacon or spot beams is 83% of the average 5V electrical power input.

Table 8. COMLINC transmitter physical specs

Model	Mass	Diameter	Thickness
	grams	mm	mm
Carclo 10158	86	70	23
Pentico 60	130	70	30
Pentico 90	no data	no data	no data

Table 9. COMLINC transmitter average and peak 5V power requirements

	Spot	Beacon
PRBS, avg, W	3.3	6.5
PRBS, peak, W	6.6	13.0
Heat generated, W	2.6	5.2

MEASUREMENTS

After the COMLINC is assembled, measurements of divergence, power and bit-error rate characterize its optical performance. Divergence is measured at a target 730 cm down range (Figure 28). The beam leaves the COMLINC collimating lens with a 60 mm diameter (Figure 29) and its focus is adjusted until the image of the 1x1 mm OSRAM KR CSLNM1.23 LED emitter is small, symmetric, and has sharp edges.

In this section, the divergence and the power in the collimated beam are measured. Optical power is measured with an MKS 818-SL detector and an MKS 2936-R readout. The 818-SL detector has its OD3 filter installed to remain in its linear range. The COMLINC was modulated with a square wave at a 50% duty cycle. The modulation rate was 1 MHz for the spot beam and 10 KHz for the beacon. The 2936-R meter display refreshes at 20 Hz and therefore returns the average power.

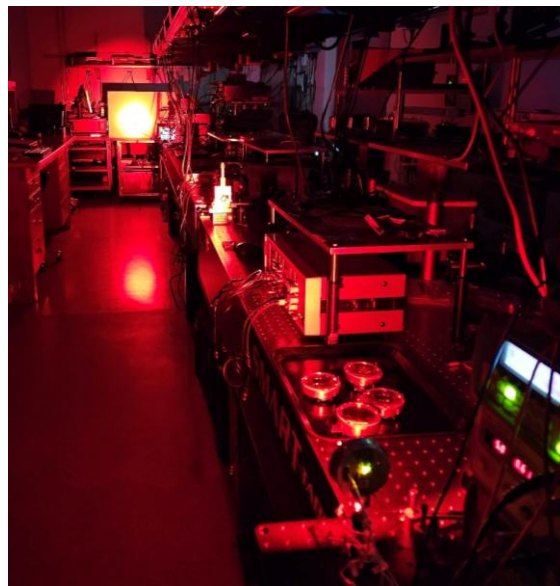


Figure 28: Focusing setup (target is 730 cm distant)

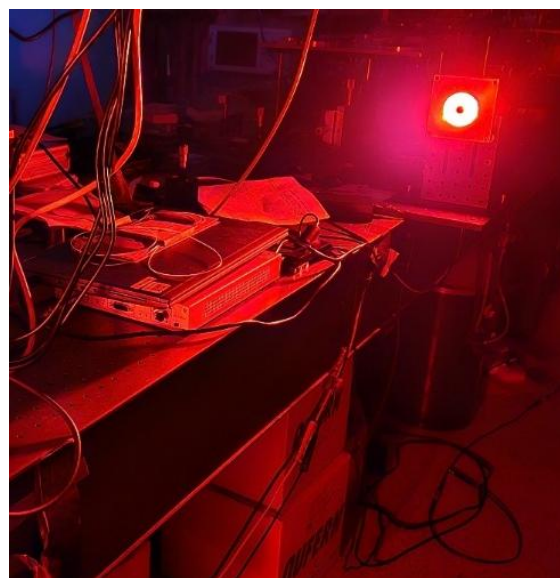


Figure 29: Looking at the transmitter exit aperture

Divergence

The divergence of the light is calculated from the width of the main lobe of the projected image which is 12 inches for the Carclo 60 mm lens (Figure 30) and 8 inches for the Pentico 60 mm lens (Figure 31). The edge of the image is the full-width half-maximum point; therefore, the calculated beamwidths are 41 milliradians (2.4 degrees) and 27 milliradians (1.6 degrees), respectively. These values match the optical model predictions. The LED emitter image from the Pentico lens is noticeably sharper.

