TBIRD: Two Years Demonstrating 200 Gbps Optical Downlink

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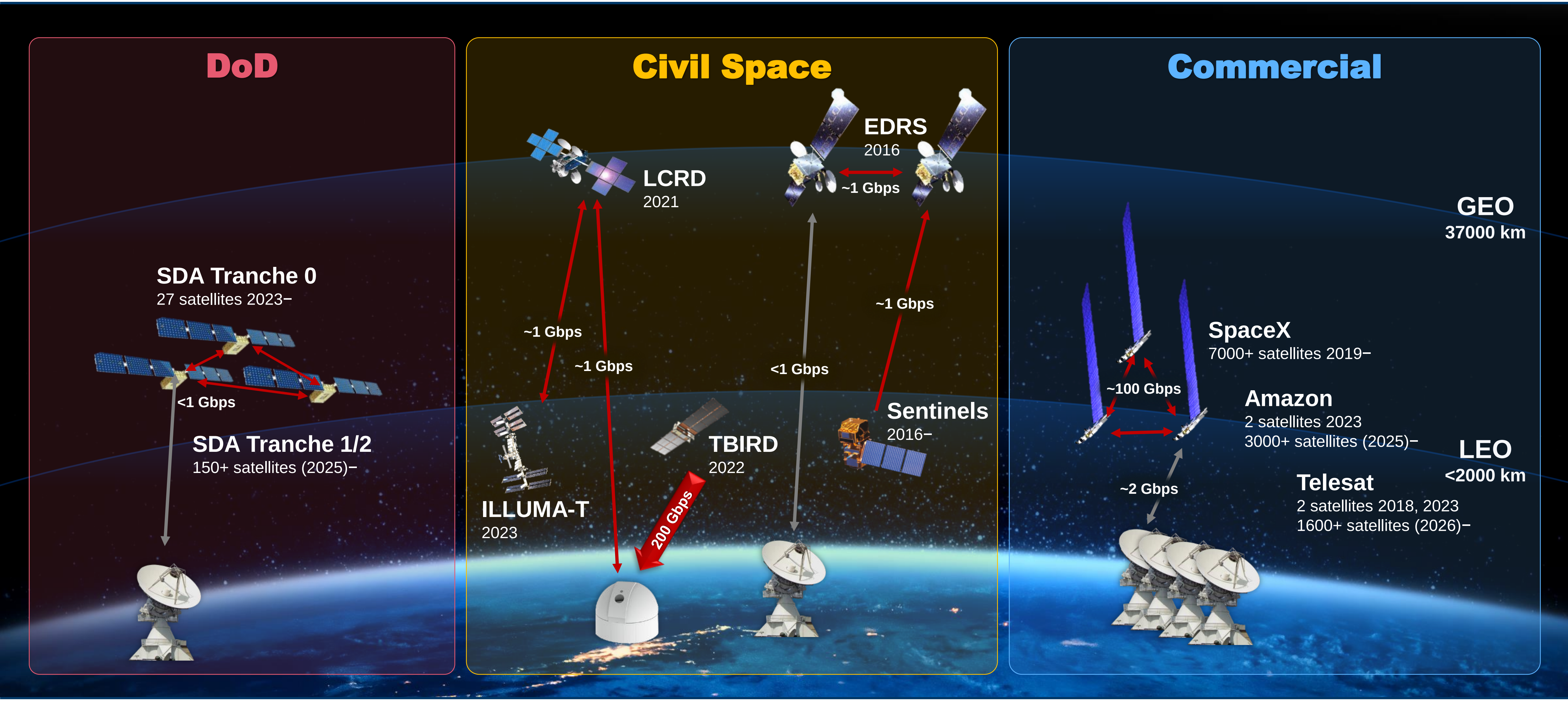
Outline

- **Motivation**
- **System Architecture**
- **Operations**
- **Conclusion and Future Work**

Current and Imminent Near-Earth Lasercom



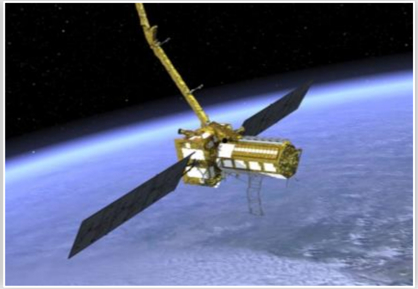
Optical
RF

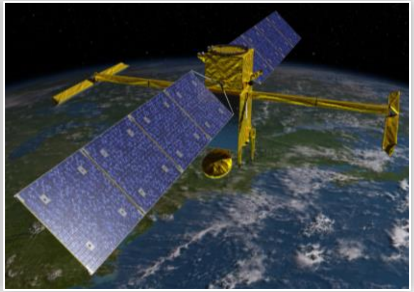
SDA: Space Development Agency
LEO: Low Earth orbit

GEO: Geostationary orbit

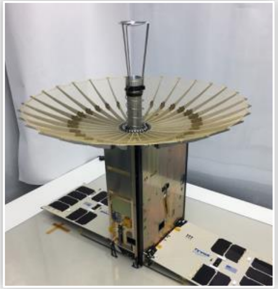
Large Data Volumes in Low Earth Orbit (LEO)

Large and Medium Satellites





Small Satellites



	Hyperspectral Imager Suite (HISUI) on International Space Station	NASA-ISRO Synthetic Aperture Radar (NISAR)	NASA Surface Water and Ocean Topography (SWOT)	JPL RainCube	GOMX-4B Hyperspectral Camera	UH Manoa Hyperspectral Thermal Imager (HyTI)
	In-orbit	(2025)	In-orbit	2019	In-orbit	2024
Data Volume	0.3 TB/day (“downlinked”)	4.8 TB/day (downlinked)	20 TB/day (generated) 1 TB/day (downlinked)	1 TB/day (generated)	2 TB/day* (generated)	8 TB/day (generated)

*Assumes 25% operational duty cycle

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State-of-the-art instruments on LEO platforms can generate raw data volumes of terabytes per day

TB: Terabyte

High-Rate Direct-to-Earth Laser Communication

RF Architecture vs Optical Architecture

RF Architecture

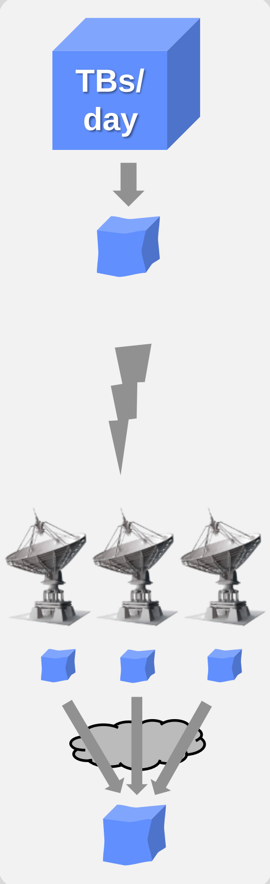
Sensor collect (raw)

On-board compression 10−100x

RF downlink 0.001−2 Gbps

Ground station network

Processing center



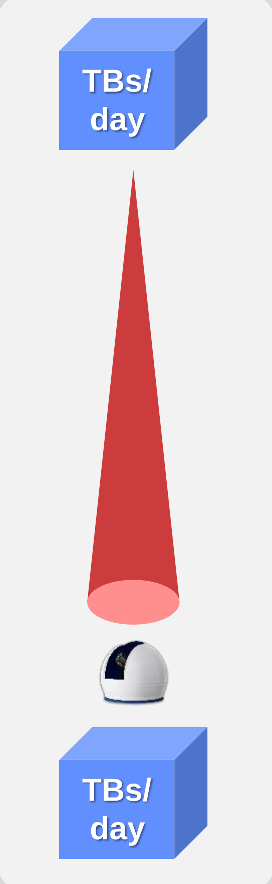
Optical Architecture

Sensor collect (raw)

Little or no on-board processing

Optical downlink 100+ Gbps

Single small ground terminal at processing center



Optical Comm Comparison to RF

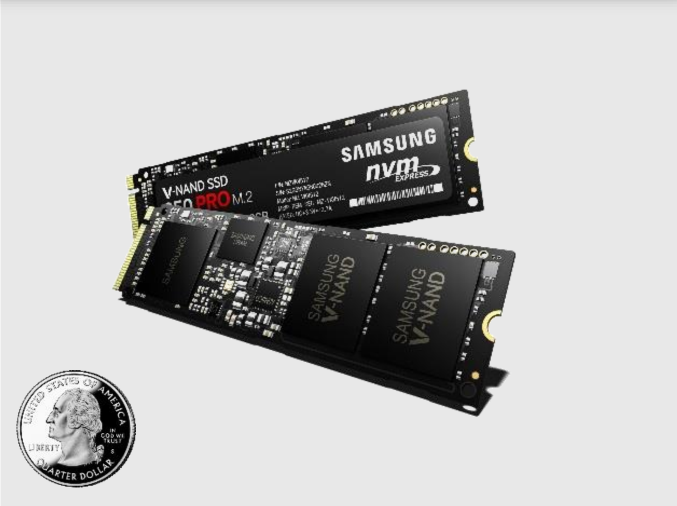
- Abundant spectrum (4.4 THz vs 40 GHz)
  - THz available, unregulated
  - Enables high data rates >100 Gbps
- High beam directivity (urad vs deg)
  - Small, low power terminals
- Challenges: pointing, atmosphere

