On-orbit results of pointing, acquisition, and tracking for the TBIRD CubeSat mission

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ABSTRACT

Since launch in May 2022, the TeraByte Infrared Delivery (TBIRD) payload on a 6U CubeSat has successfully demonstrated 100/200 Gbps laser communications and has transferred >1 TB in a pass from low Earth orbit to ground. To support the narrow downlink beam needed for high rate communications, the payload provides pointing feedback to the host spacecraft to precisely track the ground station throughout the 5-minute pass. This paper presents the on-orbit results of the pointing and tracking system for TBIRD, including initial acquisition and closed-loop tracking performance of 20–35 μrad RMS per axis. Results from on-orbit characterization of the transmit beam are also presented. Measurements of Tx/Rx alignment show stability within 20 μrad, ensuring that tracking on the uplink accurately points the downlink.

Keywords: free-space optical communication, low Earth orbit, pointing, acquisition, tracking, cubesat

1. INTRODUCTION

The TBIRD payload launched in May 2022 as part of NASA's Pathfinder Technology Demonstrator (PTD) series. The primary goal of the TBIRD mission is to demonstrate large data volume transfer from low Earth orbit (LEO) to ground with high burst rates for short duration.[1,2] TBIRD leverages commercial off-the-shelf fiber transceivers in combination with an automatic repeat request (ARQ) protocol to deliver data error-free in the presence of atmospheric fading.

TBIRD also aims to demonstrate a novel pointing architecture for lasercom missions that relies on spacecraft body-pointing with payload feedback to achieve high precision. Precision pointing of the narrow downlink beam is necessary to support high rate communications. For most lasercom missions, precision pointing is achieved with multiple dedicated actuators. For example, the NICT Small Optical Transponder (SOTA) terminal established links from LEO-to-ground with gimbals and a fast steering mirror (FSM).[3] The NASA Lunar Laser Communication Demonstration (LLCD) and Laser Communications Relay Demonstration (LCRD) terminals each have gimbals, a magnetohydrodynamic stabilized platform, and piezoelectric fiber actuation.[4] The Tesat Laser Communication Terminals supporting the European Data Relay System (EDRS) each have gimbals and FSMs.[5] TBIRD benefits from shorter link ranges in LEO as compared to GEO or lunar distances, so the link can support a larger downlink beam. As a result, low pointing losses can be achieved using payload feedback without additional actuators.

Small satellite lasercom missions such as the Optical Communications Sensor Demonstration (OCSD)[6] on a 1.5U CubeSat and OSIRISv1[7] on a 110 kg bus have demonstrated LEO-to-ground lasercom links using open-loop body pointing with accuracy in the 100s of μrad. For the TBIRD mission, an order of magnitude higher pointing precision is achieved by closing a control loop between the spacecraft host and the TBIRD payload.

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Prior to the pass, the spacecraft points towards the ground station using its standard attitude determination sensors (star trackers, gyros, etc.). The ground station also open-loop points towards the spacecraft based on ephemeris provided prior to the pass and transmits an optical uplink. The TBIRD payload uses a quad cell to spatially track the uplink and receive low-rate (2 kbps) communications to implement the ARQ protocol. When the uplink signal is strong enough to provide valid pointing feedback, the bus closes a control loop around the payload feedback to improve pointing precision. Additional details on the pointing system design and pre-flight testing are provided in [8]. The pointing architecture demonstrated with TBIRD can support smaller transmit beams than an open-loop architecture without dedicated pointing actuators.

An image of the TBIRD payload prior to spacecraft integration is shown in Figure 1. The payload takes up approximately half of the volume on a 6U (10x20x30 cm^3) CubeSat bus supplied by Terran Orbital.

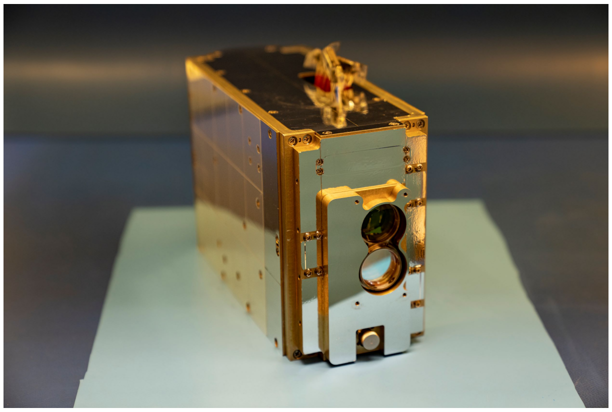

Figure 1. Image of the TBIRD payload (approximately 10x20x15 cm^3) taken prior to integration with spacecraft host. As pictured, the receive aperture is located below the transmit aperture.

