NASA's Terabyte Infrared Delivery (TBIRD) Program: Large-Volume Data Transfer from LEO

Curt Schieler, Bryan Robinson, Owen Guldner, Bryan Bilyeu, Ajay Garg, Kathleen Riesing, Jessica Chang, Farhad Hakimi, Joshua Brown, Farzana Khatri, Steven Constantine, Jamie Burnside, Don Boroson
MIT Lincoln Laboratory
244 Wood Street, MA 02421
curt.schieler@ll.mit.edu

Donald Cornwell
NASA Headquarters
300 E Street SW, Washington, DC, 20546
donald.m.cornwell@nasa.gov

ABSTRACT

Satellites in low-Earth orbit (LEO) have on-board sensors that can generate large amounts of data to be delivered to a ground user. Direct-to-Earth delivery from LEO is challenging because of the sparse contact with a ground terminal, but the short link distances involved can enable very high data rates by exploiting the abundance of spectrum available at optical frequencies. We provide an overview and update of NASA's Terabyte Infrared Delivery (TBIRD) program, which will demonstrate a direct-to-Earth laser communication link from a small satellite platform to a small ground terminal at burst rates up to 200 Gbps. Such a link is capable of transferring several terabytes per day to a single ground terminal. The high burst rates are achieved by leveraging off-the-shelf fiber-telecommunications transceivers for use in space applications. A 2U TBIRD payload is currently being developed for flight on a 6U NASA CubeSat.

INTRODUCTION

Low-Earth orbit is a desirable regime for many remote sensing and Earth-observing satellites due to its close proximity to Earth. Traditionally, these missions have been accomplished with large satellites (>500 kg) that often carry multiple exquisite instruments which may take measurements on multiple frequency channels [1]. The cumulative data volume that such instruments generate can be quite large as well. For example, the Terra satellite (launched in 1999 and still operating) carries a multispectral sensor suite that produces nearly 200 GB of data per day onboard the spacecraft [1].

Single-instrument satellites can also generate hefty data volumes. For example, ICESat-2, launched in 2018 and now operational, carries a lidar instrument that produces up to 70 GB per day after significant on-board compression [2]. Some upcoming science missions are targeting much larger data volumes. For example, the NISAR satellite (expected launch 2021) performs synthetic radar imaging (SAR) and plans to collect at least 4300 GB (4.3 TB) per day for delivery to a ground network [3]. As another example, the medium-sized 200 kg satellite for the SWOT mission expects to generate 0.9 TB of daily with its radar instrument after 20x compression [4].

Small Satellites with Big Data

It is not just large satellites that generate huge amounts of data. Smaller satellites have become increasingly capable in recent years, with the miniaturization of sensor payloads and improvements in bus power and attitude

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control [5], which suggests that their data volumes may be far from proportional to their bus size. In fact, in some cases the data volume of a small platform can be comparable to that of a much larger satellite. For instance, each 10-second SAR image that the 70 kg ICEYE-X2 satellite collects is 2.4 GB [6]. If this platform were operated with a 5% duty cycle, the acquired data volume would be about 1 TB per day.

Even CubeSat-scale satellites can carry sensor payloads that would generate enormous data volumes, were they not forced to implement substantial on-board processing for data compression. The complexity and resource usage of the custom compression algorithms are not trivial, so it is worth noting the raw sensor data volumes and the compression ratios for a few on-orbit payloads.

One example is the radar on the deployed 6U RainCube. The raw data capture of the radar sensor is 425 Mbps, which translates to 1.1 TB per day after taking into account the planned 25% operational duty cycle [7]. Using onboard compression, the payload reduces this volume to 200 MB in order to fit within the downlinking capabilities of the spacecraft.

Another on-orbit example is the HyperScout hyperspectral imager on the GOMX-4B 6U CubeSat, which performs on-board processing to transform raw data into a Level 2 data product [8]. Assuming a 25% duty cycle, the HyperScout instrument would generate 1 TB of raw data per day. Advanced onboard processing is used to reduce the data by a factor of $\sim$100 [9].