Data Delivery Example

4 min @ 100 Gbps = 3 TB/day

RF: Radio Frequency
TB: Terabyte

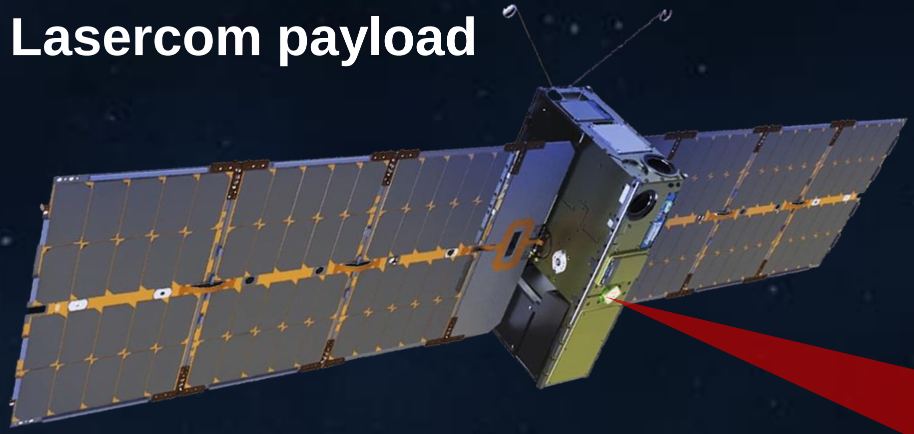
Enabling Commercial Technologies

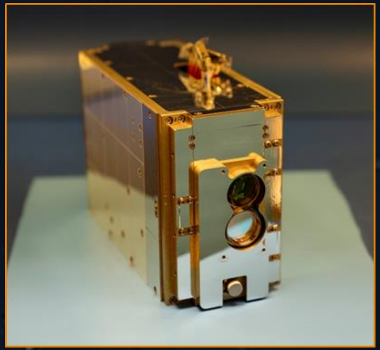
High-Rate Optical Modem	Large, High-Speed Storage	Optical Amplifier
		
100 Gbps Fiber Telecom Transceiver Compact Form Pluggable (CFP)	**>500 GB, >25 Gbps Readout Solid-State Drive (SSD)**	**~1 W Erbium Doped Fiber Amplifier Optical C-Band (~1550 nm)**
~$10k/unit	**~$100/unit**	**~$10k/unit**

Highly integrated commercial components enable small, low-power, low-cost space terminal designs

Terabyte Infrared Delivery (TBIRD) Mission

6U CubeSat in LEO
3U Lasercom payload





- **Leverage fiber telecom equipment for 200 Gbps burst delivery (terabytes per pass)**
- **Achieve robust data transfer through atmospheric channel**
- **Demonstrate body pointing architecture with payload pointing feedback**

200 Gbps downlink

Two optical ground stations (OGS):

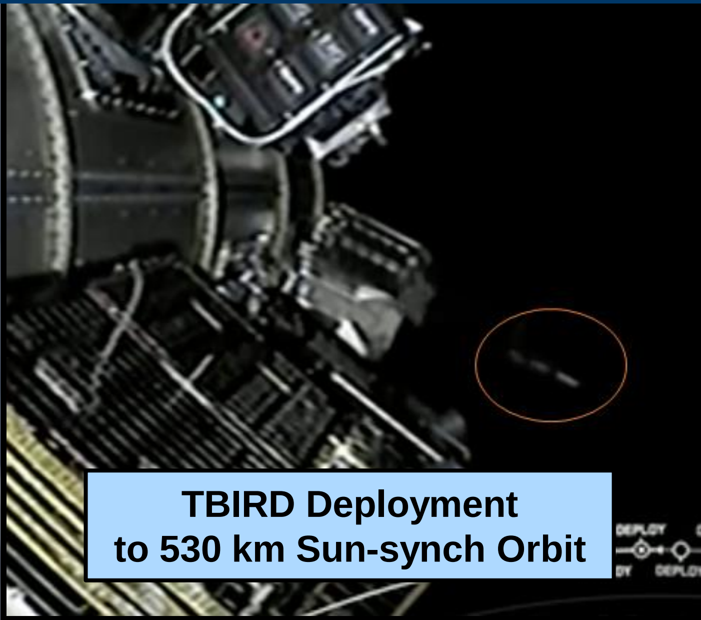
- **NASA OGS-1 in Southern California**
- **NASA OGS-2 in Hawaii**

TBIRD Demonstration

Environmental Testing
(Vibration and Thermal Vacuum)

Payload Delivery for
Spacecraft Integration

Launched: May 25, 2022
Deorbited: September 14, 2024



TBIRD Deployment
to 530 km Sun-synch Orbit

Lasercom Operations
110 Passes to
Multiple Ground Stations

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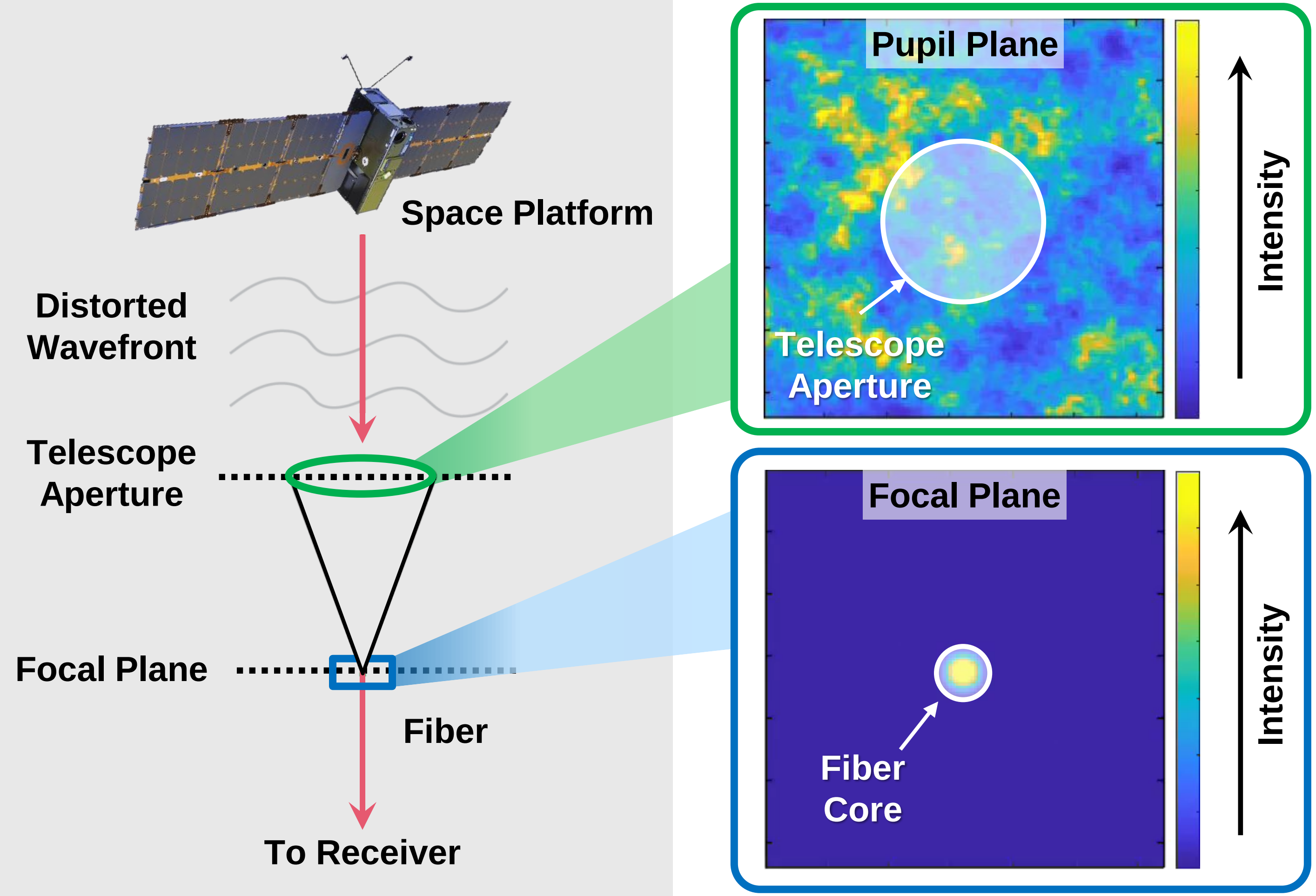
Impact of Atmospheric Turbulence on Fiber-Based Receivers

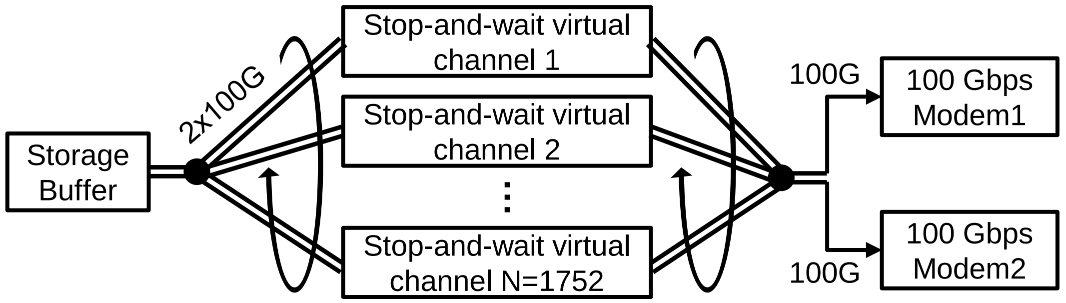


- Turbulence causes scintillation
  - Power-in-bucket fluctuations
- Turbulence causes coupling loss
  - Adaptive optics system attempts to correct wavefront
  - Spot wanders and breaks up

Communications architecture must be robust to atmospheric fading

TBIRD Automatic Repeat ReQuest (ARQ)