In this paper, the term "tracking" refers to when observations of the target are used for closed-loop feedback. "Pointing" generally refers to when there is no target feedback, although this is a broadly-used term. It should be noted that all references to pointing or tracking in the context of TBIRD refer to a scenario where the spacecraft is dynamically targeting a location on the ground, as opposed to an inertial target such as a star. Pointing or tracking on a ground target from LEO generally presents a greater challenge for spacecraft attitude control than an inertial target due to the slew maneuver. For the TBIRD orbit, a maximum slew rate of about 0.8°/s is required.

The PTD-3 spacecraft hosting TBIRD was deployed on May 25th, 2022 into a 530 km sun-synchronous orbit. Since launch, TBIRD has demonstrated LEO-to-ground links up to 200 Gbps and transferred >1 TB of data in a 5-minute pass window. Tracking performance of 20–35 μrad root-mean-squared (RMS) per axis has been demonstrated (described in Section 3). The TBIRD transmit beam was characterized on orbit (described in Section 4) at 380 μrad full-width half-max (FWHM), so the demonstrated tracking accuracy results in typical losses of <0.1 dB during the mission.

The mission test campaign is ongoing and as of December 2022, 43 lasercom passes have been conducted. This paper presents results to date focusing on the spacecraft pointing, acquisition, and tracking results. Refer to [9] for results on communications performance.

2. INITIAL UPLINK AND DOWNLINK DETECTION

After spacecraft commissioning, lasercom operations commenced in early June and the spacecraft first detected uplink signal on June 11th. The downlink was first detected two passes later on June 24th. With reliable uplink and downlink tracking, the first large volume data transfer of approximately 500 GB was achieved on June 29th, 2022. In this section, results are presented on the observed payload boresight shift post-launch, as well as telemetry from the June 29th pass.

The TBIRD mission has utilized the Optical Communications Telescope Laboratory (OCTL) as its ground station, which is a NASA JPL facility located on Table Mountain in southern California. Further details on the use of OCTL to support TBIRD can be found in [10].

Approximately 30 minutes prior to a lasercom pass, the spacecraft downlinks ephemeris data to an RF ground station which is used to produce a two-line element set (TLE). The TLE is provided to JPL operators to inform the ground telescope pointing. The uplink transmitter and downlink receivers are operated by MIT Lincoln Laboratory personnel. After initial operations on-site at OCTL, the MIT LL team transitioned to remotely operating the transmit/receive hardware in coordination with JPL operators.

The first hurdle for any lasercom mission is to achieve an initial detection. For TBIRD to successfully detect the uplink, two steps are required: (1) the ground station must point the uplink accurately enough to illuminate the spacecraft and (2) the spacecraft must be pointed to within the TBIRD field of view (FOV).

The largest source of ground station pointing error is the TLE error. For each lasercom pass, a TLE is provided by the spacecraft operators just prior to the pass. The uplink beam width is sized at about 600 μrad full width at half maximum (FWHM) to accommodate initial ground station pointing error. Accuracy of the TLE can be assessed after the pass by comparing TLE-propagated position to spacecraft telemetry informed by on-board GPS. Figure 2 shows an example of TLE position error over the course of a lasercom pass and the resulting look-angle error from the ground station. The look-angle error depends on the spacecraft range and the direction of the position error, which tends to be along-track. As a result, the largest look-angle errors are seen at the peak of the pass.