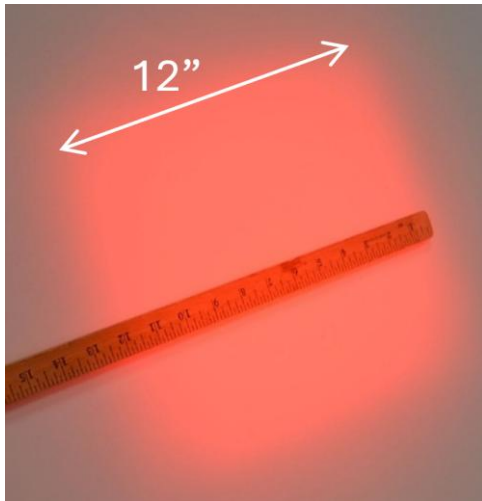


Figure 30: Divergence with a Carclo 10158 lens

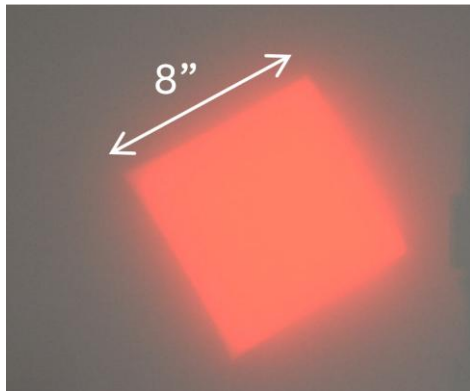


Figure 31: Divergence with a Pentico 60 lens

Irradiance

The irradiance measured with an NRC 818-SL detector placed at the target. The detector active area is 1 cm^2 and the meter display the average irradiance in $\mu\text{W}/\text{cm}^2$. Irradiance measurements were made at the center of an image and at the edge. They differ by a factor of two, indicating that the noticeable edge is the full-width half-maximum point of the light beam. The average irradiance multiplied by the area of the image is the total power in the image. This, divided by the power into the lens, which is 1.02 W, based on the LED data sheet, is the lens efficiency. The radiant intensity is computed by dividing the detector area by the solid angle defined by its diameter and 730 cm distance to the emitter.

The COMLINC configured with the Carclo 10158 and with the Pentico 60 lens were tested. The detector locations for the Carclo lens measurements are shown in Figure 32 and 33 and for the Pentico lens are shown Figures 34 and 35. The data for each are listed in tables 10 and 11, respectively. Notably, both lenses have the same efficiency, but the Pentico lens collimates more.



