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CubeSat lasercom optical terminals for near-earth to deep space communications

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ABSTRACT

We describe Fibertek's progress toward commercializing space laser communications and new features of our second-generation compact laser communication terminal (LCT). The LCT design is modular, flexible and can accommodate a variety of waveforms and data formats. Fibertek has a unit deployed in space for initial testing followed by additional units for more broad-based market applications.

Our first-generation optical telescope assembly was originally designed for NASA Deep Space CubeSat laser communications. It was customized as a complete commercial LEO LCT system which is 2U in size, 2 kg in mass, and provides Gbps data rates. The optical transceiver has a shared transmit/receive optical path that uses a laser beacon to ensure high pointing accuracy, active control of the pointing stability, and ensures a strong optical signal-to-noise ratio (SNR) during link operation. The terminal has been manufactured and tested, providing high accuracy pointing and low jitter.

Our second generation LCT system features bidirectional operation and support for an eyesafe beacon for uplink applications. Bi-directional operation is attractive for inter-satellite links (ISL), uplinks of data, pointing acquisition and tracking (PAT), position, navigation and timing (PNT), and for telemetry, tracking, and command (TT&C). The eyesafe uplink beacon makes it easier to get FCC authorization for operation.

The LCT includes a 64 mm telescope and a 1.5-µm fiber-amplifier with >2 W optical power that enables future updates to allow operation up to GEO orbit with the addition of SCPPM and 10-100 Gbit/sec.

Keywords: CubeSat, laser communications, fiber amplifier, space lasers, free-space optical communications, commercial space, PAT

1. INTRODUCTION

Fibertek is developing a CubeSat lasercom optical terminal system to support the growing need for data transmission bandwidth in near-earth and deep space science missions and as a satellite avionics communications system. This paper reports on progress made in the CubeSat lasercom terminal development, its key design features, and the expected performance of the system.

Recent space-based laser communications demonstrations have shown that high-speed optical downlink from space is possible and that high bandwidth can be achieved. Recent and upcoming space missions demonstrating space lasercom performance include:

- NASA Lunar Laser Communications Demonstration (LLCD).[1]
- NASA plans to demonstrate an Earth-based laser communications relay (LCRD).[2,3]
- The European Space Agency (ESA) European Data Relay System (EDRS).[4]
- NASA Jet Propulsion Laboratory (JPL) demonstrated an International Space Station (ISS)-to-Earth downlink (OPALS).[5]
- NASA JPL is developing the Deep Space Optical Communications (DSOC) system for the Psyche Discovery mission.[6]

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These missions have demonstrated that laser communications are feasible and is emerging as an important technological capability to increase communication bandwidth, reduce size, weight, and power (SWaP), and augment radio frequency (RF) communications.

To make lasercom affordable and appealing to the small satellite community, there is considerable ongoing activity to develop the next-generation lasercom systems into much smaller form-factors. CubeSat laser communications systems activities that have been under development over the past 5 years include:

- NASA JPL developed a compact laser communications optical terminal for deep space.[6,7,8,9]
- In 2018, the Aerospace Corporation demonstrated CubeSat lasercom downlink from low earth orbit (LEO) at 200 Mbps.[10]

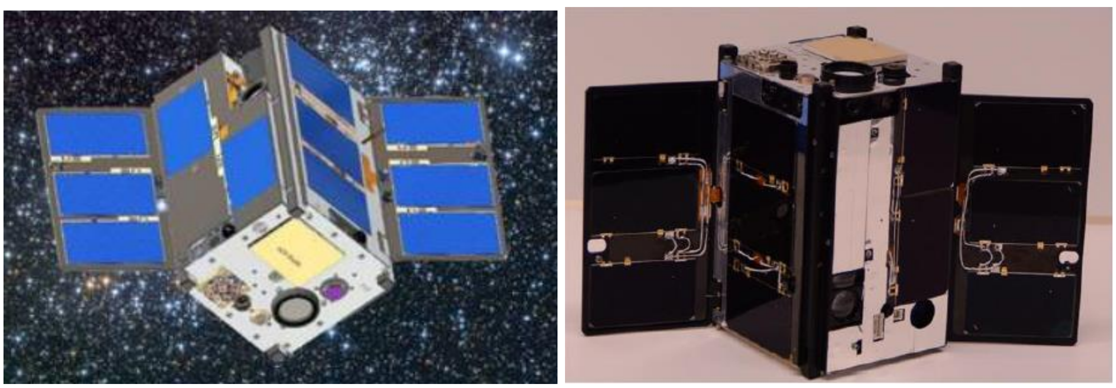

Figure 1: NASA, Aerospace Corporation: Optical Communications and Sensor Demonstration Satellite[10,11,12]

