On-orbit demonstration of 200-Gbps laser communication downlink from the TBIRD CubeSat

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ABSTRACT

Since launch in May 2022, NASA's TeraByte Infrared Delivery (TBIRD) program has successfully demonstrated 100-Gbps and 200-Gbps laser communication downlinks from a 6U CubeSat in low-Earth orbit to a ground station. The TBIRD system operates during 5-minute passes over the ground station and has demonstrated an error-free downlink transfer of >1 Terabyte (TB) in a single pass. This paper presents an overview of the architecture, link operations, and system performance results to date.

Keywords: free-space optical communications, low-Earth orbit, coherent modem, ARQ, CubeSat

1. INTRODUCTION

Recent years have seen significant growth in space-based laser communication system demonstrations and deployments.[1] The narrow beams and available spectrum of lasercom systems as compared to traditional radio-frequency (RF) systems enables operation at very high data rates while reducing the burden on the size, weight, and power (SWaP) of the transmit and receive terminals. Space lasercom systems have now been realized in a variety of regimes and link distances, including: uplinks and downlinks from lunar distances,[2] GEO-based relays servicing LEO user missions,[3–6] crosslinks in proliferated LEO constellations,[7] and direct downlinks from LEO to ground.[8–11]

Direct downlinks from LEO have relatively small link distances compared to other near-Earth data delivery architectures, which can enable higher data rates and/or smaller terminals. Lasercom demonstrations of LEO downlinks in recent years have focused on the advantages of reduced SWaP and have miniaturized terminals with very low mass and power consumption in volumes as small as 1U, while still achieving data rates that are competitive with existing RF solutions (0.1 - 1 Gbps).[8–11]

Space-to-ground RF links are generally bandwidth-constrained due to spectrum limitations; for example, X-band downlinks on both large and small satellite platforms currently operate at max data rates on the order of 1 Gbps.[12] In contrast, free space optical communication systems are generally not limited by spectrum considerations. At optical frequencies, THz of bandwidth is available for links to potentially operate at rates of 100-1000 Gbps per wavelength channel. In terrestrial fiber telecom networks, these extremely high data rates are commonplace, with 100-Gbps fiber-coupled transceivers demonstrated nearly a decade ago.[13] The fiber telecom industry has continued to mature technology significantly in the past decade: reducing form factors,

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lowering power consumption, expanding data rates to 400+ Gbps per wavelength, and standardizing waveforms for interoperability.[14,15]

Over the past few years, NASA's TBIRD program has developed a LEO direct-to-Earth architecture that leverages terrestrial fiber telecom technology to achieve a 200-Gbps downlink in a small-form-factor terminal.[16–20] Even though contact times from LEO may be only a few minutes long, bursting data down at rates of this magnitude enables data volumes of multiple terabytes (TB) in a single pass. Key elements of the architecture include multiple 100-Gbps commercial off-the-shelf (COTS) fiber transceivers, a terabyte-class on-board storage buffer capable of high-speed readout, and an automatic repeat request (ARQ) protocol that guarantees error-free data transmission in the presence of atmospheric fading. Together, these elements form a buffer-and-burst system for reliable data delivery of unprecedented data volumes from LEO.

To demonstrate this architecture, a TBIRD flight mission was developed and deployed to orbit in partnership with NASA's Pathfinder Technology Demonstrator (PTD) program.[21] The space terminal is a payload roughly 3U in volume that was built by MIT Lincoln Laboratory and hosted on a 6U CubeSat bus built by Terran Orbital (formerly known as Tyvak Nano-Satellite).[22,23] The ground terminal is located at JPL's Optical Communications Telescope Laboratory (OCTL) in southern California.[24] OCTL has a 1-m diameter telescope and adaptive optics system that were augmented by the JPL team to support the TBIRD system. The ground terminal uplink transmitter and downlink receiver and associated high speed digital electronics were built by MIT Lincoln Laboratory.

