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Transmitter and Fine Pointing System Development and Testing for the CubeSat Laser Infrared CrosslinK (CLICK) B/C Mission

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ABSTRACT

The CubeSat Laser Infrared Crosslink (CLICK) B/C mission seeks to demonstrate laser crosslinks for full-duplex communications and two-way ranging and time-transfer between two 3U CubeSats: CLICK-B and CLICK-C. Laser crosslinks between satellites can provide enhanced performance, with high data transfer rates and high precision range and timing information, using low size, weight, and power (SWaP) optical transceiver terminals. CLICK-B and CLICK-C will demonstrate laser crosslinks with data rates of at least 20 Mbps over separation distances ranging from 25 km to 580 km. CLICK-B/C will also demonstrate a ranging precision of better than 50 cm and a time transfer precision of better than 200 ps single shot over these distances. We present the design and development status and recent testing results of the laser transmitter and fine pointing, acquisition, and tracking (PAT) system, which are key to achieving these capabilities. The 1550 nm laser transmitter follows a master oscillator power amplifier (MOPA) design using an erbium-doped fiber amplifier (EDFA) for an average output power of 200 mW. A semiconductor optical amplifier (SOA) is used to achieve the pulse position modulation (PPM), ranging in order from 4 PPM – 128 PPM. The PAT system uses a microelectromechanical systems (MEMS)-based fast steering mirror (FSM) for fine pointing. A quadrant photodiode (quadcell) provides feedback for the actuation and steering of the FSM.

Keywords: laser communications, optical communications, crosslink, intersatellite, CubeSat, nanosatellite

1. INTRODUCTION

Laser crosslinks between satellites can enable high data transfer speeds for global communications constellations and provide high precision range and timing information for distributed remote sensing missions. Moreover, this can be accomplished with optical transceiver terminals that are smaller, lighter, and less power-intensive than comparable radio frequency (RF) systems, making them particularly applicable for small satellites such as CubeSats. The use of optical communications can also avoid the licensing and regulatory requirements associated with the crowded RF spectrum, and the narrower beamwidth of an optical communication signal provides greater security by being more difficult to intercept. However, this narrow beamwidth also necessitates strict pointing and tracking requirements, which can be difficult to meet within the size, weight, and power (SWaP) constraints of small satellites. Critical to establishing an inter-satellite crosslink is the pointing, acquisition, and tracking (PAT) sequence. This paper describes the CubeSat Laser Infrared CrosslinK (CLICK)-B/C mission, which seeks

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to demonstrate a full-duplex crosslink between a pair of 3U CubeSats. We present an overview of the CLICK-B/C mission, its concept of operations, and payload architecture. We focus in particular on the transmitter sub system and the closed-loop, fine PAT subsystem, which uses a beacon laser signal to provide feedback and a fast-steering mirror (FSM) to actuate the alignment of the received signal. We describe the design and development of these subsystems in detail and present results from recent testing and characterization. The testing of the transmitter includes confirming the output power and modulation of the seed laser and semiconductor optical amplifier (SOA) and characterizing the output pulse shape. For the PAT system, testing focuses characterization of the quadrant photodiode (quadcell) component. Ultimately, this technology demonstration mission seeks to enable future advanced mission concepts such as space-based radio interferometry, GPS-denied navigation, and time synchronization for synthetic aperture telescopes.

2. CLICK-B/C MISSION

The CubeSat Laser Infrared CrosslinK (CLICK) B/C mission is a technology demonstration mission jointly developed by the Space Telecommunications, Astronomy and Radiation Lab (STAR Lab) at the Massachusetts Institute of Technology (MIT), the Precision Space Systems Laboratory (PSSL) at the University of Florida (UF), and NASA Ames Research Center. Originating with the Nanosatellite Optical Downlink Experiment (NODE) project at MIT and the Miniature Optical Communications Transceiver (MOCT) project at UF,[1–4] CLICK seeks to demonstrate compact optical transceiver terminals that are cost-effective and meet the SWaP constraints of nanosatellites. The optical payloads will enable laser crosslinks to be established between two 3U CubeSats (CLICK-B and CLICK-C) for full-duplex, high data rate communications and two-way, high precision ranging and time-transfer. The CLICK-B and CLICK-C payloads will demonstrate laser crosslinks with data rates of at least 20 Mbps over separation distances ranging from 25 km to 580 km. They also seek to demonstrate a ranging precision of better than 50 cm and a time transfer precision of better than 200 ps single shot over these distances. In addition to the crosslinks, both CubeSats will be capable of performing space-to-ground downlinks. CLICK-B/C is currently anticipated to launch in summer of 2023.