2. SCIENCE AND AVIONICS NEED FOR LASERCOM

Our overall roadmap is to make the LCTs compliant with future standards-based interoperability as much as possible. The NASA SCaN office and international lasercom community members are developing interoperable standards within the CCSDS. Our modular approach can be configured to meet ultra-low cost, academic, commercial or proprietary network interoperability. Customization is provided by specialized optical transceiver cards and a software defined optical modem encoder/decoder.

Laser communications is particularly needed for NASA CubeSat science missions. Studies by NASA JPL concluded that the SWaP benefits, particularly the electrical power benefits of laser communications, is compelling for beyond geosynchronous earth orbit (GEO) applications.[13]

The Keck Institute report entitled "Optical Communication on SmallSats: Enabling the Next Era in Space" describes the benefit and need for CubeSat/SmallSat laser communications to support NASA Earth and Exploration science missions.[14] In many cases, the data rate possible from available CubeSat RF systems enables download of only a small fraction of the data. The small data stream can limit the science value of the mission and can impede mission operation planning and miss science opportunities because power and space requirements limit on-board computational and decision-making capability and the ability to reprogram in flight.

NASA science CubeSat missions like MinXSS are being deployed beyond LEO, have captured science data, and have demonstrated that precision satellite pointing is possible.[15,16] Early studies by JPL identified CubeSat laser communications as critical for exploration including planetary, asteroid, and science missions.

3. COMPACT MULTI-FUNCTION LASERCOM TERMINAL

Fibertek's approach is to develop a small, low-cost, modular multi-purpose lasercom terminal (LCT) to support NASA, DoD and commercial markets. The modular configuration allows for tailoring the system configuration for the specific application. By making the terminals small and low-cost, multiple units can be utilized on SmallSats to enable mesh or ring topology networks. Figure 2 shows an example of a SmallSat with a science payload and three LCT's to enable an intersatellite communications network while simultaneously allowing for science data collection and space-to-ground downlink for data offload. With three terminals and gimbal pointing over a hemispherical field of regard, all pointing directions are covered with double coverage in one hemisphere. With an additional terminal all directions have double coverage.

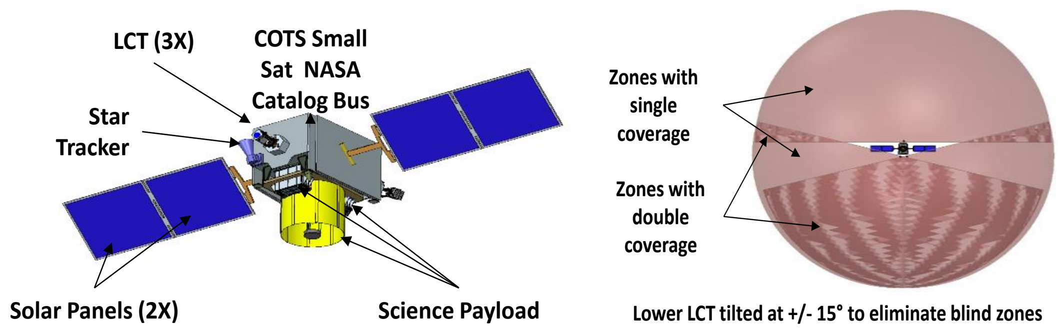

Figure 2: (Left) Example of a SmallSat with a science payload and multiple LCT's for crosslink and downlink and (Right) zones of coverage with 3 LCT's.