On May 25th 2022, the PTD-3 CubeSat was launched to a 530-km sun-synchronous orbit. Lasercom operations commenced in early June 2022. By the end of June, the TBIRD system was operating smoothly and delivering TB-class data volumes during 5-minute passes over the ground station. As of December 2022, the mission has operated over 40 passes and has demonstrated error-free downlink transfer of more than 1 Terabyte in a single pass while operating at 200 Gbps. To our knowledge, this is the highest downlink rate that has been achieved by any space platform.

This paper presents an overview of the TBIRD system (Section 2), link operations (Section 3), and system performance results to date (Section 4). Two other papers in this session provide further detail on the on-orbit results of the pointing, acquisition, and tracking system as well as the ground station telescope and back-end optics.[25,26]

2. SYSTEM OVERVIEW

A high-level block diagram of the system architecture is shown in Figure 1. The system enables the reliable transfer of data from a buffer on the space terminal to a buffer on the ground terminal at a rate of either 100 Gbps or 200 Gbps. In addition to the high-rate downlink, there is an optical uplink from OCTL to the spacecraft that provides an automatic repeat request (ARQ) feedback channel as well as a tracking beacon to enable precision body-pointing of the downlink.

Space Terminal

The TBIRD space terminal has been described in detail previously.[22,23] The payload is approximately 3U in volume, weighs less than 3 kg, and consumes 100 W of power when all components are active. The optical subassembly is a bi-static design with separate apertures for downlink transmit and uplink receive. Both optical systems are mounted in a monolithic housing that does not contain any steering mirrors. Instead, the spacecraft bus uses reaction wheels to body-point the payload. During acquisition, the bus relies on standard on-board sensors (star trackers, gyros) to open-loop point to within the payload receive field of view (+/- 0.25°). Upon detection of the uplink, the payload sends pointing error feedback to the bus which the bus attitude control system uses to close the loop and thereby point the downlink.

The downlink operates either one or two 100-Gbps channels that are wavelength division multiplexed and sent to an erbium-doped fiber amplifier (EDFA). The maximum optical power out of the transmit aperture is 800 mW (in 200-Gbps mode, the transmit power is divided evenly between the two wavelengths). A 2-TB buffer feeds one of the two downlink channels at a readout rate of 100 Gbps. There is no sensor on-board the spacecraft

