Operations and Results from the 200 Gbps TBIRD Laser Communication Mission

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ABSTRACT

Since launch in May 2022, the TeraByte Infrared Delivery (TBIRD) mission has successfully demonstrated 200 Gbps laser communications from a 6U CubeSat and has transferred up to 4.8 terabytes (TB) in a pass from low Earth orbit to ground. To our knowledge, this is the fastest downlink ever achieved from space. 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. The space and ground terminals utilize fiber-coupled coherent transceivers in conjunction with an automatic repeat request (ARQ) system to guarantee error-free communication through an atmospheric fading channel. This paper presents an overview of the link operations and mission results to date, as well as implications for future missions with high rate lasercom.

INTRODUCTION

Satellites in low Earth orbit (LEO) are generating unprecedented amounts of data. Remote sensing applications such as synthetic aperture radar (SAR) and hyperspectral imaging can generate enormous amounts of raw data. NASA's Surface Water and Ocean Topography (SWOT) satellite (2200 kg) currently in orbit will generate 20 TB of raw data per day, which is reduced to 1 TB per day through onboard processing [1]. The NASA-ISRO Synthetic Aperture Radar (NISAR) mission, a 2800 kg satellite planned to launch in 2024, will downlink 4.8 TB of data per day [2]. The Hyperspectral Imager Suite (HISUI) currently installed on the International Space Station (ISS) generates 300 GB per day, which exceeds the ISS downlink capacity and is instead stored on drives and transported via cargo ship [3].

Smaller satellites show this trend as well. The ICEYE constellation with 16 satellites (85 kg) on orbit generates image products up to 3.4 GB per 10-second dwell [4], which would exceed a terabyte per day with a 5% duty cycle. JPL's RainCube, launched in 2018, captured raw data at 425 Mbps and used extensive onboard processing to reduce by four orders of magnitude to downlink [5]. HyperScout, first demonstrated on orbit in 2018, can generate a terabyte of raw data per orbit that requires significant onboard processing to downlink [6, 7].

As small satellites continue to grow in numbers and in capability, increasing demand for downlink capability will be challenging to meet with radio frequency (RF) alone [9]. Laser communication (lasercom) offers the

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advantages of highly directed beams and large spectrum availability. The available spectrum can support very high data rates >100 Gbps per channel that are simply not achievable via RF. In comparison, highly capable space-to-ground RF links operate on the order of Gbps [10]. Very high rate optical channels are routinely used in terrestrial fiber telecommunications networks and this industry continues to drive optical transceiver technology towards lower power, smaller form factor, and higher rate.

The goal of NASA's TBIRD mission is to demonstrate a link architecture that supports very high rate (>100 Gbps) space-to-ground communication [11]. This architecture is enabled by several key commercial off-the-shelf (COTS) technologies, including two 100-Gbps fiber transceivers and terabyte-class buffers capable of high speed readout. The TBIRD architecture is shown in Figure 1 and has been described in detail in Ref. [12]. TBIRD can downlink in 100-Gbps or 200-Gbps modes.

The downlink utilizes coherent transceivers developed for fiber telecommunications networks. The transceivers operate in the 1.5-um band with dual-polarization quadrature-phase-shift-keyed (QPSK) waveforms along with soft-decision forward error correction (FEC) to achieve power-efficient error-free operation in static fiber channels. A common technique for atmospheric mitigation is to interleave FEC codewords to achieve temporal diversity, but this was not possible with the TBIRD architecture because the codeword encoding and decoding is implemented internal to the black-box COTS transceivers. A key part of the system architecture is an automatic repeat request (ARQ) protocol that guarantees error-free data transmission in the presence of atmospheric fading and is suitable for implementation external to the COTS transceiver [13]. Even though LEO-to-ground contact times are <10 minutes in duration, a 100-Gbps link enables terabytes of data to be transferred in a single pass.