Figure 32: Power in the center of colimated image from the Carclo 10158 lens

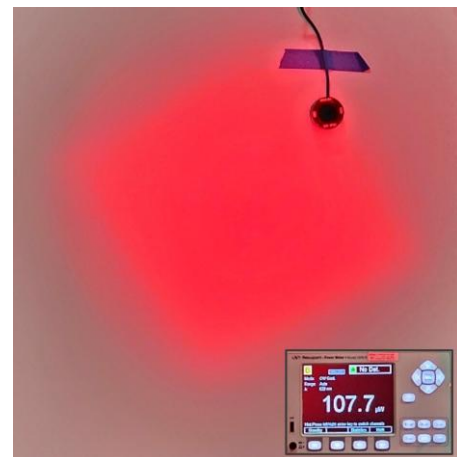


Figure 33: Power at the edge of colimated image from the Carclo 10158 lens

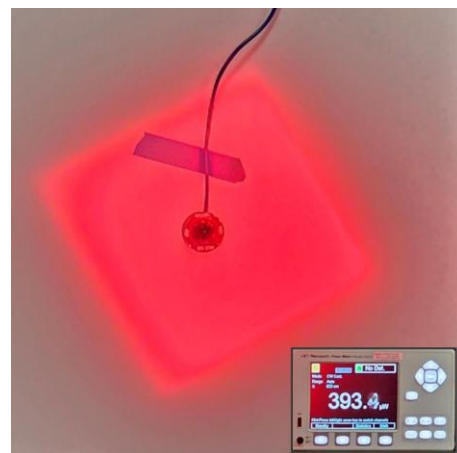


Figure 34: Power in the center of colimated image from the Pentico 60 lens

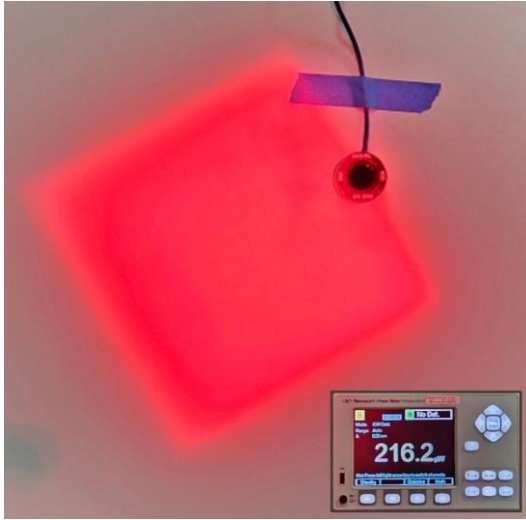


Figure 35: Power at the edge of colimated image from the Pentico 60 lens

Table 10. Carclo 60 lens performance analysis

Divergence	42	mrاد
Image size at 730 cm	30 x 30	cm
Image area	930	cm ²
Irradiance in center	182.2	μW/cm ² , avg
Irradiance on edge	107.7	μW/cm ² , avg
Total power in image	0.270	W
Lens efficiency	26%	W
Radiant intensity- center	97.2	W/sr, avg
Radiant intensity-edge	57.5	W/sr, avg

Table 11. Pentico 60 performance analysis

Divergence	28	mrاد
Image size at 730 cm	20 x 20	cm
Image area	413	cm ²
Irradiance in center	393.4	μW/cm ² , avg
Irradiance on edge	216.2	μW/cm ² , avg
Total power in image	0.252	W
Lens efficiency	25%	W
Radiant intensity- center	209.9	W/sr, avg
Radiant intensity- edge	115.4	W/sr, avg

Table 12 is a scorecard comparing the two lenses. The Carclo 10158 has outperformed its analysis. The optical model utilized a STEP file from the Carclo web site - perhaps that geometry was not accurate. The Pentico 60 has underperformed. The performance of the Pentico 90 is an estimate because it has not been built. It assumes that any modeling error is systematic and therefore like the Pentico 60. The custom lenses increase light onto the ground station by factors of at least 2 and up to 5. It is unclear why the measured results are quite different. The optical model has not been correlated at this time but there are plans to do so.

Table 12. COMLINC collimating lens scorecard

Lens	Radiant intensity, W/sr, peak	
	analysis	measured
Carclo 10158	120	194
Pentico 60	600	420
Pentico 90	1600	not available

BERT

The bit error rate test (BERT) applies a PRBS to a transmitted signal at a set bits-per-second rate. The important factors are the received power at the detector and the detector's sensitivity. For this test, a fiber splitter was used to compare two detectors simultaneously while measuring the power applied to them (Figure 36). Note that the power is the average power because the NRC 2936-R power meter and NRC 818-SL detector do not respond fast enough and only report an average power. The OD3 filter is removed because the expected power is 10s of pW.

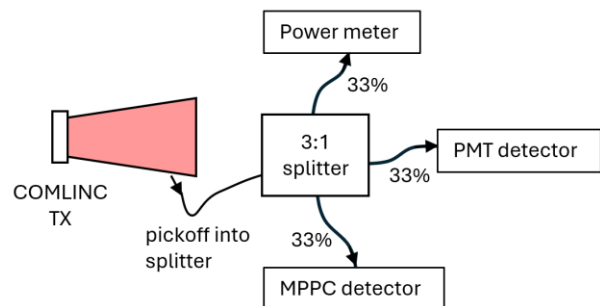


Figure 36: Bit error rate test light distribution

The detector sensitivity is displayed in Figures 37 and 38 for different signal power inputs. The Hamamatsu H14951 is the purple waveform and the Hamamatsu C14455 MPPC module is the green waveform. In Figure 37, the two detectors are simultaneously exposed to a 1 Mbps PRBS signal at 59 pW average radiant power. In Figure 38, the signal is a 1 MHz square wave signal at 10.5 pW average radiant power.

