On-orbit Demonstration of 200-Gbps Laser Communication from the TBIRD CubeSat

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LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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Data Delivery from Low-Earth Orbit

GEO

~ 40,000 km

GEO Relay

Data Delivery from Low-Earth Orbit

LEO Direct-to-Earth Lasercom Architecture*

- Smaller terminals
- Buffer sensor data during orbit
- Short contact time (~5 minutes)
- Leverage fiber telecom (100+ Gbps)
- 2 minutes * 100 Gbps = 1.5 Terabytes

*2015 Boroson et al, "A New Optical Communication Architecture for Delivering Extremely Large Volumes of Data from Space to Ground

LEO
~400-800 km

Terabyte Infrared Delivery (TBIRD)

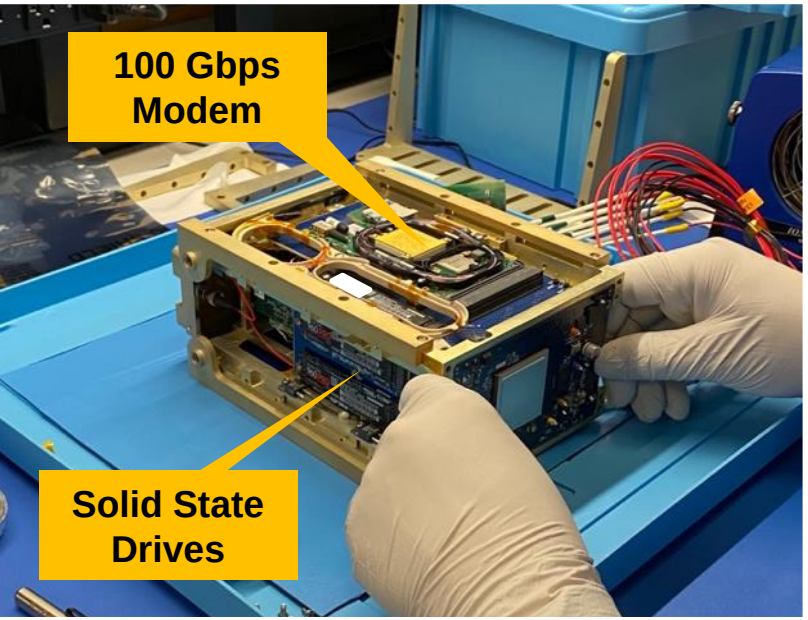
6U CubeSat in LEO (Terran Orbital / Tyvak)
3U Lasercom payload (MITLL)

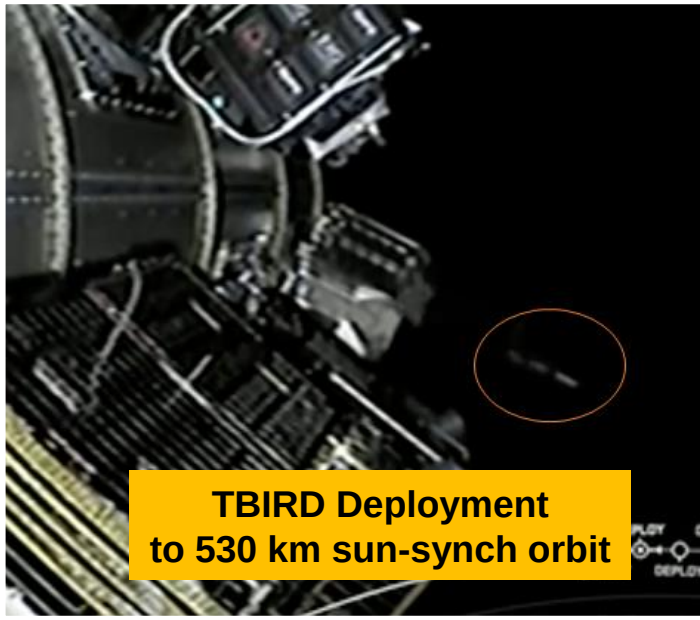
200 Gbps downlink

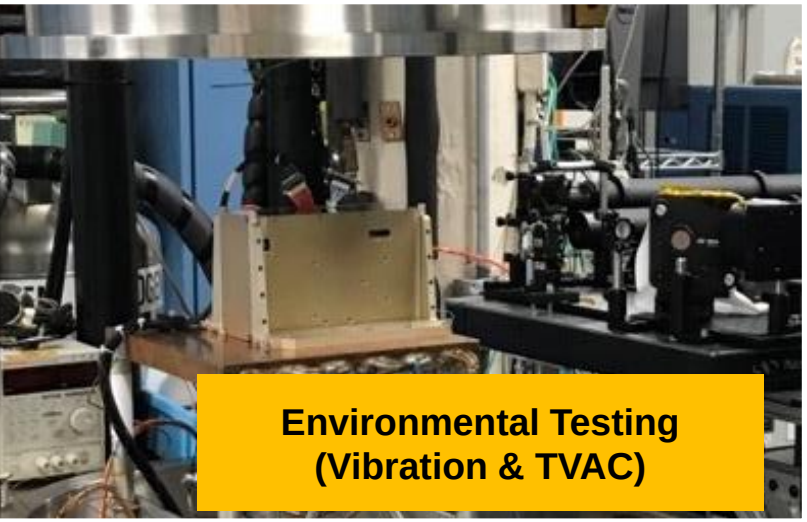
- Leverage fiber telecom equipment for 200 Gbps burst delivery (TBs per pass)
- Demonstrate robust data transfer through atmospheric channel
- 3U lasercom terminal payload hosted on 6U CubeSat
  - NASA Small Sat Pathfinder Tech Demo

Ground terminal at OCTL in Southern California
(MITLL & JPL)

TBIRD Demonstration







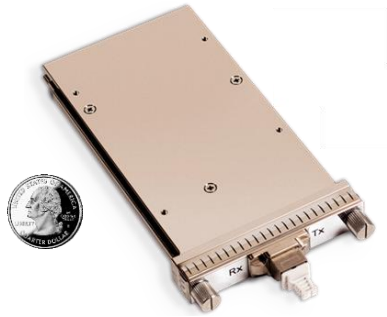
Outline

- **Architecture Overview**
- **Operations**
- **Performance Results**

TBIRD Objectives

- Cubesat closed-loop body pointing
- Downlink >1 Terabyte error-free in a pass
- Transfer from space buffer to ground buffer at 100 Gbps
- Multi-channel operation (2 x 100 Gbps)
- Validate use of terrestrial COTS components in space
  - Space environment
  - Free space fading channel
  - Doppler effects