The payload is approximately 3U in volume and draws up to 100 W of power while downlinking at 200 Gbps. A low-rate uplink received by the payload is used for spatial tracking of the ground terminal and implementation of the ARQ protocol. The payload relies on the spacecraft to body-point and provides feedback at 10 Hz for the bus to track. NASA JPL's Optical Communication Telescope Laboratory (OCTL) facility is the ground station for the TBIRD mission [14]. OCTL has a 1-m telescope with adaptive optics to couple signal into single-mode fiber.

The TBIRD payload is hosted by the Pathfinder Technology Demonstrator 3 (PTD-3) 6U CubeSat supplied by Terran Orbital. On May 25th 2022, the TBIRD payload was launched to a 530-km sun-synchronous orbit. Initial results of on-orbit performance can be found in Refs. [8, 15]. As of May 2023, the mission has operated over 60 passes, has a achieved an end-to-end error-free throughput of 200 Gbps, and has transferred up to 4.8 TB in a single pass. To our knowledge, TBIRD has demonstrated the fastest downlink ever achieved from space.

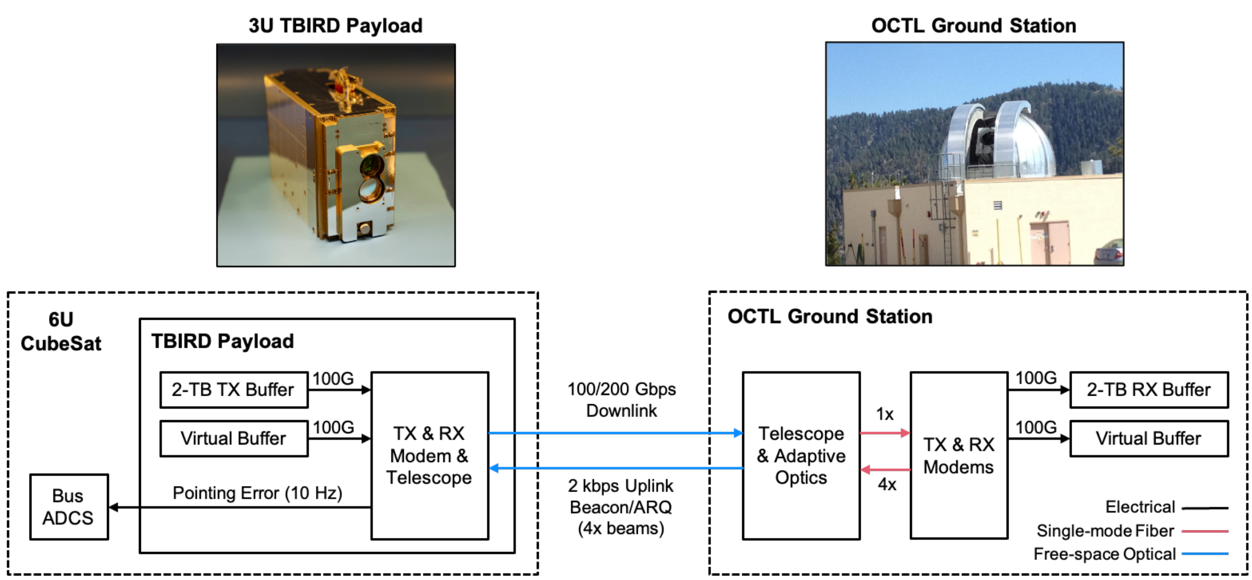

Figure 1: *TBIRD architecture from Ref. [8]. TBIRD enables buffer-to-buffer transfer from LEO-to-ground over a 100 or 200 Gbps downlink. A low-rate optical uplink supports an automatic repeat request (ARQ) protocol to ensure error-free data delivery and also serves as a beacon for spatial tracking to provide pointing feedback to the spacecraft bus.*

OPERATIONS

Summary

After launch in May 2022, within a month lasercom operations were running smoothly. TBIRD operated from June–November 2022 to complete its nominal 6-month mission and resumed in April 2023 for extended operations. Given the sun-synchronous orbit, passes occur at a local time of approximately 2AM or 2PM which allowed for both nighttime and daytime lasercom experiments.