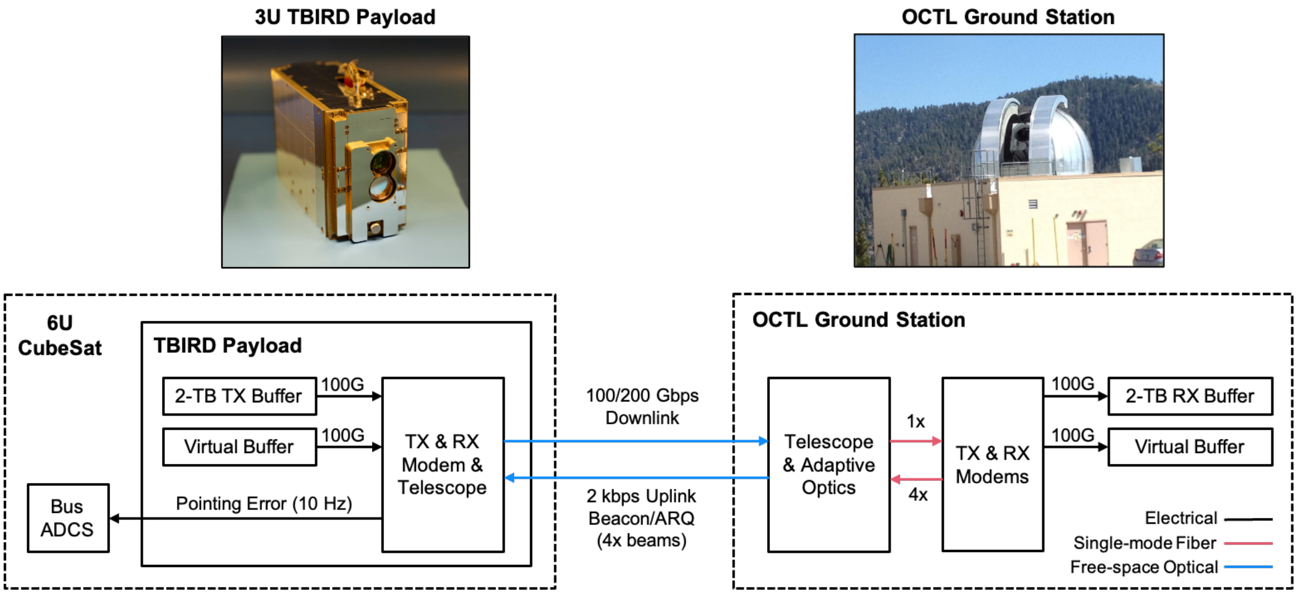

Figure 1: The TBIRD system supports buffer-to-buffer data delivery over a 100/200-Gbps LEO-to-ground downlink. The space and ground terminals each contain a 2-TB buffer built with high-speed solid state drives. A low-data-rate optical uplink provides ARQ feedback to guarantee error-free data delivery and also serves as a spatial tracking beacon. The spacecraft bus relies on the tracking beacon to body-point the payload and downlink beam accurately. The ground terminal uses adaptive optics to couple the downlink to single-mode fiber as required by the receiver.

to fill the 2-TB storage, but payload component telemetry is written to the drives during operation. The bulk of the storage consists of image and video files that were loaded during the payload build.

The downlink leverages coherent transceivers that are used in fiber telecommunications networks. The transceivers operate in the 1.5-um band and utilize dual-polarization QPSK waveforms along with soft-decision forward error correction (FEC) to achieve power-efficient error-free operation in static fiber channels. To mitigate data outages due to atmospheric fading and other sources of fluctuation in received power, the TBIRD system augments the transceivers with a custom layer-2 ARQ protocol. The ARQ system guarantees that all dropped frames are eventually retransmitted until receipt is successful, thereby ensuring error-free data transfer.

ARQ System

The TBIRD ARQ system is designed to achieve high throughput efficiency in the presence of fast (millisecond-second class) fluctuations in received power. The implementation is a custom selective-repeat protocol that is multiplexes stop-and-wait ARQ subsystems to form a set of virtual channels with no idle transmission time. Data at the space terminal are encapsulated in ARQ frames for transmission over the downlink. ARQ frame size is adjustable, but nominally the frames are around 15 MB in 100-Gbps mode and 30 MB in 200-Gbps mode, corresponding to a frame transmission time of $\sim$1 ms.

The uplink repeatedly sends positive acknowledgements of ARQ frames that are successfully received at the ground terminal. An ARQ message consists of one bit per virtual channel; there are 1752 virtual channels so that the each message fills most of the payload of a single Reed-Solomon (223,255) uplink codeword. A CRC appended to each ARQ message allows the uplink receiver at the space terminal detect whether the message is valid or not. When a valid uplink message is received, the space terminal updates the status of all the virtual channels. New ARQ frames are transmitted for channels that acknowledged reception, while all other channels require retransmission of their ARQ frames.

Ground Terminal

The ground station for the TBIRD mission is OCTL, which contains a 1-m aperture telescope in a Coudé focus configuration with a bench-top adaptive optics (AO) system for coupling the downlink to single-mode fiber. OCTL is the primary station for the LCRD mission (OGS-1) that began operation in early 2022, and actively supports GEO links with its LCRD Optical Ground Station (LOGS) setup.[27,28] For the TBIRD mission, augmentations were made to the existing LOGS setup to accommodate differences in optical and operational requirements, e.g., uplink/downlink wavelengths and tracking a LEO spacecraft. The setup can switch between LCRD and TBIRD modes with few adjustments when both missions operate on the same day.

The single-mode fiber output of the AO system is pre-amplified, wavelength demultiplexed, and sent to ground modem hardware for demodulation and decoding. Data frames that are successfully received are written to the ground buffer at 100 Gbps. After a pass, the data on the ground buffer is downloaded slowly to a server for file retrieval and analysis.