Space Terminal



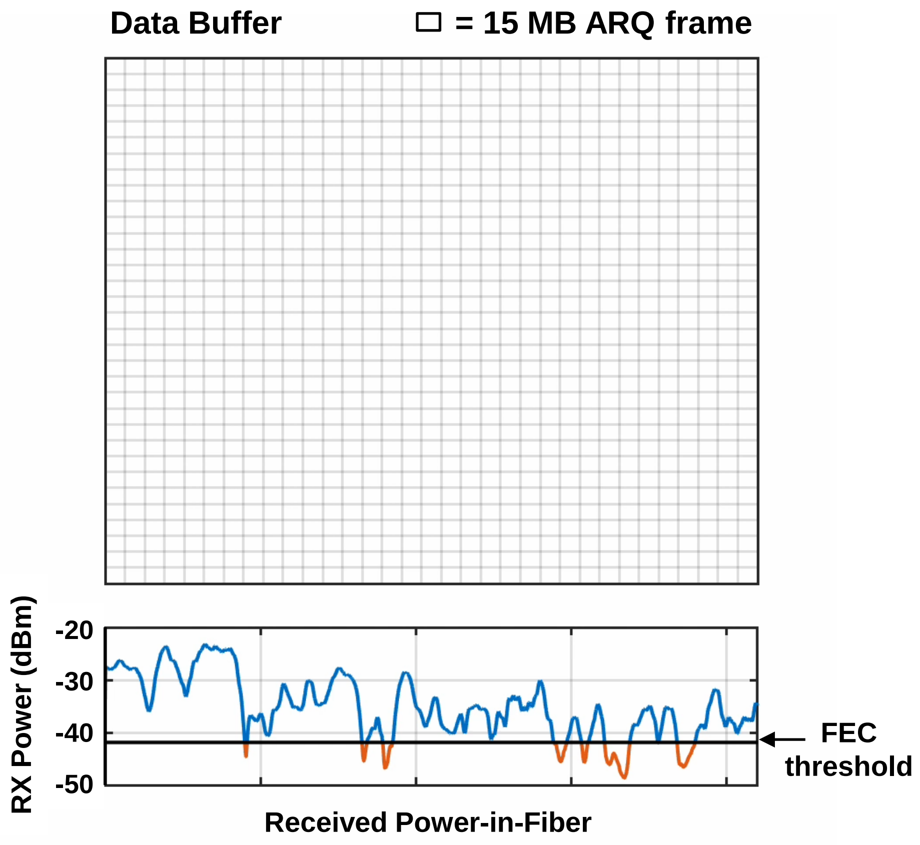
- **Selective-repeat ARQ**
- **Large ARQ frames (15/30 MB)**
- **~2000 virtual channels**

100 or 200 Gbps Downlink

~2 kbps Uplink Feedback

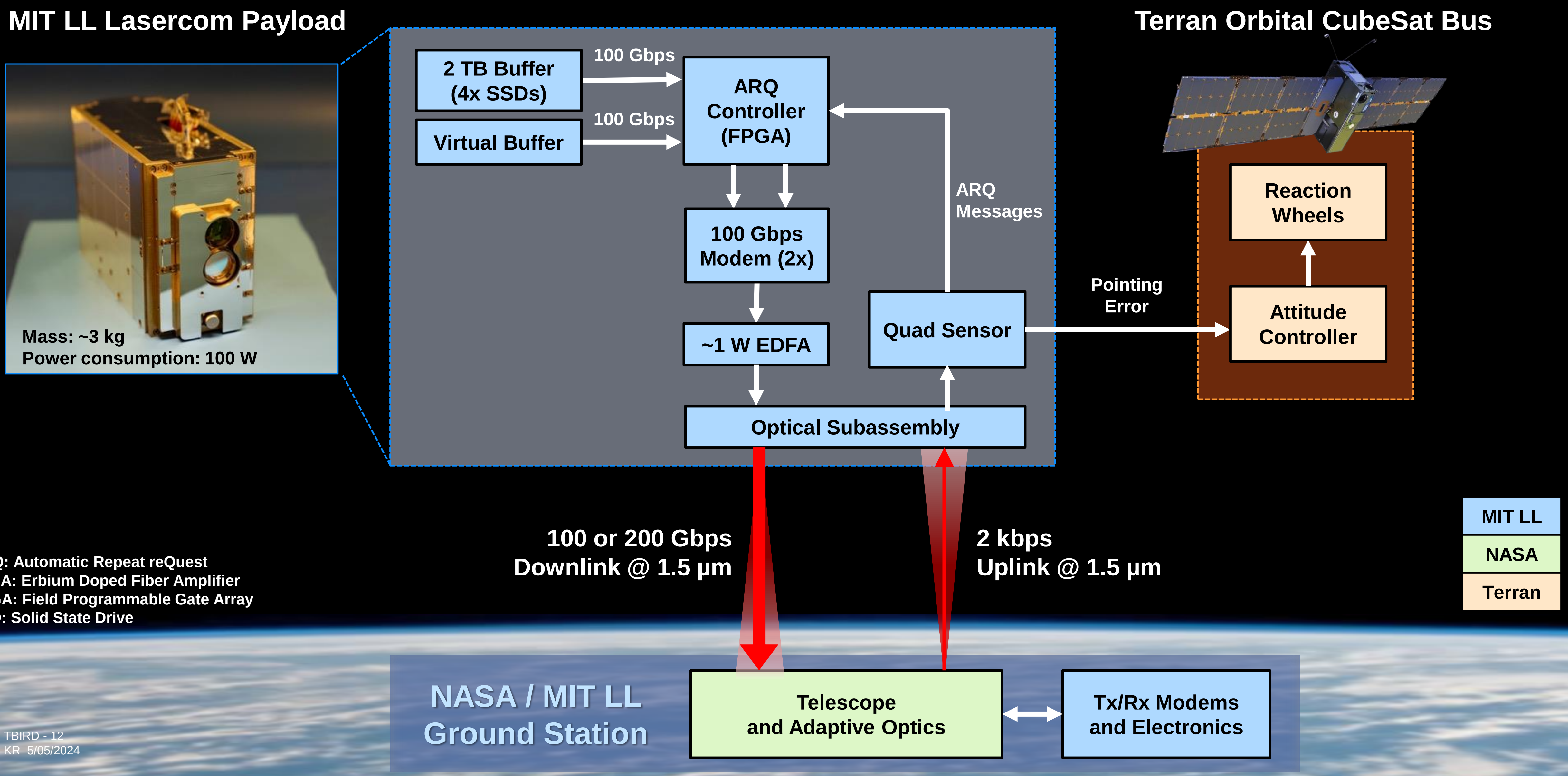
~kbps sufficient for kHz class fading dynamics

Ground Terminal



FEC: Forward Error Correction
MB: Megabyte

System Architecture



ARQ: Automatic Repeat reQuest
EDFA: Erbium Doped Fiber Amplifier
FPGA: Field Programmable Gate Array
SSD: Solid State Drive

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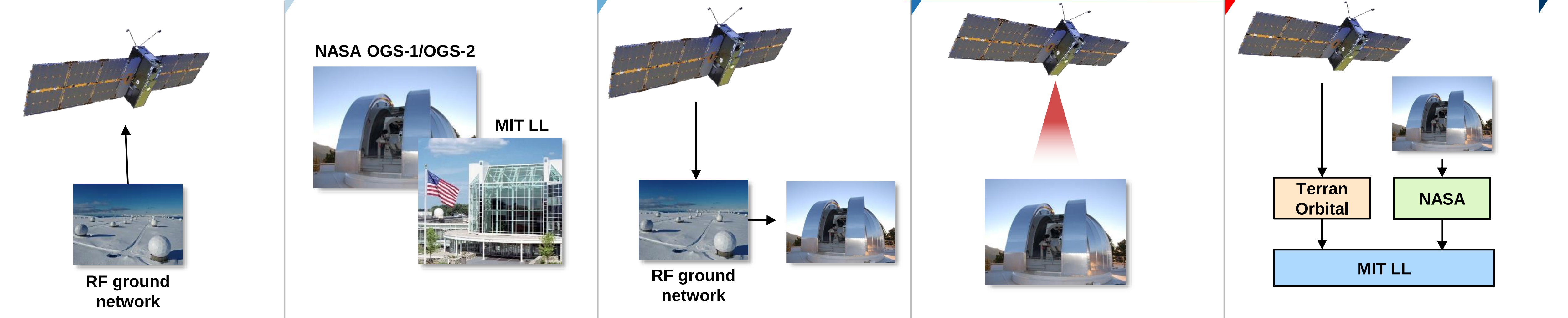
Timeline to Support a ~5-minute Pass

Schedule Pass 2+ hours before pass	Ready Ground Station 2 hours before pass	Receive Ephemeris 10 – 15 min before pass	Pass (~ 5 min)	Analyze Telemetry



Schedule Pass

- Terran Orbital uploads MIT LL pass script over RF link
- Terran Orbital configures spacecraft for lasercom pass

Ready Ground Station

- NASA OGS and MIT LL operators perform system checkouts
- NASA OGS: telescope and AO system
- MIT LL (remote): uplink transmitter and downlink receiver

Receive Ephemeris

- Fresh ephemeris data downloaded from on-board GPS
- NASA OGS receives TLE 10 minutes before pass

Pass (~ 5 min)

- 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

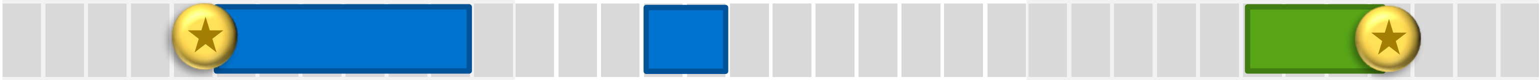
Analyze Telemetry

- Spacecraft and ground telemetry aggregated at MIT LL for analysis
- Integrated telemetry analysis essential for debugging