The CLICK-B/C phase of this mission is preceded by an initial risk-reduction phase. A single 3U CubeSat, CLICK-A, which features a similar optical transceiver terminal with several key components and technologies of CLICK-B/C, was launched to the International Space Station (ISS) in July 2022. The CLICK-A payload lacks a receiver channel and will be used to demonstrate space-to-ground downlinks of at least 10 Mbps. All 3 CLICK CubeSats utilize the XB3 3U CubeSat bus platform developed by Blue Canyon Technologies (BCT). At the time of writing, CLICK-A is anticipated to deploy from the ISS and begin operations in September 2022.

Mission operations will be conducted by MIT STAR Lab, using the KSATLite ground station network to establish S-band radio contacts with the CubeSats. The primary optical ground station for downlink demonstrations is the Portable Telescope for LaserCom (PorTeL), located at the MIT Wallace Astrophysical Observatory. PorTeL is based on a 28 cm aperture consumer astronomical telescope and features a 5 W, 976 nm laser beacon.[5]

2.1 Mission Concept of Operations

The CLICK-B/C mission concept of operations is illustrated in Figure 1. Similar to CLICK-A, CLICK-B and C will be deployed from the ISS into low Earth orbit (LEO) in the same orbital plane. After the initial bus and payload checkouts are complete, differential drag maneuvers will be performed to allow the two CubeSats to drift apart. These drag maneuvers are accomplished by commanding to spacecraft to assume high or low drag orientations using the reaction wheel-based attitude control system of the BCT bus. Crosslink demonstrations will conducted over various ranges. After the maximum separation distance is achieved, the attitude configuration of the CubeSats will be reversed, allowing them to approach and eventually pass each other.

At the start of a crosslink demonstration experiment, each CubeSat will begin to point its payload aperture at the other using ephemeris information uplinked over RF during a previous ground station pass. Next, an S-band RF crosslink will be established, and the orbital state of each CubeSat will be determined using its onboard GPS. This information will be exchanged via the crosslink, and will serve as the basis for the open loop pointing. CLICK-B and C will then transmit their beacon lasers at the opposite CubeSat, where the signal will be received by a wide field-of-view (FOV) beacon tracking camera. Using image processing, the centroid of the beacon laser spot can be determined and used to generate the pointing angle error, which enables the payload to