The TBIRD uplink is a binary pulse position modulation (PPM) waveform at 1.5-um that is simultaneously transmitted on 1-4 co-boresighted beams for spatial diversity to mitigate fading. The beams are launched from 4 sub-apertures of OCTL's 1-m telescope with a transmit beamwidth of 600 µrad full-width half max. This wide beamwidth allows the telescope to illuminate the space terminal with open-loop pointing during the acquisition sequence at the beginning of a pass.

The uplink provides a 1.8-kbps user rate (after accounting for FEC overhead) that is primarily used for ARQ signaling. A very small fraction of the signaling is used for terminal-to-terminal messaging, which has been useful for certain on-orbit experiments (such as triggering the start of a pointing scan or manually mis-pointing the satellite) since there is no RF link available during a pass for commanding the spacecraft or payload from the ground.

3. OPERATIONS

The PTD-3 spacecraft was deployed by a SpaceX Transporter-5 rideshare to a 2am/2pm sun-synchronous 530-km orbit, which has allowed the mission to perform link experiments in daytime and nighttime conditions. A total of 43 links have been conducted in the first 6 months of operation. The mission has focused on operating during passes that reach a peak elevation angle of at least 40°, which occur every 1-2 days on average due to the highly inclined orbit. In practice, the link experiment cadence was dominated by factors other than line-of-sight availability during the initial months of operation, such as ground station telescope timesharing with other on-going programs and operator staffing constraints.

Operations for each pass are coordinated by MIT Lincoln Laboratory and involve: space and ground preparations before a pass, link acquisition and laser communications during the pass itself, and telemetry aggregation following a pass.

Several hours before a pass, the spacecraft is configured for the pass experiment via an RF uplink. Real-time RF communication is not available during a pass, so all spacecraft and payload commanding and telemetry is completely automated by design. Approximately 30 minutes before the start of the pass, the spacecraft downlinks fresh ephemeris data to an RF ground station which is used to produce a two-line element (TLE). The TLE is provided to the JPL telescope operators for open-loop pointing the uplink to illuminate the spacecraft. The use of fresh ephemeris data has proved to be critical for successful acquisition. In some initial passes where recent spacecraft ephemeris was not available for the telescope operators, a staler TLE from a public database was used instead but with limited success.

The sequence of events during a pass are: uplink detection, spacecraft pull-in and tracking, downlink detection and tracking, and adaptive optics loop closure, which then results in light coupled to fiber and high rate downlink communications. The uplink is generally detected by the payload receiver at 12° elevation angle. Upon detection, the payload begins sending pointing feedback to the bus. Pull-in time is typically 10-30 seconds, after which the uplink signal is tracked at an accuracy of 20-35 urad RMS, keeping downlink pointing losses negligible throughout the pass.[25] The spacecraft has a contingency spiral pointing scan available to assist the acquisition process, but this has not been employed since it is able to open-loop point at the ground station to within the payload field of view.

Once the downlink is pointing accurately, the ground station first receives light on an acquisition camera and uses this information to correct the gimbal pointing. 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 two deformable mirrors. The sequence from downlink detection to AO loop closure is not automated and requires an operator at OCTL to activate some of the hardware, which typically completes in 5-10 seconds.

Once the adaptive optics loops are closed and the downlink is coupled to single-mode fiber, the receiver can begin decoding ARQ frames if there is sufficient power in fiber. The space terminal has already begun transmitting frames well before the start of a pass, but this is acceptable because those frames are recovered by the ARQ system once the link closes.

Uplink and downlink communication continues throughout the pass until 20° elevation angle on the descent, at which point the spacecraft powers down the payload. On some passes, there are brief link outages such as when the telescope performs a sun-avoidance maneuver (during a day-time pass) or when there is azimuth catch-up at particularly high elevation angles, but the system is able to re-lock quickly after those events. The mission has also operated passes on partially cloudy days, and has been able to demonstrate robust downlink data transfer despite only having brief periods of link availability when the spacecraft line-of-sight is between clouds.