The shape of the responses affect the bit error rate measurement results. The spikey response within a “1” may be due to what is called dynode/anode depletion. It is encouraging that there is signal, but the USRP software that finds “1” in the response does not currently do very well with the spikey waveform. When more power is incident on the detector, then the bottom of a spike does not reach “0” and the USRP software can detect a “1” successfully. Removing the spikes is an ongoing effort.



Figure 37: Simultaneous response of the H14951 PMT and C14455 MPPC detectors to a 59 pW avg power, 1 Mbps PRBS signal

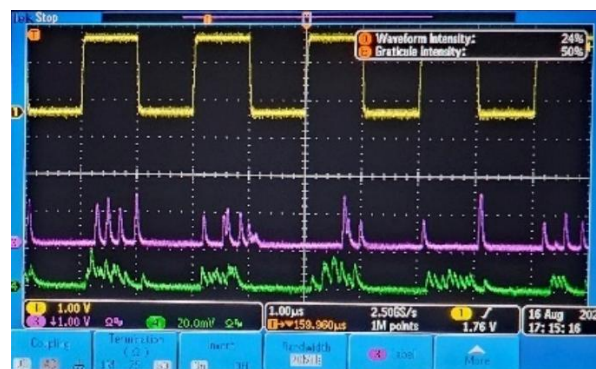


Figure 38: Simultaneous response of the H14951 PMT and C14455 MPPC detectors to a 10.5 pW avg power, 1 MHz square wave signal

GROUND SYSTEM

Design

The COMLINC ground telescope is designed to be low cost and easy to use. The starting point is a commercial telescope with a portable tripod. Two Celestron RASA optical tube assemblies (OTA), 8 inch and 11-inch were procured along with a strain-wave gear motor system (iOptron HAZ71) with no counterweight and a very heavy-duty tripod (iOptron Tri-Pier). The 8-inch telescope is shown in Figure 39, and it has been used in

all the tests presented here. The 11” diameter will be tested next because the link budget requires that aperture. Several of the tests presented here will have to be repeated with it.



Figure 39: The COTS 20 cm ground station without a detector installed.

A portable COTS amateur telescope that can track low earth orbiting satellites has been demonstrated.^{4,11} The COMLINC OGS telescope is fast, F/2.2, and the H14951 PMT detector area is intentionally large to create a large field of view of 1 degree. This will help to ensure that the satellite is in the field of view even with errors in the two-line-element set, tracking, and the mount model. In an ideal configuration, no additional tracking camera or software to keep the COMLINC transmitter light located at specific point on a focal plane would be needed. However, if needed, this more capable but complicated ground architecture can be realized.

The ground segment hardware architecture (Figure 40) is currently a tracking telescope, a computer to drive it, a PMT detector, a red bandpass filter, and a Universal Software Radio Peripheral (USRP) to decode the optical communication signal. The software for tracking low-earth-orbiting satellites is currently commercially available from iOptron but only tracks the ISS, which was sufficient for a tracking demonstration test. The software on the USRP for decoding the communications signal complements the encoding software in the FPGA on the satellite and release and licensing is in work.

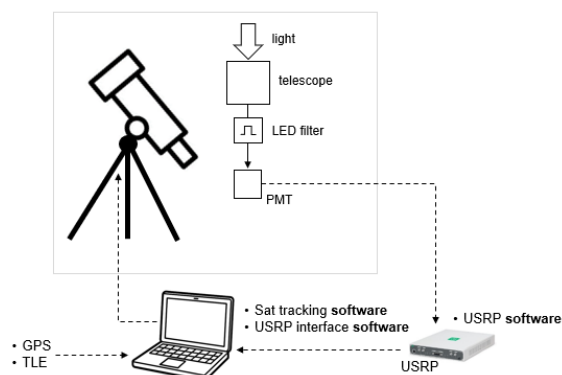


Figure 40: Ground segment architecture.

Weather is a significant problem for free-space optical communication, and a solution is to proliferate ground stations. Figure 41 is the cloud cover over the United States on one day (NOAA Goes-19, Band 2, 0.64 μm , red, visible). If ground stations existed in the locations shown, then there would be clear skies for some. Coordination of optical communication passes can be simple - the satellite could talk to each ground station whenever a valid overflight (high enough telescope elevation, satellite in eclipse) occurs. The satellite could download its memory and repeat the downloads. Because there is no optical handshaking, bad packets will have to be overcome either with forward error correction (not currently implemented but can be) or by repetitive transfer by cycling through the memory as a matter of course. Another solution for retrying bad packets without handshaking could be to send a list of them to the satellite via whatever uplink means is available.