AO: Adaptive Optics
TLE: Two Line Element set

Operations Summary

Campaign 1	Campaign 2	Campaign 3
Jun – Nov 2022 **43 Lasercom Passes with OGS-1**	**Apr – May 2023** **22 Lasercom Passes with OGS-1**	**Jun – Sep 2024** **29 Lasercom Passes with OGS-2**



Launch
May 22, 2022

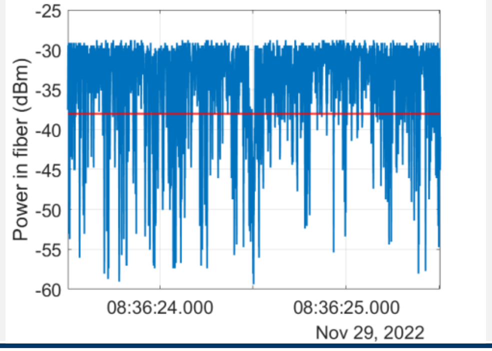
Deorbit
Sep 14, 2024

Campaign 1
- >1 TB in a pass
- Performance limited by ground station fiber coupling loss
- 1.4 TB in 3 minutes

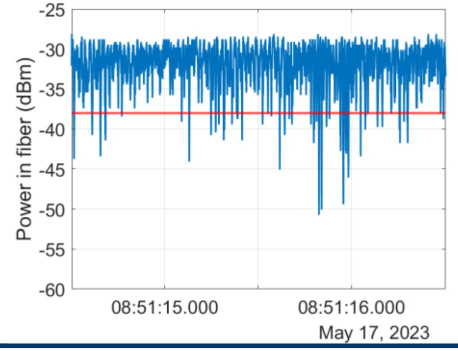
Campaign 2
- 13 passes >1 TB
- Ground station fiber coupling loss improved
- 4.8 TB in 5 minutes

Campaign 3
- 7 passes >1 TB
- Sustained full-rate 200G throughput
- 3.6 TB in 3 minutes

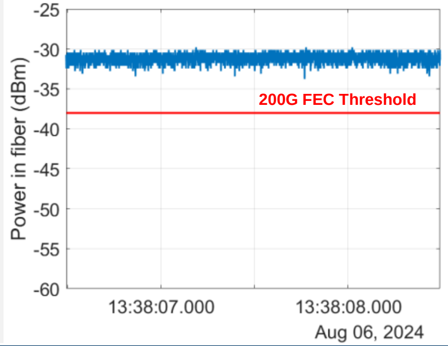
Measured Power in Fiber, 60° Elevation



Measured Power in Fiber, 60° Elevation

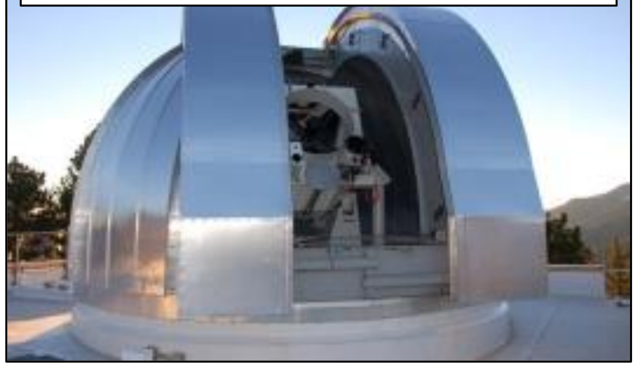


Measured Power in Fiber, 30° Elevation



TBIRD used two NASA ground stations:

OGS-1
1-m Telescope on Table Mountain, CA

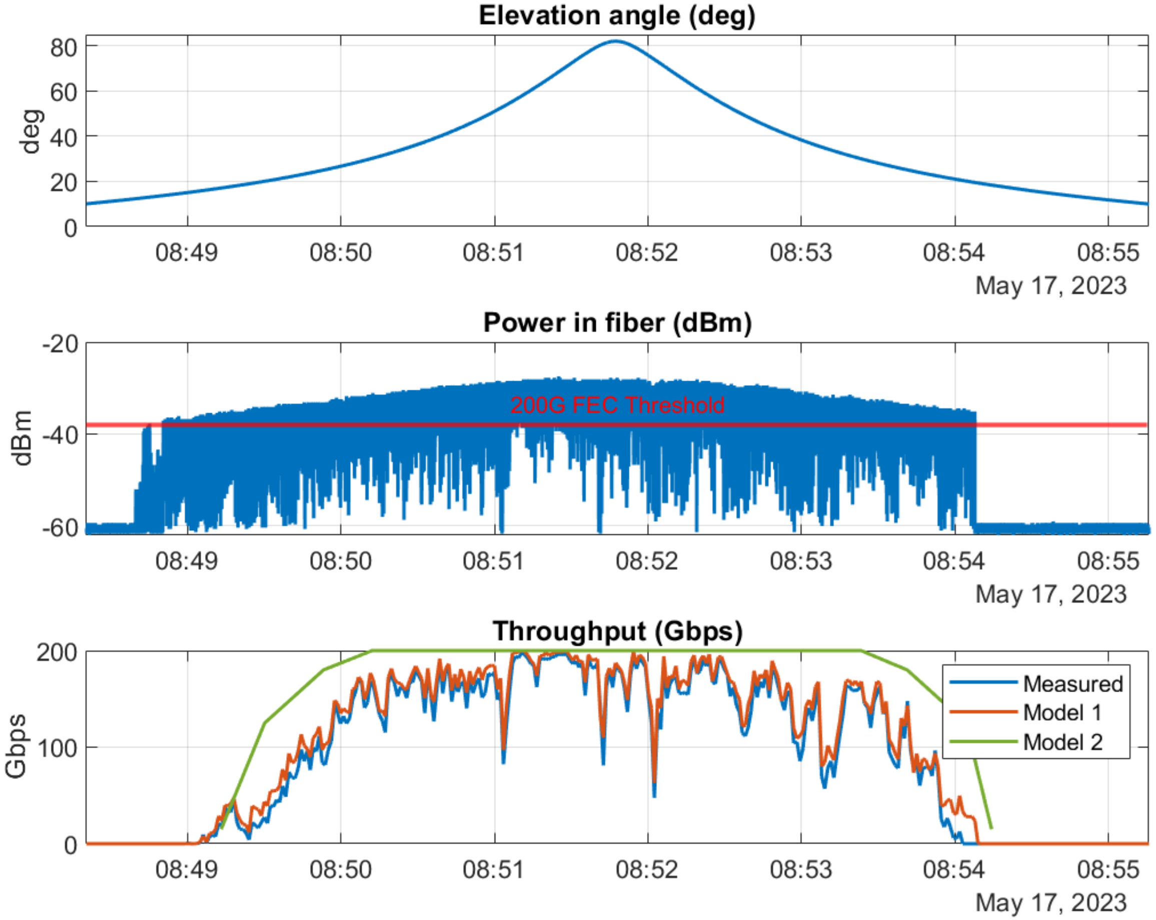


OGS-2
60-cm Telescope on Haleakala, HI

OGS: Optical Ground Station
TB: Terabyte

Data Delivery Example 5/17/23
Campaign 2 at OGS-1

- **Throughput is the end-to-end error-free data rate (1-second averaging)**
- **Coupling loss was worse than expected in an atmospherically-limited channel**
- **ARQ performed reliably in channel with significant fading**
- **Downlinked 4.8 TB error-free in 5 minutes**
- **Reached 200 Gbps throughput for brief periods**

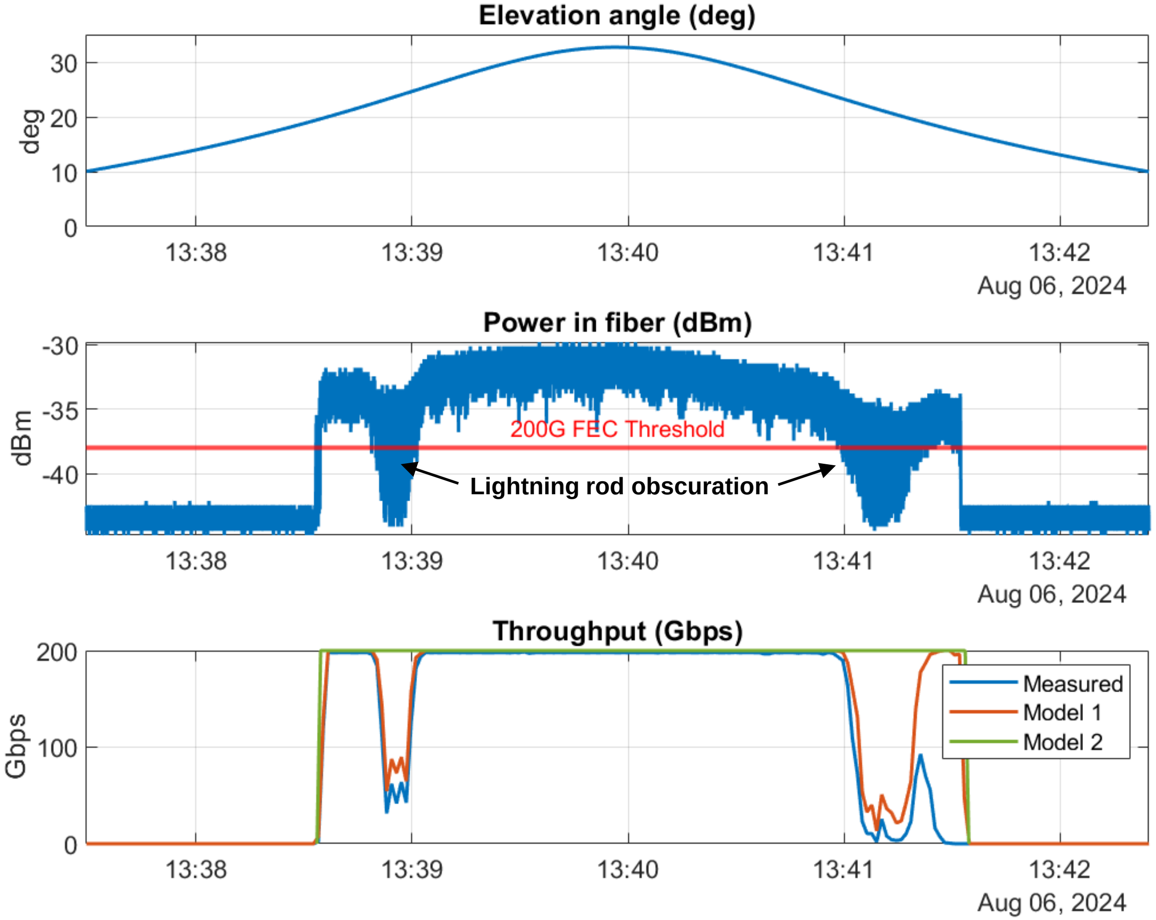


Measured
Model 1: Expected throughput with measured power in fiber
Model 2: Expected throughput with expected power in fiber

