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Cubesat Lidar Concepts for Ranging, Topology, Sample Capture, Surface, and Atmospheric Science

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ABSTRACT

This paper discusses progress Fibertek is making toward development of next-generation remote sensing lidar technology for cube, micro, and small satellite (smallsat) platforms. Our general finding is that small, relatively inexpensive cube/micro/small satellite lidars are feasible and that numerous applications are possible.

Lidar is not traditionally thought of as being suitable for cube and smallsat applications because of the cost, complexity, mass, and power typically associated with ground- and space-based earth and planetary lidars. This paper describes our performance modeling and concept lidar designs that are 2-4U in size, 2-3 kg, draw 10-25 W, and are capable of science and satellite proximity operations.

This paper will discuss lidar concepts for multiple applications. Short-range proximity lidars are capable of 50-degree field of view (FOV), scanning angle up to 500 m and can support three-dimensional (3D) imaging for satellite rendezvous operations and comet/asteroid sample capture missions. Long-range cubesat lidar configurations can support up to 1,000 km range and can be used for planetary body topology mapping and altimetry. Lidars with multi-wavelength capability can measure surface properties of solid ices found in outer planets and moons and can tell the difference between liquid and solid phase. Cubesat atmospheric lidars can measure aerosol backscatter intensities and characterize cloud layer structures, for example, as seen around Pluto, Charon, and Enceladus. Lidar measurements of atmospheric gas including water, carbon dioxide (CO2), and methane are also possible in small form factors.

INTRODUCTION

New advances in lidar design, architectures, and laser and detector technology enable space lidar instruments for new planetary and earth science measurements at dramatically lower cost and size, weight, and power (SWaP) than previous generations of remote sensing lidar. Science measurements not previously feasible or practical are now becoming possible and attractive. Similarly, ultra-compact lidars can support topology, ranging, navigation, and constellations management and can be used for landing and sample capture rendezvous operations. The goal of this paper is to provide a sampling of what lidar is capable of and packaging SWaP reduction opportunities to stimulate the science and smallsat avionics community to identify possible near-term missions that can drive lidar forward. A brief list of cubesat, smallsat, and rover applications include:

Science Applications

- Topology and terrain mapping: Identification of ancient lakes, rivers, tectonics, fissures, and overall planetary body Geodesy
- Surface compositional mapping: Spectral identification of minerals and solid ices (water, methane, CO2, and others) in the 1-4 um bands from a spacecraft or orbiter
- Atmospheric studies: Aerosol densities, range-resolved clouds, layers, and optical depth
- Trace gases: Methane, CO2, water vapor
- Dynamic studies of plumes from places such as on Pluto, Enceladus, Europa, and Mars

Navigation, Communications, Proximity Operations, 3D Imaging

- Near-range lidar: Proximity operations including satellite docking and servicing

- Asteroid/comet sample capture
- 3D imaging
- Constellations management at 1 km to 10,000 km

This paper describes design concepts for driving high-performance lidars in 2U to 6U SWaP. In most cases below, the laser technology can support full planetary (500 km) range lidar from a 60-cm receiver telescope aperture and ~ 100 W instrument power budget, and can be scaled down to cubesats by operating the lidars at lower duty cycles (~ 20%) to reduce the system power draw to < 20 W. The inherent ultra-compact size and mass enable cubesat demo missions to establish feasibility for either cubesat or smallsat missions, streamlining the development process and reducing the cost and time to develop.

RANGING, PROXIMITY OPERATION, SAMPLE CAPTURE, 3D IMAGING, SATELLTIE SERVICING – 2 U CUBESAT CONCEPT

The lidar design shown in Figure 1 provides multi-function capability and can make long-range and short-range 3D imaging measurements. The lidar is capable of 3D imaging for 10-degree cone angles at long range and 60-degree cone angles at short range. This broad FOV can also be used for locking and tracking onto other satellites for communications and constellation formation flying management. The lidar offers long-range capability in a simple, lightweight, low-power configuration suitable for small platforms for a wide variety of missions. The small form factor is ideal for cubesat constellation ranging, communications, and proximity operations.

Long-Range Capability: The long-range capability supports ranging to objects from 1 m to >100 km. It has the ability to adjust the data averaging, allowing this instrument to serve a variety of missions including precise 3D positioning. This capability can be used to find and track objects far away. As a science instrument, it can be used for making Geodesic measurements of asteroids, comets, planetary objects, and topographic maps either as the object rotates or by orbiting the object.