4. DEVELOPMENT ROADMAP

Fibertek has built two versions of the lasercom terminal. The first is a 2U package (10 cm x10 cm x 20 cm) package that can be used as a single unit. It can be installed directly into a body-pointed satellite, such as a nanosat or CubeSat. The single unit design can also be deployed on a gimbal since the mass is only 2 kg. The second version consists of two separate 1U module, where the light (1 kg) weight optical head assembly can be mounted on a gimbal for coarse-pointing and the control and power electronics can be placed remotely, inside a spacecraft for example, for easier thermal management. The separate optical and electronics assemblies are attractive for the configuration shown in Figure 2 where multiple intersatellite links (ISL) are supported while simultaneously pointing a science payload in another direction.

Fibertek has completed the development of the first-generation commercial space-grade LCT for LEO downlink applications. Our mature first generation LCT features 1 Gbps data downlink and fine-tracking to a 1-µm uplink beacon. The first protoflight unit was integrated into a 6U CubeSat and launched in 2018. A second unit is scheduled to be launched in 2019. Both terminals are part of pilot efforts for commercial satellite customers for upcoming LEO satellite networks.

Fibertek's is currently developing our second generation LCT. Our second generation LCT system features bidirectional operation and a high-sensitivity 1.5-µm beacon sensor. Bi-directional operation is attractive for inter-satellite links, up-linking of data, pointing acquisition and tracking (PAT), position, navigation and timing (PNT), and for telemetry, tracking, and command (TT&C). The first prototype of the second-generation unit is currently being fabricated and will be delivered to NASA in 2019.

Additional upgrades to increase the transmit power and radiation hardening of the electronics are in progress to support extended range and reliability for GEO applications. Fibertek is scheduled to fabricate and deliver two units for space flight in 2020.

5. DESIGN PROPERTIES

Figure 3 shows the 2x1U configuration Gen1 flight LCT hardware. The Gen2 flight hardware in development has nearly identical packaging with the addition of an optical fiber between the modules for transport of the received uplink signal to the modem transceiver. The lasercom optics module (LOM) contains a large 64mm telescope which is used as a common transmit and receive aperture. The monolithic optical assembly includes the bulk transmit and receive aft optics. The LOM module also includes the fast steering mirror and beacon position sensing detector board for precision pointing and point-ahead capability. The beacon sensor is upgraded for higher sensitivity and compatibility with a 1.5-µm beacon. For near-earth applications, a position sensing detector is used. For longer range applications the position sensing detector is replaced with a focal plane array for extended sensitivity and deep space communications.

The lasercom electronics module (LEM) consists of the power distribution unit (PDU), RF modem with optical transceiver, erbium doped fiber amplifier (EDFA) and a system controller. The PDU supports 12 or 28 V unregulated bus supply and provides power to all LEM and LOM subsystems. The modem has a Gigabit Ethernet (GbE) client interface, FPGA-based encoding/decoding and an optical transceiver for the FSO interface. The modem supports on/off keying (OOK), pulse position modulation (PPM), and in the future, differential phase shift keying (DPSK). The radiation tolerant EDFA provides up to 3 W output transmit power to support extended ranges and data rates. The radiation-tolerant FPGA-based system controller interfaces with the host through RS-485 communications for control and telemetry data. The system controller also handles the fast acquisition, fine-pointing and point-ahead correction in conjunction with the fine-steering mirror and beacon sensor on the LOM module. The LEM and LOM modules weigh ~1 kg each for a total system weight ~2 kg.

