Pointing, acquisition, and tracking for the TBIRD CubeSat mission: system design and pre-flight results

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ABSTRACT

The Terabyte InfraRed Delivery (TBIRD) program will establish a communication link from a nanosatellite in low-Earth orbit to a ground station at burst rates up to 200 Gbps. The TBIRD payload is currently in the process of integrating with the 6-U CubeSat host bus and pre-flight testing has been completed. An overview of the pointing, acquisition, and tracking system for TBIRD is provided as well as a summary of results from pre-flight testing. TBIRD relies on the spacecraft bus to implement fine pointing corrections supplied by its quad sensor at a rate of 10 Hz. The measured accuracy of pointing feedback is about 10 μrad RMS per axis. A custom optical assembly was designed for transmitter/receiver alignment stability which was measured to be within 25 μrad two-axis through environmental testing. With TBIRD feedback in the loop, single axis pointing accuracy of the downlink is predicted to be about 30 μrad RMS.

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

1. INTRODUCTION

The TBIRD mission aims to demonstrate a new optical communications system architecture that can deliver terabytes of data per day from a CubeSat in low-Earth orbit (LEO).[1–4] TBIRD utilizes commercial fiber telecommunications transceivers to achieve very high burst rates up to 200 Gbps from LEO to ground. A low-rate uplink is used for retransmission requests to enable error-free communications in the presence of atmospheric fading, and the uplink is also used to provide pointing feedback for the host spacecraft. The TBIRD payload is roughly 3U and is manifested on a 6U CubeSat as one of the NASA Pathfinder Technology Demonstrator missions. Figure 1 shows the high-level TBIRD architecture.

Laser communications (lasercom) terminals mounted on larger spacecraft typically include actuation stages such as gimbals or fast steering mirrors. For small spacecraft, size constraints make the addition of such actuators a challenge. Small satellite pointing performance has improved substantially in recent years and the ASTERIA mission showed that CubeSat bus pointing stability of <10 μrad is achievable.[5] 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 that a LEO-to-ground lasercom link can be established using open-loop body pointing. OCSD has a pointing accuracy of 419 μrad 3σ, and OSIRISv1 has a pointing requirement of 727 μrad. The TBIRD mission aims to demonstrate even more precise body pointing using closed-loop payload feedback.

The uplink is received by a quadrant photodiode on TBIRD and digitally processed. TBIRD pointing feedback is provided to the bus at 10 Hz that is accurate to 10 μrad RMS given sufficient signal, as described in Section 3. Based on results from simulation and integration testing as described in Section 4, a nominal downlink pointing accuracy of 30 μrad per axis is anticipated.

TBIRD is a bistatic system, so a major design consideration is to ensure that the transmit (Tx) and receive (Rx) boresights are stable and that any misalignment can be corrected. This is of particular concern due to the relatively high power draw of the payload (∼105 W at 200 Gbps downlink) that results in self-heating. While an earlier design called for a commercial off-the-shelf (COTS) Tx collimator, early thermal vacuum (TVAC) chamber testing found that the COTS collimator stability was not sufficient to support the mission. A custom Tx/Rx optical assembly was designed, as described in Section 2.2, that maintained a boresight stability of about

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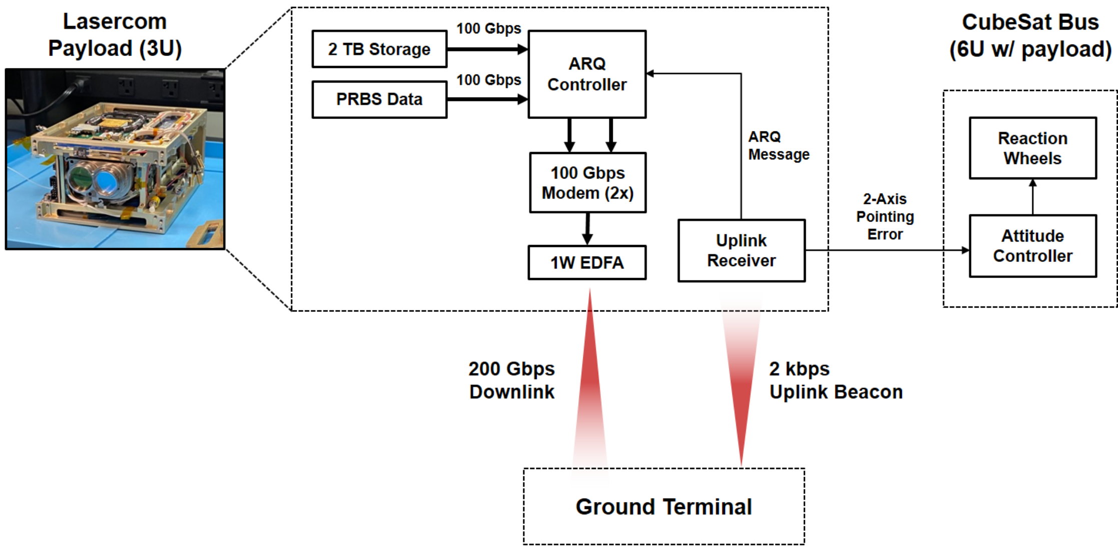