ARQ: Automatic Repeat reQuest
TB: Terabyte

Data Delivery Example 8/6/24
Campaign 3 at OGS-2

- **Coupling loss maintains signal well above FEC threshold**
- **Downlinked 3.6 TB error-free in 3 minutes**
- **Sustained 200 Gbps throughput**
- **Campaigns 2 & 3 successfully demonstrated Doppler compensation**



Measured
Model 1: Expected throughput with measured power in fiber
Model 2: Expected throughput with expected power in fiber

TBIRD has demonstrated record-breaking downlink speeds

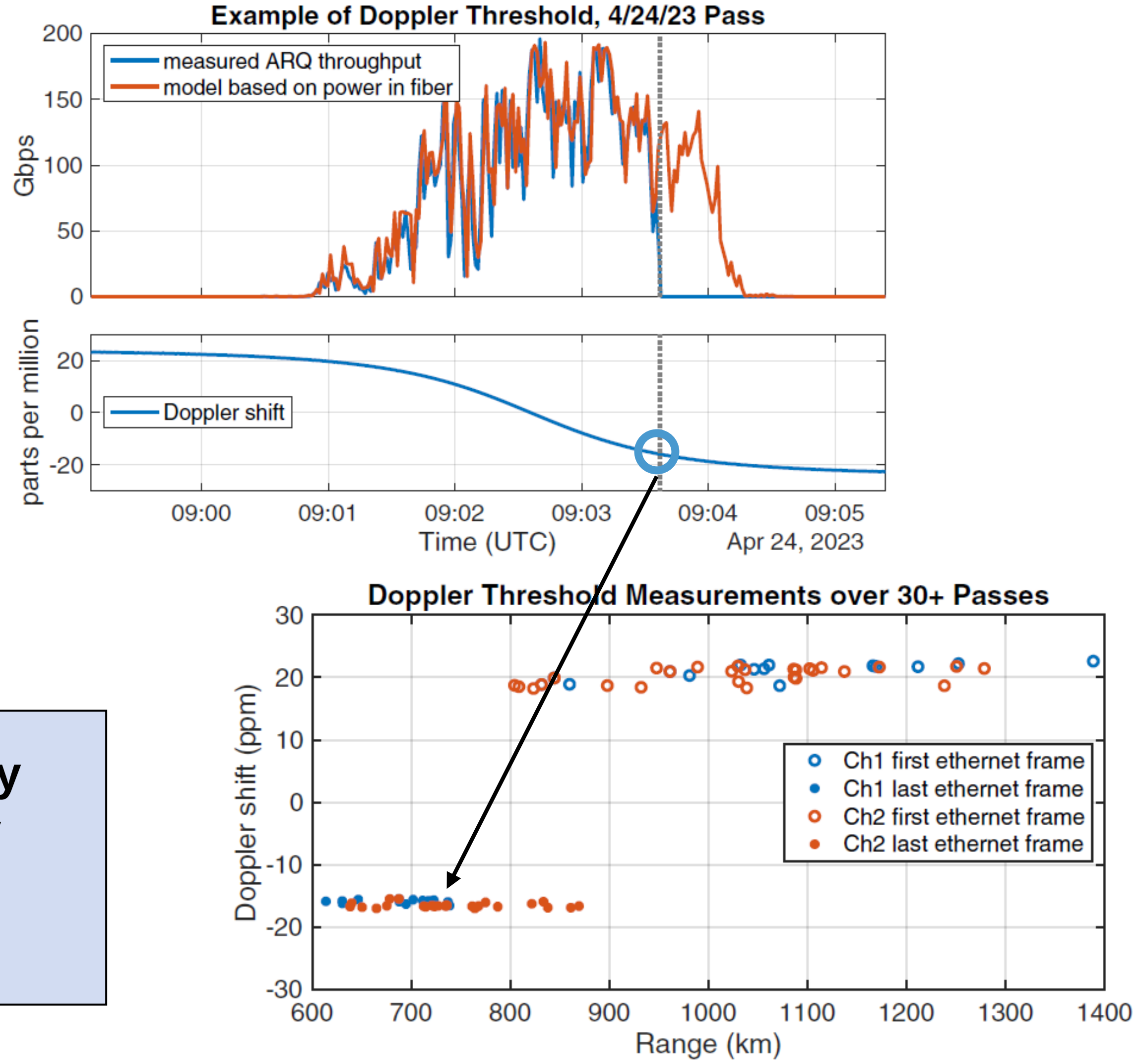
TB: Terabyte

Doppler Compensation

Doppler affects:
(1) optical frequency and
(2) clock frequency

- **TBIRD transceivers allow external adjustment of (1) but not (2)**
  - As a result, Doppler acceptance could not be fully tested in lab
  - Doppler effects on (2) were expected to be a system limitation

Adjusting receiver's optical frequency during passes was sufficient to fully compensate effects of Doppler, contrary to initial expectations

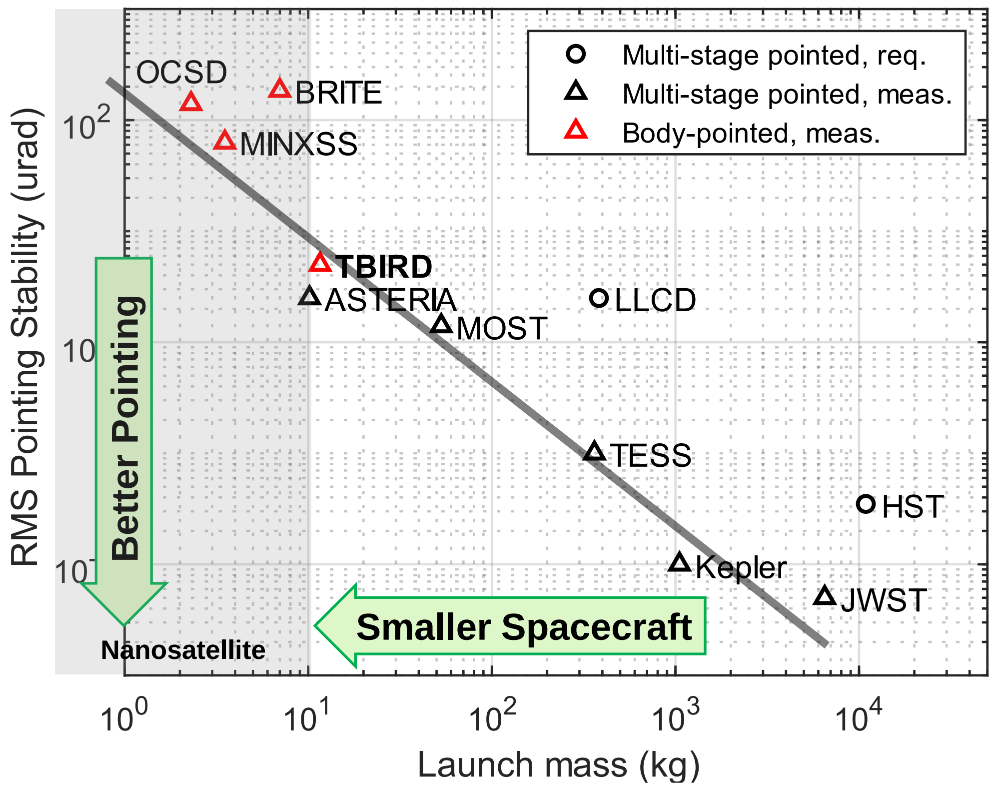


Doppler acceptance window was identified by collecting data over many passes

State-of-the-Art in Nanosatellite Pointing

- **TBIRD pointing stability is 5 urad RMS**
  - **5 urad = 1 arcsec = 0.0003°**
- **TBIRD has demonstrated best-in-class body pointing performance**
- **First nanosatellite to achieve arcsecond-class pointing at high slew rates (up to 1 deg/s)**
- **TBIRD pointing feedback improves body-pointing by an order of magnitude**