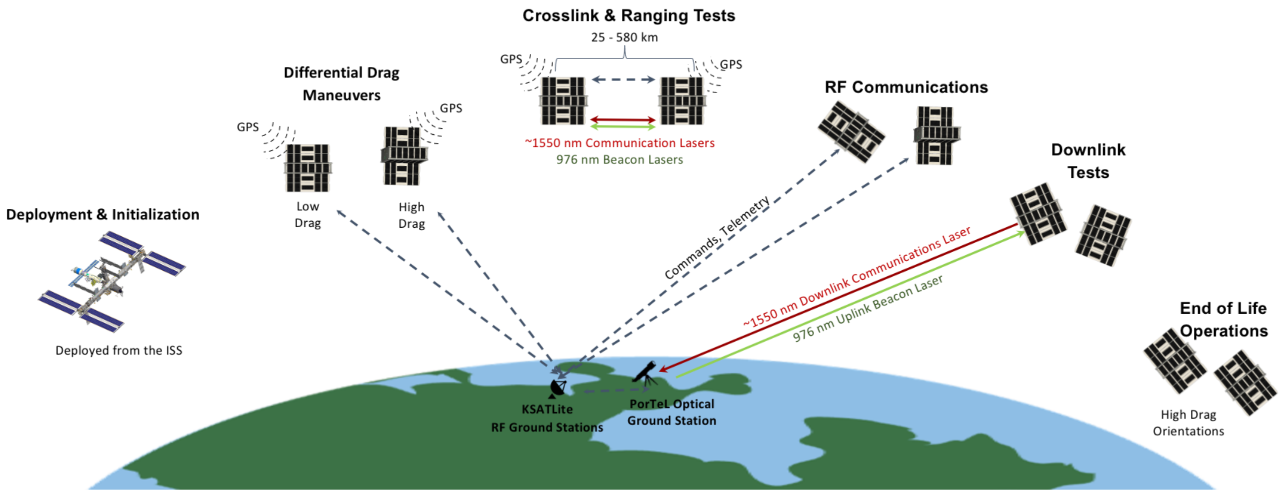


Figure 1. CLICK-B/C Mission Concept of Operations

initiate its closed loop coarse pointing mode. After improving the bus body pointing, the beacon laser signal will be acquired by a narrow FOV quadrant photodetector (quadcell) and the CubeSats will begin transmitting their transmit lasers. The beacon signal on the quadcell is be processed to further determine the pointing angle error, which is used to steer the fast steering mirror (FSM), initiating the closed loop, fine pointing mode. By steering the FSM, the received transmit signal will be aligned with the avalanche photodiode (APD)-based receiver. The crosslink demonstration experiment will last at most 10 minutes, after which the received data and payload and bus telemetry will be downlinked to ground via RF links. CLICK-B and CLICK-C will also conduct downlink experiments with PorTeL following a similar procedure.[6,7]

Once the full CLICK mission demonstration has been completed, CLICK-B and CLICK-C will both be commanded into a high drag orientation in order to expedite their natural orbital decay.

3. CLICK-B/C PAYLOAD

At approximately 1.7 kg, the CLICK-B/C payload follows a 1.5U form factor. As shown in Figure 2, it contains the optical bench, laser optoelectronics, pointing, acquisition, and tracking (PAT) system) and control electronics. The optoelectronics and fiber raceway are located under the optical bench with PAT components, while the control electronics are mounted on the rear of the payload. Following the design of CLICK-A, the payload leverages commercially available components such as fiber optic standard 1550 nm seed lasers and erbium-doped fiber amplifiers (EDFA) and Raspberry Pi microcontrollers.

The optical bench accommodates the near-1550 nm transmit path, near-1550 nm receive path, and the 976 nm beacon transmit and receive paths. These are illustrated in more detail in Figure 3. CLICK-B and CLICK-C use slightly different wavelengths for spectral isolation: CLICK-B transmits 1537 nm, while CLICK-C transmits 1563. The payload's transmitted beacon laser has a separate aperture from the near 1550 nm transmit and receive aperture, such that the beacon laser is fixed to the structure of the payload and thereby steered with the body pointing of the bus. The 250 mW average power beacon laser has a beamwidth of 22 mrad FWHM. On the opposite CubeSat, this beacon signal is received on the beacon tracking camera for coarse pointing. The near-1550 nm transmit lasers are reflected and passed through the dichroic filters, which reflect the transmit signal of each payload while passing the received signal to the receiver. The CLICK-B and CLICK-C payloads use dichroics with opposite reflecting/passing characteristics in accordance with their respective wavelengths: CLICK-B passes 1563 nm and reflects 1537 nm, while CLICK-C passes 1537 nm and reflects 1563 nm. One more dichroic filter reflects the received 976 nm beacon signal to the quadcell while passing the near-1550 nm transmit signal to the microelectromechanical systems (MEMS)-based FSM and passing receive signal to the APD. The