Figure 1. High-level block diagram of TBIRD mission. A combination of stored data and a psuedorandom binary sequence (PRBS) are transmitted on a 200 Gbps downlink. A 2 kbps uplink enables error-free transmission using an automatic repeat request (ARQ) protocol.

20 μrad in testing. To correct for unknown boresight misalignment on-orbit, an algorithm to optimize received power at the ground was implemented and tested on an engineering unit representative of flight hardware.

An overview and initial results of the TBIRD pointing, acquisition, and tracking system was provided in Ref. [8]. In this paper, we provide an update on the pointing system and results from testing of the flight unit. The organization of the paper is as follows: Section 2 describes the key design aspects of both hardware and software as they relate to pointing, Section 3 presents results from flight hardware testing, and Section 4 extends the test results to the anticipated overall downlink pointing performance.

2. POINTING SYSTEM DESIGN

2.1 Overview

The TBIRD architecture is aimed at supporting very high rate downlinks, up to 200 Gbps in the as-built terminal with scalability to higher rates in future systems. A low-rate 2 kbps optical uplink is used to implement a retransmission protocol and to provide closed-loop pointing feedback to the bus. During a lasercom pass, the bus will open-loop point towards the ground station. The TBIRD payload sensor has a field of view (FOV) larger than the expected open-loop pointing error of the bus. This enables uplink detection as soon as sufficient power is available, above approximately 20° elevation. Once the uplink is detected, the payload begins sending two-axis observed pointing error to the bus. The bus closes its control loops around the payload feedback to achieve precise pointing during the lasercom pass. Feedback is provided at 10 Hz and is accurate to about 10 μrad RMS per axis, which enables higher closed-loop bandwidth than is achievable with typical bus sensors.

TBIRD is a bistatic system with a 1.2 cm diameter transmit beam and a 2.3 cm diameter receive aperture. A bistatic design was pursued to reduce the size and complexity of the optical assembly and avoid the issue of Tx/Rx isolation, but the challenge of a bistatic design is to ensure Tx/Rx alignment stability. The lasercom components draw a significant amount of power and the payload tends to self-heat during a pass, which introduces the risk of thermally-induced misalignment. After determining that COTS collimators could not achieve sufficient stability over temperatures expected on orbit, the transmit and receive apertures were redesigned into a monolithic structure. To compensate for any Tx/Rx misalignment on orbit, TBIRD software includes a routine to optimize received power at the ground station. As TBIRD makes small pointing adjustments, the ground station measures received downlink power and communicates the measurement over the uplink. TBIRD uses these measurements to optimize power received at the ground station.

The receiver on TBIRD is a quad sensor that is used for both uplink communication and pointing information. There are three main requirements on the quad sensor: (1) to provide a full FOV large enough to support acquisition given open-loop bus pointing error, (2) to supply low-noise angle measurements to enable precision pointing, and (3) to have a tracking FOV large enough to support point ahead offset and Tx/Rx boresight offset. The tracking FOV refers to the angles over which the quad sensor is not spatially saturated, and it is substantially smaller than the full FOV of the quad sensor. The quad sensor can be moved out of focus to increase the spot size and therefore the tracking FOV at the expense of added noise, which was a design trade for the system. On the flight unit, the quad sensor has a full FOV of $\pm 0.25°$ with the quad sensor positioned slightly off of focus to produce a tracking FOV of ± 250 μrad.