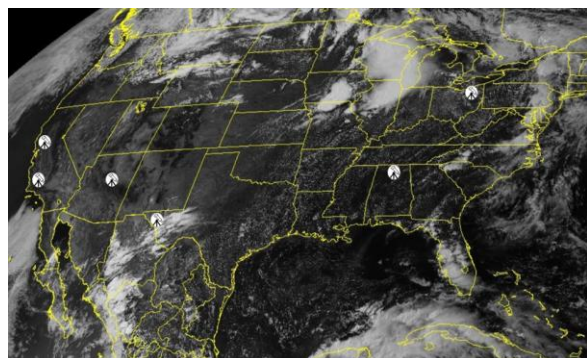


Figure 41: Example of cloud cover over the United States and notional location of 6 optical ground sites

After describing the COMLINIC transmitter specifications, the optical ground architecture, and proposing a satellite concept of operations, some satellite requirements become apparent (Table 13).

Table 13. Satellite requirements to use COMLINIC

Req #	Requirement
1	The satellite must know its position in space and the correct time
2	The ground sites must be preloaded before launch and may be updated later
3	The satellite must autonomously compute the time of overflight of a ground station and must compute the pointing angles to aim the LED transmitter at the telescope
4	The satellite must autonomously point with accuracy better than ± 0.5 degrees to be in line with the link budget presented earlier
5	The satellite orbit must be at an altitude of less than 600 km if the link budget presented is to be accurate and if there is to be enough time for any sizeable download.

Testing

The two main concerns with the portable ground station are tracking smoothness of the telescope and possibly overwhelming the PMT with skylight. Portable systems have been built that tracked low earth orbit satellites.^{3,11} However, this equipment is different and needs testing for smoothness. The second concern was the effect of light pollution and starlight on the signal to noise ratio of the configuration. The COMLINIC ground station PMT collects light from its complete field of view. The benefit of using the entire detector area is that the satellite position errors and the telescope mount errors will be small in comparison so the satellite will likely be in view. The penalty is that light other than the COMLINIC transmitter is collected which raises the noise floor.

To address the first concern, the ISS was tracked. A very high-elevation ISS pass was used to verify the mount tracking authority. The 8" diameter COMLINIC ground telescope was configured for this task with a camera and located on the roof of a building at Aerospace in El Segundo, CA. The mount was aligned to the sky using the camera to image the starfield. A computer program, the iOptron *Ultimate Orbit Tracker*, was employed (Figure 42) to control the mount based on the latest ISS TLE. The camera recorded the tracking quality of the ISS.

During the test, the ISS looks like a bright dot in a large dark field. Throughout the pass, the ISS dot did not jitter. This will be helpful if it is necessary to employ optical feedback to keep the satellite at a particular location in the field of view. The ISS did drift within the field of view, but its rate of drift across the field of view was 10s of seconds. More tracking attempts are required to determine if this drift can be reduced by a better sky

alignment and statistically test the accuracy of the two-line-element sets.

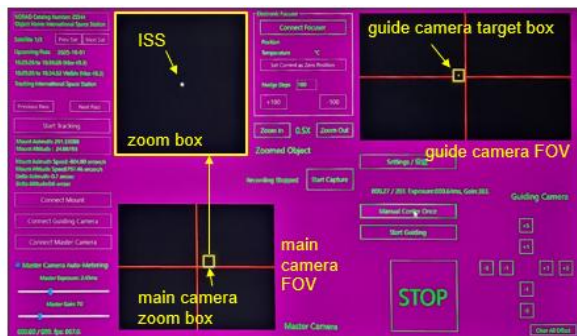


Figure 42: iOptron software for tracking the ISS

To measure the signal to noise, the 8" telescope was configured as shown in Figure 43 with the PMT at its focus. The PMT was amplified and displayed on an oscilloscope. A 617 nm LED was in a box modulated with a square wave at 1 MHz frequency and 50% duty cycle. The LED light in the box entered a 1:3 fiber splitter and one fiber ended in a collimator that entered the telescope, simulating a signal from the satellite. Another fiber, which carried equal power, was terminated into the 818-SL pW power meter.