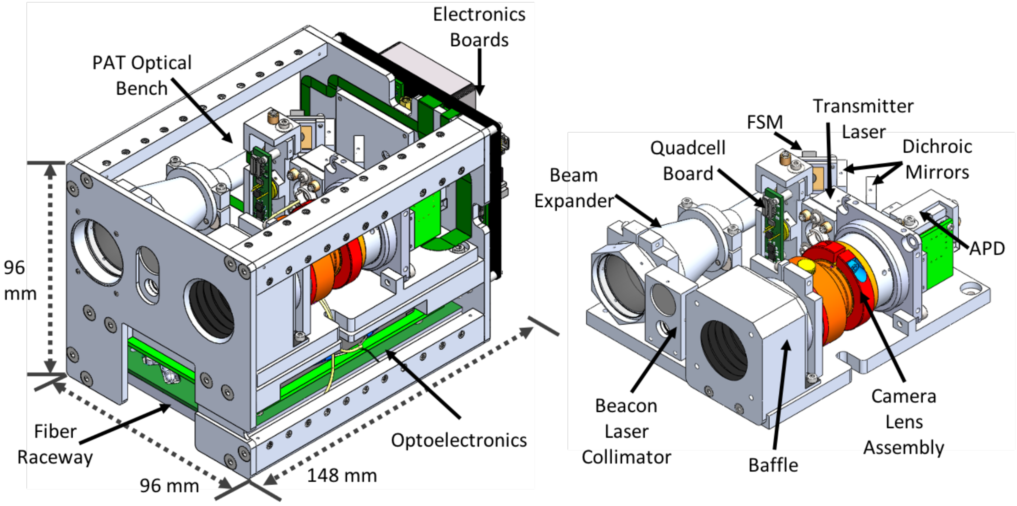


Figure 2. CLICK-B/C Payload Structure and Mechanical Design

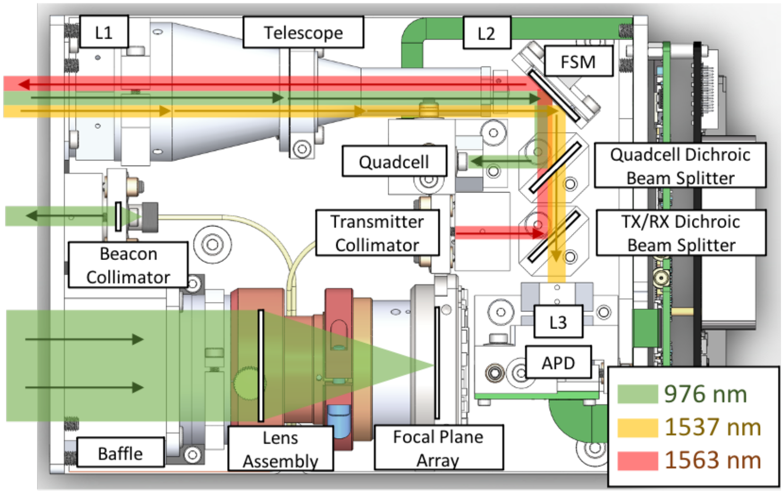


Figure 3. CLICK-B/C Payload Optical Design

FSM is located at the exit pupil of a 10.5x telescope beam expander, which expands the transmit signal that exits the payload via the 25.4 mm aperture and focuses the incoming transmit and beacon signals.

For the receiver, a 1 GHz bandwidth APD is used, equipped with two bandpass filters to minimize stray light. The receive chain can select between a time-to-digital converter (TDC)-based approach and an analog-to-digital converter (ADC)-based approach. The latter uses a matched filter and provides a higher signal-to-noise ratio at the expense of digital processing complexity, while the former provides high timing accuracy with less digital processing[8, 9]

The payload control electronics include a Raspberry Pi Compute Module 3-based CPU board. Running Linux, this module manages the payload command and data handling and interfaces with the spacecraft bus. It also connects to the beacon tracking camera and runs the coarse PAT software that involves processing images from the camera. This board features a chip scale atomic clock (CSAC) as a high precision reference clock for the ranging measurements. The fine PAT software, transmit laser modulation and control, and receiver chain digital signal processing are implemented on a Microsemi SmartFusion2 FPGA on a separate board.

