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CLICK-A: Optical Communication Experiments from a CubeSat Downlink Terminal

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ABSTRACT

The CubeSat Laser Infrared CrosslinK (CLICK) mission is a technology demonstration of low size, weight, and power (SWaP) CubeSat optical communication terminals for downlink and crosslinks. The mission is broken into two phases: CLICK-A, which consists of a downlink terminal hosted in a 3U CubeSat, and CLICK-B/C, which consists of a pair of crosslink terminals each hosted in their own 3U CubeSat. This work focuses on the CLICK-A 1.2U downlink terminal, whose goal was to establish a 10 Mbps link to a low-cost portable 28 cm optical ground station called PorTeL. The terminal communicates with M-ary pulse position modulation (PPM) at 1550 nm using a 200 mW Erbium-doped fiber amplifier (EDFA) with a 1.3 mrad FWHM beam divergence. CLICK-A ultimately serves as a risk reduction phase for the CLICK-B/C terminals, with many components first being demonstrated on CLICK-A. CLICK-A was launched to the International Space Station on July 15th, 2022 and was deployed by Nanoracks on September 6th, 2022 into a 51.6° 414 km orbit.

We present the results of experiments performed by the mission with the optical ground station located at MIT Wallace Astrophysical Observatory in Westford, MA. Successful acquisition of an Earth to space 5 mrad FWHM (5 Watts at 976 nm) pointing beacon was demonstrated by the terminal on the second experiment on November 2nd, 2022. First light on the optical ground station tracking camera was established on the third experiment on November 10th, 2022. The optical ground station showed sufficient open, coarse, and fine tracking performance to support links with the terminal with a closed-loop RMS tracking error of 0.053 mrad. Results of three optical downlink experiments that produced beacon tracking results are discussed. These experiments demonstrated that the internal microelectromechanical system (MEMS) fine steering mirror (FSM) corrected for an average blind spacecraft pointing error of 8.494 mrad and maintained an average RMS pointing error of 0.175 mrad after initial blind pointing error correction. With these results, the terminal demonstrated the ability to achieve sufficient fine pointing of the 1.3 mrad FWHM optical communication beam without pointing feedback from the terminal to improve the nominal spacecraft pointing. Spacecraft drag reduction maneuvers were used to extend mission life and inform the mission operations of the CLICK-B/C phase of the mission. Results from the spacecraft drag maneuvers are also presented.

Introduction

Nanosatellites are used to host novel technologies and sensor packages, some of which produce data at rates which outpace the ability of nanosatellites to transmit that data to the ground. This data bottleneck reduces the utility of a satellite to provide measurements from the unique perspective that space offers. Traditionally, radio frequencies are used for communication for both the mission critical communication, commonly referred to as telemetry, tracking, and command (TT&C) as well as bulk data downlink of mission data to the ground. To transmit at higher rates, missions use more bandwidth, higher power, sometimes use higher radio frequencies. These approaches have limitations and drawbacks, such as large apertures and higher loss[1].[2] As an alternative to radio frequencies, optical communications for CubeSats have been in development to increase the amount of data transmitted from space to the ground and between satellites.

Free Space Optical Communication

Optical communication offers many benefits over radio for high bandwidth communications, such as the lack of licensing requirements, a lower size, weight, and power (SWaP), and the inherent security offered by narrow beam divergences. Two of the largest obstacles to wide-scale adoption of optical communication to small satellites is susceptibility of the optical signals to weather and the required fine pointing of the transmit beam. While the use of a global network of optical communication ground stations and crosslinks between satellites can help to mitigate the impact of weather, the fine pointing of the transmit beam must be addressed by the terminal in space transmitting. The fine pointing requirement is driven by the THz frequencies used in optical communications. These frequencies offer narrow beam divergences, which enable transmit powers to be lowered on the terminal in space, but drive much finer pointing requirements of the beam than radio frequencies.[3]

Previous Demonstrations

There have been previous demonstrations of optical communications from CubeSat platforms that have helped to develop this technology. The Aerospace Corporation was first to demonstrate optical communications from a CubeSat platform. The NASA-funded Optical Communications and Sensor Demonstration (OCSD-B/C) terminals were 1.5U CubeSats able to establish 200 Mbps links to a 40 cm ground station.[4] This terminal achieved pointing required for optical communications through pointing the body of the satellite with 0.024° 3σ (0.419 mrad) pointing accuracy.[5] The beam divergence was different for each of the two spacecraft with OCSD-B having 0.06° (1.047 mrad) FWHM divergence and OCSD-C having 0.15° (2.618 mrad) FWHM divergence angle. Successful 200 Mbps links were reported with the OCSD-B terminal. The optical transmit wavelength was 1064 nm using on-off keying modulation at optical powers between 2-4 W. The terminal required 10-20 W to operate the transmitter. This terminal has been since flown on other missions such as R^3 CubeSat.[6]

The TeraByte Infrared Delivery (TBIRD) mission from MIT Lincoln Lab is a NASA-funded mission to transmit extremely large amounts of data from space to the ground. The TBIRD terminal (3U in volume) is hosted in a 6U CubeSat. The terminal was designed and built by MIT Lincoln Lab and utilizes consumer-off-the-shelf (COTS) compact form pluggable (CFP) fiber telecommunication modules and solid-state drives to enable 200 Gbps downlinks from a 3U CubeSat.[7] The mission has achieved 200 Gbps downlink data rates and transmitted 1.4 TB during a single downlink experiment to NASA JPL's 1-m OCTL optical ground station. This terminal also utilizes spacecraft body pointing, which is improved through a quadrant photodiode onboard the terminal. This quadrant photodiode uses an uplink pointing beacon laser as a pointing reference to provide pointing error feedback to the spacecraft attitude control system. This terminal uses dual-polarization QPSK waveforms with a 900 mW Erbium-doped fiber amplifier (EDFA). This terminal requires 100 W of power to transmit at maximum data rates.[8] The beam divergence of this terminal is 380 FWHM μrad and has reported results of 20-35 μrad RMS closed-loop tracking performance.[9]