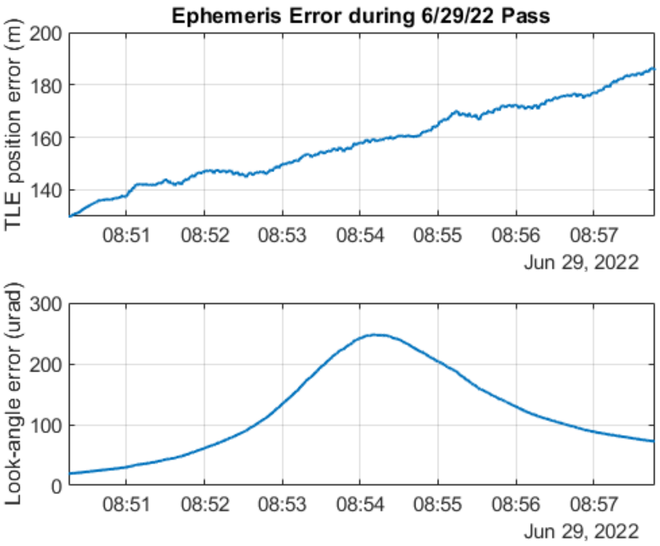

Figure 2. Orbit ephemeris error and resulting look-angle error for a pass on June 29th, 2022. The TLE was generated with spacecraft telemetry informed by on-board GPS 27 minutes before the pass.

Over the approximately 40 lasercom passes attempted thus far, TLE position error has ranged from 10–300 m with an average of about 125 m for TLEs propagated less than an hour. If the TLE is propagated longer than an hour, the error typically exceeds what is required for uplink detection, so a TLE based on recent ephemeris data is essential for successful operations. Once the downlink is detected, the ground station can track it to mitigate the TLE error. The acquisition process benefits from the fact that the look-angle error tends to be smaller at low elevation angles, and once the ground station is tracking on the downlink it can easily correct the TLE error through the rest of the pass.

Assuming the ground station is illuminating the spacecraft, the spacecraft pointing error must be within the FOV of the payload sensor for uplink detection to occur. The FOV of the TBIRD quad sensor was designed to be larger than the expected open-loop pointing error to enable instantaneous acquisition. The largest source of uncertainty was the payload boresight in the spacecraft body reference frame. The orientation of the payload line-of-sight must be known relative this frame for the spacecraft attitude determination and control system to accurately point the payload. While this can be measured on the ground, some shift due to launch is to be expected. As a contingency, a spiral scan was implemented in spacecraft software to be able search for the uplink in the event that open-loop pointing error exceeded the FOV of the payload sensor.

To reduce risk, the payload boresight was measured relative to the spacecraft body frame using a theodolite before and after spacecraft vibration testing. Figure 3 summarizes the measurements of payload boresight in the spacecraft frame. A shift of 0.22° was observed between the final measurement on the ground and the on-orbit boresight, likely due to mechanical shift caused by vibration during launch. The shift was within the FOV of the payload sensor so scanning for the uplink was not required. After uplink detection, the payload boresight vector was updated in the spacecraft software to improve open-loop pointing on subsequent passes.

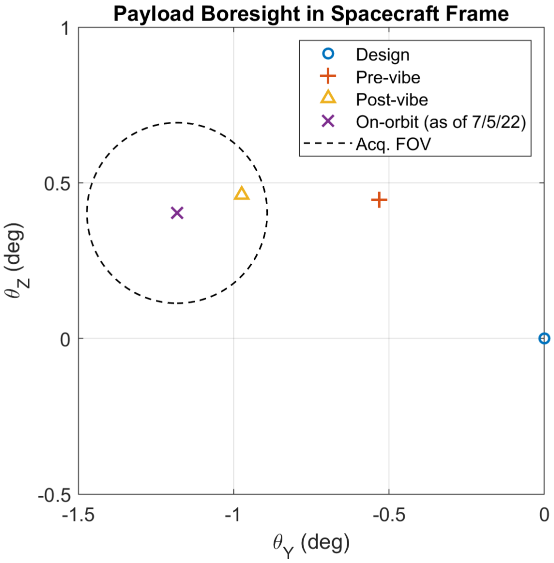

Figure 3. Payload boresight relative to the spacecraft body frame. The payload was designed to nominally align with the spacecraft +X axis, and payload alignment was measured before and after spacecraft vibration testing. The shift between the final alignment measurement on the ground and the on-orbit alignment was within the field of view of the TBIRD quad sensor, allowing instantaneous acquisition.