Data Delivery from LEO

Clearly, both large and small satellite platforms are capable today of generating massive amounts of data, on the order of a terabyte per day. And it is entirely possible that they could benefit from generating even more, were it not for the current communication bottleneck in transferring data from LEO to Earth. Presently, the approach to the LEO data delivery problem is generally some combination of radio-frequency (RF) communication (either direct-to-Earth or through a GEO relay), a network of ground stations, and on-board data compression.

Data from LEO can either be delivered directly to a ground terminal or relayed to another satellite (traditionally in GEO) which then transfers the data to ground. The relay approach has the advantage of being low-latency, but because of the long distances involved in LEO-GEO and GEO-Ground links, it requires communication terminals that have large size, weight, and power (SWaP).

The alternative to the relay is to transfer data directly to a ground terminal. This approach is especially appealing for small satellites because the short link distance means that the spacecraft's communication terminals can be made much lower in SWaP. However, the contact time with a given ground station may only be a few minutes per day, which can severely limit the data volume that can be downlinked.

For example, consider a satellite in a 600 km altitude, 51° inclination orbit and a ground terminal at 42° latitude. Such a satellite is above 10° elevation angle with respect to the ground terminal for about 45 minutes a day on average. If a state-of-the-art 100 Mbps RF link were able to operate at full rate for that entire duration, the resulting data volume would be only be 30 GB downlinked per day. Thus, in order to handle a raw generation of, say, 1 TB per day, many ground stations and/or on-board compression would be needed, incurring the cost of operating that network of ground stations and a potential reduction in data quality.

TBIRD Approach

NASA's TBIRD program plans to demonstrate a new architecture for the LEO data delivery problem that is capable of transferring multiple terabytes per day from a low-SWaP space terminal to a small, low-cost ground terminal. This magnitude of data transfer is achieved by utilizing a portion of the THz of available optical spectrum to operate very high-rate (>100 Gbps) direct-to-Earth laser communication links. Sensor data can be buffered up at relatively low rates during collection and then burst down to ground during brief ground station contacts. The smallness of the space and ground terminals is made possible by the high beam directivity at optical frequencies and the use of highly integrated fiber telecom technologies. As with all LEO direct-to-Earth systems, there is inherent latency in the data delivery due to the infrequency of the links, as well as additional latency incurred due to weather-related outages. As such, TBIRD system is intended for delay-tolerant users.

This new architecture was introduced in Ref. [10], while the TBIRD program itself was presented in Ref. [11] and accompanied by data volume performance analysis in Ref. [12]. The data volume delivery of the system depends on mission geometry, but here is one example to give a flavor of the anticipated performance. Consider a satellite in a 600 km altitude, 51° inclination orbit with a 200 Gbps TBIRD payload. Figure 1 shows how many terabytes per day on average could be delivered to a single ground terminal in a given location on Earth. The analysis accounts for cloud-based outages, which explains the variation in data volume for ground terminals at the same latitude.

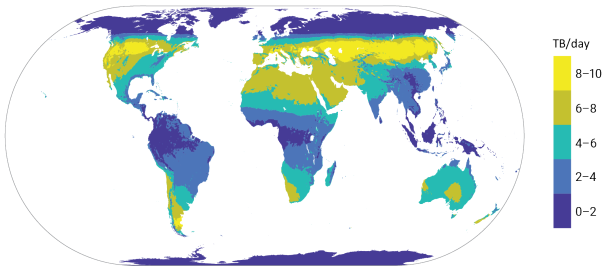

Figure 1: *Terabytes per day delivered from a 200 Gbps TBIRD terminal to a single ground terminal from 600 km altitude, 51 deg inclined orbit. The model incorporates cloud-based outage statistics.*

In this work, we provide an overview of the 2U payload being developed for an upcoming flight demonstration on a 6U CubeSat. The host CubeSat bus for the flight demo is being procured as part of NASA's Pathfinder Technology Demonstrator (PTD) project [13].