The CLICK Mission

The CubeSat Infrared CrosslinK (CLICK) mission is designed to advance the state of the art for optical crosslinks and ranging between CubeSats, neither of which has yet been demonstrated by a CubeSat. The mission is funded by NASA Space Technology Mission Directorate (STMD) Small Spaceraft Program (SSTP). The mission is comprised of two phases, CLICK-A, which is a 3U CubeSat that hosts the CLICK-A optical communications downlink terminal, and CLICK-B/C, which is a pair of 3U CubeSats each hosting an optical communication terminal capable of full-duplex crosslinks as well as ranging. The goal of the mission is to establish a 20 Mbps optical crosslink between the two spacecraft at distances between 25-580 km and demonstrate optical ranging capability down to 0.5 m. The focus of this paper will be on the CLICK-A operations and results.

System Overview

The CLICK-A mission is a risk-reduction effort to demonstrate key technologies that are used in the CLICK-B/C terminals. The design integration experience and in-space operation of key technologies will increase the confidence in those components for their role in the CLICK-B/C terminal. The COTS components that CLICK-A and B/C terminals share are a microelectromechanical system (MEMS) fine steering mirror (FSM) from Mirrorcle Technologies, a silicon CMOS camera, camera lens assembly, and an Erbium-doped fiber amplifier. The spacecraft for this phase of the mission hosts the CLICK-A downlink optical communications terminal designed to transmit at rates between 5-50 Mbps. The flight model of this terminal is shown in Figure 1. It is paired with a low-cost optical ground station based on a hobby-level astronomy telescope and necessary backend optics and receivers to enable optical communications.

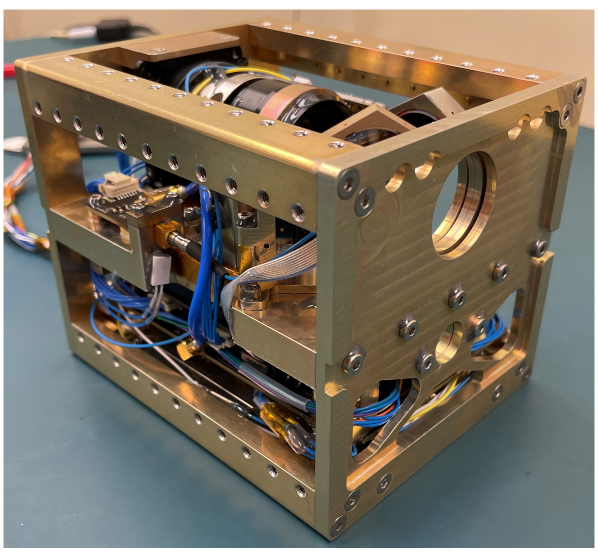

Figure 1: Flight model of CLICK-A terminal.

The CLICK-A spacecraft was launched on July 15th, 2022 to the International Space Station (ISS) on the CRS-25 mission as part of the soft-stowed cargo through Nanoracks. The CLICK-A CubeSat was deployed from the ISS on September 5th, 2022 into a 51.6° 414 km orbit. The mission uses the KSATlite ground station network, with three radio ground stations located in New Zealand, Chile, and Spain, for the spacecraft operations and commanding downlink experiments.

CLICK-A Terminal

The CLICK-A terminal utilizes pulse position modulation (PPM) with a 5 ns slot width. The design uses a master oscillator power amplifier (MOPA) design with a directly modulated seed laser. The modulation is performed through using wavelength "chirp" of the seed laser, where the laser is pulsed with current causing a minor shift in the output wavelength.[10] This wavelength modulation is transformed into an intensity modulation through the use of a three port fiber optic circulator and an athermal fiber Bragg grating (FBG), which provides narrowband (10 Ghz) optical filtering of the seed laser signal. The seed laser is pulsed and the wavelength is shifted into the narrowband reflection window of the FBG causing an intensity modulation on the output of port three of the fiber optic circulator. The output of this circulator is fed into a 200 mW EDFA from Nuphoton Technologies (with its own input photodiode monitor) and amplified. There are two tap couplers to monitor and control the pulse modulation. The fiber optic component assembly is shown in Figure 2.

The unique optical design of the CLICK-A terminal enables the terminal to independently control the fine pointing of the transmit beam and reject most of the mispointing induced from the body pointing of the spacecraft. This optical design is shown in Figure 3. As depicted in Figure 2, the fiber optic component assembly has a 980 nm calibration laser multiplexed into the same fiber containing the amplified transmit 1550 nm light. Both of these wavelengths enter free-space through a pigtailed aspheric fiber collimator where they are directed towards a MEMS FSM that provides tip/tilt control to point the light. The two wavelengths are reflected off the FSM towards a dichroic beam splitter which reflects 99% of the transmit light and directs it out of the terminal through a dual bandpass filter (bandpass windows at 1550 nm and 975 nm). The dichroic beam splitter passes 98% of the calibration laser light which then reflects off a mirror. The reflected light then encounters the dichroic again where it reflects 2% and is directed to a lens and camera assembly. The calibration laser is focused onto the focal plane of the silicon CMOS camera and provides angular knowledge of the the position of the FSM. The calibration laser is tunable in power by controlling the drive current of the laser diode. To know where to point