100 Gbps COTS Transceiver
Terrestrial fiber telecom

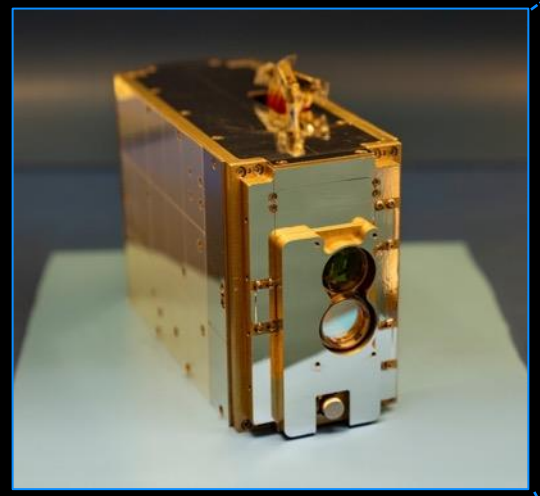


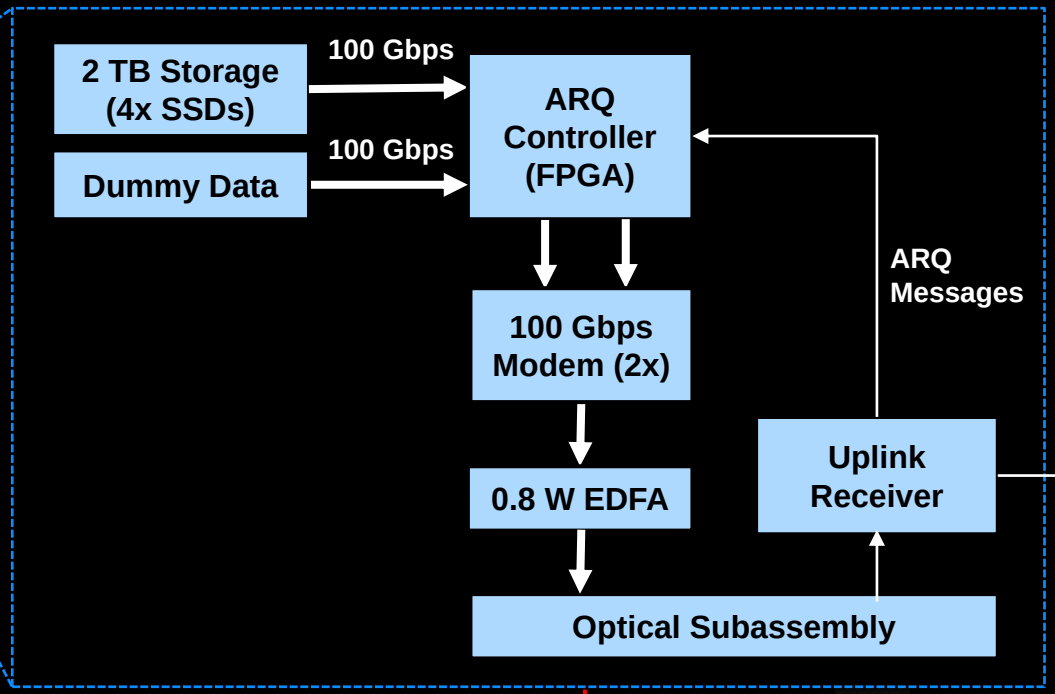
- Dual-polarization QPSK
- ASIC for DSP and FEC

COTS: Commercial Off The Shelf

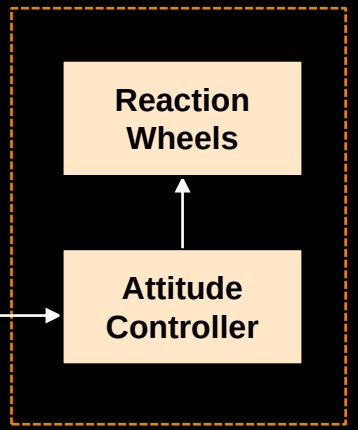
Communication and Body-Pointing Architecture

MITLL Lasercom Payload





Tyvak CubeSat Bus



Pointing Error

100/200 Gbps Downlink @ 1550 nm

2 kbps Uplink Beacon/ARQ

Ground Terminal

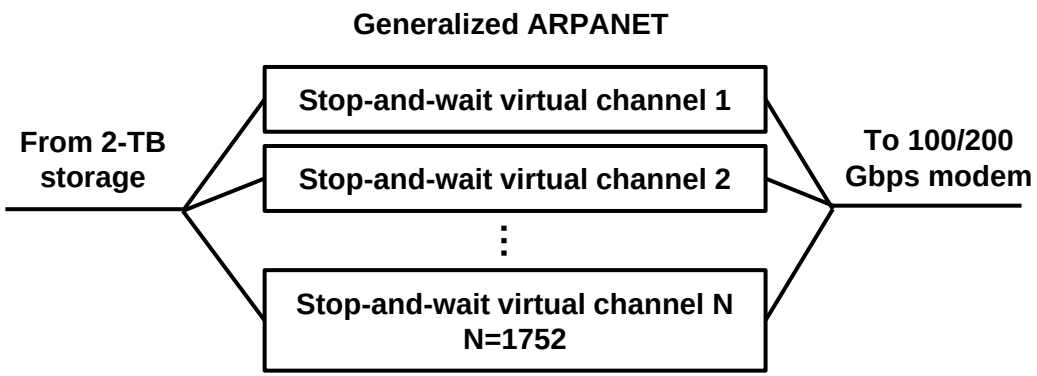
JPL/MITLL Ground Terminal

ARQ: Automatic Repeat reQuest
SSD: Solid State Drive
EDFA: Erbium Doped Fiber Amplifier

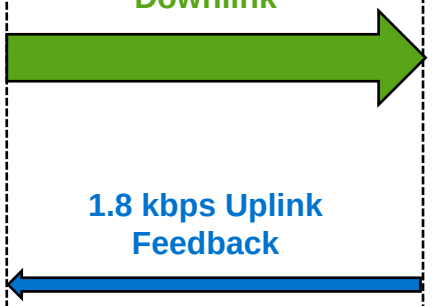
MITLL
JPL
Tyvak

TBIRD Automatic Repeat ReQuest (ARQ)