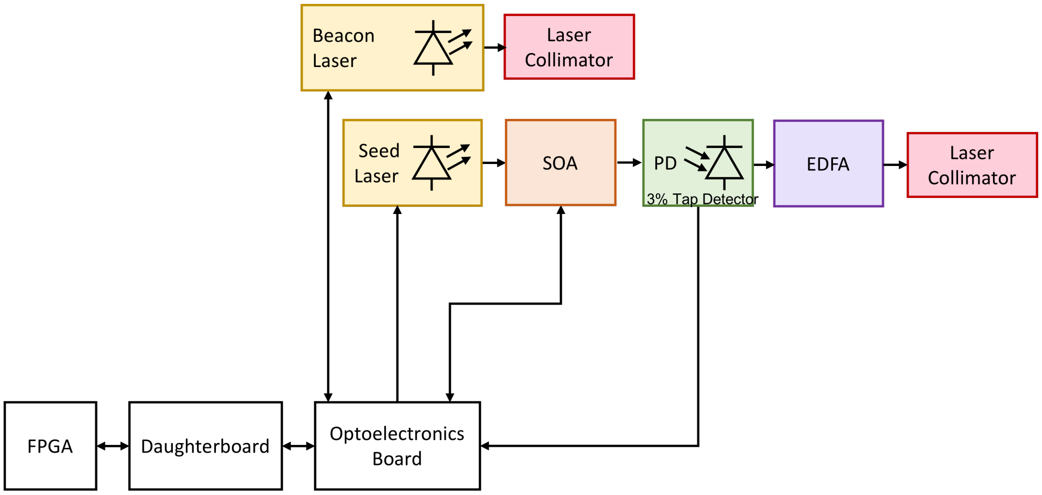


Figure 4. CLICK-B/C Transmitter Architecture

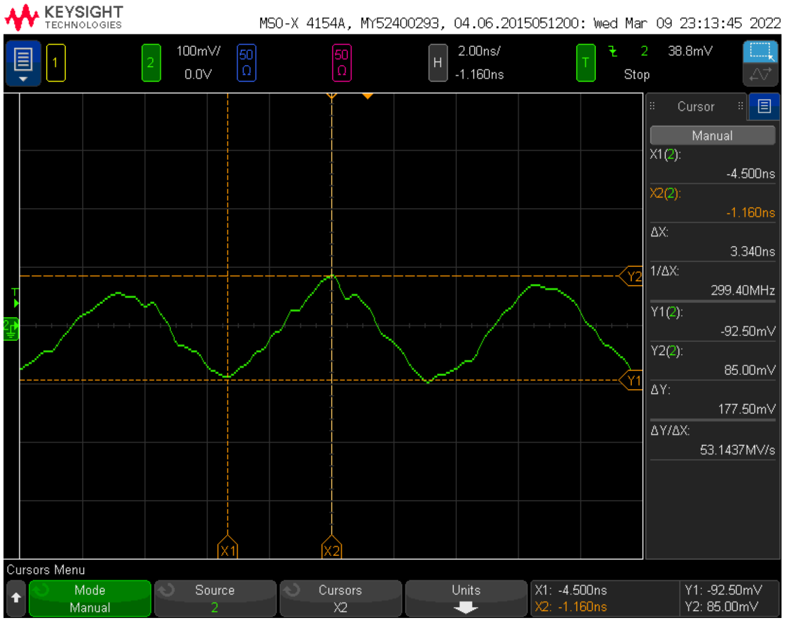
3.1 Transmitter

The architecture of the transmitter for the CLICK-B/C payload is shown in Figure 4. A micro-integrated tunable laser assembly (μITLA) is used for the seed laser, and a semiconductor optical amplifier (SOA), acting as a shutter, is used to modulate its output. This signal is then amplified with an EDFA and directed to the laser collimator, providing the 200 mW average, 71 urad FWHM beam. The modulated signal from the SOA is also connected to an integrated tap photodiode for monitoring and control of the SOA. The use of the SOA for modulation has been tested and the output pulse shape, pre-EDFA, is shown in Figure 5. The pulse shape was measured directly from the APD, and the waveform shown here corresponds to a 150 MHz, 50% duty cycle (modulation, resulting in a train of 6.6 ns pulses. This supports the modulation requirements of the CLICK mission, which uses pulse position modulation (PPM) with a 10 ns slot width and a programmable guard time. This result also shows the full-scale, near 200 mV peak-to-peak response from the APD, demonstrating the operation of both SOA and APD components.

The CLICK-B and C payloads support a range of PPM orders from PPM-4 to PPM-128, corresponding to data rates of 50 Mbps down to approximately 5 Mbps. With an increase in PPM order, the average output power of the transmitter is halved, proportional to the duty cycle. Figure 6 shows the transmitter average output power measured across PPM orders. The optical output power from the SOA is approximately 15 dBm maximum. The measured output power follows the expected performance at lower PPM orders but shows some implementation loss at higher orders due to the large duty cycle.