2.2 Optical Assembly

The primary consideration in the design of a custom optical assembly was to minimize Tx/Rx boresight misalignment and drift, and in particular thermal drift. This is critical to the overall pointing performance, and this section describes the key design aspects of the assembly. Measurements on the flight unit showed <25 μrad boresight misalignment through environmental testing as described in Section 3.1.

The TBIRD optical assembly consists of two optical paths, Tx and Rx, shown in Figure 2. Components are mounted into a singular titanium housing, which is referred to as the 'optical monolith'. Grade-4 titanium was chosen as the material for the optical monolith due to its relatively high thermal conductivity and its coefficient of thermal expansion (CTE) match with the N-LAK12 optical glass used for the lenses. A titanium grade with higher thermal conductivity was chosen to reduce potential thermal gradients. In order to athermalize the optical assembly, radial bond-line thicknesses were determined through analysis to match polymer expansion with the gap resulting from differing lens and barrel expansion.

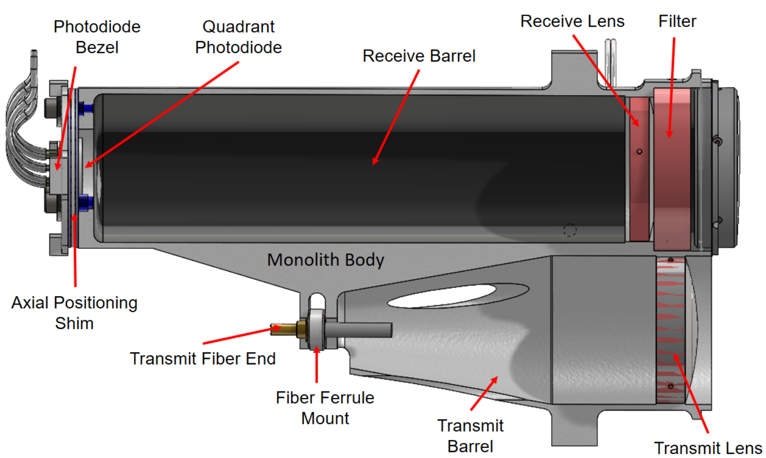

Figure 2. Side view of TBIRD optical assembly with components labeled.

In addition to the selection of a titanium grade with relatively high thermal conductivity, two other specific strategies were employed to reduce any potential thermal gradients across the optical monolith as shown in Figure 3. First, a large amount of thermal mass was designed into the shape of the titanium monolith body at the point where it mounts to the chassis. The large flange-shaped feature which runs across the entire width and height of the monolith is designed to provide a large thermally conductive path between the three mounting points of the monolith.

The second strategy was to place thermally-insulating Garolite shims between the three mounting points of the monolith and the chassis to which they mount. These thermal shims reduce the amount of heat that can be conducted into or out of the optical monolith. The flexural design of the three mounting points of the optical

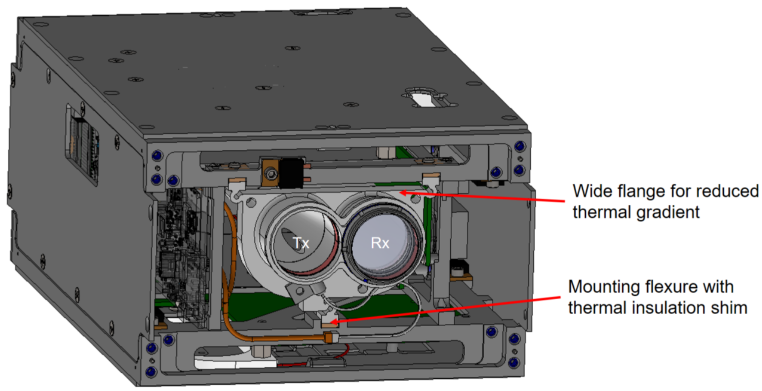

Figure 3. TBIRD optical assembly mounted in the chassis.

monolith are primarily to accommodate differences in thermal expansion between the titanium monolith and the aluminum chassis.

2.3 Software

The pointing software on TBIRD is responsible for acquiring samples from the quad sensor and demodulating the uplink signal to determine the location of the signal on the quad sensor. TBIRD signal processing for the pointing system is performed on a COTS rad-hard microcontroller, and higher-level communications processing is performed on a field programmable gate array (FPGA).