Downlink detection came two passes after uplink detection, once a polarity mismatch between the bus and payload was corrected. With the pointing, acquisition, and tracking sequence performing nominally, TBIRD was able to successfully achieve high-rate downlinks. Telemetry from the first high data volume pass on June 29th, 2022 is shown in Figure 4. Uplink power is first detected at 12° elevation, or a range of 1637 km. The TBIRD payload begins sending pointing feedback to the bus. After a pull-in time of about 20 seconds, the bus tracks the uplink signal to an accuracy of about 15 μrad RMS per axis. Once the bus has corrected its pointing, downlink power is detected at the ground station. The ground station first receives light on an acquisition camera and uses this information to correct the gimbal pointing. The accuracy of gimbal pointing depends on the accuracy of the TLE provided to track the spacecraft, but it is generally small relative to the uplink beamwidth. The gimbals steer the signal onto a wavefront sensor which is used for fine tip/tilt correction with a fast-steering mirror and higher order phase correction with deformable mirrors.[10] The adaptive optics system couples light into fiber to support communications.

The uplink power shown in Figure 4 is measured by the TBIRD quad sensor. There are several dips in power that can be observed in the profile. It has been determined that this is due to the uplink beams intersecting with the spiders holding the secondary mirror on the ground telescope. The uplink beams rotate at the telescope

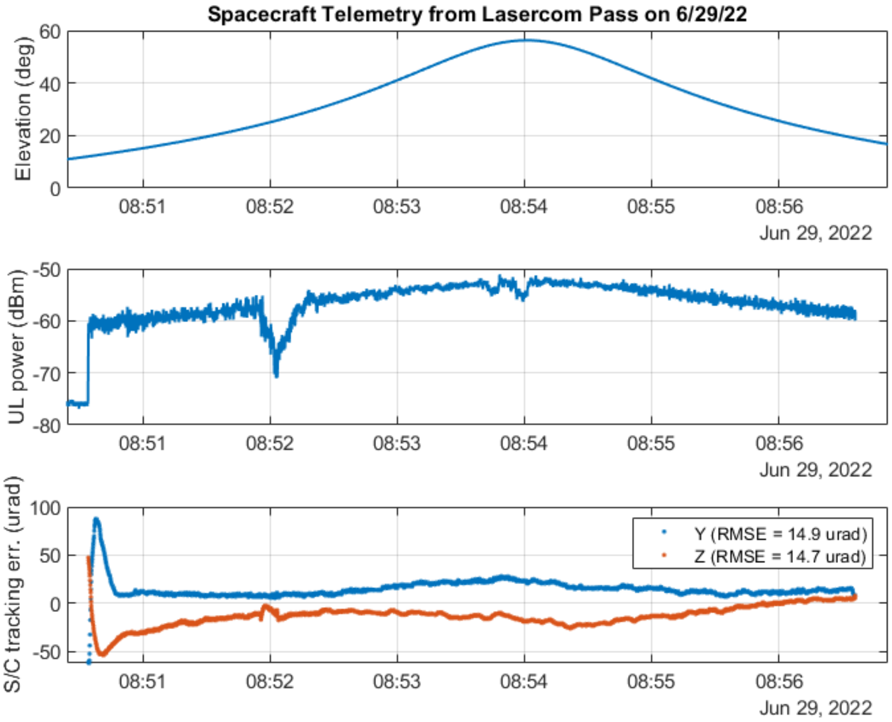

Figure 4. TBIRD telemetry of measured uplink (UL) power and tracking error from first high data volume downlink on June 29th, 2022. Approximately 500 GB of data was transmitted in 3 minutes. Initial uplink and downlink detection occurred at 12° elevation and both signals were tracked until the programmed end of pass at 20° elevation.

aperture as a function of azimuth and elevation angles of the gimbals due to the Coudé path, so at particular orientations spider interference can be observed in the uplink power received at the spacecraft. Given the large slew angles of a LEO pass, this is typically observed on every pass but it has not caused an uplink communications dropout or a loss of track.

The lower plot in Figure 4 shows the spacecraft tracking error during the pass. Tracking error throughout the pass remains small relative to the downlink beamwidth, in this case keeping pointing losses below 0.1 dB. It has been observed that the pointing error is dominated by a low frequency (<0.02 Hz) drift through the pass. It should be possible to reduce this error further with modifications to the closed-loop controller. Details on overall closed-loop tracking performance throughout the mission are provided in Section 3.