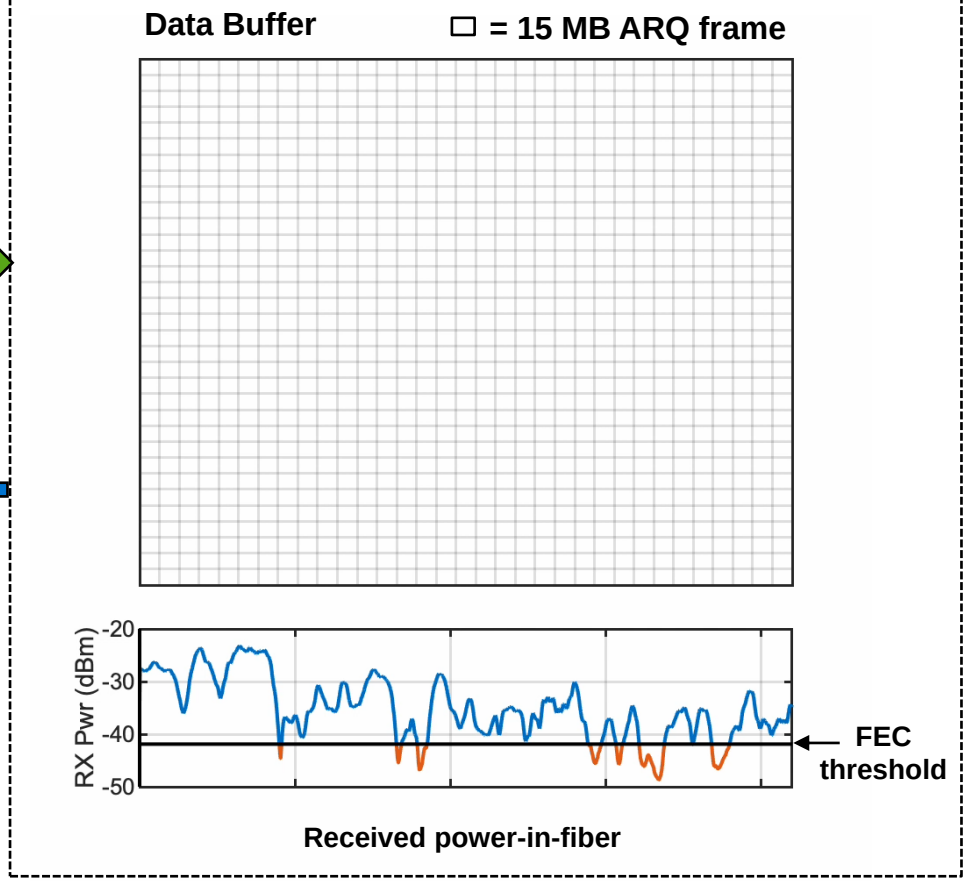
Space Terminal



- **Selective-repeat ARQ (random access)**
- **Large ARQ frames (15/30 MB)**
- **~2000 virtual channels**

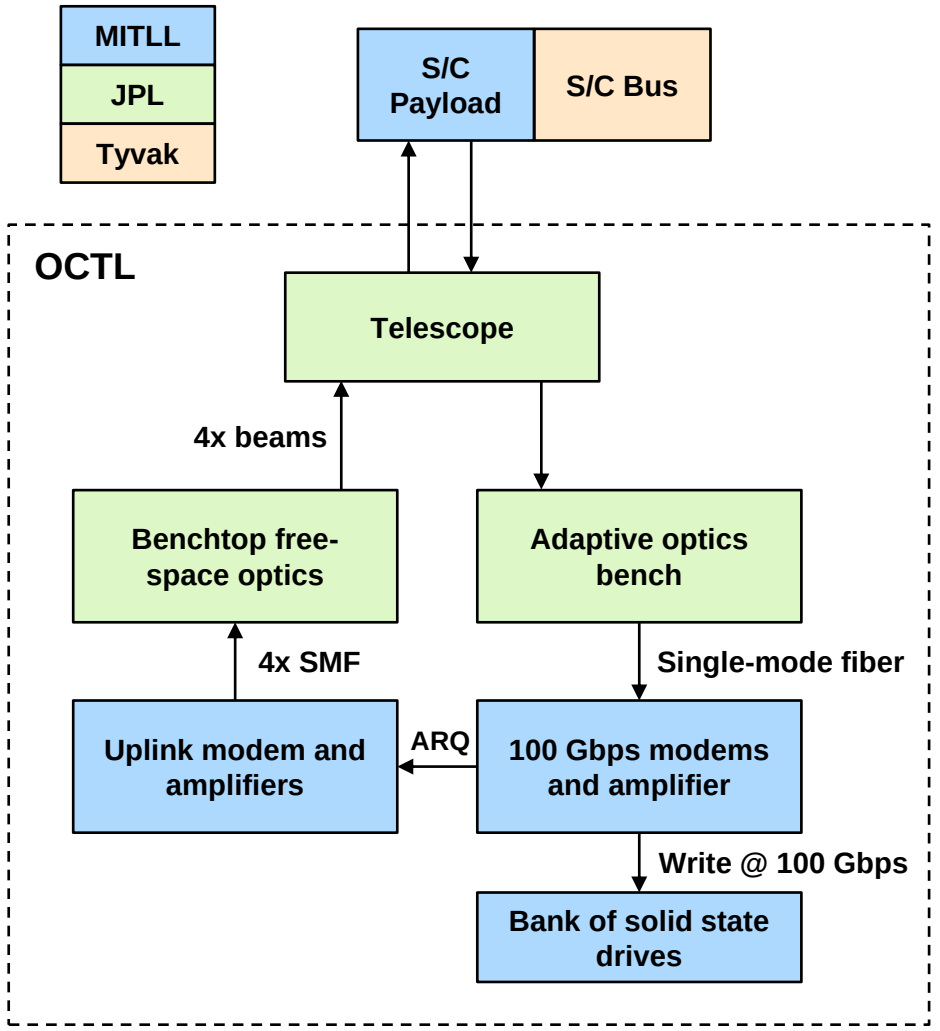


Ground Terminal



Ground Terminal at OCTL

- MITLL downlink and uplink modems
- JPL telescope and adaptive optics
  - Augmentation of LCRD OGS-1 setup
- Receive (downlink)
  - 1-m aperture
  - Adaptive optics
  - 200 Gbps max data rate
  - 100 Gbps write to SSDs
- Transmit (uplink)
  - 4-transmit beams for diversity
  - ~600 urad FWHM
  - ~10 W total transmit power