TBIRD Demonstration on a CubeSat

The intent of the CubeSat mission is to demonstrate the essential capabilities of the TBIRD architecture, namely the error-free transfer of data from a space buffer to a ground buffer at 100 Gbps and the potential for scalability to even higher burst rates. A simplified block diagram of the optical communication terminal being developed is shown in Figure 2.

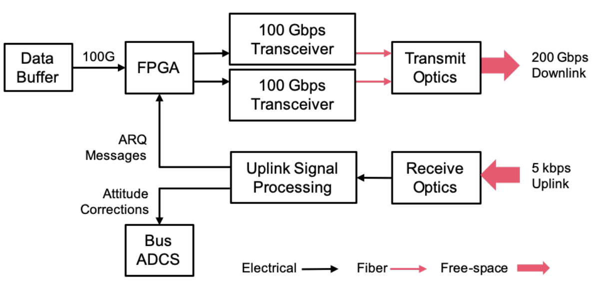

Figure 2: *Block diagram of TBIRD payload.*

A 2 TB space buffer consisting of high-speed solid-state drives reads out data at 100 Gbps to a fiber-telecom optical transceiver for encoding and modulation onto an optical carrier. A second 100 Gbps optical transceiver is fed by PRBS data. The outputs of the two transceivers are ∼1550 nm optical fiber signals, which are coupled together with a wavelength division multiplexer and sent through a 1 W Erbium-doped fiber amplifier. The transmit telescope is a 1.2 cm diameter fiber-optic collimator.

The space terminal is capable of transferring data to a ground terminal at 200 Gbps. However, the fiber-telecom transceivers used to accomplish this cannot achieve a reliable link on their own in the presence of turbulence-induced atmospheric fading. Data frames are undecodable if they arrive when the signal has faded below the transceiver's forward error-correction threshold. To make the system error-free, an Automatic Repeat reQuest (ARQ) protocol is used to inform the space terminal about which data frames were received correctly at the ground terminal so that it knows which frames need to be retransmitted. An FPGA is used to handle the various high-speed interfaces involved in the space terminal and implements the high-rate data frame processing required by the ARQ protocol.

The ARQ protocol uses an optical uplink to send feedback messages at 5 kbps. This data rate may seem low at first glance, but it suffices to maintain the optimality of the protocol employed. Analysis of this feedback rate requirement can be found in Ref. [14]. The feedback uplink is not required to be an optical link per se, but it is convenient in this case because an uplink beam is also being used as a spatial tracking beacon to aid in the pointing of the space terminal, as described next.

Pointing, Tracking, and Acquisition (PAT)

For the upcoming demonstration on a CubeSat platform, the TBIRD payload relies on the bus to point the entire spacecraft using reaction wheels. In fact, the only actuators on the spacecraft are these reaction wheels, as the optical terminal does not use gimbals or fast-steering mirrors. The optical transmit beam has a divergence of less than 150 µrad, which means that the bus pointing requirement is a fraction of this beamwidth.

While CubeSat bus pointing capabilities have improved considerably in recent years, a pointing requirement on the order of ∼20 µrad would be difficult to achieve with an ADCS system that relies solely on a star tracker for feedback. Instead, the PAT system for the TBIRD demonstration works as follows. First, the bus uses its native capabilities to point the spacecraft to within about 1° of the ground terminal. The TBIRD payload then uses a wide field-of-view 2 cm optical receiver to detect and observe an uplink beam and supply the bus with fine attitude corrections based on its observations.

In this manner, the TBIRD payload is able to command the bus to point and track on the received uplink beam. Since the transmit and receive optics on the payload are very closely aligned with each other, the transmit pointing requirement can be achieved. More details and analysis of this PAT approach can be found in Ref. [15].

Payload Development Status

The payload components are currently being packaged for inclusion in a 2U form factor, as shown in Figure 3. A critical part of this packaging has been the development of compact high-speed digital electronics boards that are necessary for controlling and interfacing with the solid-state drives and optical transceivers.