3.2 Fine PAT System

The CLICK-B/C closed loop, fine PAT system is illustrated in Figure 7. The 3 kHz sine modulated beacon signal from the opposing CubeSat is acquired with the 25.4 mm, 10.5x magnification telescope. The magnification provides a larger geometric light collection area onto the Silicon quadcell detector and multiplies the measured angle to improve pointing error sensitivity. The 4 quadrants of the quadcell are each connected to 10 MΩ transimpedance amplifiers (TIAs), followed by operational amplifier-based 3 kHz bandpass filters. Each channel is then digitized by a 64 kHz, 24-bit delta-sigma ADC, which is connected to the payload FPGA. The rest of the digital signal processing (DSP) demodulation chain that recovers the amplitude of the sine-modulated beacon signal is implemented on the FPGA. First, the in-phase and quadrature components of the signals from each quadrant are retrieved and filtered using 1000 tap Finite Impulse Response (FIR) filters. The CORDIC (COordinate Rotation Digital Ccmputer) algorithm is then used to calculate the amplitude and phase of the 4 signals. The location of the beacon signal spot on the quadcell is calculated using the amplitude from each quadrant. Its coordinates serve as error feedback for the fine PAT PID (Proportional Intergral Derivative) control loop, which is implemented on the soft processor of the FPGA. The output of the PID controller is passed to



MSO-X 4154A, MY52400293, 04.06.2015051200: Wed Mar 09 23:13:45 2022

100mV/
0.0V
2.00ns/
-1.160ns
2 38.8mV
Stop

X1(2): -4.500ns
X2(2): -1.160ns
ΔX: 3.340ns
1/ΔX: 299.40MHz
Y1(2): -92.50mV
Y2(2): 85.00mV
ΔY: 177.50mV
ΔY/ΔX: 53.1437MV/s

Figure 5. Measured Pulse Shape

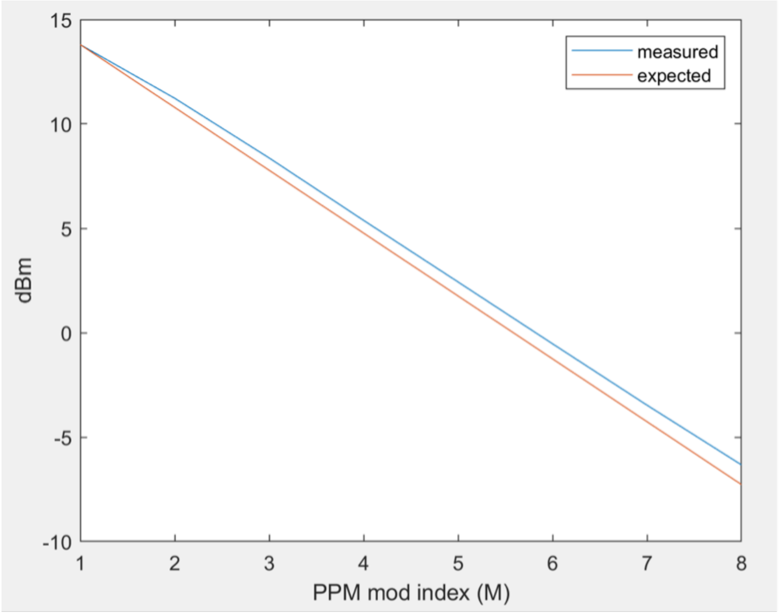


Figure 6. Transmitter Measured and Expected Output Power

a 16-bit digital-to-analog converter (DAC), followed by a tunable lowpass filter, before being amplified to drive the MEMS FSM. Using this closed-loop approach, the beacon spot is steered using the FSM to the center of the quadcell, thereby aligning the concurrently received transmit signal on the receiver APD.

The performance of the quadcell dictates the pointing and disturbance rejection capability of fine PAT system. A key performance metric is the device noise, the characterization of which is currently ongoing. The power spectral density of the quadcell dark noise for each quadrant channel is shown in Figure 8, and reported in Table 1s. These noise values are below the expected noise from initial simulations, and the measurements validate the functioning of the receive chain.