After the pass completes, various space and ground telemetry sets are aggregated at the operations center. Within a few hours, the spacecraft downlinks bus and payload telemetry that were recorded during the pass to an RF ground station, including bus ephemeris, pointing and tracking data, and communication system telemetry. A similar set of recorded ground station telemetry is collected, including telescope tracking, acquisition camera and wavefront sensor readout, high rate (>10 kSam/s) power-in-fiber measurements, and receiver telemetry from the modem and ARQ protocol. Given that passes are only a few minutes long, this comprehensive and centralized telemetry set proved invaluable for understanding and debugging unexpected system behavior, especially early in the mission.

Following 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 0.5 TB was achieved on June 29th. Over the following months, successful data delivery experiments continued in more communication modes and link conditions (cloudy, day/night, varying peak elevation angles). Along the way, various improvements were made to the ground station adaptive optics system that increased the data volume achieved during a pass to more than 1 TB. Additional experiments were also performed to characterize aspects of the pointing system, such as open-loop body pointing performance and downlink beamwidth. More details on these pointing results can be found in the companion paper in this session.[25]

4. PERFORMANCE RESULTS

This section presents telemetry and performance results from a pass in November 2022, shown in Figure 2. This was a clear-sky night pass that reached a peak elevation angle of 78°. Initial detection occurred at 12° elevation and the uplink and downlink were tracked until the programmed end of pass at 20° elevation, totaling about 6 minutes. The communication system was operated in 200-Gbps mode and achieved a total data volume transfer of 1.4 Terabytes over a 3-minute period in the middle of the pass, as shown in Figure 2b.

The overall TBIRD downlink performance can be understood by dividing the link into three major subsystems. The first subsystem is the space terminal, which uses its pointing system to deliver irradiance to the ground terminal. The second subsystem is the telescope and adaptive optics, which couples the received beam into fiber. The third subsystem is the communication receiver which takes in fiber and outputs data. As discussed next, the delivered irradiance and the communication receiver have performed as expected and have good agreement with system models. The telescope and adaptive optics subsystem has enabled the transfer of large data volumes but the performance is not turbulence-limited and subsystem improvements could increase data volume further.

Figure 2c shows the irradiance that the space terminal delivered to the ground station telescope. The irradiance measurement was derived using calibrated telemetry from the wavefront sensor in the adaptive optics system, sampled at 1 Hz during the pass. The model assumes the link parameters given in the table in Figure 3 (for 30° elevation), informed by both payload build measurements and on-orbit measurements. The downlink beamwidth in the model is 380 µrad full-width half-max (FWHM), which was measured on orbit with an experiment in which the bus performed a high-resolution grid scan during a pass.[25] The agreement between irradiance measurement and model demonstrates that the closed-loop body pointing system and the ground telescope tracking performed well for the entirety of the pass.

Power in fiber coming out of the adaptive optics system was measured by tapping the received fiber signal off to a log-amp photodetector setup that sampled with high dynamic range (to resolve deep fades/fluctuations) at 25 kSam/s and recorded those samples for the duration of the pass. The power-in-fiber telemetry was used to calculate the peak power in fiber during the pass, shown in Figure 2d. This was calculated at 5 Hz by taking the maximum power achieved in each 200-ms interval during the pass. The resulting profile increases with higher elevation angle and shorter range, which is consistent with the behavior of the received irradiance in Figure 2c and symmetric about the peak of the pass. For much of the pass, the peak power in fiber is well above the measured FEC threshold of approximately -38 dBm in the 200-Gbps operating mode. However, the throughput had irregular behavior during the pass and did not reach the full 200 Gbps as seen in Figure 2e. The reason for this behavior was that there was a substantial amount of fluctuation in the power coupled to fiber by the adaptive optics system, causing communication dropouts that lowered the throughput. These power fluctuations occurred much faster than the 5 Hz envelope filter used to calculate Figure 2d. It was determined that the fluctuations were not driven by atmospheric turbulence strength but instead by internal disturbances in the telescope and back-end optics that were not adequately compensated by the adaptive optics control loop. The AO was able to correct higher order phase modes and form an appropriate spatial pattern (i.e. a spot) in the focal plane, but the residual uncorrected tilt caused the spot to jitter, leading to large (>20 dB) dynamic losses in the coupling to fiber.