3. TRACKING PERFORMANCE

The data presented in this section covers 18 lasercom passes between 6/28/22 and 10/5/22. Passes that had atypical pointing experiments, inconsistent links due to poor weather, or other pass anomalies unrelated to the pointing system were excluded from the dataset. Three of the passes occurred in daytime and the remaining 15 were in eclipse. This dataset covers about 50 minutes of tracking sampled at 10 Hz. The initial 20 seconds after transitioning from open-loop (no payload feedback) to closed-loop tracking are excluded from the data to allows time for the error to settle.

Tracking in this context refers to the portion of a lasercom pass where the spacecraft has closed a control loop around the TBIRD payload feedback. The point-ahead angle and Tx/Rx offset must be added to the payload feedback in order to point the downlink. This calculation is performed by the spacecraft, and the resulting error signal is fed into a proportional-integral-derivative (PID) controller. The results presented in this section include the point-ahead angle and Tx/Rx offset, so they are a measure of downlink pointing error.

A histogram and cumulative distribution function (CDF) of closed-loop tracking error from these passes is presented in Figure 5. Looking at the two-axis CDF in Figure 5, 90% of the time two-axis error is below 60 μrad and 50% of the time it is below 30 μrad. The per-axis RMS error across all the passes is 35 μrad about the Y axis and 20 μrad about Z. Given the payload's downlink beamwidth of 380 μrad FWHM, the resulting pointing loss is 0.6 dB worst-case, and typically $<$0.1 dB. The tracking performance demonstrated on orbit could support a smaller downlink beam to deliver more power to ground on future missions. Improvements in tracking performance would allow for even smaller beams, further improving link efficiency.

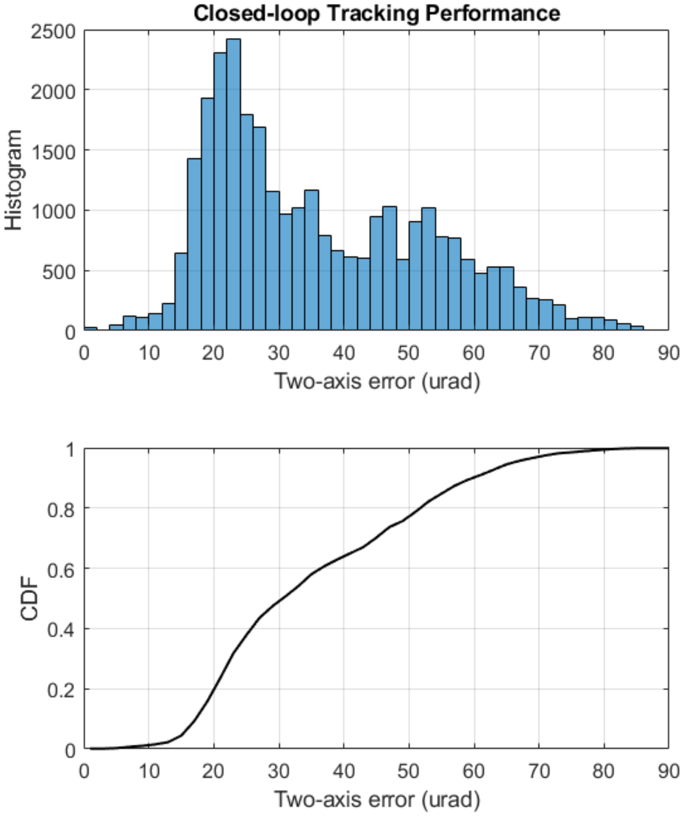

Figure 5. Closed-loop tracking performance during 18 lasercom passes between 6/28/22 and 10/5/22. The top plot shows a histogram of about 50 minutes of accumulated data collected at 10 Hz. The bottom plot shows a cumulative distribution function (CDF) of the aggregated data.

The control signal during closed-loop tracking consists of three components: a feedforward torque signal to drive the open-loop trajectory, a gyroscopic cancellation term, and a feedback correction based on the error measured by the payload. As can be seen in Figure 4, the tracking error is dominated by a low frequency ($<$0.02 Hz) drift that occurs throughout the pass. The low-frequency observed tracking error is consistent with errors in the feedforward or gyroscopic cancellation torques that the feedback correction is not fully compensating. Errors in the feedforward and gyroscopic cancellation torques could be due to a number of sources including inertia tensor uncertainty, reaction wheel misalignment, gyro scale factor error, gyro misalignment, etc. Improving tracking performance could be achieved by addressing these error sources directly or improving feedback control compensation of the error.