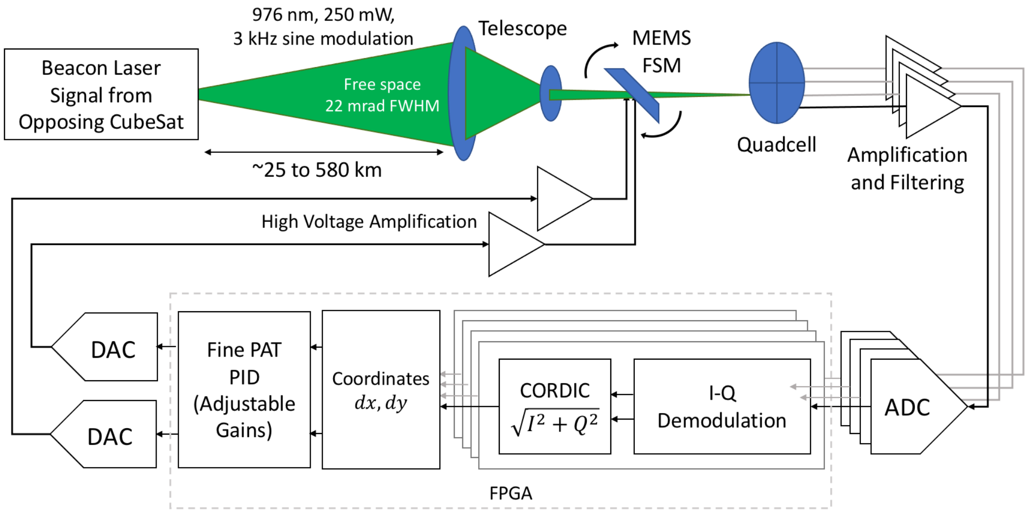


Figure 7. CLICK-B/C Fine Pointing, Acquisition, and Tracking (PAT) Sequence

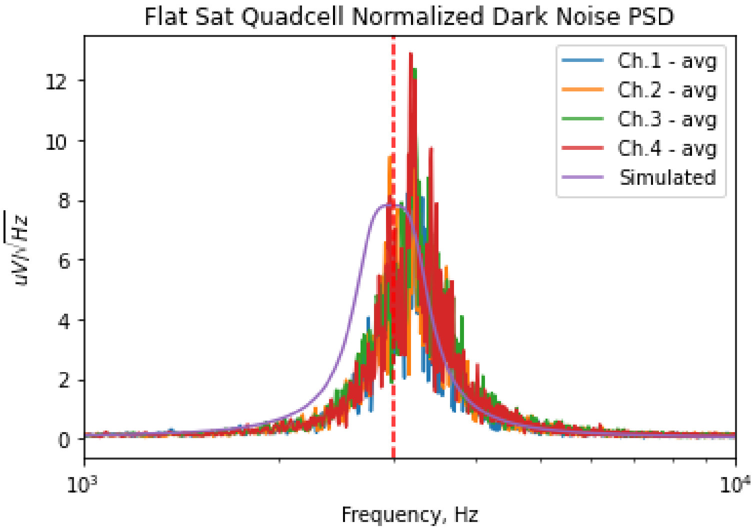


Figure 8. Normalized Quadcell Dark Noise PSD

4. FUTURE WORK AND CONCLUSION

Currently, the CLICK-B/C engineering development unit (EDU) is being assembled, and the optical performance of the bench is being evaluated. Final revisions of the payload electronics boards are being fabricated and tested, in parallel with continued software development and component characterization. For the transmitter subsystem, the next step will be to characterize the pulse shape at the end of the transmit fiber train, and for the fine PAT subsystem, the next steps will include the demonstration of the beam detection and FSM actuation in a more flight-like configuration. The final assembled EDU will be subject to environmental testing, including thermal vacuum chamber (TVAC) and vibration testing to verify its performance in orbital and launch conditions. In the future, the CLICK-B and CLICK-C flight units will be built, assembled, and integrated in parallel before delivery to BCT for integration with the satellite bus and spacecraft-level environmental testing. CLICK-B/C is anticipated to launch, deploy, and begin operations in 2023.

Table 1. CLICK-B/C Quadcell Dark Noise Measurement per Channel

	Channel 1	Channel 2	Channel 3	Channel 4
Normalized Integrated Dark Noise [mV]	54.1	56.8	65.6	62.7

ACKNOWLEDGMENTS

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