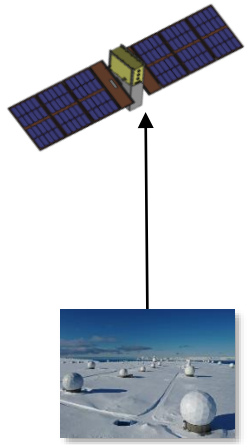
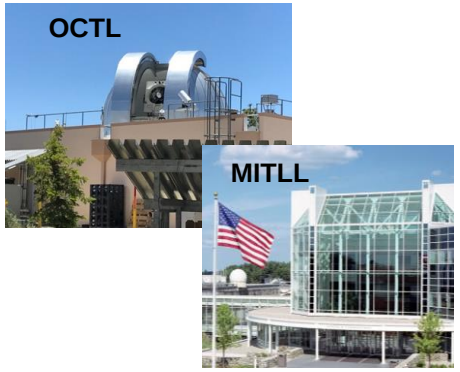
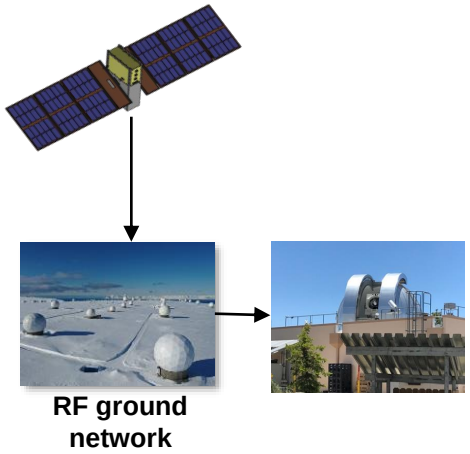
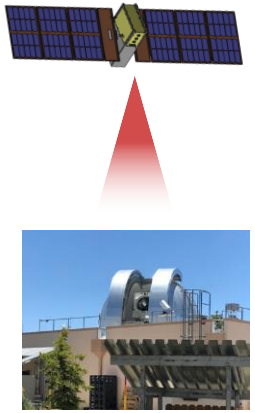
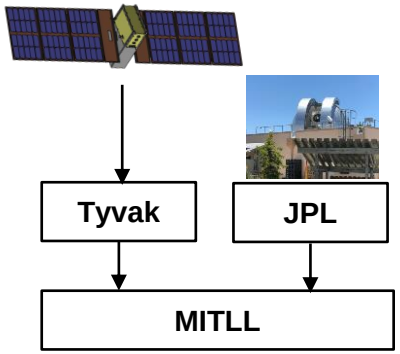


S/C: Spacecraft
SMF: Single mode fiber
OCTL: Optical Communications Telescope Laboratory
FWHM: Full Width Half Max

Outline

- **Architecture Overview**
- **Operations**
- **Performance Results**

Operations Timeline to Support a ~5-minute Pass

2+ hours before pass	2 hours before pass	10-15 min before pass	Pass (~ 5 min)	Telemetry aggregation and analysis
 RF ground network				
• Tyvak uploads MITLL pass script over RF link • Tyvak configures S/C for lasercom pass	• OCTL and MITLL operators perform system checkouts • OCTL: telescope and AO system • MITLL (remote): uplink transmitter and downlink receiver	• Fresh ephemeris data downloaded from on-board GPS • OCTL receives TLE 10 minutes before pass	• Spacecraft and payload are fully automated (no RF link available) • Ground transmitter and receiver equipment automated • Telescope and AO software require some human-in-the-loop control	• Spacecraft and ground telemetry aggregated at MITLL for analysis • Integrated telemetry analysis essential for debugging