In the 6-month nominal mission, 43 lasercom passes were executed. Nighttime passes were prioritized given that atmospheric turbulence is typically less than in daytime, allowing for better signal coupling into fiber. Of the 43 lasercom passes, 29 were nighttime passes and 14 were daytime. After the 6-month mission, payload health and status checkouts were performed weekly until operations resumed in April 2023. During extended operations 25 lasercom passes are planned which are ongoing as of this writing.

Improvements in ground station coupling into fiber have resulted in better link performance compared to what was reported in Ref. [8]. The highest data volume passes are summarized in Table 1. The maximum elevation of these passes ranges from 57° to 86°, and large data volumes have been achieved in both daytime and nighttime conditions.

Table 1: *Summary of passes with highest data volume delivered. The maximum elevation of the pass, whether the pass was during daytime or nighttime, and total data volume delivered are reported.*

Date	Elevation	Day/Night	Data Volume
05/17/2023	82°	Night	4.8 TB
04/28/2023	63°	Night	3.6 TB
05/14/2023	57°	Day	3.4 TB
05/11/2023	70°	Day	3.1 TB
05/08/2023	86°	Day	2.9 TB
05/07/2023	61°	Night	2.2 TB
05/02/2023	59°	Day	1.9 TB
04/24/2023	60°	Night	1.8 TB
04/21/2023	82°	Night	1.5 TB
04/25/2023	82°	Day	1.4 TB

Pass Timeline

The typical timeline for a lasercom pass is shown in Figure 2. At least 6 hours before the pass, MIT LL engineers provide a script to Terran Orbital engineers that will configure the payload for the desired experiment (e.g., 100 Gbps or 200 Gbps mode). Terran Orbital engineers upload this pass script and configure the spacecraft via an RF ground network to schedule a lasercom pass.

About 2 hours before the pass, operators at OCTL and MIT LL begin ground system checkout. Actions are coordinated via teleconference. MIT LL operators first perform a checkout of the ground modems using payload emulator hardware on-site at OCTL, followed by a checkout of the uplink amplifiers (3×3 W and 1×1.6 W beams). A transmit beam from the payload emulator is provided to OCTL operators to check out the adaptive optics (AO) system. Power in fiber is optimized and unaberrated fiber coupling is measured. OCTL operators also exercise the telescope control and perform an on-sky background prior to the pass.

It is essential for the ground station to have accurate spacecraft ephemeris to illuminate the spacecraft during acquisition. The spacecraft uses its last RF ground contact prior to the pass to downlink ephemeris informed by on-board GPS, which occurs about 15 minutes prior to a daytime pass and about 30 minutes prior to a nighttime pass. Terran Orbital packages this data into a two-line element set (TLE) that is sent to the OCTL operators about 10 minutes prior to the pass. Inaccurate TLEs or challenges with TLE delivery have been the most common reason for a failed pass contact.

The uplink begins transmitting just prior to the pass. The spacecraft begins transmitting the downlink at around 10° elevation. The uplink is detected at 12° elevation and the spacecraft closes a track loop around the payload pointing feedback. While the bus pull-in takes around 20 seconds to fully settle, within a few seconds pointing is sufficient to detect the downlink at the ground station.

The downlink is first detected on an acquisition camera, and a control loop is closed to correct gimbal pointing based on acquisition camera feedback. This steers the downlink onto the wavefront sensor in the AO system, allowing the AO tip/tilt and deformable mirror loops to be closed to couple power into fiber. The process of downlink detection to AO loop closure takes about 10 seconds.

The entire acquisition process is completed within about 20 seconds of initial uplink detection, and for the duration of the pass data transfer occurs any time power-in-fiber exceeds the modem FEC threshold. The ARQ protocol ensures that frames are retransmitted until acknowledged as received on the uplink channel, resulting in error-free data delivery. Outages occasionally occur during a pass (due to e.g., intermittent clouds) and in that case the acquisition process is repeated. The ARQ protocol is robust to these outages and data transfer resumes as soon as power returns.