The throughput achieved during the pass, i.e. the end-to-end error-free data rate, is shown in the solid blue curve in Figure 2e, along with two models. The measured throughput is calculated with 1-s averaging and reached 150 Gbps during the pass. Throughput is less than the operating rate of 200 Gbps due to the presence of ARQ. For example, 150 Gbps throughput at a point on the plot means that during that one second of operation, 75% of the data transmitted (some of which may have been repeated) was received error-free while 25% had errors (and, thus, would have to be retransmitted).

Throughput Model 1 was calculated using the high-rate power-in-fiber telemetry recorded during the pass. The model uses that time series in conjunction with ARQ protocol parameters and known characteristics of the telecom transceivers used for the TBIRD mission.[22] As seen in the figure, Model 1 has close agreement with received throughput. This shows that the receiver (and the ARQ system) performed as expected for most of the pass, given the power-in-fiber profile that occurred. Near the end of the pass there is deviation from the model when the throughput drops to zero even though there is sufficient power in fiber. It was determined that this occurred because the Doppler shift started to exceed the acceptance range of the transceivers.

Throughput Model 2 is an atmosphere-limited model that shows the potential system improvement that could be achieved by either reducing or correcting for the internal tilt disturbances in the telescope and back-end optics. This mission model, summarized in a previous work,[20] uses turbulence simulations to derive a time-series of power in fiber and assumes an additional 3 dB of system loss for margin. Applying this model to the 11/29 pass suggests that the potential improvement is several minutes of sustained throughput at 200 Gbps and a data volume of more than 3 Terabytes.

The final subfigure is Figure 2f, which shows the measurement and model of the uplink irradiance received by the space terminal. During this pass, the uplink waveform was sent on 3 of the 4 possible transmit beams. The received power was measured by the space terminal at 10 Hz, the rate at which the payload provides pointing feedback to the bus. For the entirety of the pass, the irradiance was well above the receiver communication threshold of $-65\,\mathrm{dB\,W/m^2}$. After initial detection of the uplink signal, the receiver proceeded to decode $\sim$350 codewords carrying ARQ messages (which was all of the transmitted codewords), until the end of the pass. There were a few dips throughout the pass where the received power deviated from the link model; it was determined that these were due to the uplink beams rotating and, at certain azimuth and elevation angles, intersecting with the spiders holding the secondary mirror to the telescope.

