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Advances in CubeSat Laser Communications Transceiver

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ABSTRACT

This paper describes progress toward supporting full duplex Earth-to-ground links and intersatellite links (ISLs) capable of supporting mesh networks around Earth, the sun, and deep space. The paper reviews recent advances in compact free space optical (FSO) terminals at Fibertek and potential uses for a NASA Science Enabling Technologies for Heliophysics (SETH) mission and ISLs in general. The laser communications terminal (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 to be 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 low Earth orbit (LEO) LCT system which is 2U in size, 2.5 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 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 bi-directional operation and support for an eye-safe beacon for uplink applications. Bi-directional operation is attractive for ISLs; uplinks of data; pointing, acquisition, and tracking (PAT); position, navigation, and timing (PNT); and telemetry, tracking, and command (TT&C). The eye-safe 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 geosynchronous Earth orbit (GEO) and deep space.

Keywords: CubeSat, laser communications, fiber amplifier, space lasers, free-space optical communications, commercial space, PAT, SETH, Heliophysics, intersatellite, network

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]

These missions have demonstrated that laser communications are feasible and 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]
- During 2018-2019, the Aerospace Corporation demonstrated CubeSat lasercom downlink to Earth from LEO at 200 Mbps[10] and has conducted experiments developing lessons learned on the practical implementation of FSO (Figure 1).

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

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-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] Early studies by JPL identified CubeSat laser communications as critical for exploration including planetary, asteroid, and science missions. In many cases, the data rate possible from available CubeSat RF systems enables download of only a small fraction of the data. NASA science CubeSat missions like MinXSS are being deployed beyond LEO, have captured science data, and have demonstrated that precision satellite pointing is possible with an accuracy necessary to support optical communications.[15,16]

COMPACT MULTI-FUNCTION LASERCOM TERMINAL FOR HELIOPHSICS NETWORKS

Fibertek’s approach is to develop a small, low-cost, modular multi-purpose lasercom terminal 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 used on SmallSats to enable mesh or ring topology networks. NASA and Fibertek are working on a concept mission called SETH to demonstrate an optical downlink to Earth as a step toward enabling a low-cost Heliophysics constellation of sun observing small satellites as shown in Figure 2. The SETH mission would be a downlink to earth from distances up to 1.2 AU.

Fibertek is working with NASA GSFC and JPL to develop laser communications capability as part of a network of next-generation distributed sun sensing networking using small satellites.[17] The reduced SWaP of Fibertek’s LCTs enables seamless integration of multiple units with small satellites for omnidirectional connection capabilities.

To support distributed mesh networks for operational mission use our approach is to develop low-cost FSO terminals so that eventually three or four terminals can be installed on each satellite as shown in Figure 3. With FSO terminals a SmallSat with a science payload and three LCTs can talk to neighboring satellites 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. An additional terminal provides double coverage in all directions to enable distant entity constellations.

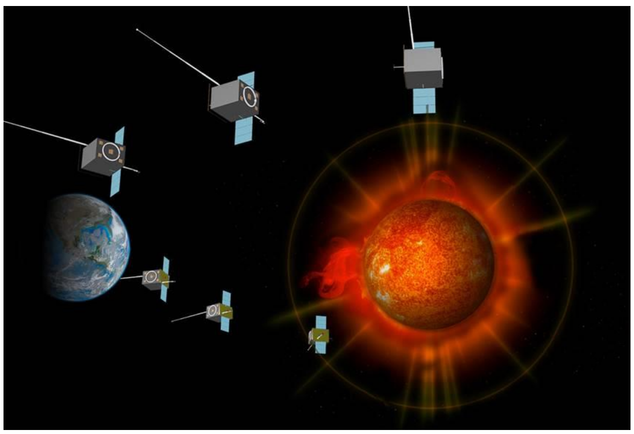

Figure 2: Conceptual remote entity constellation application using multiple LCT units per satellite.

DEVELOPMENT ROADMAP

Fibertek has built two versions of the lasercom terminal. The first is a 2U (10 x 10 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 because the mass is only 2 kg. The second version consists of two separate 1U modules, where the lightweight (1 kg) 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 3 where multiple intersatellite links 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.

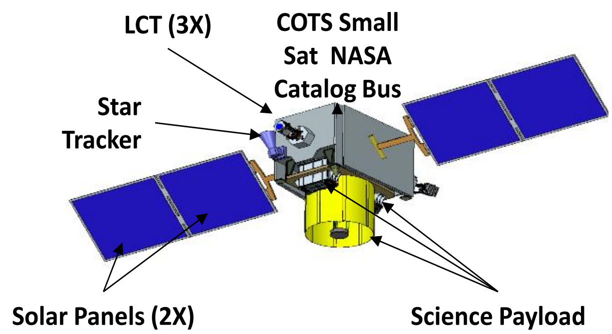

Figure 3: Fibertek is adding full duplex capability to support intersatellite link capability to support mesh Earth, Sun for Heliophysics missions like SETH or deep space networks. Supports PPM and OOK.

Fibertek is currently developing our second generation LCT. Our second generation LCT system features bi-directional operation and a high-sensitivity 1.5-µm beacon sensor. Bi-directional operation is attractive for intersatellite links; up-linking of data; pointing, acquisition, and tracking (PAT); position, navigation, and timing (PNT); and 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 spaceflight in 2020. The recent upgrades in development include a further radiation hardened version of the LCT for up to 100 krad total ionizing dose (TID) resistance and single-event mitigation circuitry for a third-generation terminal for operation at GEO and beyond.

DESIGN PROPERTIES

The lasercom optics module (LOM) (Figure 4) contains a large 64 mm 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 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.

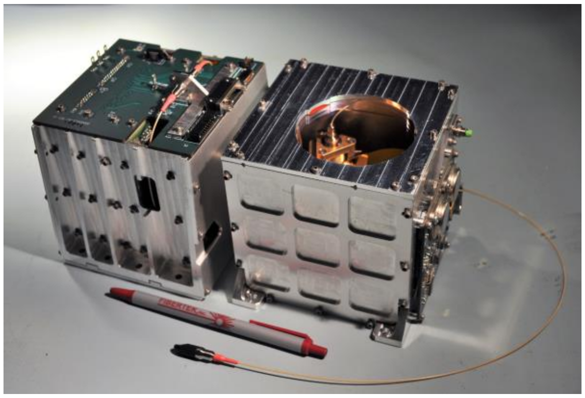

Figure 4: 1x2U CubeSat lasercom terminal consisting of (left) electronics module and (right) optical module

The lasercom electronics module (LEM) (Figure 4) consists of the power distribution unit (PDU), RF modem with optical transceiver, erbium-doped fiber amplifier (EDFA), and a system controller. The PDU supports 12V or 28V unregulated bus supply and provides power to all LEM and LOM subsystems. The modem has a Gigabit Ethernet (GbE) client interface, field programmable gate array (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. The LEM and LOM weigh ~1.25 kg each for a total system weight ~2.5 kg.

Key design features include:

- CubeSat form-factor for up to Gbps data links from LEO to GEO orbits.
- Low SWaP: ~ 2.5 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.

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