While the microcontroller has the advantage of using very little power, it also has very limited processing resources. An earlier design (see Ref. [8]) called for a binary pulse position modulation scheme with dead time inserted for signal synchronization. This scheme baselined 10 samples per slot at asynchronous fixed intervals, and the time required to process each sample on the microcontroller made it infeasible. To reduce the sampling rate, the software was modified for synchronous sampling at 2 samples per slot. On the flight unit, the slot rate is set at 4 kHz to support a 2 kbps uplink.

The microcontroller software computes a discriminant which is mapped to pointing feedback with a lookup table. Pointing feedback is averaged and provided to the bus at 10 Hz, along with flags indicating if the feedback is valid (sufficient signal and synchronization) and spatially saturated in each axis.

In the event that the Tx/Rx misalignment on-orbit is larger than anticipated, a routine for pointing optimization using feedback from the ground station has been implemented and tested. TBIRD will inject an additional pointing offset into the bus feedback and the ground station will use the optical uplink to communicate measured power at fixed time intervals. Tx pointing can be optimized based on observed power at the ground.

3. TEST RESULTS

3.1 Tx/Rx Boresight Alignment

The Tx/Rx boresight alignment is a critical consideration for TBIRD because any unknown misalignment will contribute directly to Tx pointing error. If the misalignment is known, it can be compensated for with offset tracking of the received signal.

To measure the boresight, a collimated source and camera are aligned to each other using a retroreflector. The quad sensor on TBIRD is then aligned to the collimated source with an adjustable fold mirror. TBIRD's transmitter is turned on and its position is measured on the camera to produce boresight misalignment.

In addition to static boresight misalignment due to mechanical tolerances, a major concern is dynamic boresight misalignment due to thermal effects. The TBIRD payload heats up significantly during a 5-minute lasercom pass. To understand the effect of environmental conditions on boresight misalignment, the Tx/Rx

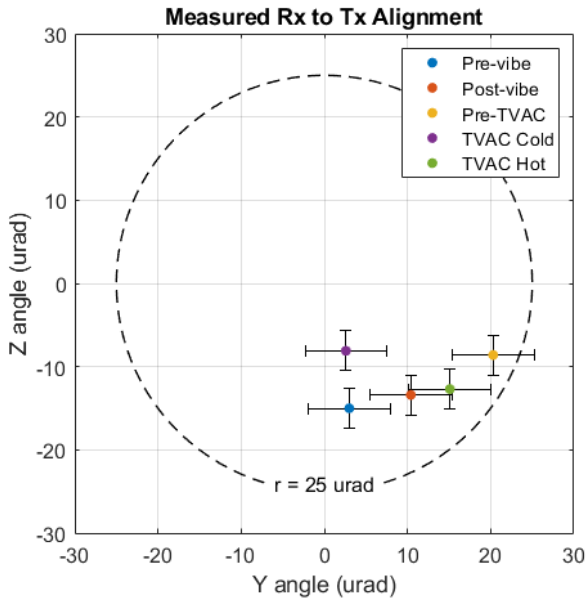

Figure 4. Tx/Rx alignment measurements before and after vibration testing and during thermal vacuum testing. Error bars shown are 1σ measurement noise. The measurement average is (10, -12) μrad Rx to Tx misalignment. All measurements are within 25 μrad misalignment.

alignment was measured throughout the environmental test process, including pre- and post-vibration testing and at cold and hot conditions during TVAC. These measurements are shown in Figure 4.

The average misalignment from Rx to Tx was (10, -12) μrad, and the maximum difference between two measurements was 18 μrad, which may be within the measurement accuracy of the testbed. The boresight stability measured on the ground leaves margin for additional misalignment to be accommodated on orbit.

3.2 Quad Sensor Field of View

The full FOV of the quad sensor defines the open-loop bus pointing error that TBIRD can accommodate during acquisition. To measure the FOV, a large grid scan was performed with a fast steering mirror (FSM). Figure 5 shows the power measured on the quad sensor sensor cell relative to peak. The signal begins to drop off just beyond the design FOV of $\pm 0.25°$ but is detectable out to $\pm 0.4°$ if sufficient power is supplied.