AO: Adaptive Optics
S/C: Spacecraft

OCTL: Optical Communications Telescope Laboratory
TLE: Two Line Element

Operations Summary

Key

- Launch
- Daytime Pass
- Nighttime Pass
- Operational Issue

May

S	M	T	W	T	F	S
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
29	30	31				

June

S	M	T	W	T	F	S
			1	2	3	4
5	6	7	8	9	10	11
12	13	14	15	16	17	18
19	20	21	22	23	24	25
26	27	28	29	30		

July

S	M	T	W	T	F	S
					1	2
3	4	5	6	7	8	9
10	11	12	13	14	15	16
17	18	19	20	21	22	23
24	25	26	27	28	29	30
31						

August

S	M	T	W	T	F	S
	1	2	3	4	5	6
7	8	9	10	11	12	13
14	15	16	17	18	19	20
21	22	23	24	25	26	27
28	29	30	31			

September

S	M	T	W	T	F	S
				1	2	3
4	5	6	7	8	9	10
11	12	13	14	15	16	17
18	19	20	21	22	23	24
25	26	27	28	29	30	

October

S	M	T	W	T	F	S
						1
2	3	4	5	6	7	8
9	10	11	12	13	14	15
16	17	18	19	20	21	22
23	24	25	26	27	28	29

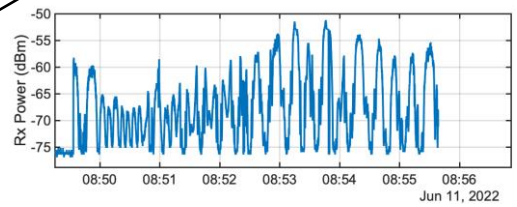
November

S	M	T	W	T	F	S
		1	2	3	4	5
6	7	8	9	10	11	12
13	14	15	16	17	18	19
20	21	22	23	24	25	26
27	28	29	30			

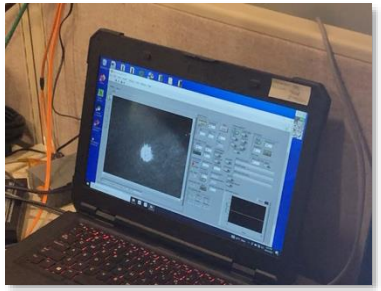
December

S	M	T	W	T	F	S
				1	2	3
4	5	6	7	8	9	10
11	12	13	14	15	16	17
18	19	20	21	22	23	24
25	26	27	28	29	30	31

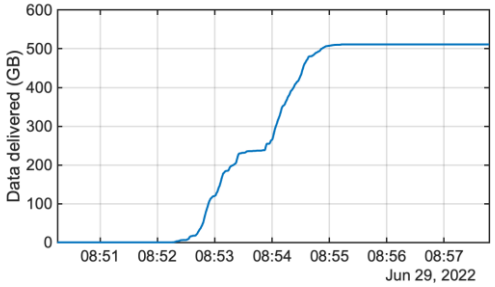
First uplink detection



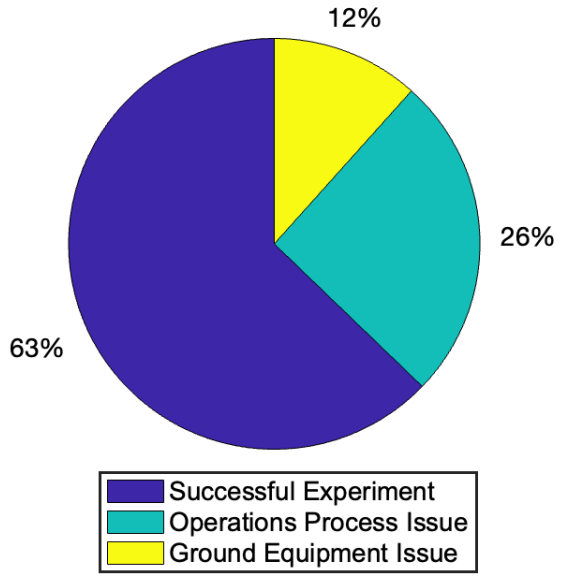
First downlink light



First large data volume delivered (500 GB)

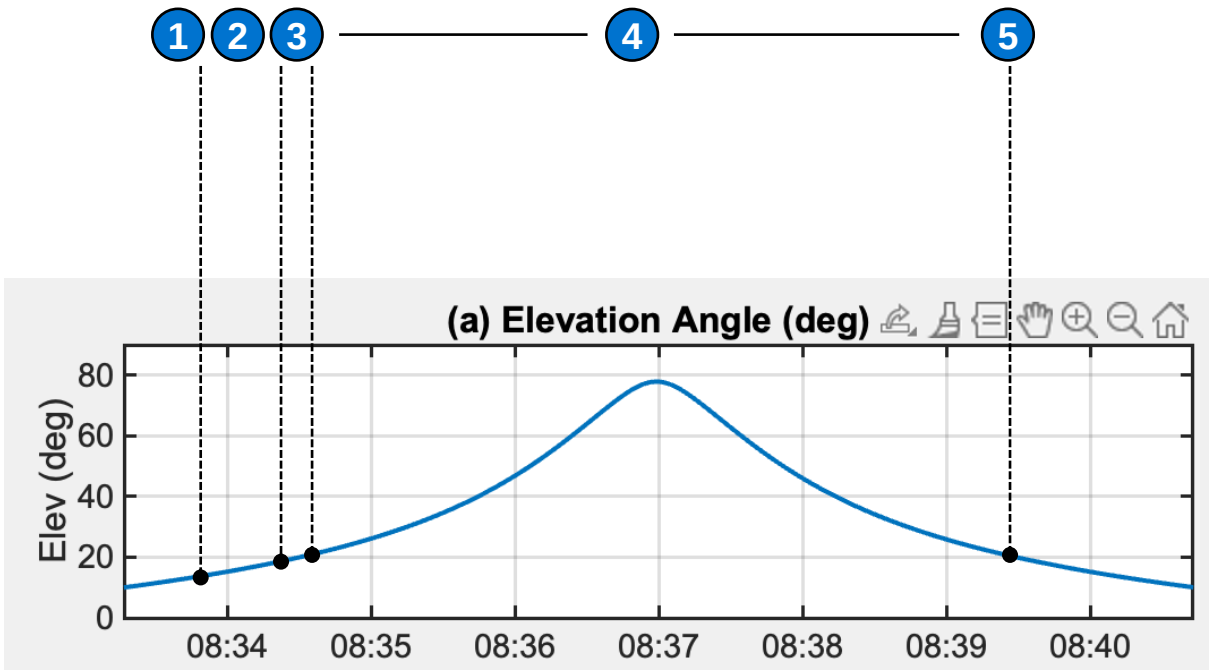


Pass Outcomes (N=43)



Typical Timeline of an Operational Pass

1. **Uplink detection at 12°**
2. **Spacecraft pull-in and track (10-30 sec)**
3. **Downlink acquisition and AO loop closure (5-10 sec)**
4. **Comm whenever power-in-fiber is above FEC threshold**
5. **Programmed end of pass at 20°**