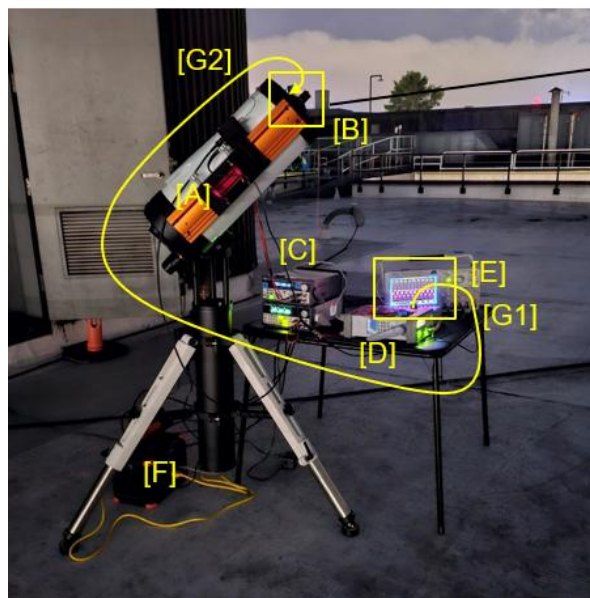


Figure 43: COMLINC optical ground station. [A] 8" telescope with [B] PMT mounted. Support equipment is [C] PMT power supplies, [D] waveform generator, [E] oscilloscope, [F] portable power supply, [G1] COMLINC Tx with fiber to a collimator [G2] at the entrance of the telescope

Figure 44 shows the result from a signal to noise test at The Aerospace Corporation location in El Segundo, CA. This is an urban location, and the sky has significant

scattered light. To reduce this impact, the telescope is configured with an RGB_R (595-690 nm) filter. However, the filter spectral width is wide because the LED is 617 nm with a full spectral width of 50 nm. In each plot, the purple trace is the PMT response, and the yellow trace is the COMLINC transmitter signal. The top image is without a communication signal superimposed, and the background light is evident. The bottom image adds a 1 MHz, 100 pW square wave optical signal to the background. The presence of modulation is visible, and this is encouraging. But a BERT was not done, so it is unclear if the SNR is sufficient for data to be extracted. A BERT was not done because it was not ready to be incorporated at the time of the test. Also, the signal level at 100 pW is almost 5-10x more than what is now understood to be expected.

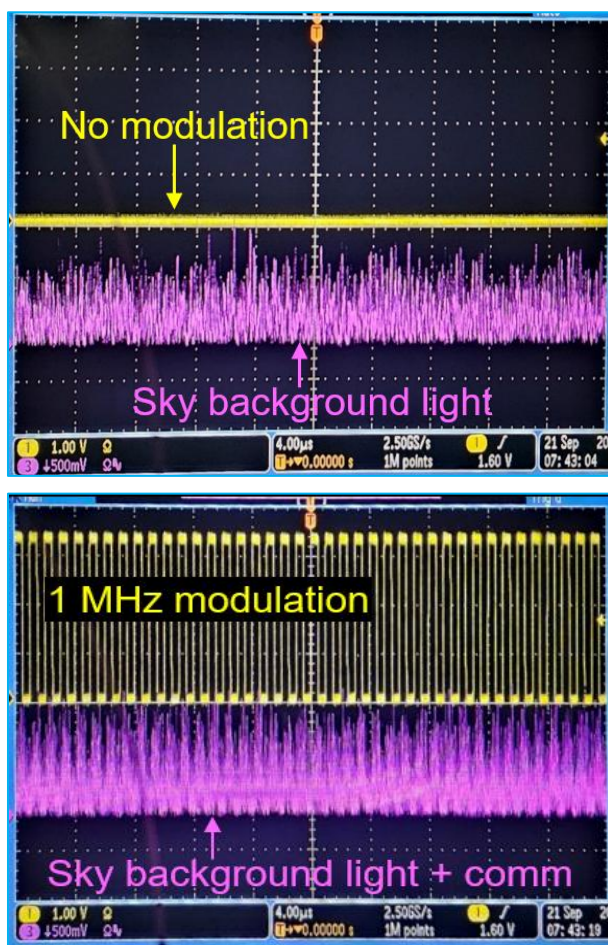


Figure 44: COMLINC optical ground station SNR test in an urban environment; (Top) just background light; (bottom) adds comm signal