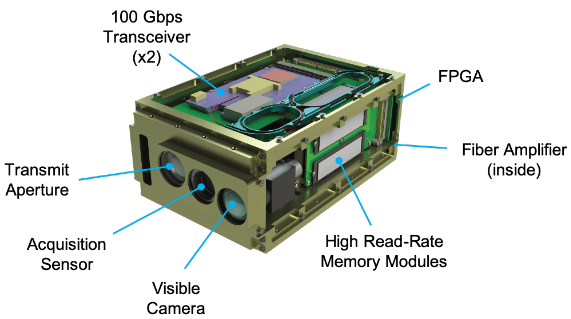

Figure 3: *TBIRD Payload (2U).*

Key components (such as the solid-state drives, optical transceivers, and fiber amplifier) have undergone a suite of environmental tests, including shock and vibration, thermal vacuum, and radiation (gamma and proton). The transceivers have also been operated over simulated atmospheric fading channels to verify communication performance and inform the development of the ARQ protocol.

Ground Terminal

A ground station to support the CubeSat demonstration is also being developed. The ground terminal is based on a low-cost 40-cm telescope and mount suitable for tracking a LEO satellite. A back-end adaptive optics system will couple the received light to optical fiber, which will be amplified and sent to a fiber telecom transceiver for the demodulation and decoding of data frames. The ground system will also provide an optical uplink that will serve as a tracking beacon and support the ARQ protocol.

REFERENCES

[1] C. L. Parkinson, A. Ward, and M. D. King, "Earth Science Reference Handbook," *National Aeronautics and Space Administration*, 2006.

[2] H. W. Leigh *et al.*, "Development of onboard digital elevation and relief databases for ICESat-2," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 53, no. 4, pp. 2011–2020, 2014.

[3] M. M. Kobayashi *et al.*, "NASA's high-rate Ka-band downlink system for the NISAR mission," *Acta Astronautica*, 2019.

[4] D. E. Fernandez *et al.*, "SWOT project mission performance and error budget," *JPL Doc. D-79084*, 2017.

[5] M. N. Sweeting, "Modern small satellites-changing the economics of space," *Proceedings of the IEEE*, vol. 106, no. 3, pp. 343–361, 2018.

[6] "First radar image from ICEYE-X2." `https://www.iceye.com/press/`. Accessed: 2019-06-01.

[7] E. Peral *et al.*, "The radar-in-a-cubesat (RAINCUBE) and measurement results," in *IEEE International Geoscience and Remote Sensing Symposium*, pp. 6297–6300, 2018.

[8] M. Esposito *et al.*, "Demonstration in space of a smart hyperspectral imager for nanosatellites," in *32nd Annual AIAA/USU Conference on Small Satellites*, 2018.

[9] M. Soukup *et al.*, "HyperScout: Onboard processing of hyperspectral imaging data on a nanosatellite," in *Proceedings of the Small Satellites, System & Services Symposium (4S) Conference, Valletta, Malta*, 2016.

[10] D. M. Boroson *et al.*, "A new optical communication architecture for delivering extremely large volumes of data from space to ground," in *AIAA SPACE Conference*, vol. 4658, 2015.

[11] B. S. Robinson *et al.*, "Terabyte Infrared Delivery (TBIRD): A demonstration of large-volume direct-to-earth data transfer from low-earth orbit," in *Proc. SPIE*, vol. 10524, 2018.

[12] C. M. Schieler and B. S. Robinson, "Data volume analysis of a 100+ Gb/s LEO-to-ground optical link with ARQ," in *Proc. SPIE*, vol. 10524, 2018.

[13] J. Marmie *et al.*, "NASA's pathfinder technology demonstrator," in *31st Annual AIAA/USU Conference on Small Satellites*, 2017.

[14] C. M. Schieler, B. S. Robinson, and D. M. Boroson, "Data delivery performance of space-to-ground optical communication systems employing rate-constrained feedback protocols," in *Proc. SPIE*, vol. 10096, 2017.

[15] J. Chang *et al.*, "Body pointing, acquisition and tracking for small satellite laser communication," in *Proc. SPIE*, vol. 10910, 2019.