Pointing Stability for Precision Pointed Missions



TBIRD has demonstrated the best body-pointing to date at high slew rates

RMS: Root Mean Squared

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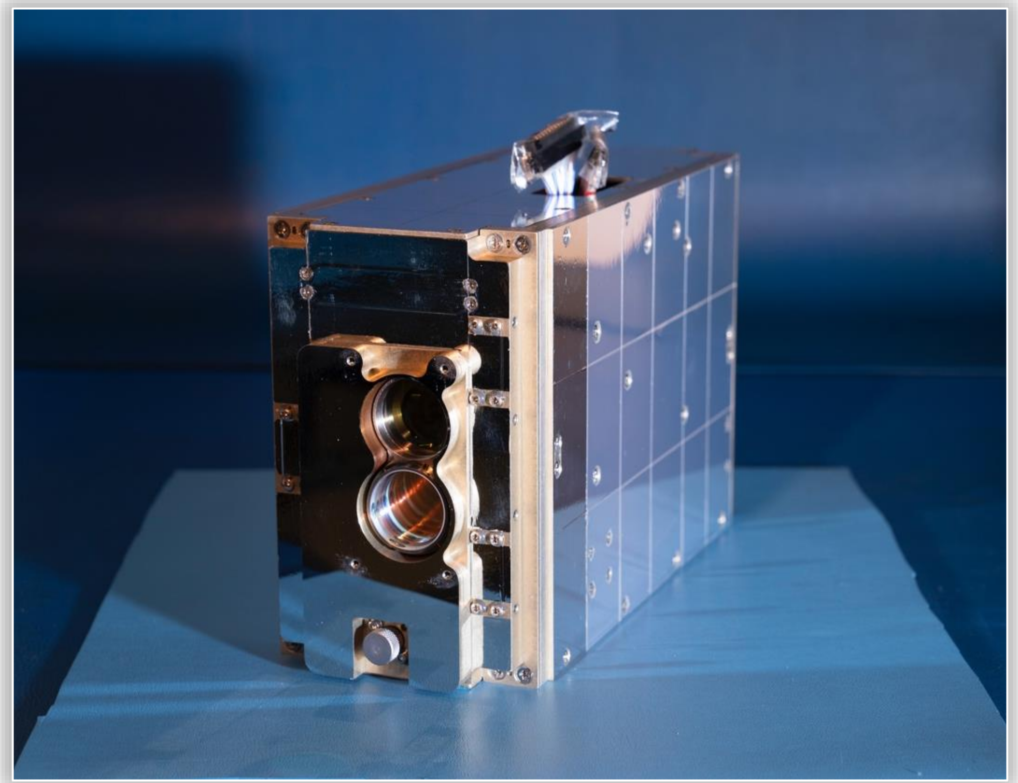
Summary

- **TBIRD operated successfully from May 2022 to September 2024**
- **Key achievements**
  - **~5-urad Cubesat closed-loop body pointing**
  - **100/200 Gbps downlinks from LEO**
  - **Downlinked >1 terabyte error-free in 20 passes through the atmosphere at 2 ground stations**
  - **Performed end-to-end transfer from space buffer to ground buffer at 100 Gbps**
  - **Validated use of terrestrial COTS components in space**
- **All primary mission objectives met**



COTS: Commercial Off-the-shelf
LEO: Low Earth Orbit

Implications for Future High Rate Lasercom Systems

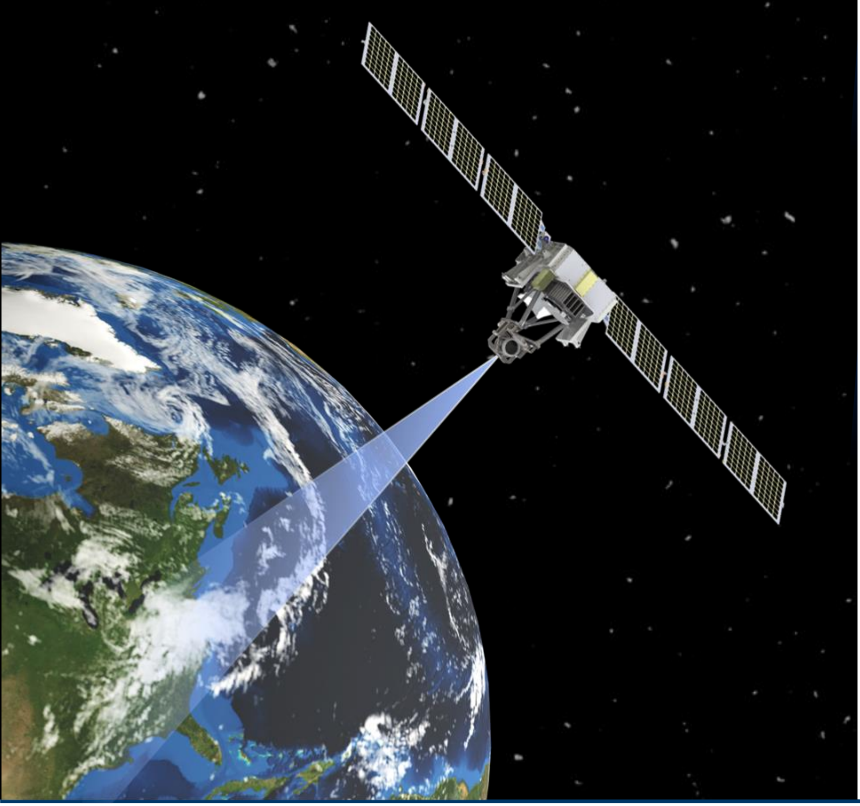
- **Pointing accuracy demonstrated with TBIRD (5 urad RMS) could support much narrower lasercom beams**
- **Narrower beams enable more data delivery with smaller ground terminals**

	TBIRD (Demonstrated)	System 1: Very Small Ground Terminal	System 2: Higher Data Rate
Beamwidth	380 urad	100 urad	100 urad
Ground terminal aperture	100 cm & 60 cm	25 cm	60 cm
Max data rate	200 Gbps	200 Gbps	800 Gbps
Data delivery	Several terabytes per pass	Several terabytes per pass	Tens of terabytes per pass

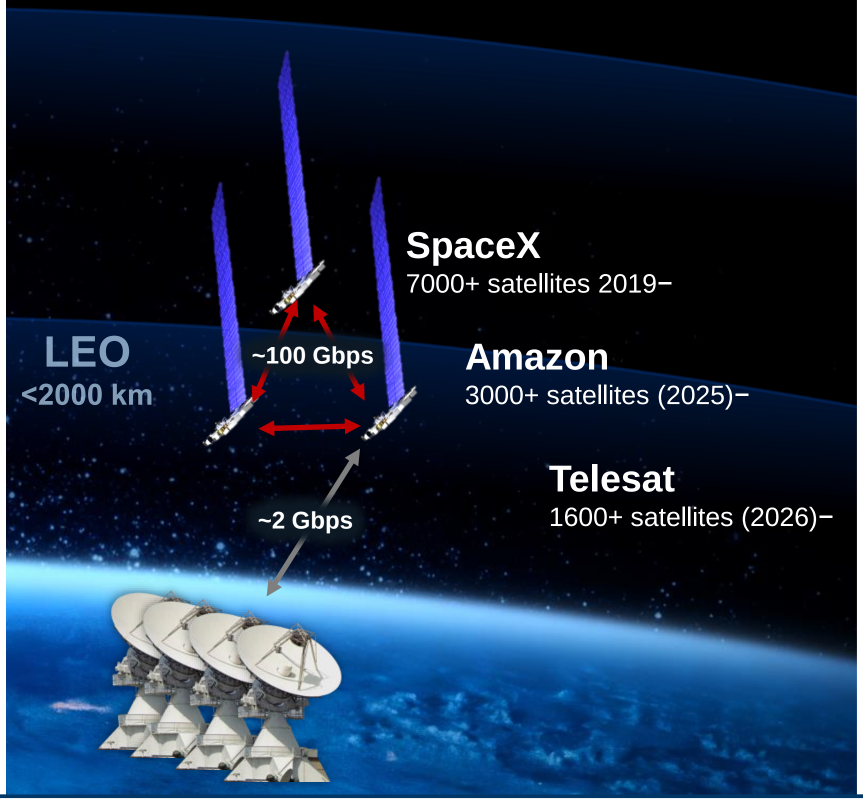
RMS: Root Mean Squared
TB: Terabyte

Meeting Future Needs

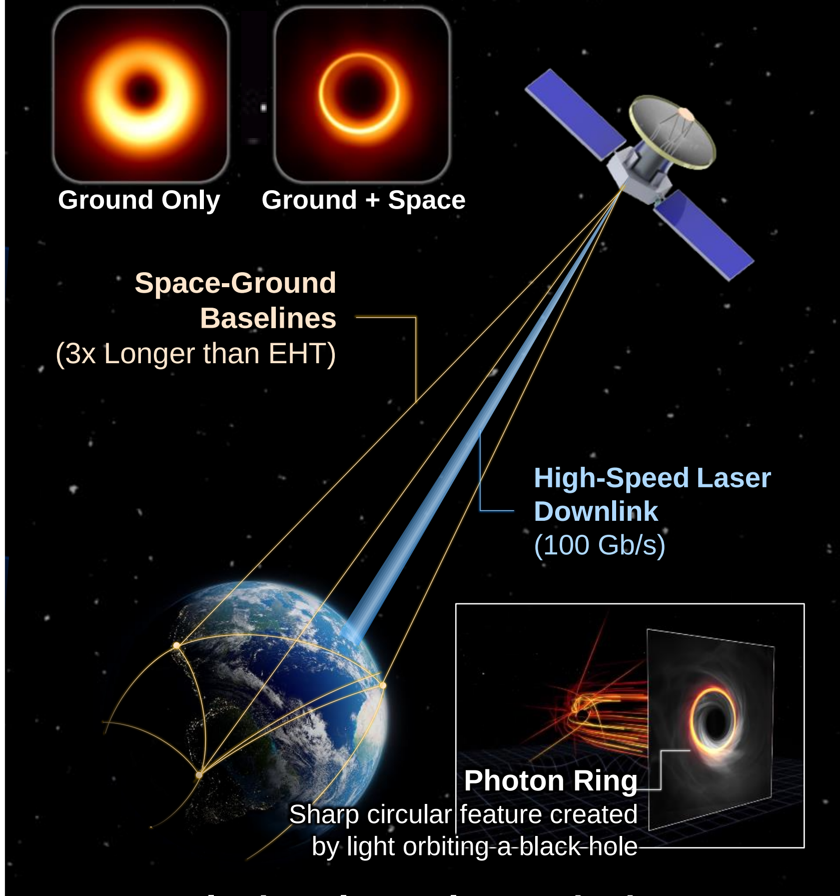
Earth observation missions



Enabling additional capability for commercial constellations



Longer range missions for science needs



Black Hole Explorer Mission

ISR: Intelligence, Surveillance, Reconnaissance
TB: Terabyte
LEO: Low Earth Orbit
EHT: Event Horizon Telescope