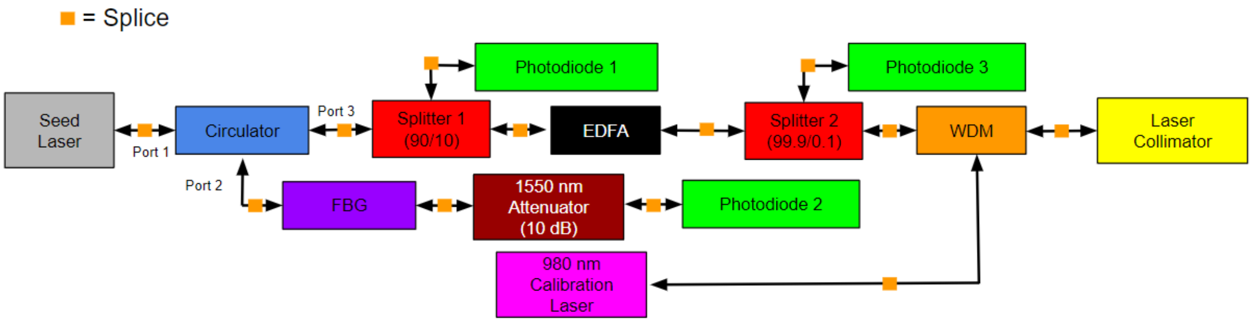

Figure 2: Fiber optic assembly of the CLICK-A terminal.

the transmit beam, the optical ground station has a high power laser, called a beacon, pointed towards the satellite that is used as a pointing reference. This beacon light is 976 nm and once it makes it to the CLICK-A CubeSat, passes through the dual band-pass filter and dichroic beam splitter to be imaged by the camera lens assembly. By tracking the beacon spot on the focal plane, the terminal can sense the mispointing of the spaccraft and control the FSM to attempt to correct for this pointing error.

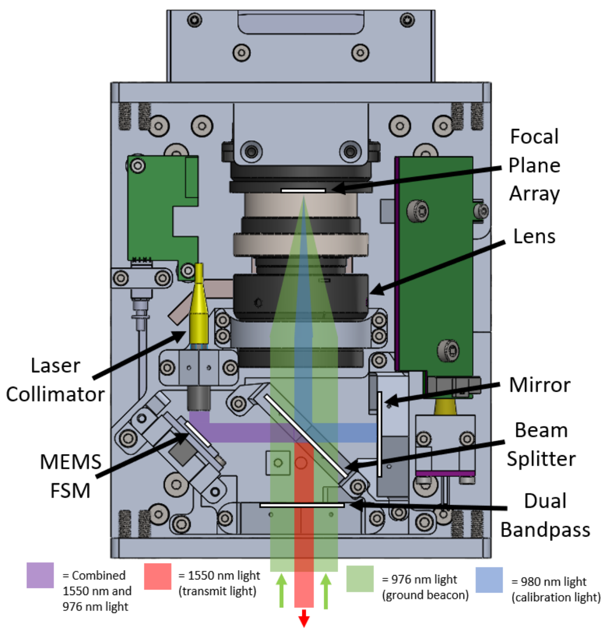

Figure 3: Optical design of the CLICK-A terminal.

To differentiate the beacon spot from the spot of the calibration laser on the focal plane, the calibration laser briefly turns on to determine the mirror angle and is set to an optical power that requires much less integration time (0.1 μs vs. 3-10 μs) at the focal plane detector than the beacon signal (which being having propagated distances of 300-1000 km is much less optical power). When the calibration laser is off, the integration time of the camera is auto-tuned to support a spot that is easy to track with the beacon tracking algorithm. The utilization of a silicon CMOS camera with a short focal length lens for beacon and calibration laser tracking enables the CLICK-A terminal to have a large field of view (~10.6°). The large field of view allows the spacecraft to mispoint ±5° and still have the beacon be seen on the tracking camera. The CLICK terminals also have the capability to feedback the angular offset of the beacon to the spacecraft attitude control system to correct for the mispointing, but this was not attempted successfully before the spacecraft de-orbited.

PorTeL Optical Ground Station

A low-cost portable optical ground was developed for the NODE optical communication terminal (later to be called CLICK-A).[11] This optical ground station was further developed for use on the CLICK mission to improve the optical back end, as shown in Figure 4, as well as to increase its field of view.[12] The optical ground station is based on the Celestron CPC1100 telescope, which comes with its own motor driven azimuth-elevation mount. Attached on top of the telescope is a star camera to provide alignment between the telescope mount and the sky. This star camera is also used in the initial blind pointing of the telescope. The back end of the telescope hosts an shortwave infrared (SWIR) tracking camera that is used for tracking of the transmit beam of the optical communication terminal. The tracking knowledge is fed to controllers of the telescope mount and a fine steering mirror. This fine steering mirror was included to ensure sufficient coupling of the received light onto a 200 μm avalanche photodiode (APD). Significant (-53.9 dB) spectral filtering is implemented to sufficiently isolate the beacon signal from the received light in case there is any scattering of the beacon signal back into the telescope. The APD is mounted via a XY translation stage that allows co-boresighting of the sensor to the center of the SWIR tracking camera. The output of the APD is connected to an oscilloscope with sufficient bandwidth to capture the 5 ns pulses of the space terminal.

The optical ground station is located inside a roll-top roof shed at the MIT Wallace Astrophysical Observatory in Westford, MA. The location and siting of the ground station shed involved consideration of laser safety requirements on the ground-to-space beacon. The proximity of the MIT campus to the Logan International Airport was not compatible with the use of the optical ground station near campus due to the planned 5 Watt Earth to space laser beacon. The shed was built around an already existing bedrock pillar. The walls the shed provide a minimum elevation angle of 30° which supports laser safety requirements.