4. DOWNLINK BEAM CHARACTERIZATION

Two lasercom pass opportunities were used to perform a scan in order to characterize the transmit beam on orbit on 9/16/22 and 9/17/22. In these scans, offsets were injected into the payload pointing feedback to steer the bus through a grid pattern. The scale of this scan was approximately ±200 μrad in each axis. Power was measured at the ground and post-processed with spacecraft telemetry to get an estimate of the normalized downlink signal intensity. Range loss was compensated to isolate the effect of pointing loss. Results from one of these scans is shown in Figure 6.

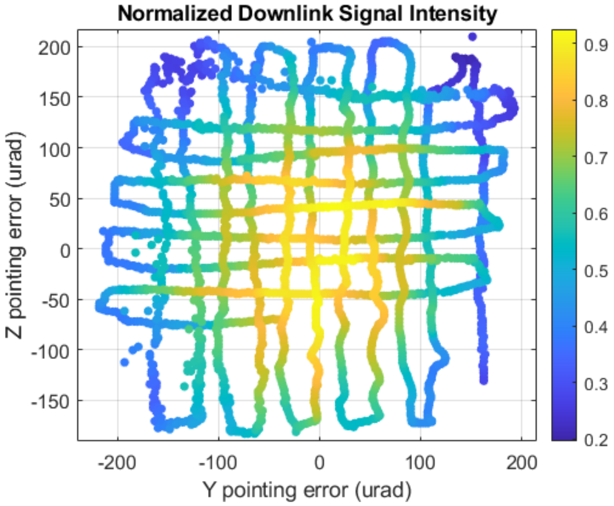

Figure 6. Normalized downlink power received during a grid scan performed by the bus on 9/16/22. A 2D Gaussian was fit to this data to yield an estimate of the payload Tx/Rx alignment as well as the Tx beam width of 380 μrad FWHM.

A 2D Gaussian was fit to the data shown in Figure 6 to estimate the Tx/Rx alignment as well as the Tx beamwidth. The beamwidth was measured to be about 380 μrad FWHM, although it has some asymmetry between the axes which was also observed in pre-flight measurements. The scan was repeated and the resulting estimate of beamwidth was consistent to within a few percent.

In addition to downlink beamwidth, the characterization scan provided a measurement of the Tx/Rx alignment. Tx/Rx alignment is an important consideration for bistatic lasercom terminals such as TBIRD that have separate transmit and receive apertures. The reason Tx/Rx stability is important is because it affects the downlink pointing error, and there is no means of directly observing it on orbit. The received signal is spatially tracked with an offset that consists of the point-ahead angle and a fixed Tx/Rx alignment offset. Ideally the Tx/Rx alignment offset would be zero, but machining and assembly tolerances inevitably impart a small alignment error. Measurements of Tx/Rx alignment on the ground indicated a $(10, -12)$ μrad receive-to-transmit misalingment that was incorporated into payload flight software. If the Tx/Rx alignment offset shifts from the predetermined value, this can result in mispointing of the downlink despite accurate tracking of the uplink.

A significant amount of design effort for the payload build focused on maintaining Tx/Rx stability, as described in 8. A major design challenge for TBIRD was mitigating thermal drift, since the payload tends to self-heat significantly during a lasercom pass. An "optical monolith" was designed to house the transmit and receive optics. The optical monolith was thermally isolated from the rest of the payload and constructed of titanium to minimize thermal gradients.

Measurements of Tx/Rx alignment were taken on the ground before and after payload vibration testing as well as in thermal vacuum testing. The transmit beam characterization scans performed on orbit provided additional measurements of Tx/Rx alignment on orbit. The measured Tx/Rx alignment from ground and on-orbit measurements are shown in Figure 7. The mean Tx/Rx misalignment is 15 μrad with a standard deviation of 10 μrad. The shift observed on-orbit relative to ground measurements is <20 μrad. The Tx/Rx offset can be modified in payload flight software to compensate for the shift, so the absolute magnitude of the Tx/Rx misalignment is not as critical as the stability of the misalignment over time.