Outline

- **Architecture Overview**
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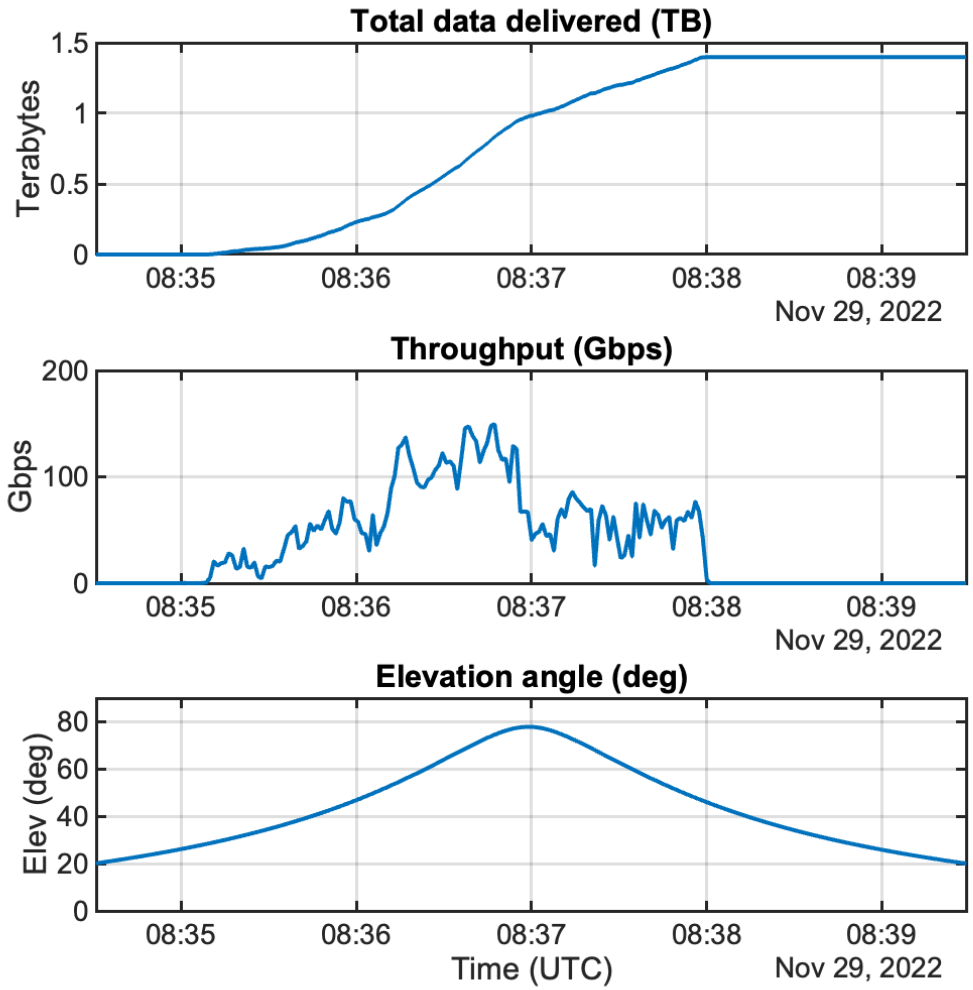
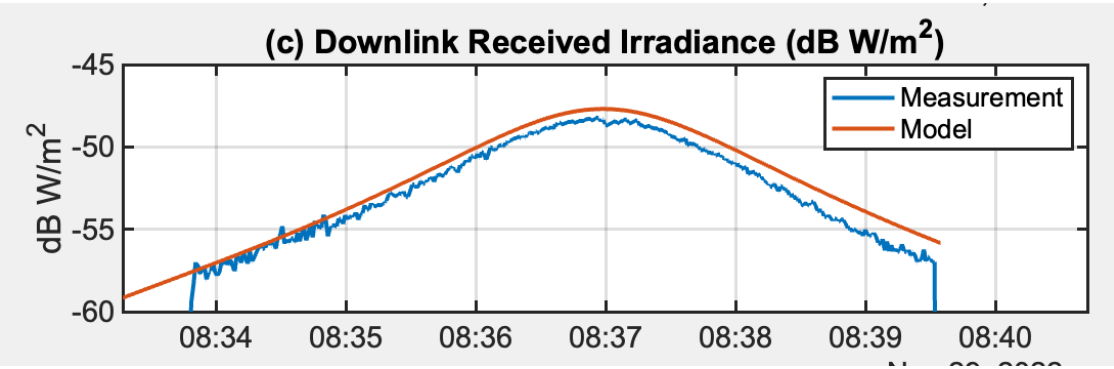
Data Delivery Example (11/29/22)

- **Operated in 200 Gbps mode (100 Gbps on two wavelength channels)**
- **Downlinked 1.4 TB error-free in 3 minutes**
- **Achieved ~150 Gbps throughput (measured with 1-second averaging)**

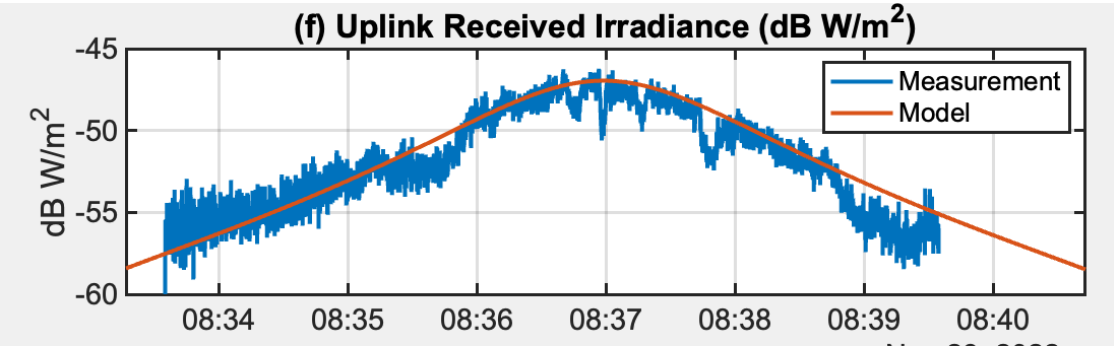


Downlink and Uplink Irradiance (11/29/22)

- Irradiance measured using calibrated telemetry from AO wavefront sensor
- Model uses 380-urad FWHM beamwidth as measured on-orbit
- Closed-loop body pointing is stable and delivers expected irradiance to OCTL