Backup Slides

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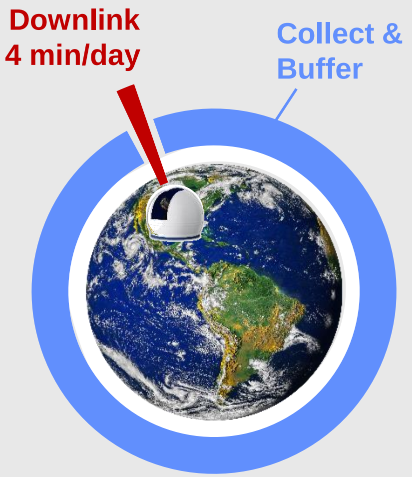
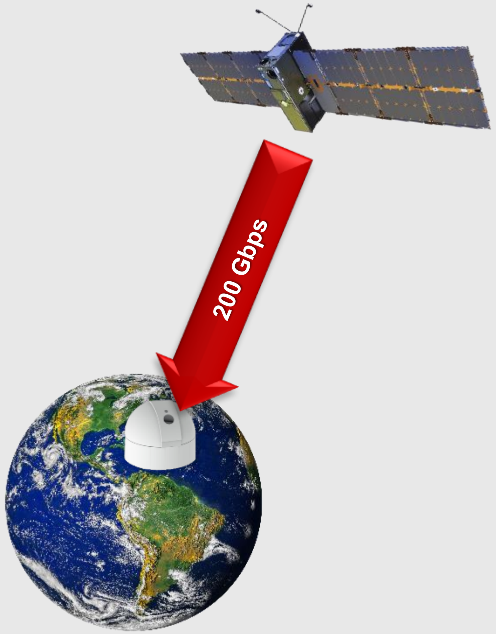
TBIRD Objectives

1 Downlink >1 terabyte error-free in a pass

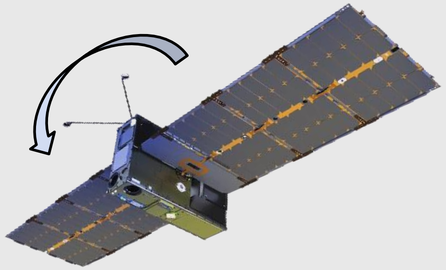


4 min @ 100 Gbps = 3 TB/day

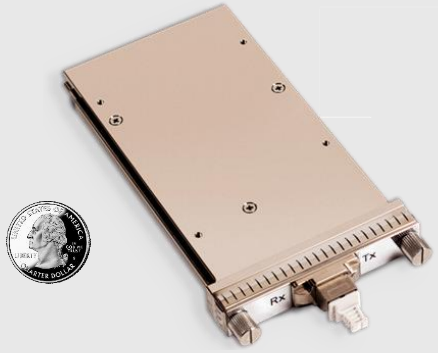
2 Achieve 200 Gbps downlink



3 Demonstrate precision closed-loop body pointing



4 Validate use of terrestrial commercial off-the-shelf (COTS) components in space



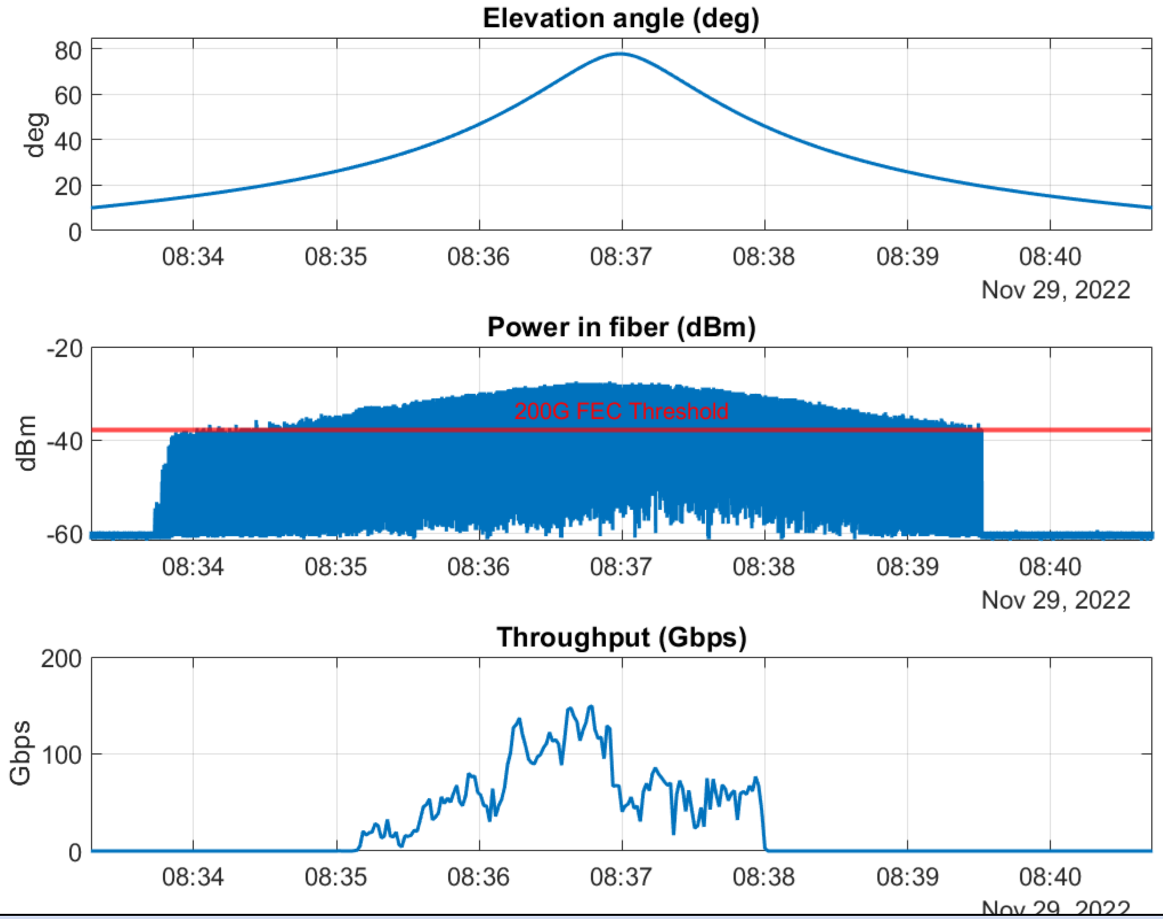
100 Gbps COTS Transceiver
Terrestrial Fiber Telecom

- Dual-polarization QPSK
- ASIC for DSP and FEC

COTS: Commercial Off-the-Shelf
QPSK: Quadrature Phase Shift Keying
DSP: Digital Signal Processing
FEC: Forward Error Correction
ASIC: Application-specific Integrated Circuit

Data Delivery Example 11/29/22
Campaign 1 at OGS-1 with Poor Coupling

- **Operated in 200 Gbps mode**
- **Throughput is the end-to-end error-free data rate (1-second averaging)**
- **Extreme coupling loss at ground station**
  - **Longest duration above FEC threshold is 150 ms**
  - **Data delivered in 1000s of 1–10 ms intervals**
- **Despite these conditions, system used ARQ system to deliver 1.4 TB error-free**