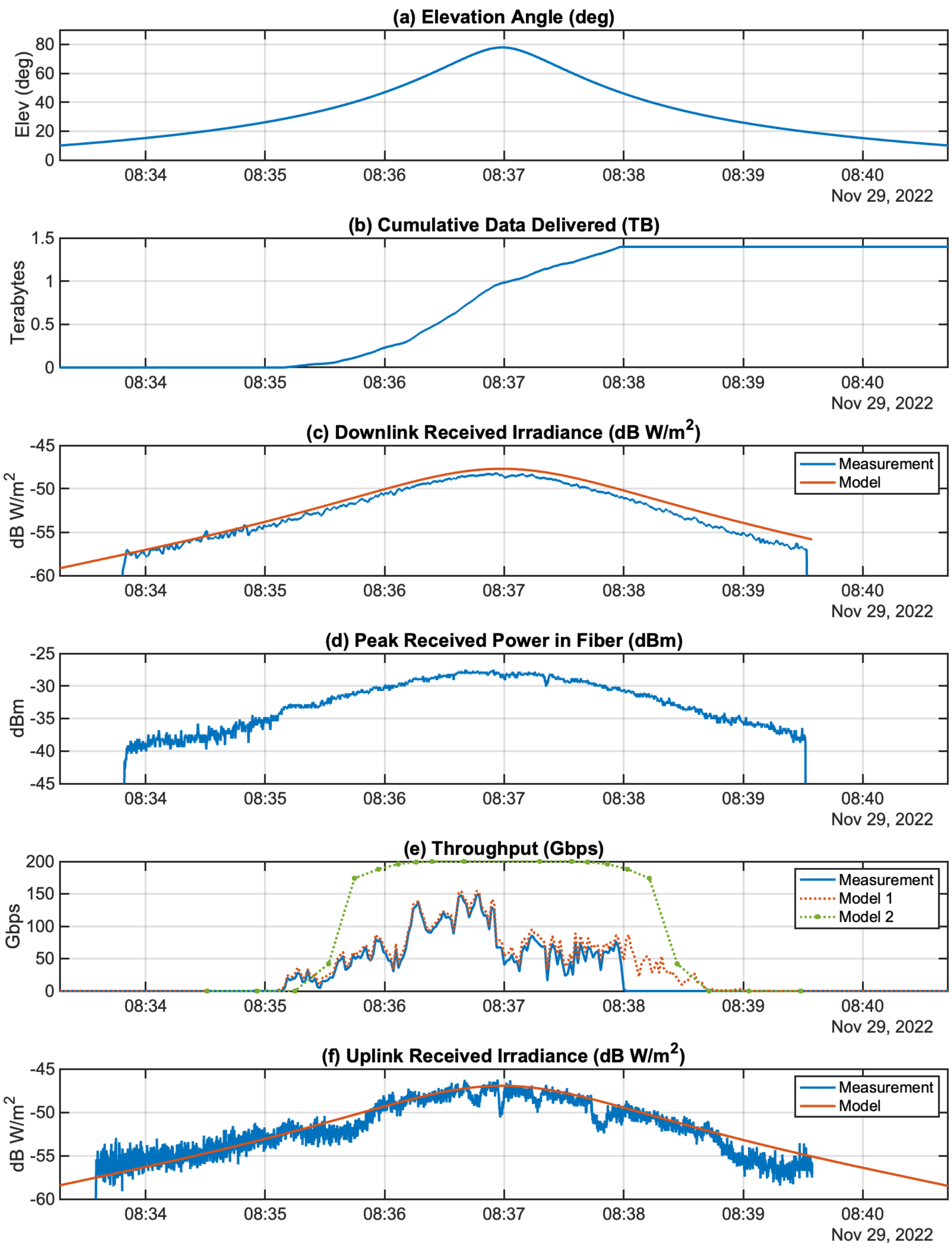

Figure 2: Telemetry and performance results from a TBIRD pass. Time axes are in UTC. Initial uplink detection occurred at 12° elevation. (b) The downlink operated in 200-Gbps mode and transferred 1.4 Terabytes error-free. (c) The throughout, calculated with 1-s averaging, reached 150 Gbps during the pass. (d) The downlink irradiance was stable throughout the pass as the closed-loop body pointing system tracked the uplink. (e) The peak envelope of the received power in fiber, calculated by post-processing the 25 kSam/s raw timeseries and then taking the maximum power achieved in each 200-ms interval. (f) The uplink irradiance received by space terminal was stable and provided the tracking signal and an error-free ARQ uplink feedback channel.

Downlink Irradiance Link Model, 30° Elevation		
Parameter	Value	
Tx optical power (0.9W)	−0.5	dBW
Tx optics loss	−0.3	dB
Tx antenna gain (380 µrad)	79.0	dBi
Tx pointing loss (50 µrad)	−0.2	dB
Range loss (930 km)	−130.4	dB/m^2
Atmospheric loss	−0.5	dB
Rx Irradiance	−52.9	dB W/m^2

Figure 3: Downlink irradiance model for 30° elevation angle. The model assumes a beamwidth of 380 µrad FWHM and bounding pointing error of 50 µrad, both of which are derived from on-orbit measurements. Comparison to the measured irradiance over the pass in Figure 2 is obtained by scaling the range and atmospheric loss depending on the elevation angle.

5. CONCLUSION

Since launch in May 2022, the TBIRD mission has demonstrated 100-Gbps and 200-Gbps downlink rates from a LEO nano-satellite to the OCTL ground station, resulting in error-free data transfer exceeding 1 TB in a pass. The mission has conducted over 40 passes in the first six months of operation and is on-going. Closed-loop body pointing has been successful in keeping downlink pointing losses to a fraction of a dB. A data volume of 1.4 Terabytes has been downlinked in a single pass and could be increased with improvements to the ground station.

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