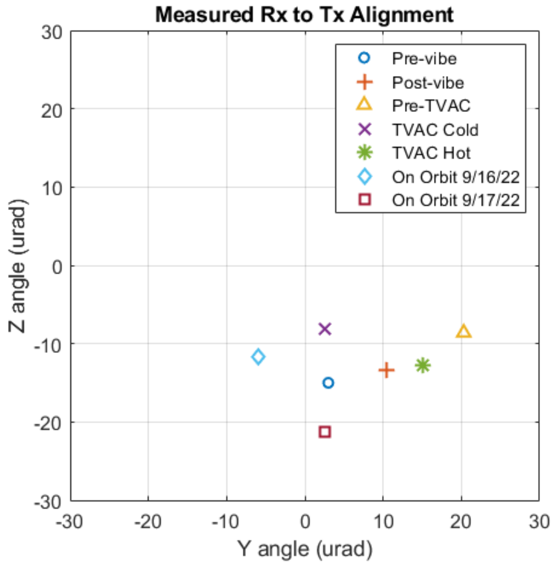

Figure 7. Measurements of transmit to receive boresight before and after launch. The mean Tx/Rx misalignment is 15 μrad with a standard deviation of 10 μrad.

The observed Tx/Rx alignment shift is small relative to our downlink beamwidth, as intended by design. By looking at component temperatures on-orbit, it is clear that the "optical monolith" is effectively thermally isolated from the self-heating components of the payload. Figure 8 shows component temperatures during a lasercom pass on 11/30/22. While the payload electronics experience significant heating of 15°C–35°C, the optical monolith heats by $<2°$C. This indicates that the thermal isolation of optical monolith is performing as designed and mitigating thermal effects on Tx/Rx alignment.

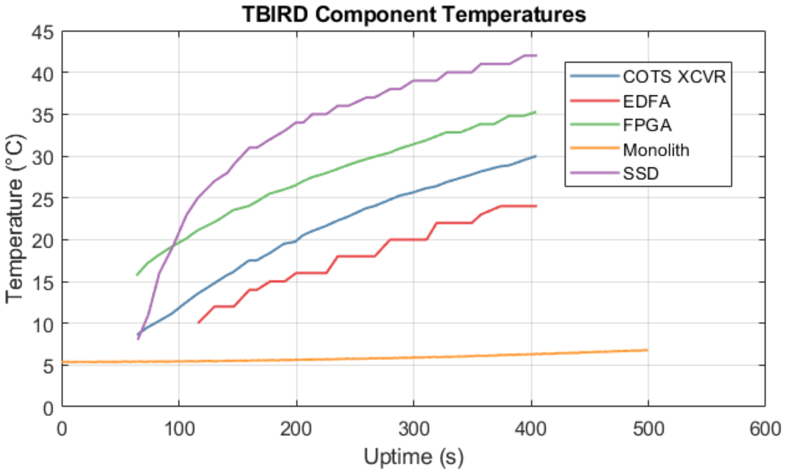

Figure 8. TBIRD component temperatures measured on orbit during a lasercom pass on 11/30/22. The commercial transceiver (COTS XCVR), erbium-doped fiber amplifier (EDFA), field programmable gate array (FPGA), and solid state drive (SSD) experience significant heating ranging from 15°C–35°C, while the optical monolith that houses the Tx and Rx optics heats by $<2°$C. The successful thermal isolation of the optical monolith supports Tx/Rx alignment stability.

5. CONCLUSION

Since launch in May 2022, the TBIRD mission has demonstrated 100/200 Gbps downlink rates from LEO to ground as well as data transfer exceeding 1 TB in a pass. In this work, initial on-orbit results were presented of the pointing, acquisition, and tracking performance of the system. Closed-loop tracking performance of 20–35 μrad RMS per axis has been achieved thus far, keeping typical pointing losses <0.1 dB for the 380 μrad FWHM downlink beam. Scans were performed on orbit to characterize the transmit beam on the payload which indicate that Tx/Rx alignment stability is within 20 μrad on-orbit. The demonstrated tracking accuracy and Tx/Rx alignment stability could support narrower beams on future missions.

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