Sources of open-loop pointing error include mechanical/thermal payload shift relative to the bus, ephemeris error, external torque disturbances, sensor noise, and actuator limitations. The payload Rx boresight will be measured relative to the spacecraft body frame prior to launch once integrated into the host spacecraft. It is expected that the open-loop pointing will be sufficient to acquire without needing to search, but a search scan has been developed and tested if needed on orbit.

3.3 Quad Sensor Pointing Measurements

TBIRD uses a quad sensor to receive the uplink signal and provide pointing feedback to the bus. The discriminant describes the location of the signal in two axes on a normalized scale, and a mapping converts the discriminant to an angle measurement. The quad sensor is intentionally defocused to produce a larger spot on the sensor and therefore a larger tracking FOV.

To generate the discriminant mapping, a fast steering mirror scans a grid across the quad sensor with short dwells at each point. An autocollimator records the FSM tip/tilt position to provide a "truth" angle that must be scaled and de-rotated to match the quad sensor axes. The grid scan was performed in TVAC across multiple power levels and different thermal conditions to emulate the orbital environment.

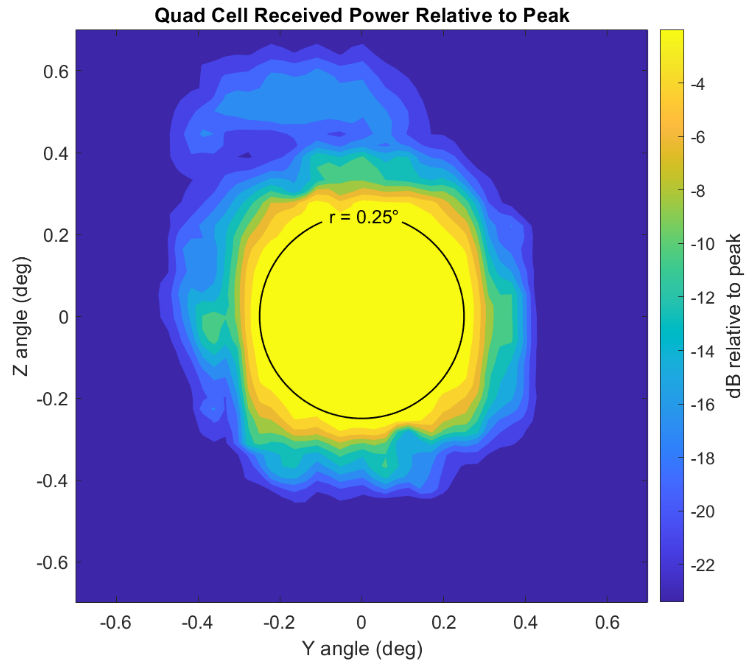

Figure 5. Results of a large scan performed to determine the quad sensor field of view. Power relative to peak (-54 dBm) is shown and the desired FOV of $\pm 0.25^{\circ}$ is achieved.

Figure 6 shows data from 9 scans (5731 points) taken across these conditions that was used for mapping the discriminant to output angle space. The cross-boresight axes are defined as Y and Z by convention to match the spacecraft body frame. The mapping is a linear, piecewise function that spans [-237, 289] μrad in Y and [-286, 237] μrad in Z. TBIRD must support offset tracking to compensate for the point ahead angle (maximum of 50 μrad for a 500 km orbit) as well as any Tx/Rx boresight misalignment. The measured Tx/Rx boresight misalignment was within 25 μrad as described in Section 3.1. This leaves at least 160 μrad of FOV margin to account for any launch-induced misalignments, on-orbit thermal effects, and bus pointing error.

The accuracy of the fit was 6.1 μrad root-mean-square (RMS) in Y and 5.1 μrad RMS in Z. The mapping was assessed against independent datasets at different power levels, shown in Figure 7. There is increased noise at -72 dBm, which is approximately the minimum operational power for the system. The effects of signal saturation begin to appear at -54 dBm as the error shows some structure. Error tends to increase near the edges of the discriminant map where spatial saturation occurs.

Within the desirable signal power range, the expected accuracy of the TBIRD pointing angle feedback is about 10 μrad RMS per axis. Feedback is provided at 10 Hz, but the closed-loop pointing bandwidth of the bus is $<$1 Hz which allows additional noise to be filtered out from the TBIRD feedback.