The pass is scheduled to complete at 20° elevation. After the pass, the spacecraft downlinks payload and attitude control telemetry via RF. The ground station logs telemetry on pointing and received power. MIT LL engi-

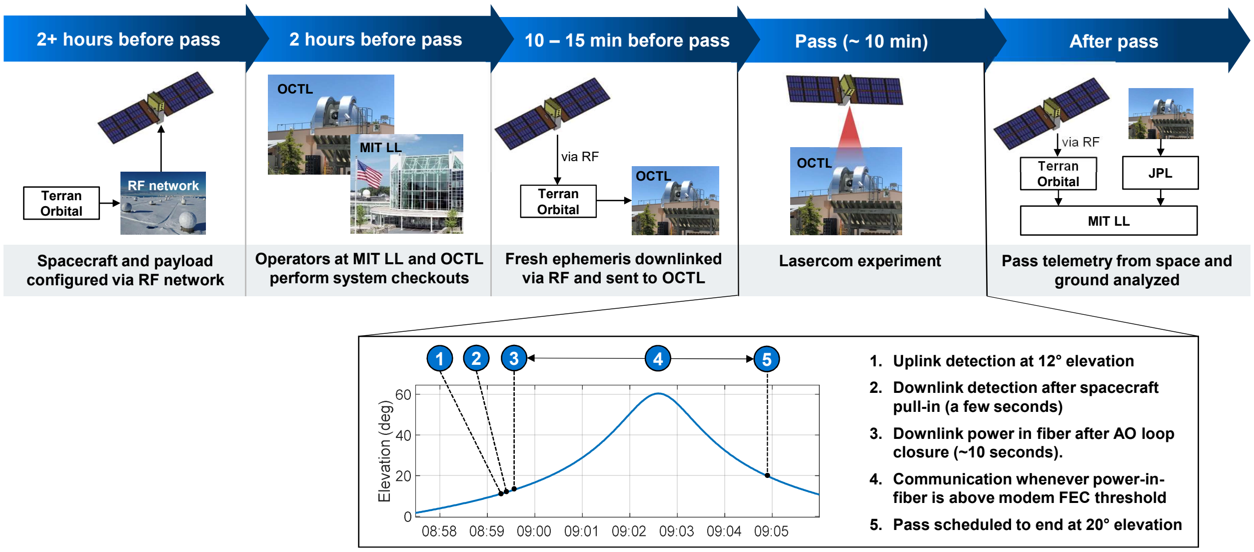

Figure 2: *Timeline of activities to support a TBIRD lasercom pass.*

neers aggregate the telemetry for analysis and to inform the next lasercom experiment.

ON-ORBIT PERFORMANCE

Payload

All components of the lasercom payload have operated nominally on orbit. The total operational time for the payload on-orbit is just over 10 hours.

Payload power consumption measured in various operational configurations is shown in Table 2. In 200 Gbps mode, one additional COTS modem is active relative to the 100 Gbps mode, and this draws an additional 20 W. Supplying data from on-board storage requires 4 active solid state drives (SSDs), which draw 15 W to 20 W of additional power.

Table 2: *Maximum power consumption for each lasercom operational mode.*

Mode	Max Power (W)
200 Gbps from SSDs	99
200 Gbps from virtual buffer	84
100 Gbps from SSDs	80
100 Gbps from virtual buffer	62

Given the 60 W to 100 W peak power consumption during lasercom operations in a small CubeSat package, the payload tends to significantly self-heat. This limits the on-time duration of the payload and significant design effort went into thermal management.

Figure 3 shows the temperature of payload components during a pass. The transceiver (XCVR), FPGA, erbium-doped fiber amplifier (EDFA), and SSDs all heat up significantly during the pass, about 3 °C to 4 °C per minute. The optical "monolith" which houses the transmit and receive paths was designed to be thermally isolated from the electronics to avoid thermal drift, which was effective given its steady temperature. The transmit and receive boresights have remained very stable on orbit [15].