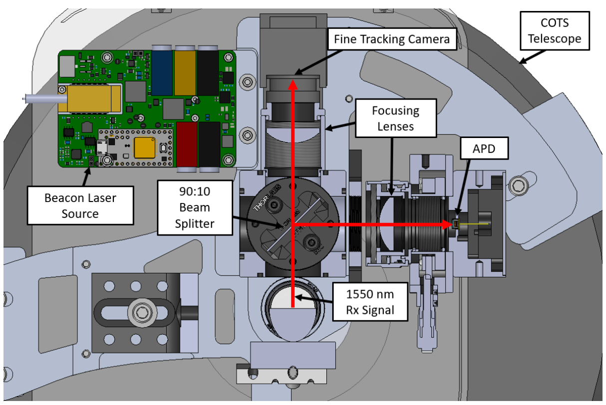

Figure 4: PorTeL optical ground station back end for tracking and receiving downlink optical signals.

The downlink terminal is designed to work with a laser beacon as a pointing reference. This laser source was developed by MIT STAR Lab for use on the CLICK mission.[13] It is capable of 5W of constant laser output with a wavelength of 976 nm. The laser source is also able to be modulated at 3 kHz, which is required for compatibility with the CLICK-B/C pointing, acquisition, and tracking system. The beacon laser source is mounted on the optics platform at the backend of the telescope, as shown in Figure 4. This mounting location proved to be an issue with operations, as the beacon diode emitted enough stray light out of the diode package to be detectable on the fine tracking SWIR camera. The optical path of the receive signal was isolated from the beacon diode through an enclosure around the beacon laser diode source to isolate its stray emission from the optics near it. As shown in Figure 5, the 5 W beacon laser fiber output is coupled to a variable zoom collimator mounted to the side of the telescope with a 105 μm multimode optical fiber.[14]

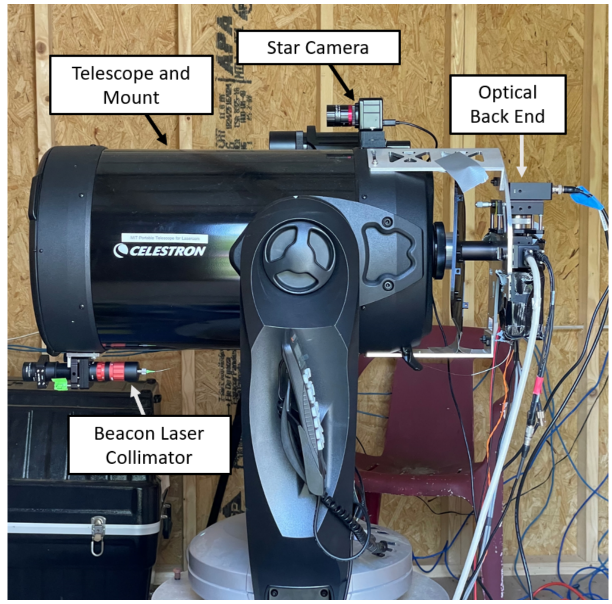

Figure 5: PorTeL optical ground station components.

Optical Downlink Experiments

Communications with the CLICK-A spacecraft occurred at least once a day to monitor the spacecraft health telemetry and fix any issues that arose since last contact. This telemetry included the GPS data since the last radio contract. This data was key to understanding the evolution of the error of between the satellite's actual and predicted position. The preparation for an optical downlink experiment began with propagating the orbit of the spacecraft over the next few weeks to understand when the spacecraft would pass over the optical ground station. The overpasses that occurred during the night and had a minimum elevation angle of 40° were chosen as candidate optical downlink passes. Due to the susceptibility of optical frequencies to attenuation from water vapor, overhead clouds prohibit the successful operation of optical communication experiments. The weather at the optical ground station was monitored for whether there would be clear skies during the experiment. If a candidate pass had clear weather, an optical downlink experiment was planned. The latest NORAD Two-line element set (TLE) for the spacecraft is improved upon by using

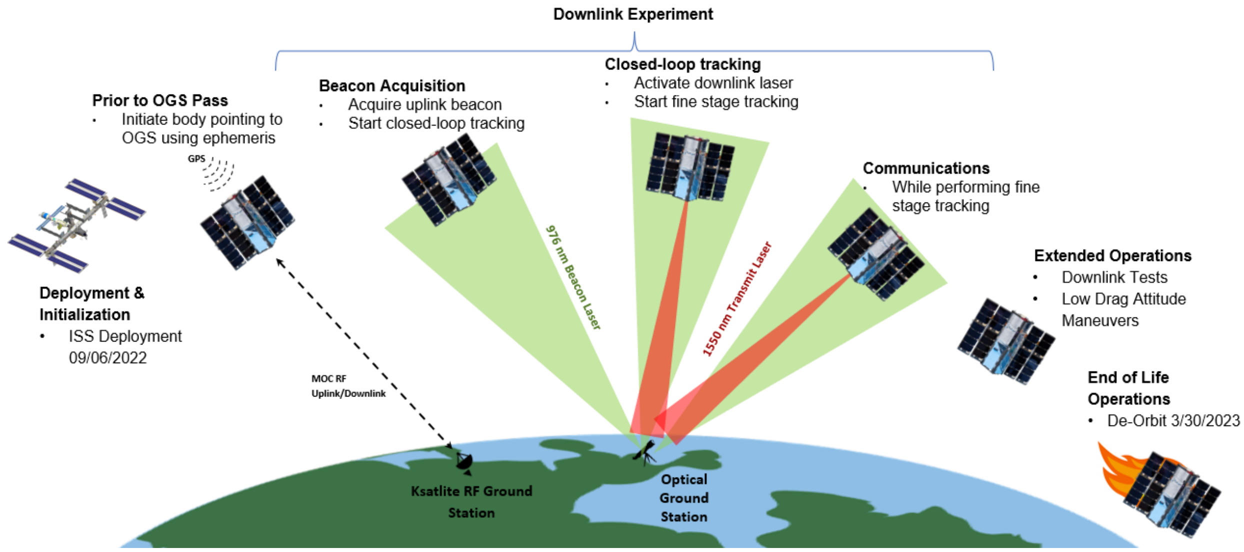

Figure 6: Concept of operations for the CLICK-A mission.