The discriminant mapping was evaluated against a simulated fade profile applied to the uplink signal, which was found not to have a significant affect on performance. It was found that reading out from the solid state drives (SSDs) significantly increases noise on the quad sensor due to electrical interference. In 200 Gbps communications mode, the uplink is required to supply at least -60 dBm power to overcome the additional noise from the SSDs. Between -60 dBm and -54 dBm the performance is consistent with the results shown in Fig. 7. This limited dynamic range can be accommodated by adjusting the uplink power during a pass.

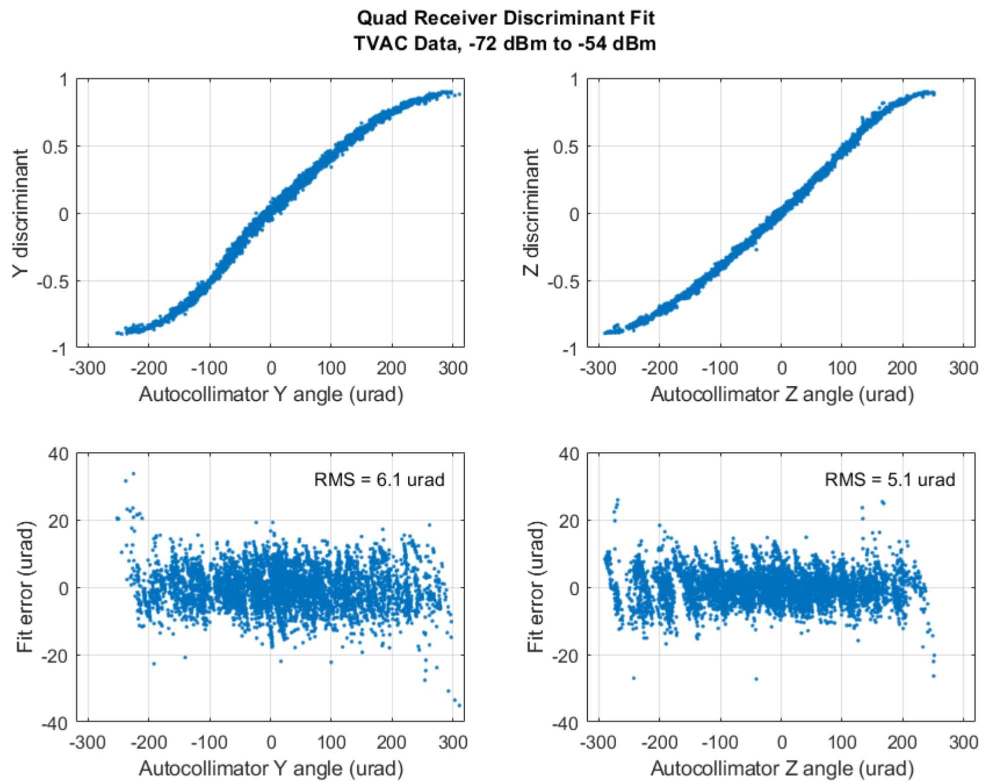

Figure 6. Results of fitting the quad sensor discriminant measurement to truth angles measured by an autocollimator. The normalized discriminant measurements (top left, top right) are fit with a piecewise linear function to produce a mapping to angles. The fit error (bottom left, bottom right) is 6.1 μrad RMS in Y angle, and 5.1 μrad RMS in Z angle.