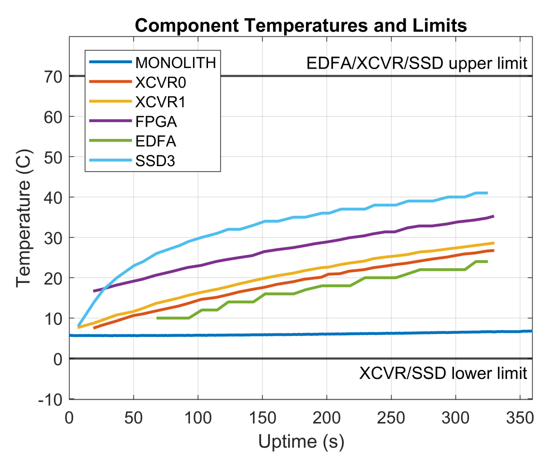

Figure 3: *Temperatures and thermal limits for payload components measured during 200-Gbps downlink on May 17th, 2023. All electronic components were active during this pass.*

The payload has not been operated for more than 10 minutes consecutively given the duration of LEO-to-ground links. Based on the thermal trends, the payload could be operated in this mode for up to 18 minutes before reaching upper temperature limits on some components, starting with one of the SSDs. On a larger spacecraft platform, thermal management would be less constraining and the payload could potentially operate longer.

Data Volume

In extended operations, TBIRD has been able to achieve a maximum throughput of 200 Gbps and regularly downlink terabytes of data per pass (see Table 1). Improvements in fiber coupling at the ground station have resulted in better link performance relative to the initial 6-month mission. This has also allowed the mission to demonstrate large data volumes over a variety of atmospheric conditions at the ground station.

Figure 4 presents results from the highest data volume pass as of this writing on May 17th, 2023. The uplink is acquired at 12° elevation (1490 km range) and the downlink is acquired moments later. Error-free data transmission started at 15° elevation (1330 km range) and continued until the scheduled end of pass at 20°. Throughput of 200 Gbps is briefly achieved but shows some irregularity with dropouts, which is due to ground station internal disturbances as described in Ref. [8]. A total of 4.8 TB were delivered error-free over the 5-minute pass.

In addition to the measured throughput, Figure 4 shows two throughput models. Model 1 gives a prediction of throughput based on power-in-fiber measurements recorded at 25 kHz during the pass. This model incorporates ARQ protocol parameters and the ground transceiver characteristics, as described in Ref. [12]. Model 1 predictions match the measured throughput closely through the pass, indicating that the realized end-to-end system is in good agreement with the model.

Model 2 shows the predicted performance given an atmosphere-limited channel. This model incorporates turbulence simulations as described in Ref. [16] (note that predictions in Fig 4 exclude the 3 dB unrealized margin). The gap between measured throughput and Model 2 predictions shows the potential impact of ground station improvements in fiber coupling performance.

An interesting feature of this pass is that the throughput at low elevations was not limited by the Doppler tolerance of the ground transceivers, which had initially been observed. Shifting the frequency on the ground transceiver in the positive direction prior to the pass and in the negative direction near the peak of the pass effectively resolves the limitation of Doppler tolerance. This will be discussed further in a future publication.