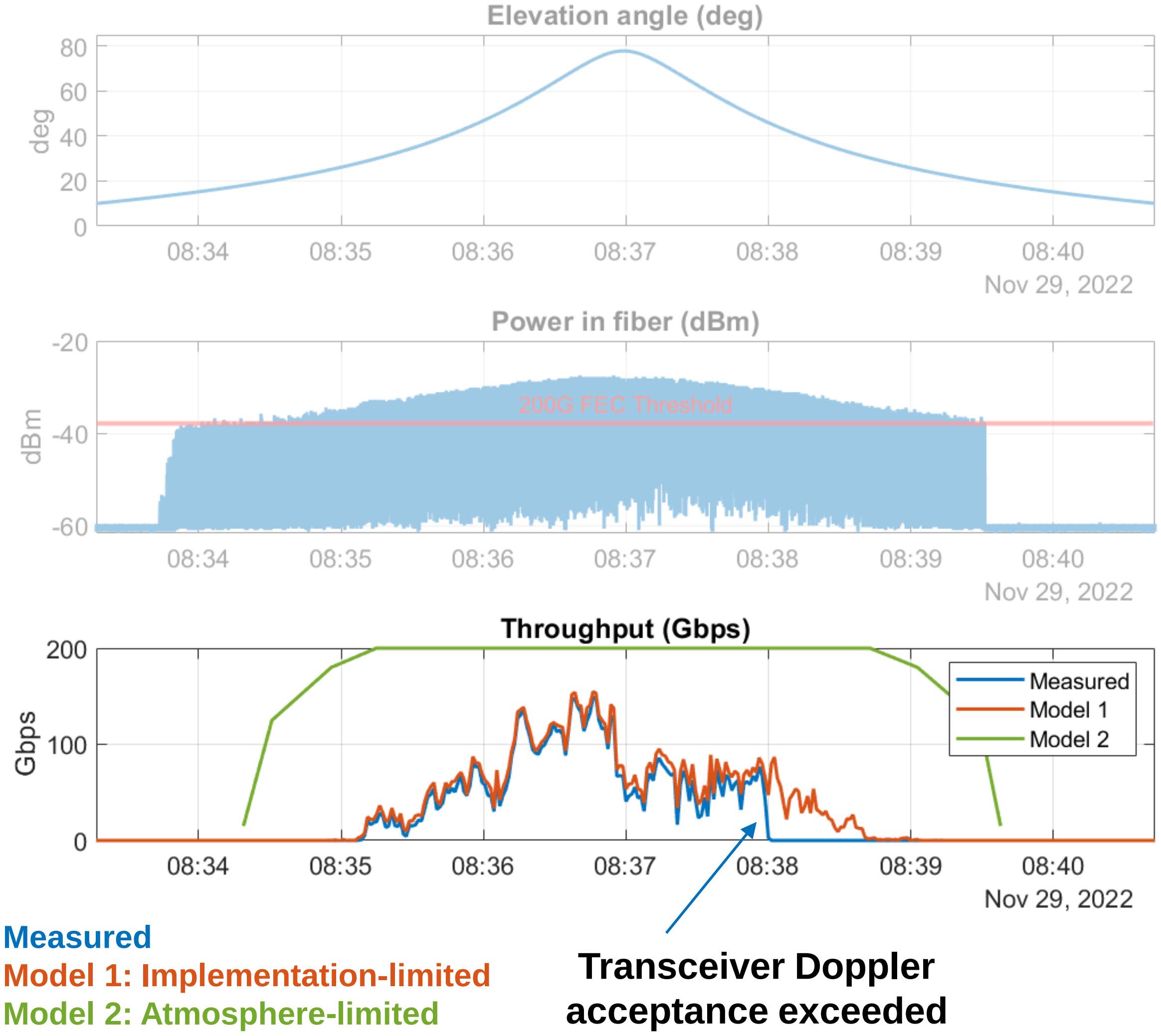


In an extreme fading channel, ARQ system enabled error-free delivery of 1.4 TB in 3 minutes

FEC: Forward Error Correction
TB: Terabyte
ARQ: Automatic Repeat reQuest

Throughput Measurement and Models 11/29/22
Campaign 1 at OGS-1 with Poor Coupling

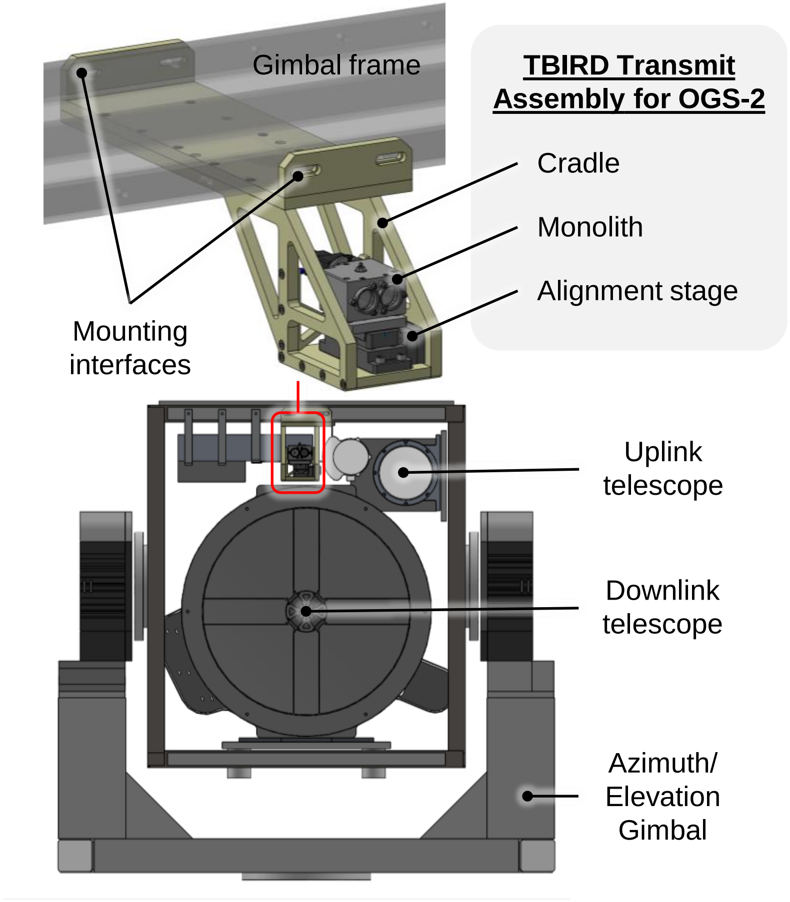
- **Model 1: Implementation-limited**
  - Uses high rate power-in-fiber capture
  - Incorporates transceiver characteristics and ARQ protocol parameters
  - Shows receiver is operating as expected given the power-in-fiber profile
- **Model 2: Atmosphere-limited**
  - Uses turbulence simulations to derive power in fiber
  - Shows potential performance with ground station improvements (~6 TB/pass)
- **Doppler compensation successfully demonstrated in Campaigns 2 & 3**



ARQ: Automatic Repeat reQuest
TB: Terabyte

OGS-2 Modifications to Support TBIRD

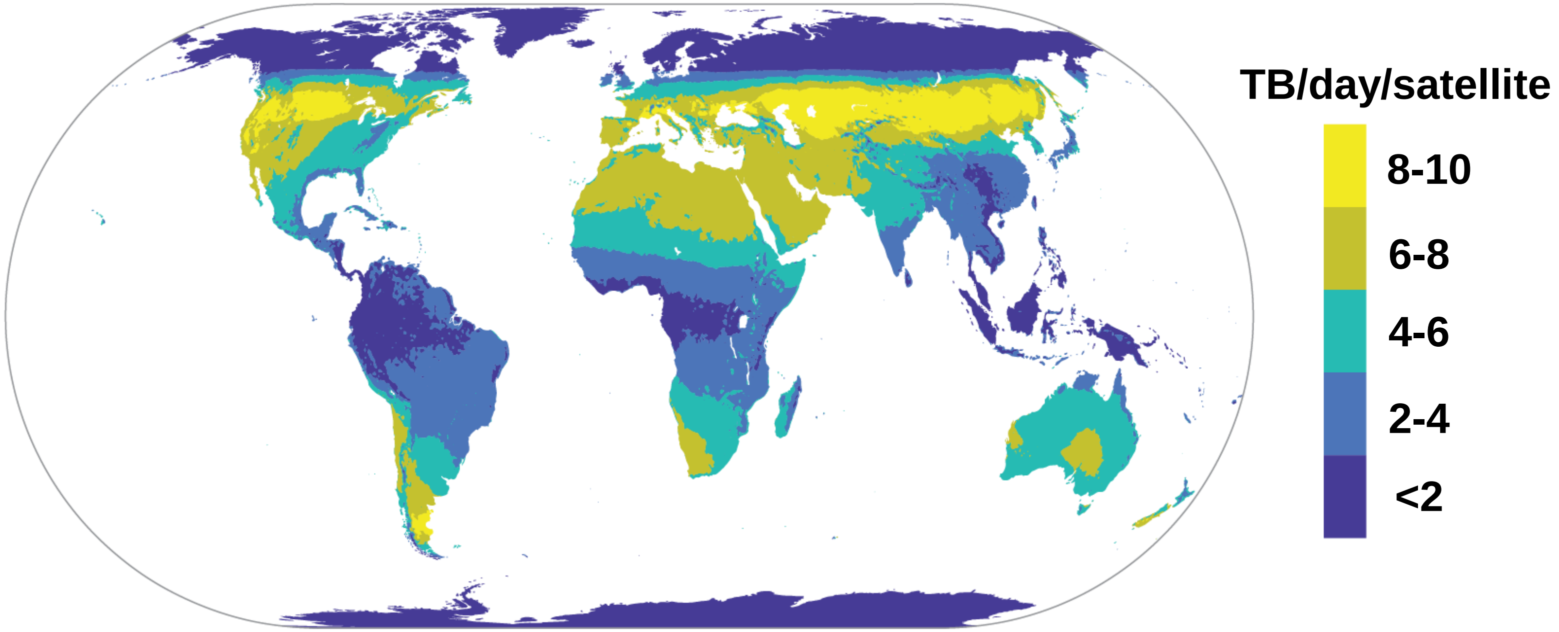
- **Existing downlink telescope and adaptive optics system used with little modification**
- **Quick-turn transmit assembly installed in May 2024**
  - **Existing uplink telescope incompatible with TBIRD wavelengths**
  - **TBIRD transmit assembly aligned to existing uplink telescope using a star**
- **Minor software upgrades for use with TBIRD**



Global Architecture Using TBIRD Technology

- **Existing / planned LEO constellations already use high-rate optical crosslinks**
- **TBIRD architecture enables high-rate optical downlinks**
- **Active external interest in licensing TBIRD technology**

Average Terabytes per day from LEO to Earth



600-km LEO, 51° inclination to 40 cm ground terminal
Link analysis accounts for cloud statistics

LEO constellations and ground station networks using TBIRD architecture could deliver unprecedented amounts of data

LEO: Low Earth Orbit
TB: Terabyte