a SGP4 batch least squares orbit fit to the most recent GPS data from the spacecraft. This is crucial to predict where along the orbital track the satellite would be located for use in the blind pointing of the optical ground station. The approach is that the spacecraft must first detect the beacon. The beacon beam divergence is sized for a 3 km position error in predicted spacecraft location and if the optical ground station is not pointed to within that error, the terminal would not be able to see the beacon on its focal plane array. The terminal uses the spot from the beacon on its focal plane to know where to command the internal pointing mirror since any angular error between the spacecraft and the terminal presents itself as beacon spot movement on the focal plane. Once the terminal has successfully detected the beacon and determined its angular error, the mirror controller drives the mirror to an angle that corrects for the mispointing and directs the transmit laser to the optical ground station. Once the ground station is able to see the transmit laser on its fine tracking camera, it can closed-loop control the mount to better point the beacon laser. The concept of operations for the mission, including a nominal downlink experiment, is shown in Figure 6.

The spacecraft is commanded to schedule a downlink experiment in the day leading up to the experiment. Up to 15 minutes before the planned experiment start time, the satellite would turn on the terminal and begin its pre-experiment self-tests to ensure nominal operation of all relevant terminal subsystems, such as the FPGA to read and write registers, EDFA status, seed laser tuning, PPM modulation test (verifying successful ability to modulate from PPM4-PPM128), and a pointing, acquisition, and tracking (PAT) self test that calibrates the controller of the FSM.

The implementation and alignment of the APD sensor on the optical ground station proved to be a challenge in the beginning phase of operations. The APD used for the development of the terminal was a custom sensor board with a Voxtel RDC1-NJAF APD sensor. This APD sensor was discontinued and the board used for this sensor stopped functioning, at which point the program decided to speed up the development of the APD sensor board for the CLICK-B/C terminal. The updated APD sensor board is designed for the Laser Components IAG200H5 APD sensor. Issues with the board were discovered and it was determined that more development would be required for it to be successfully operated. Commercial APD solutions were then investigated and a Thorlabs APD430C was chosen due to having sufficient bandwidth and low enough noise equivalent power to be used for the ground station. Initial co-boresight attempts demonstrated that a more advanced optomechanical mounting solution would be needed for meeting the co-boresight requirements between the APD and the center of the fine tracking camera. This was implemented in early February 2022, with unfortunately not enough time left to for the team to successfully couple light onto the APD sensor before the orbit started decaying rapidly.

Experiment Results

For most of the mission, only the optical ground station at MIT Wallace Astrophysical Observatory was set up to support downlink experiments. Partner optical ground stations were considered as options to support more downlink experiment opportunities and test the terminal with different optical receivers. The results discussed in this work only cover the experiments performed with MIT Wallace optical ground station.

The optical downlink experiments began in October 2022 after spacecraft and terminal commissioning. Six downlink experiments were attempted to the optical ground station at the MIT Wallace Astrophysical Observatory, with half of them being partial successes. Meeting the necessary requirements for attempting an optical downlink experiment proved to be challenging with a single ground station located in Massachusetts operating during the winter months. A large portion of the candidate passes were not able to be attempted due to weather issues. A summary of the attempted optical downlink experiment attempts can be seen in Table 1. Three of the optical downlink experiments that were attempted either did not detect the ground beacon on the terminal beacon tracking camera, or the tracking algorithm was fooled by stray light. Of the three that did detect and track the beacon, only one did not produce signal acquisition of the transmit laser on the optical ground station fine tracking camera. This was potentially due to co-boresight misalignment between the beacon collimator and the fine tracking camera. The experiments that did detect the ground beacon with the terminal beacon tracking camera produced pointing data for both the spacecraft blind pointing and the correction by the MEMS FSM fine pointing system. The results of the three experiments that successfully produced beacon tracking and fine pointing control by the MEMS FSM on the terminal are shown in Table 2.

The first optical downlink experiment attempt occurred on October 28th, 2022 did not result in signal acquisition of the beacon on the terminal beacon tracking camera or transmit on the optical ground station fine tracking camera. The team had prepared for optical downlink experiments through tracking bright low Earth orbit satellites, but setting up and operating a full optical downlink experiment resulted in many lessons rolled into future experiments. The next attempt was on November 2nd, 2022 and produced the first beacon acquisition on the terminal beacon tracking camera. The tracking of the beacon spot on the beacon tracking camera occurred for 25.8 seconds. The third experiment was on November 11th, 2022 and produced the longest tracking time of the beacon on the terminal beacon tracking camera of 94.5 seconds as well as the first light on the optical ground station fine tracking camera. Closed-loop tracking of the optical ground station was also achieved during the November 10, 2022 experiment attempt. The last successful experiment was on November 29th, 2022 and maintained tracking of the beacon for 65.8 seconds with a brief window of closed-loop tracking by the optical ground station.

Across all these experiments, a large initial spacecraft (S/C) blind pointing error required the FSM to operate near the edge of its angular control authority. This is can be seen in Figure 7, where the spacecraft initial pointing error and correction is plotted relative to the total angular control authority of the FSM for the November 11th, 2022 experiment.

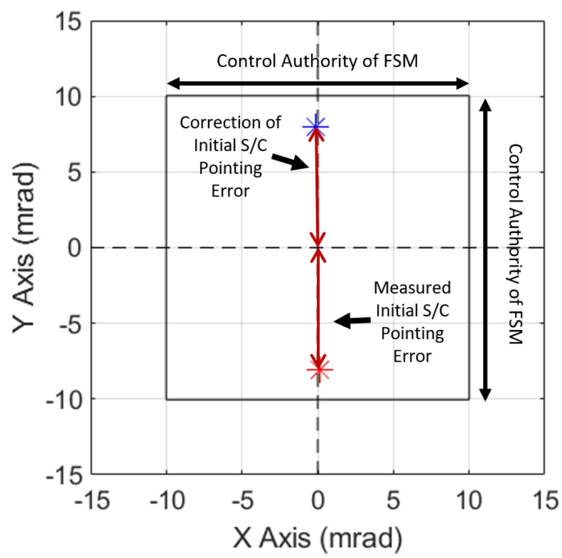

Figure 7: Focal plane offsets required to correct for initial spacecraft pointing error for the November 10, 2022 downlink experiment. The red star is the location of the beacon spot on the beacon tracking camera. The blue star is the initial FSM position to correct for initial spacecraft pointing error.