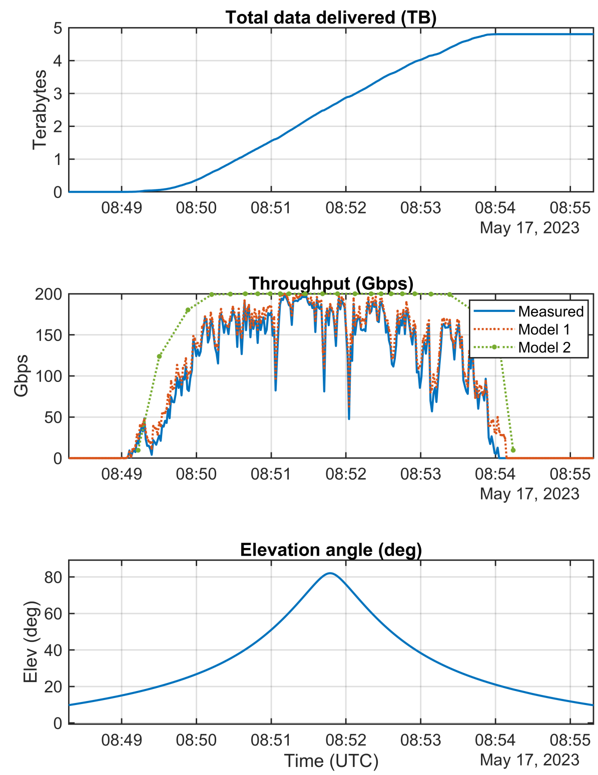

Figure 4: *Results from highest data volume pass, which transferred* 4.8 TB *in 5 minutes. Throughput is the end-to-end error-free data rate averaged over* 1 s*. Model 1 is the predicted throughput based on the measured power-in-fiber during the pass. Model 2 is the predicted throughput in an atmosphere-limited channel.*

Pointing

Accurate pointing of the downlink beam is essential to support high data rates. The TBIRD payload measures the angles of an uplink beacon to provide pointing feedback at 10 Hz to the spacecraft bus. The bus then closes a control loop to track on the uplink signal.

Detailed results on the pointing performance are presented in Ref. [15]. The overall root-mean-square (RMS) tracking error was measured at 20 µrad and 35 µrad in the payload cross-boresight axes from June–November 2022. The TBIRD transmit beamwidth was measured on orbit to be 380 µrad full-width half-max (FWHM), resulting in typical pointing losses <0.1 dB. Given the on-orbit pointing performance, a much smaller beamwidth could be supported on a similar system in future missions.

Modifications to the control algorithm could improve pointing performance further. The tracking error is dominated by bias and low frequency (<0.01 Hz) drift through the pass. Figure 5 shows the averaged power spectral density (PSD) of tracking error across all lasercom passes with standard pointing conops (n = 34), which includes passes from June–November 2022 and April–May 2023.

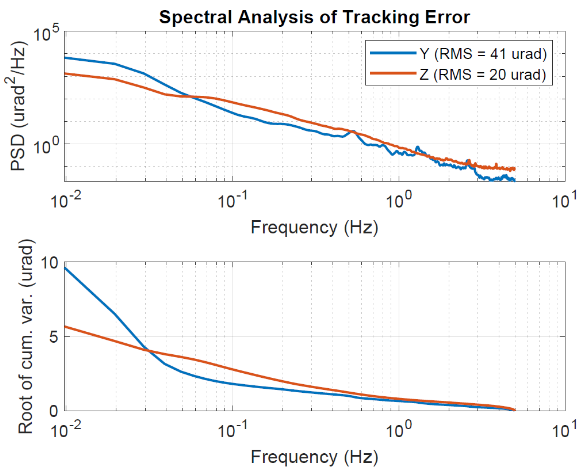

Figure 5: *Spectral contributions to tracking error. The top plot shows the tracking error PSD averaged across 34 lasercom passes between June 2022 to May 2023. The bottom plot shows the square root of the cumulative integral of the PSD from infinity to zero.*

Taking the square root of the integral of the PSD in the reverse direction (from infinity to zero), the RMS error contribution from components above 0.01 Hz in frequency is 6 µrad in Z and 10 µrad in Y. This contribution is small compared to the overall RMS error of 25 µrad in Z and 41 µrad in Y, indicating that the vast majority of error is low frequency.

The DC bias alone contributes 15 µrad of error in Z and 34 µrad in Y. The remainder of the low frequency error is likely error in the feedforward trajectory (due to many possible factors, e.g. inertia tensor error) that the feedback controller is unable to mitigate as-implemented due to a small integral control component. Increasing the integral control gain should significantly reduce these low frequency errors. At some point increasing this gain will affect stability margins, but the on-orbit controller is far from that point. Given that pointing loss is typically small even with these errors, controller improvements have not been pursued.