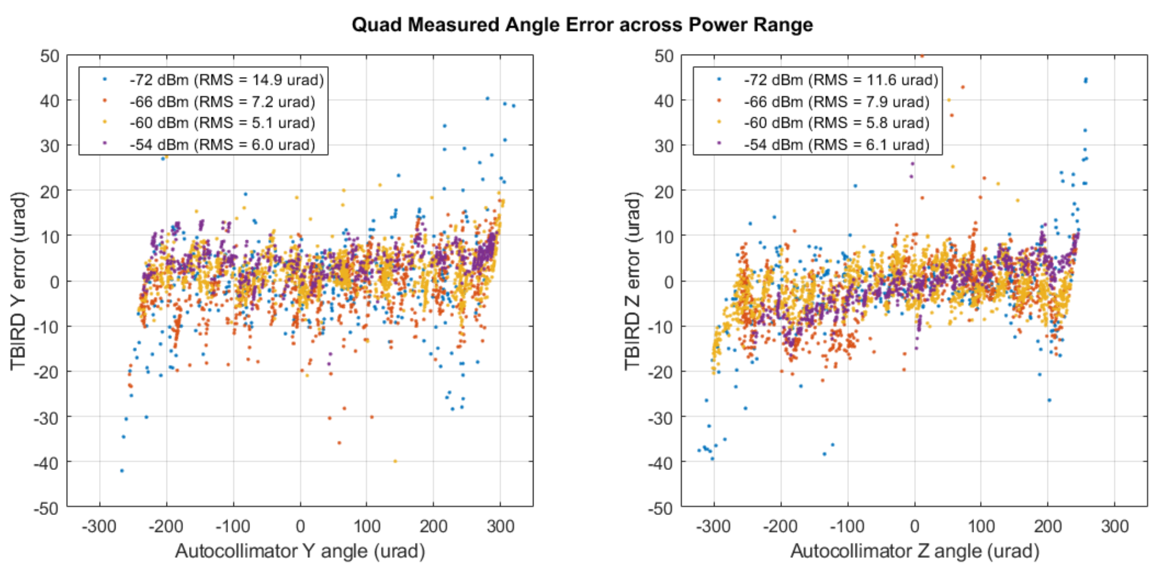

Figure 7. The accuracy of measured pointing angles is assessed against grid scans ranging in power from -72 dBm to -54 dBm. At -72 dBm, noise is increased and bias error begins to appear at the edges of the linear field of view. At -54 dBm, bias begins to appear due to saturation of the quad sensor.

4. PREDICTED POINTING PERFORMANCE

4.1 Bus Pointing Simulation

In the early phases of mission development, a time-domain simulation was developed in MATLAB Simulink to model the overall pointing performance of a generic 6U CubeSat bus. This helped to define pointing requirements and specifications for the bus. The results presented in this section are intended to give a sense of expected performance on a generic 6U CubeSat bus, but the final pointing analysis for the TBIRD mission was performed by the bus vendor and is not included here.

An example pass with a maximum elevation of 80° for a 500 km orbit is simulated. TBIRD feedback is made available to the bus at 20° elevation. Prior to the availability of TBIRD feedback, open-loop bus pointing is achieved with typical bus attitude determination and control sensors. When TBIRD feedback is available, it feeds directly into the controller to replace the error estimates from the attitude filter. TBIRD provides a measurement of pointing error in the cross-boresight axes, and the third axis is supplied by the attitude filter. The controller bandwidth for the cross-boresight axes is increased to 0.15 Hz when TBIRD feedback is available.

Sources of error in the simulation include payload boresight misalignment, sensor noise, sensor misalignments, inertia knowledge error, reaction wheel misalignments, and torque quantization. Figure 8 shows a time series of pointing error for the simulated pass. When TBIRD feedback becomes available, the bus closes its controller around the TBIRD feedback and achieves 13.5 μrad and 7.1 μrad RMS in Y and Z. Error is dominated primarily by actuator limitations, in particular the quantization of applied torque. This also results in one axis outperforming the other, since the axis with a lower moment of inertia (in this case, Y) is more affected by the limitations on torque resolution.