This test setup was moved to a dark-sky location at the Los Pinos Ranger Station in the Los Padres National Forest. The location is 80 miles north of El Segundo and exemplifies the benefit of a portable ground station.

Figure 45 shows the results of the test there. The setup is identical except that the magnitude of the communication signal is less at 72 pW. The background is significantly less, and the communication signal is much clearer. In the future, this test will be repeated as a BERT with the appropriate signal level of 10 pW.



Figure 45: COMLINC optical ground station SNR test in an rural environment; (Top) just background light; (bottom) adds comm signal

REGULATION

The LED transmitter is believed to be exempt from registration with the Laser Clearing House. It is not a laser (a stimulated emission and therefore coherent radiation process) and has a divergence in the 10s milliradians versus a typical laser divergence of 1 milliradian or less. The light intensity on a target is therefore less, and permanent damage is unlikely. Also, the spectral linewidth of an LED is typically 25 nm or more and for a laser it is 1 nm or less. The dispersion of light through refractive optics prevents concentrated focus and damage is unlikely.

FLIGHT TEST

The COMLINC power measurements in the lab and link budget worksheet are all complete, so the next step is to characterize the performance via a flight test. The first COMLINC engineering model (EM) unit will fly on a NASA R5 CubeSat mission slated for July 2026. The satellite will aim the transmitter towards a 28 cm ground telescope described and power on the spot beam with the PRBS operating at 100 Kbps. The Naval Postgraduate School will also participate in the test with their 40 cm telescope that can be tasked to track COMLINC.

TRL6

The COMLINC transmitter has been tested to TRL 6. It was subjected to GEVS qualification vibration, thermal cycled, and operated in TVAC to verify its heat management. In addition, in TVAC a special test to confirm that the large acrylic lens will not crack or defocus when the chamber walls are reduced to -100°C was done. There were no failures or degradation noted in each test. While more testing can be done, the transmitter appears robust, and it was delivered to the NASA R5 program.

CONCLUSION

COMLINC is a low-cost space-to-ground optical communication link, and it is intended to be an S-band radio substitute to avoid RF congestion and the RF licensing process. This paper documented the design and testing of the optical transmitter and an optical ground station to receive it. Key issues in this system were defined and measured and there is room for improvement in each area. The temperature of the spot LED can be reduced with a better mounting substrate. A more efficient lens solution may be found if different geometric constraints are applied. Even the LED itself may be replaced by a diode laser to benefit from a much smaller collimating optic, if direct-current modulation at 10 MHz can be successfully achieved. The ground station and detector presented were tested for tracking and sky darkness impact on SNR, but no work was done to limit the field of view on the detector or actively track an object. Both areas have had others do work, so it was not a priority. All these improvements will increase link margin. A multi-kilometer BERT is planned, and it will increase confidence in the link budget. The first demonstration satellite flight, planned for July 2026 will demonstrate the usefulness of this system.

A low cost and easy to implement solution were requirements of this system, intended to lower the cost of entry for optical communication. This goal so far has been met. Once designed, the system was assembled quickly. The non-recurring engineering effort to resolve the engineering details consumed the budget - the piece

parts were not expensive. COTS parts and software were used wherever possible, but the driver circuit board assembly and the Pentico lenses were custom and not off-the-shelf. The same is true for the FPGA software that encodes the data and that interfaces with the satellite processor and the USRP software that conditions the detector electrical output and decodes the optical data—they too were custom. All the custom elements will be available via an open-source license like The Aerospace Corporation SatCat5 software. The ground segment is entirely purchased components at this time, but it has not been refined or tested as much as the transmitter, and when it is, there may be some customization that also will be available via open-source license.

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