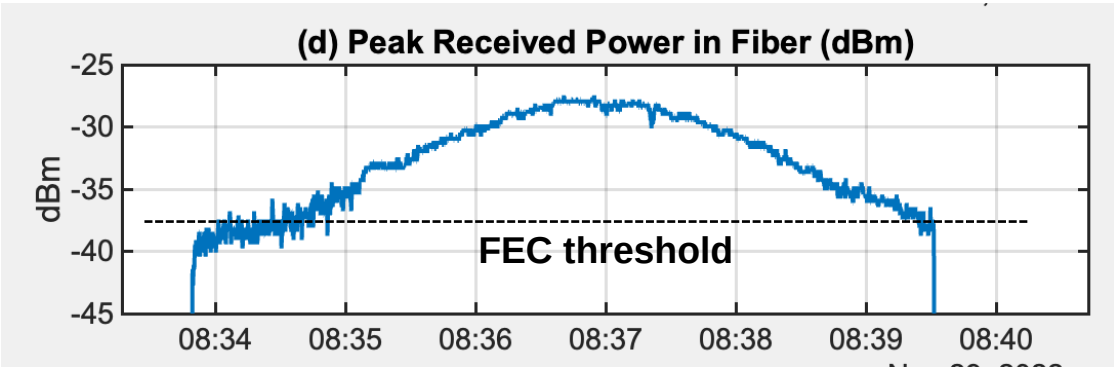


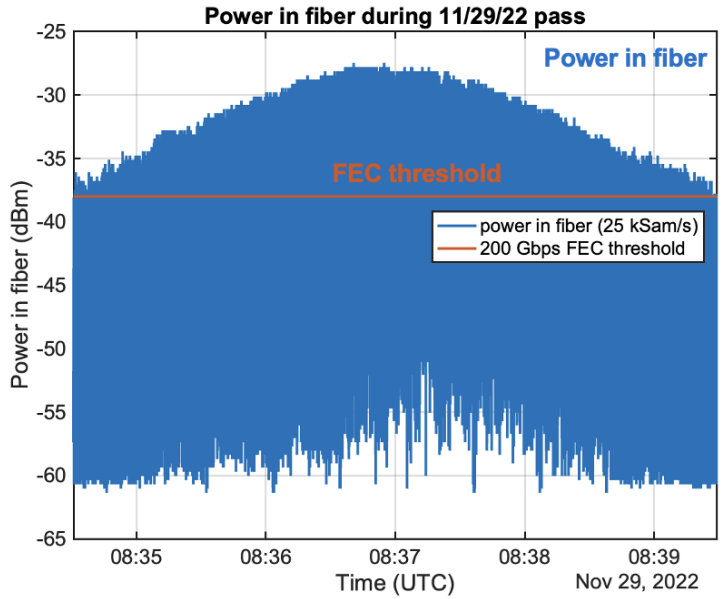
- Uplink irradiance measured by payload quad cell agrees with link model
- Irradiance was above comm threshold for the entire pass, resulting in error-free ARQ feedback channel



Power in Fiber (11/29/22)

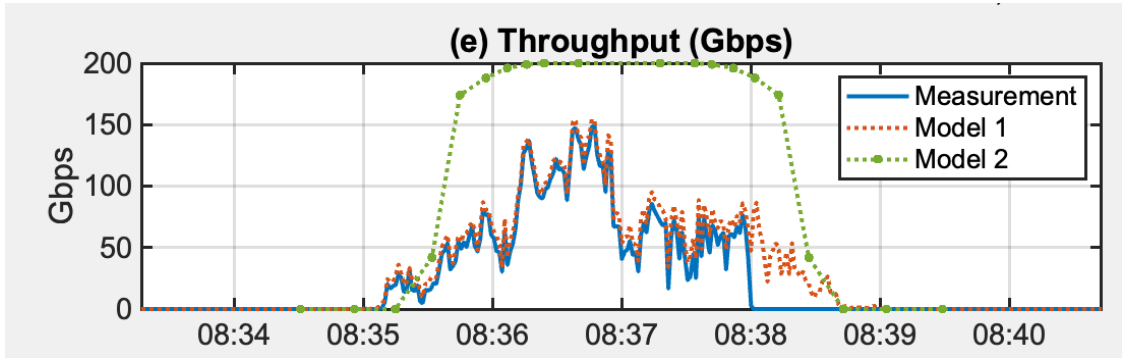
- Power in fiber recorded at 25 kSam/s for duration of pass
- Peak power calculated by applying 5 Hz envelope filter
  - Behavior consistent with irradiance profile
  - Increases with elevation angle, symmetric about pass apex
  - Well above FEC threshold for much of the pass
- Large fluctuations present not turbulence-limited
  - Due to internal tilt disturbances in the ground station optical path that the adaptive optics system does not fully correct

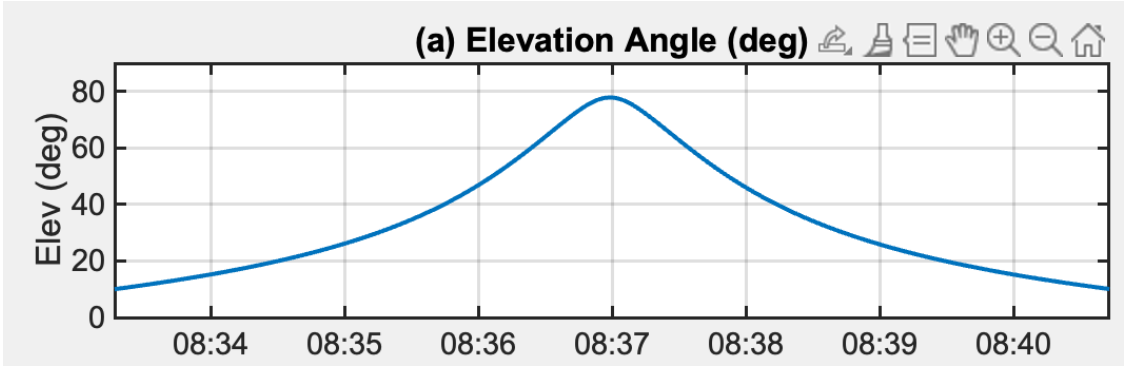




Throughput Measurement and Models (11/29/22)