To determine this initial spacecraft blind pointing error, the beacon tracking camera images the beacon, and the terminal converts the beacon spot to an initial pointing error through the conversion of 1 pixel being equal to 0.098 mrad. The FSM is set to a position that is the reverse angle of the initial spacecraft blind pointing error. Once these coarse angular errors are corrected, the FSM could

Date	AOS-LOS Duration (min)	Max Elevation (°)	Min Range (km)	3D Tracking Error (km)	Spacecraft Beacon Camera	OGS IR Cam	OGS APD
2022-10-28	0.5	43.5	565.7	4.29	No	No	N/A
2022-11-02	2.27	56.6	469.2	2.88	Yes	No	N/A
2022-11-10	2.77	70.3	414.9	0.73	Yes	Yes	N/A
2022-11-29	1.90	59.6	441.4	1.13	Yes	Yes	No
2022-02-16	1.25	43.0	451.2	9.4	No	No	No
2022-02-25	2.18	71.4	321.2	0.49	No	No	No

Table 1: Optical downlink attempts by the CLICK-A terminal to the optical ground station at the MIT Wallace Astrophysical observatory.

correct for the smaller spacecraft blind pointing errors sensed on the beacon tracking camera. Spacecraft blind pointing errors (after initial coarse angular correction) and the FSM pointing error (difference between the commanded and measured angle) are shown in Figure 8 with a -3 dB circle drawn to show what pointing error would have caused a 50% loss of transmit power at the ground station.

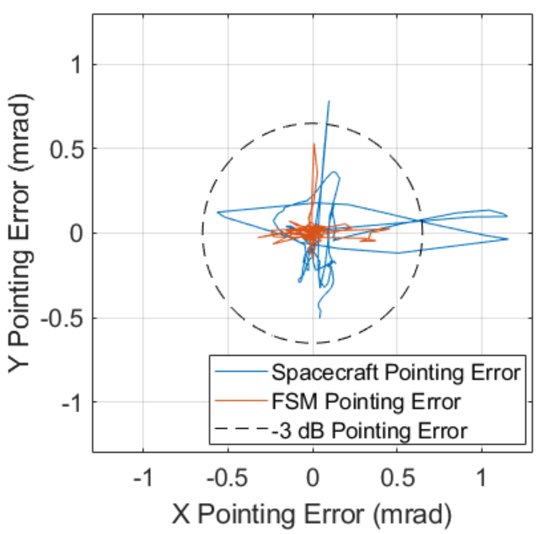

Figure 8: Spacecraft pointing error (after initial 8.038 mrad correction) and FSM pointing error over 94.5 seconds of tracking during November 10th, 2022 optical downlink experiment. The circle represents the -3 dB pointing error of the transmit beam.

As shown in the fourth column in Table 2, the initial spacecraft blind pointing error was significant for all the experiments (between 8.038 and 9.195 mrad). The FSM control authority was ± 10 mrad and the initial blind spacecraft pointing errors required the FSM to use most of its control authority for correction. All initial blind spacecraft pointing errors were within the angular control authority of the FSM and the terminal was able to correct for this coarse mispointing before beginning the fine tracking. As noticed on the November 11th and November 29th experiments, the spacecraft attitude control system would slowly roll the spacecraft along the optical terminal's pointing axis (likely due to the another control goal of the spacecraft attitude control system) resulting in additional coarse pointing error that the FSM had to correct for. For these two experiments, once the roll mispointing error extended beyond the angular control authority of the FSM, the pointing residuals increased dramatically. The optical communication terminal had the capability to feed the coarse pointing errors it sensed to the spacecraft to correct for this error, but this capability was not enabled for the experiments with the optical ground station at the MIT Wallace Astrophysical Observatory. The FSM pointing errors in Table 2 include both the total beacon tracking time (including the errors caused by the spacecraft roll going beyond the angular control authority of the FSM) as well as the FSM pointing residuals that account only for the spacecraft pointing errors that are addressable by the FSM angular control authority.

Only the November 11th, 2022 experiment produced tracking results where the spacecraft maintained pointing within the angular control authority of the FSM. This can be seen by the total FSM pointing error statistics matching the addressable FSM pointing error statistics in Table 2. The pointing results of this experiment are shown in Figure 10. The (b) and (c) plots within this figure show the X and Y axis spacecraft errors as well as the commanded and resulting FSM angle. It can be seen that the FSM performed well in correcting for the body pointing errors that were present. The November 11th, 2022 experiment demonstrated a mean pointing error of 0.071 mrad and an RMS error of

Date	Beacon Track Time (s)	Beacon Exp. Range (μs)	Initial S/C Blind Pointing Error (mrad)	Max S/C Blind Pointing Error (mrad)	Total FSM Pointing Error (mrad)		Addressable FSM Pointing Error (mrad)				
					RMS	Mean	Min	Max	Mean	RMS	σ
11-02 2022	25.83	8.9-79.9	9.195	16.504	1.006	0.663	0.042	0.563	0.152	0.197	0.128
11-10 2022	94.50	3.9-13.5	8.038	8.541	0.115	0.071	0.003	0.533	0.071	0.115	0.091
11-29 2022	65.84	4.3-10.6	8.25	20.273	1.652	0.627	0.008	0.995	0.116	0.214	0.180

Table 2: Beacon camera and pointing data from optical downlink experiments that detected and tracked the ground beacon laser.