The demonstrated pointing accuracy could support a smaller beamwidth on a future system, and with controller improvements pointing errors below 20 µrad RMS per axis should be achievable. The additional link margin gained by reducing beamwidth can be used in a variety of ways, some of which are explored in the following section.

IMPLICATIONS FOR FUTURE MISSIONS

The TBIRD mission has demonstrated numerous multi-terabyte downlinks from a nanosatellite platform in a variety of link conditions. For this pathfinder mission, the downlink beam was a relatively wide by laser communication standards (380 µrad FWHM) and the ground station was a relatively large aperture diameter (1 meter). The wide beamwidth was a conservative design and provided margin against potential flight risks and uncertainties, but ultimately the on-orbit measurements of pointing error described in the previous section show that a much smaller beamwidth (∼100 µrad) could be supported with the same closed-loop body pointing approach. On the ground side, the existing ground station infrastructure at OCTL was suitable for an initial technology demonstration, but a 1-m telescope would be oversized for a future system.

In this section, we use the on-orbit measurements of the TBIRD system to provide a performance prediction for two hypothetical future systems:

- **System 1**: 200 Gbps from a nanosatellite with 100 µrad beamwidth to a 25-cm (10-inch) diameter ground terminal
- **System 2**: 800 Gbps from a nanosatellite with 100 µrad beamwidth to a 60-cm diameter ground terminal

Both systems benefit from a smaller beamwidth. System 1 exploits the large increase in power delivered from the space terminal to considerably reduce the size and complexity of the ground terminal while still maintaining a 200-Gbps data rate. A 25-cm ground terminal is small enough that a full adaptive optics solution may not be required to achieve good coupling to fiber; tip-tilt compensation may be adequate in this regime, which would reduce the cost and complexity of the ground system [17].

System 2 exploits the large increase in power to boost the data rate to 800 Gbps, using a larger (but still modest) 60-cm terminal. One way this data rate could be realized is by wavelength-division multiplexing four 200-Gbps commercial telecom transceivers. Telecom technology has matured significantly since the inception of the TBIRD architecture and 200-Gbps devices are available that are half the size and consume less power than the older 100-Gbps form factor that the TBIRD mission is currently flying [18].

The link analysis for these systems is performed using the modeling approach that gave rise to Model 2 in Figure 4. To keep the system comparison simple, the only parameters modified are the downlink beamwidth, downlink pointing error, and ground terminal aperture

Table 3: *Link budget and throughput model of the on-orbit TBIRD system and two potential future systems for the case of orbital altitude* 500 km *and 25° elevation angle. The wavelength in all cases is* 1.5 µm. *Systems 1 and 2 take advantage of a smaller beamwidth to reduce ground terminal size substantially (System 1) or more modestly and increase the data rate (System 2).*

Parameter	On-orbit Model	System 1 Model	System 2 Model
Tx optical power	−0.5 dBW (0.9 W)	−0.5 dBW (0.9 W)	−0.5 dBW (0.9 W)
Tx optics loss	−0.3 dB	−0.3 dB	−0.3 dB
Tx antenna gain	79.0 dBi (380 µrad)	90.4 dBi (100 µrad)	90.4 dBi (100 µrad)
Tx pointing error	−0.2 dB (50 µrad)	−1.9 dB (40 µrad)	−1.9 dB (40 µrad)
Range loss	−258.4 dB (1030 km)	−258.4 dB (1030 km)	−258.4 dB (1030 km)
Atmospheric loss	−0.6 dB	−0.6 dB	−0.6 dB
Rx antenna gain	126.0 dBi (1-m diam)	114.4 dBi (25-cm diam)	122.0 dBi (60-cm diam)
Rx static loss	−4.0 dB	−4.0 dB	−4.0 dB
Rx avg coupling loss	−5.7 dB	−5.7 dB	−5.7 dB
Rx avg power in fiber	−34.9 dBm	−36.6 dBm	−29.0 dBm
Transceiver rate	200 Gbps	200 Gbps	800 Gbps
Fading factor at avg PIF	0.9	0.7	0.9
Throughput	180 Gbps	140 Gbps	720 Gbps

diameter. In practice, different ground terminal sizes and architectures will have different fiber coupling loss and fade statistics, but generally smaller terminals can perform more efficiently since fewer spatial modes need to be compensated. Hence, the predictions for System 1 and System 2 can be considered conservative since the baseline model is the 1-m OCTL telescope.