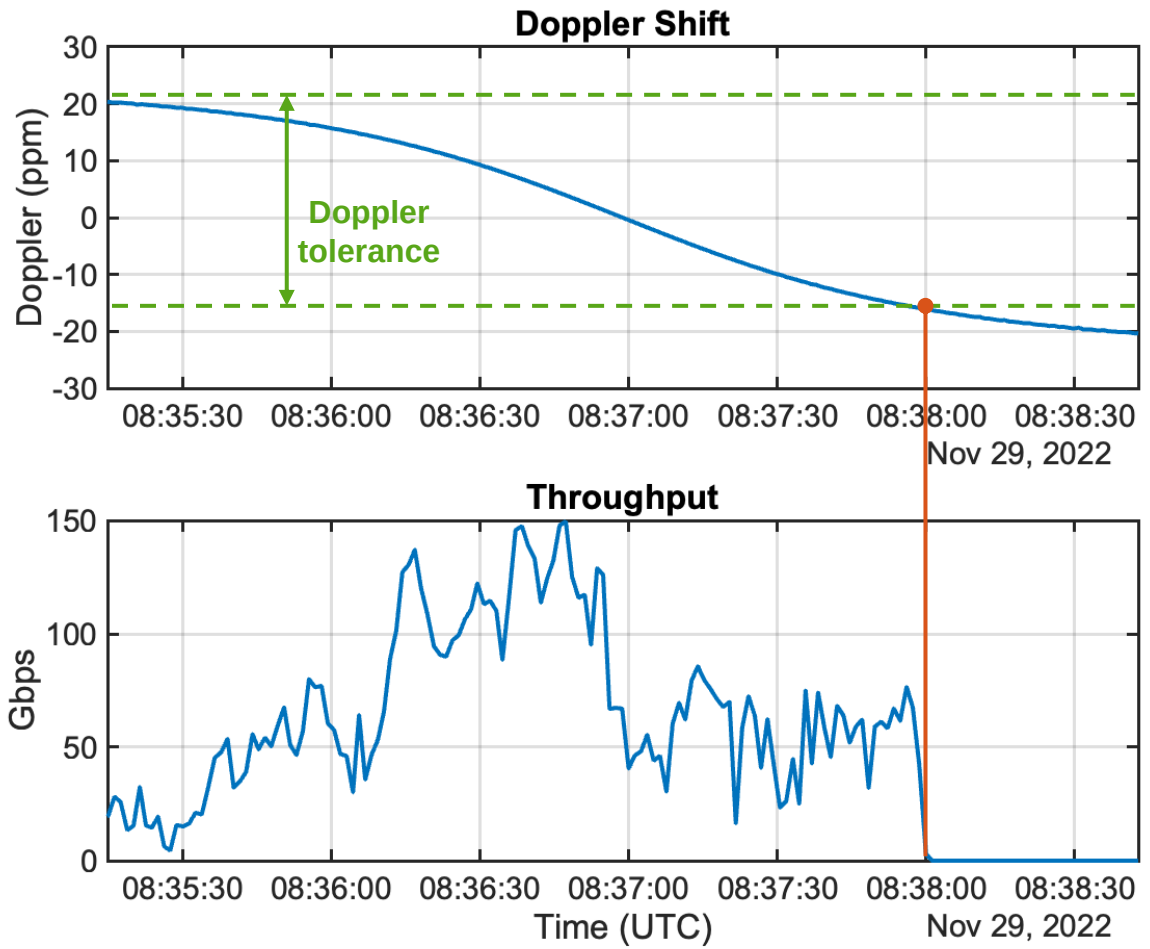
- **Throughput is the end-to-end error free data rate**
- **Model 1**
  - **Uses 25 kSam/s power-in-fiber capture**
  - **Incorporates transceiver characteristics and ARQ protocol parameters**
  - **Shows receiver is operating as expected given the power-in-fiber profile**
- **Model 2**
  - **Atmosphere-limited model**
  - **Uses turbulence simulations to derive power in fiber**
  - **Shows potential performance with ground station improvements**





Impact of Doppler Shift during Pass

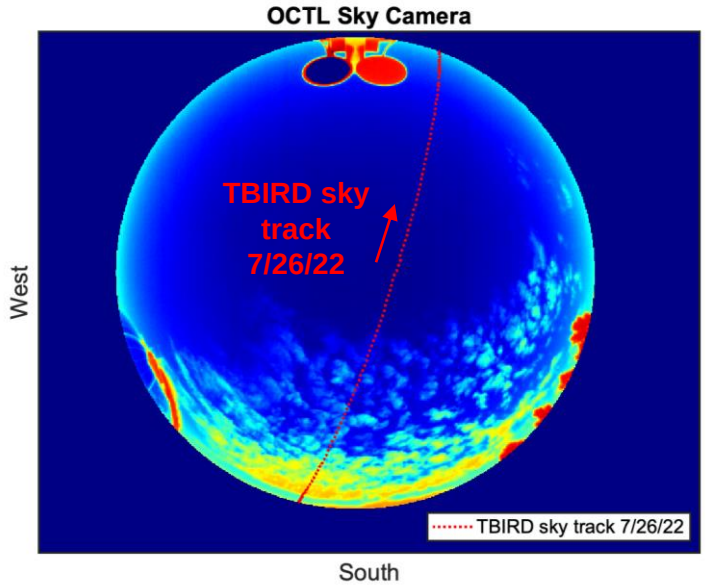
- **Large doppler shifts cause COTS transceivers to fail to decode**
- **Doppler tolerance of current configuration was estimated from post-pass analysis of telemetry**
- **Not fully testable in lab due to challenge of measurement with COTS hardware**

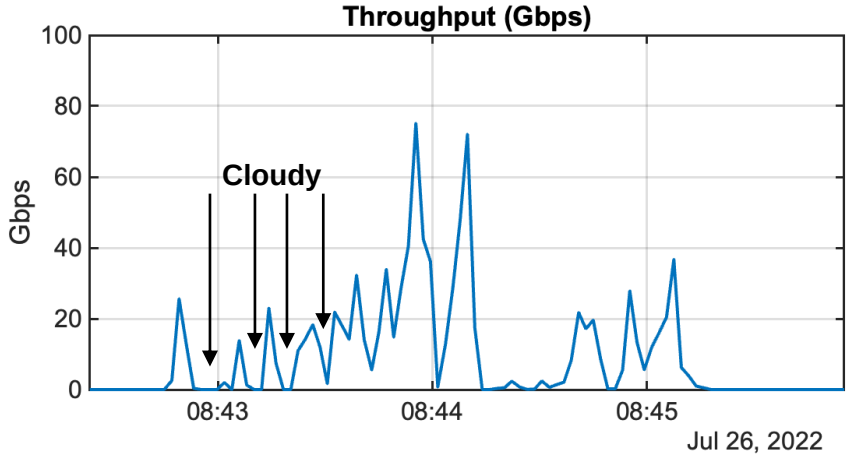


COTS: Commercial Off The Shelf

Data Transfer from Space SSDs to Ground SSDs

- **Space SSDs**
  - Preloaded data from flight build
  - Additional telemetry writing on orbit
  - Read at 100 Gbps
- **Ground SSDs**
  - Write at 100 Gbps
- **Experiment Example (7/26/22)**
  - Partially cloudy
  - 240 GB downlinked to ground buffer
  - Ground buffer transferred to server after pass for file retrieval
  - ARQ system ensured reliable delivery





SSD: Solid State Drive

Summary

- **TBIRD launched in May 2022 and has operated successfully for 6 months**

- **Key Achievements:**
  - **~30-urad Cubesat closed-loop body pointing**
  - **100/200 Gbps downlinks from LEO**
  - **Downlinked >1 Terabyte error-free in a pass**
  - **Validated use of terrestrial COTS components in space**
  - **Performed end-to-end transfer from space buffer to ground buffer at 100 Gbps**

- **Mission continues in 2023**