0.115 mrad. The November 11th, 2022 experiment also produced the first closed-loop tracking results of the optical ground station to the transmit beam. The pointing error of the optical ground station during closed-loop control of the mount is shown in Figure 9. These results did not use the FSM, and still achieved sufficient pointing to couple light on the APD.

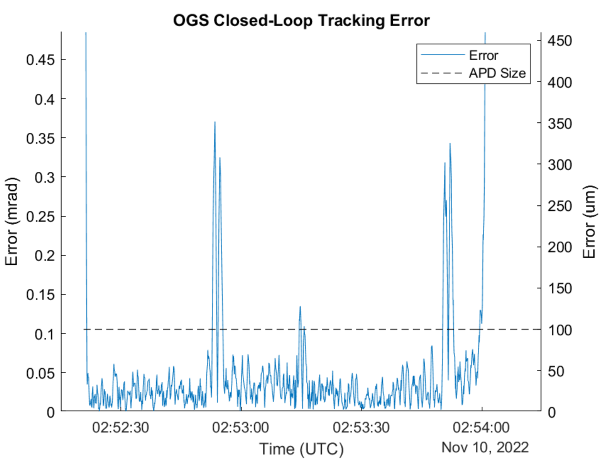

Figure 9: Tracking error of optical ground station for November 11th, 2022 experiment optical downlink experiment.

The results of these experiments show the improvement in the pointing of the transmit laser that the FSM fine pointing mechanism produces. The blind pointing of the spacecraft resulted in initial pointing errors that are roughly 6.5 times the angular beam divergence of the 1.3 mrad FWHM transmit beam. This amount of blind pointing error means the transmit laser would not have illuminated the optical ground station. Other terminals have used extended spiral or scan patterns to determine the correct angular offset of the transmit beam to the pointing system, which require multiple downlink attempts. The coarse angular correction the FSM provided enabled the optical ground station to be illuminated the second optical downlink attempt where the beacon was detected on the terminal. Once the coarse error was corrected, the FSM was able to maintain an average RMS pointing error of 0.175 mrad, well within the -3 dB pointing error value of 0.65 mrad. The FSM pointing error of the three experiments had mean pointing errors all less than 0.2 mrad and RMS error values between 0.115 and 0.214 mrad.

Low Drag Life Extension

The CLICK-A spacecraft was deployed from the ISS at an altitude of 414 km. During the mission there was an increasing amount of solar activity. The increase in solar activity causes the thermosphere to swell and increase the density of the atmosphere in lower Earth orbits. This increase in the density of the atmosphere led to the CLICK-A spacecraft orbit decaying faster than originally predicted. In the first 6.5 months of operations, the satellite was in a nominally sun-pointing mode, which oriented the spacecraft to have solar panels face the sun. This orientation could potentially allow the spacecraft to orient with the largest face of the spacecraft normal to the direction of the velocity of the satellite. This orientation causes the maximum amount of drag on the satellite and leads to faster rates of orbital altitude reduction. A low drag orientation was implemented to extend the lifetime of the satellite in mid-February 2022. Shown in Figure 11 is the altitude vs. time on orbit of the CLICK-A spacecraft.