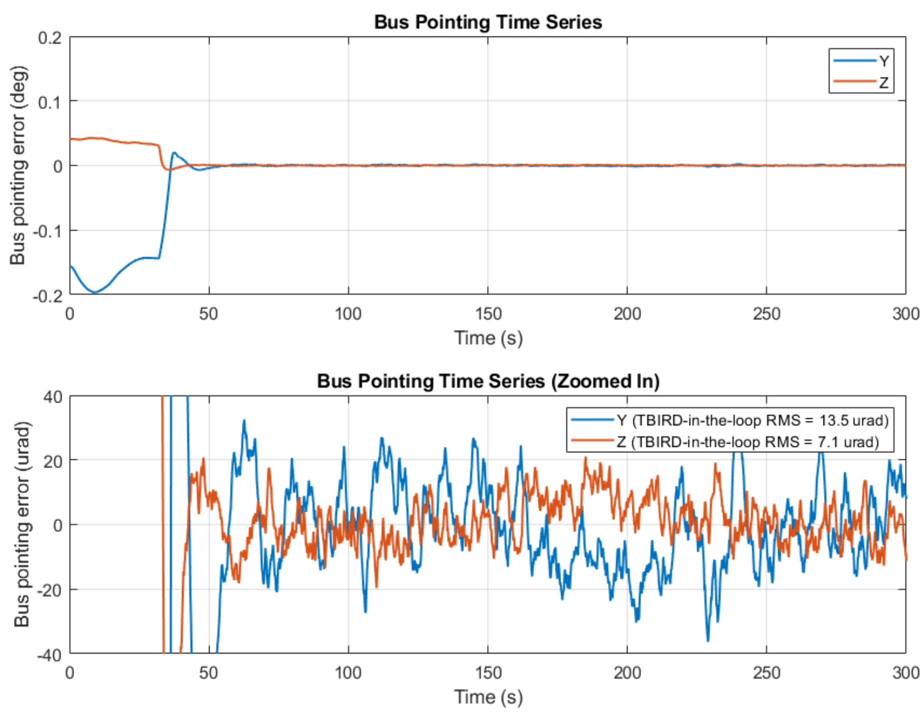

Figure 8. Time series of pointing error in a simulated lasercom pass. TBIRD feedback is made available at 20° elevation, or approximately 35 seconds into the simulation. The bus pulls in on the signal and settles in about 20 seconds to achieve a closed loop RMS error of 13.5 μrad in Y and 7.1 μrad in Z.

Based on Monte Carlo simulation, the expected bus pointing accuracy is approximately 15 μrad RMS in the worse-performing axis. To validate the simulation, an integrated flat-sat test was performed with engineering units of the payload and spacecraft bus. Detailed results from that test are not covered here, but performance was consistent with the simulation predictions.

4.2 Expected Downlink Pointing Accuracy

Based on the results presented in Section 3, some predictions can be made about expected on-orbit pointing accuracy. Table 1 summarizes the expected contributions to Tx pointing error.

Table 1. Expected contributions to Tx pointing error based on pre-flight testing.

Error Source	**Nominal Contribution, 1-axis (μrad)**
Unknown static Tx/Rx misalignment	15
Thermal Tx/Rx misalignment	15
Rx sensor bias	10
Bus pointing error	15
Root-sum-squared (RSS)	28

The first two error sources related to Tx/Rx alignment are informed by measurements from Sec. 3.1. The unknown static Tx/Rx misalignment is a combination of measurement error on the ground and launch-induced misalignments. The pre-/post-vibe shift observed on the ground was within the measurement error of the testbed, so this term is dominated by limitations of the measurement. The thermal Tx/Rx misalignment as measured through TVAC did not show a large shift, and is also bounded by the measurement error of the testbed.

The Rx sensor bias is informed from Sec. 3.3. The effect of sensor noise is captured in the bus pointing error term in Table 1, but any bias in the Rx sensor will be implemented by the bus. While the error is zero-mean in ideal conditions, at high/low power conditions some bias appears, which increases towards the edges of the tracking FOV.

The bus pointing error carries the most uncertainty, since it is informed primarily by simulation and testing on the ground. One of the aims of the TBIRD mission is to characterize what body pointing performance can be achieved with precise pointing feedback.

While the Rx pointing accuracy can be observed directly with the TBIRD quad sensor, the Tx pointing accuracy can only be observed indirectly based on received power at the ground. The as-built Tx divergence was measured as 450 μrad full-width half-max. Pointing losses for the mission are expected to be <0.5 dB worst-case. An earlier design (see Ref. [8]) called for a diffraction-limited 130 μrad Tx divergence, which the predicted pointing accuracy would be able to support.

5. CONCLUSION

The TBIRD mission aims to demonstrate 200 Gbps downlink from LEO to ground. This paper described the major aspects of the pointing, acquisition, and tracking system for TBIRD and presented results from testing of the TBIRD flight unit prior to delivery. TBIRD relies on the spacecraft host to body point the downlink and provides precise pointing feedback from the uplink signal. From pre-flight testing, the measured accuracy of TBIRD pointing feedback is about 10 μrad RMS per axis. To maintain Tx/Rx boresight stability, a custom optical assembly was designed that maintained <25 μrad two-axis alignment through environmental testing. With TBIRD feedback in the loop, one-axis pointing accuracy of the downlink is predicted to be about 30 μrad RMS, which keeps pointing loss below <0.5 dB. The TBIRD payload has been delivered for integration with the host spacecraft and is scheduled to launch in June 2022.

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