Table 3 compares the link budgets of the TBIRD on-orbit model and the two hypothetical systems, for the case of a 25° elevation angle. The first section of rows tabulates the various optical losses along the path, culminating in an average power coupled into fiber. The second section uses that average power-in-fiber value along with turbulence simulations and the TBIRD ARQ parameters to derive a fading factor. The base transceiver rate multiplied by the fading factor gives the predicted end-to-end throughput that is guaranteed error-free due the ARQ repeats.

Figure 6 shows the predicted throughput versus time for Systems 1 and 2 during example passes that reach peak elevation angles of 30° and 70° . The total data transfer for these passes ranges from 3.8 TB to 6.3 TB for System 1 (25-cm ground terminal, max rate of 200 Gbps) and 20.3 TB to 28.4 TB for System 2 (60-cm ground terminal, max rate of 800 Gbps).

For missions with high-rate sensors and large on-board data generation, the communication requirement is the number of terabytes that need to be downlinked per day. The number of passes per day that get above, say, 30° depends on the inclination angle of the satellite and the latitude of the ground terminal, but even just one pass per day to a System 1 or 2 ground terminal would be an extremely capable architecture (and many geometries would yield multiple contacts per day). With System 2, a single ground terminal could enable 10s of terabytes per day. With System 1, the smaller ground terminal could be deployed at multiple sites to also receive an aggregate of 10s of terabytes per day. Data-rich missions that are currently communication constrained would benefit greatly from such a capability.

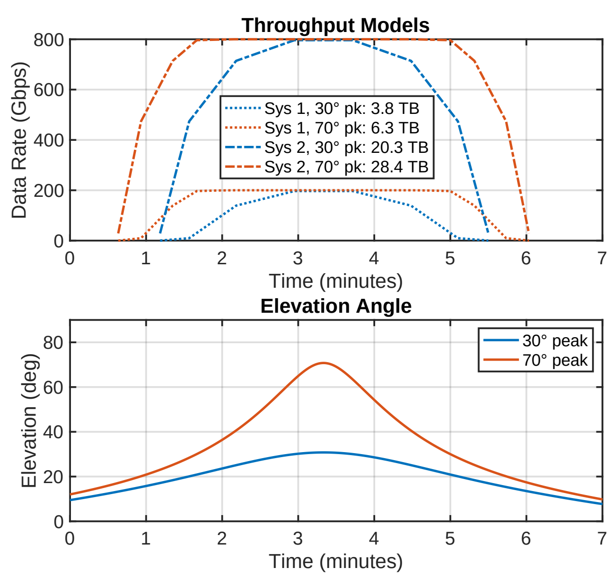

Figure 6: *Predicted throughput and data volume for two hypothetical future systems, both utilizing a narrower* 100 µrad *downlink beamwidth. System 1 uses a 25-cm ground terminal and operates at 200 Gbps, whereas System 2 uses a 60-cm ground terminal and operates at 800 Gbps.*

CONCLUSION

Since launch in May 2022, the TBIRD mission has demonstrated 100-Gbps and 200-Gbps downlink rates from a CubeSat in LEO. Over 60 links have been performed to date. End-to-end error-free data transfer up to 4.8 TB in a single pass has been achieved, with many passes exceeding 1 TB. On-orbit pointing performance can support narrower downlink beams on future missions, allowing for smaller ground terminals or higher data rates as potential trades. The TBIRD mission is ongoing and additional experiments are planned.

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