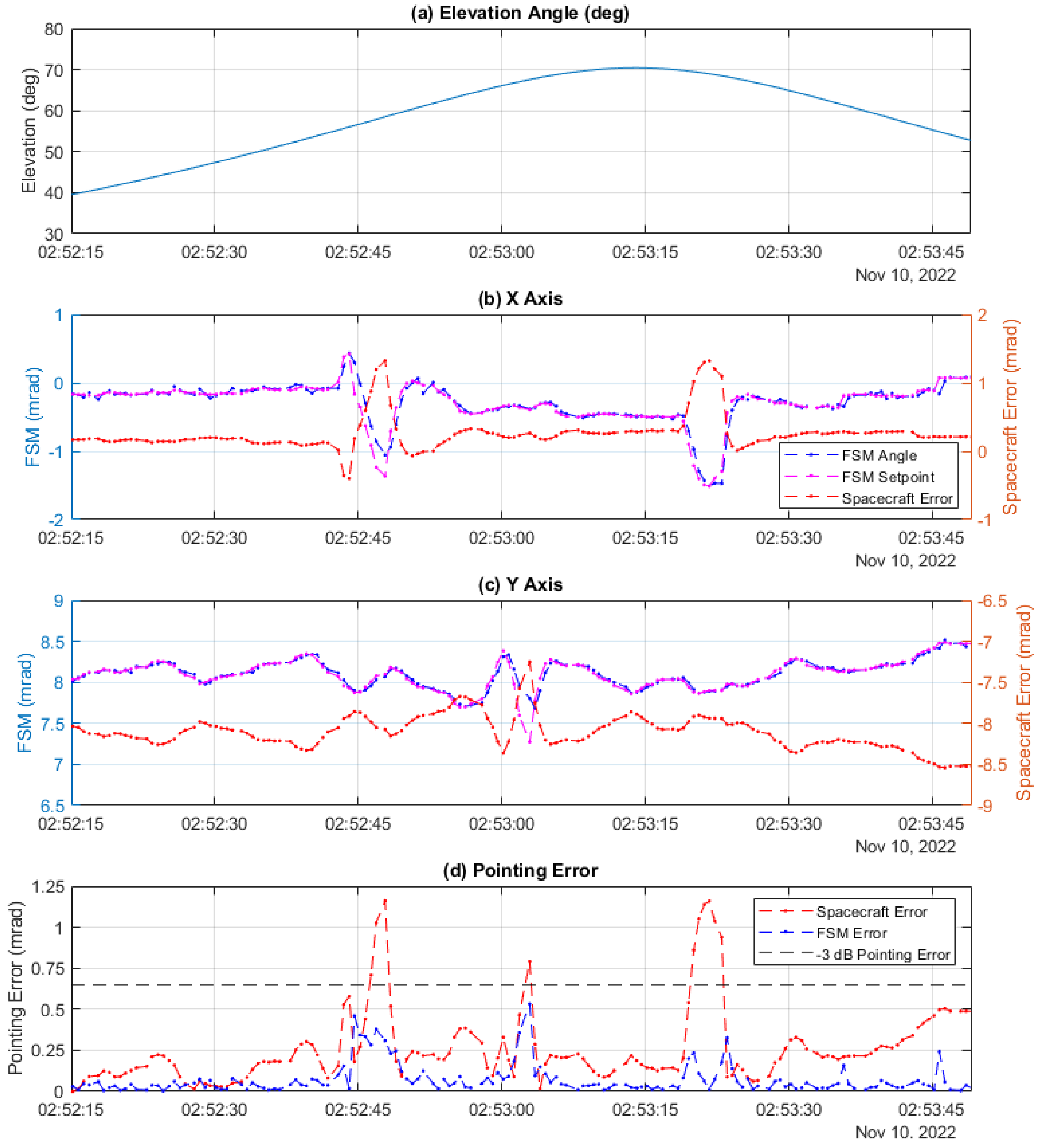

Figure 10: Pointing data over the beacon tracking time from November 10th, 2022 experiment. (a) Elevation angle of optical downlink experiment from acquisition of signal (AOS) to loss of signal (LOS) on the terminal beacon tracking camera. (b) FSM angle and spacecraft pointing error as measured on the X axis of the beacon tracking camera. (c) FSM angle and spacecraft pointing error as measured on the Y axis of the beacon tracking camera. (d) Spacecraft pointing error (after initial coarse angle removed) and total FSM error (difference between commanded angle and measured angle). The -3 dB line represents a 50% loss of power of the transmit beam.

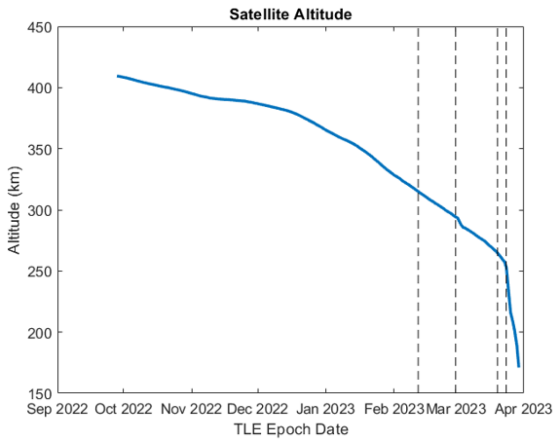

Figure 11: Altitude of CLICK-A spacecraft over mission lifetime.

The first vertical line corresponds to the initial implementation of this low drag orientation. The second and fourth lines denote times when the spacecraft entered safe-mode, which orients the spacecraft in a sun-pointing mode and led to significant reductions in altitude. The third line is when the terminal was disabled by a radiation-related event.

The B* term reported in a spacecraft TLE is used in the SPG4 propagator to estimate the atmospheric drag on a satellite. Shown in Figure 12 is the B* term over the mission lifetime of the CLICK-A mission.

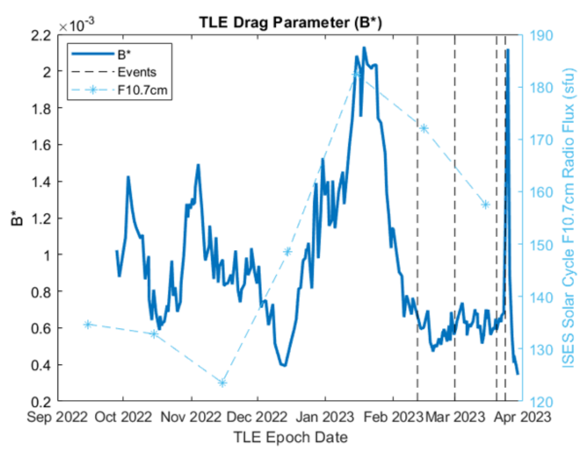

Figure 12: B* term of the CLICK-A two-line element set over mission lifetime.

The right Y-axis is tracking the F10.7 term, which is the solar radio flux at 10.7 cm (2800 MHz) and is a typical indicator of the activity of the sun. It can be see that the B* term generally increased in the presence of increased solar activity until the implementation of the low drag orientation in mid February 2022. It was noted that a sudden low drag orientation change caused delays in updates to the spacecraft TLE. A progressive change in orientation was pursued that allowed for updates to the TLE to continue to happen. These low drag operations lessons are useful for the CLICK-B/C mission as the range control between the satellites is maintained through differential drag orientations.

Conclusion

The CLICK-A mission is a risk reduction effort for the an optical communication crosslink mission, CLICK-B/C. Launched on July 15th, 2022 and deployed from the ISS on September 5th, 2022, the CLICK-A mission successfully demonstrated key technologies for the CLICK-B/C terminal over the seven month mission lifetime. Six optical downlink experiments were attempted with three partial successes. The MEMS FSM was able to correct for an average blind spacecraft pointing of 8.494 mrad and maintain average RMS pointing error of 0.175 mrad after initial blind pointing error correction. The FSM was able to demonstrate significant independent coarse and fine pointing error correction from its host spacecraft, a key enabler in wide-scale adoption of optical communications in small satellites. The low-cost optical ground station was able to acquire and track the transmit laser within the required pointing accuracy to maintain the signal on a 200 μm avalanche photodiode. Low drag operations were implemented to extend mission life and lessons from these operations provided valuable data on how changing satellite attitude can be used to alter the atmospheric drag force acting on the satellite. These lessons will be fed into the CLICK-B/C mission operations to maintaining range control between the two satellites.

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