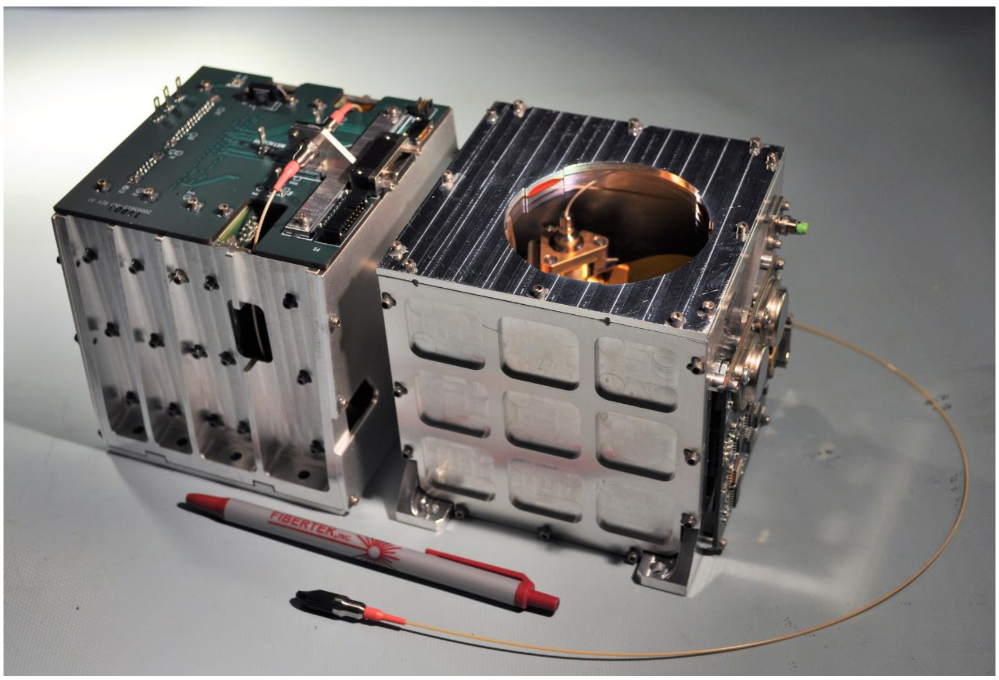

Figure 3: 1x2U CubeSat lasercom terminal consisting of (left) electronics module and (right) optical module

Key design features include:

- CubeSat form-factor for up to Gbps data links from LEO to GEO orbits.
- Low SWaP: ~ 2 kg and < 30 W for general near-earth missions.
- Modular design of optics and avionics and scalable to longer space links.
- Power and size can be customized based on receiver apertures, power budgets, and cost.

- Passive and active fine-steering beam-pointing stabilization.
- Design supports position sensitive detectors or focal plane arrays for beacon tracking.
- Supports OOK, PPM, and in the future, DPSK modulation formats.
- Diffraction-limited shared transmitter/receiver (Tx/Rx) aperture telescope.
- Athermalized monolithic optical design of fiber-coupled optical telescope for lasercom transmit/receive.
- Satellite body-pointing or two-axis gimbals for coarse point/track.
- System can be made cost-effectively for high-reliability Class A/B missions or low-cost missions.

6. FINE AND COARSE POINTING AND TRACKING

A high-performance lasercom link requires beam control to compensate for the satellite platform on-orbit jitter and track the narrow transmit beam pointing to the receiver aperture. To achieve this a multi-level approach is used including passive and active elements.

Coarse pointing can be achieved by body pointing or gimbal pointing using satellite ephemeris position data provided by a high-precision star-trackers, for example, or other external sources on the satellite. Our LCT PAT sensor has a wide FOV, > 2 mrad, that is well within the pointing resolution of precision space qualified gimbal mounts. It is also well within the ability of SmallSats and CubeSat pointing precision performance. Several satellite manufactures can support <100 μrad (3σ) pointing control at ~1 Hz rate.

An inner-loop fine-steer control is provided by the LCT's FSM which provides compensation for the remainder of the pointing and platform jitter by locking onto a beacon optical signal. The FSM control loop provides the pointing precision required to close a low-loss optical link. **Figure 4** shows laboratory test results demonstrating reduction in uncontrolled 60-μrad 50-Hz bandwidth jitter noise to less than 10-μrad residual jitter with active fine-steering control.

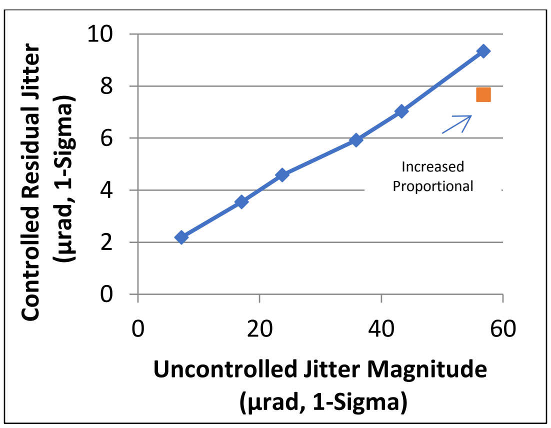

Figure 4: On-Orbit Fine-Steering Jitter Mitigation, Residual Jitter vs. Uncontrolled Jitter

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