Short-Range Proximity Operations, Rendezvous, Sample Capture: The short-range lidar can operate over a 60-degree cone up to 500 m for docking, rendezvous, and sample capture. The large FOV and range determination to < 15 cm enables 3D imaging, complements camera data, and enables precision docking if used for spacecraft-to-spacecraft rendezvous. When used as part of autonomous ground navigation control (GNC) systems it can be used to avoid obstacles and optimize sample capture.

The overall lidar is designed to provide all the functionality of the two lidar systems being deployed on the NASA OSIRIS-Rex mission in a single, small form factor design.

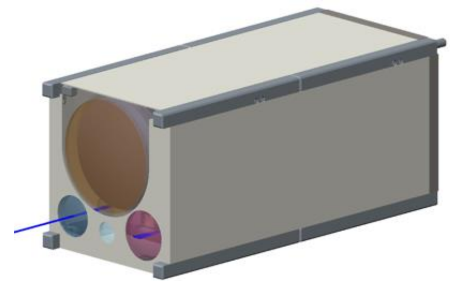


Figure 1: Fibertek 2U Cubesat Lidar Concept Design. Includes long-range (100 km) and short-range proximity operations and communications capability.

Highlight of Key Performance Capabilities and Design Features

The following highlights the key capabilities and overall design features of this lidar:

- **Unprecedented range resolution in small package.** The lidar provides the opportunity for unprecedented range (>100 km), range resolution, (~ 15 cm), and 10-degree scanning angle in the standard configuration.
- **2U SWaP:** Ultra-low-size (10x10x20 cm), mass (2 kg), and power (14.3 W).
- **Commercial components:** The lidar design leverages production of commercial off-the-shelf (COTS) sensors, COTS laser diodes, and space-qualified electronics technology. Most parts are traceable to space. Higher performance >> 1,000 km may require custom optics.
- **Multi-function:** Deign suitable for cubesat, smallsat, or Orion-sized space launch system (SLS) vehicles.
- **Laser communications:** Can support 10-1000 Kbps optical satellite-to-satellite communications depending on how the system is configured, distance between satellites, and receiver aperture size. The communications signal can also be used as a second means of range determination using well-defined and demonstrated designs.

- **Wide-field 3D imaging lidar for proximity operations and sample capture:** Can support Proximity Operations and Formation Flying in the future with minor hardware changes and software updates. To provide the widest possible FOV without including active mechanisms to reconfigure the optics, we propose to include a second detector, laser, and MEMS scanner. Using the same drivers and detection electronics this nearly identical system will have a wide +/- 30-degree (60-degree full angle) field of regard (FOR). In close proximity to the target the lidar can be generated at up to 1M pixels/second at ranges up to 500 m.

- **Performs the same function as two OSIRIS-Rex lidars**. The OSIRIS-Rex mission was launched in 2016 on a mission to capture and return a sample from an asteroid. The mission has two lidars on board, a single beam lidar for terrain mapping topology and characterizing the Geodesy of the asteroid, and a second 3D flash lidar to guide the GNC systems the last 100 m to the surface. Our concept 2U lidar is capable of performing both functions.

- **Rendezvous, docking, and satellite servicing:** The lidar combined long-range and short-range capabilities are ideal for rendezvous and proximity operations. The long-range lidar would be used to slowly approach the docking satellite from 20-50 km away and the short-range lidar can provide the wide-angle 3D imaging frames as the satellite approaches the asteroid, comet, or docking spacecraft. The short-range lidar would work with the docking camera system and GNC system.

- **This lidar can be adopted to measure methane, carbon dioxide, and water vapor:** The lidar can be modified to detect methane, water vapor, and carbon dioxide. The range and accuracy performance will depend on the availability of specialized lasers and detectors around absorption features suitable for either surface or atmospheric measurements.

Lidar Range Performance

An example of a lidar's range performance curves is shown in Figure 2. The time to make the measurement (y axis) versus the range (x axis) as a function of background solar light is shown. For low light levels, range measurements in excess of 100 km can be made in < 1 second. Longer ranges can be made with 10 s and 100 s measurements. In high-background-light conditions such as earth moonlight, the range performance is reduced to 10-30 km. Ranging to >1,000 km is possible in the small form factor by using higher power, customized laser technology as discussed in the Trace Gas section below.

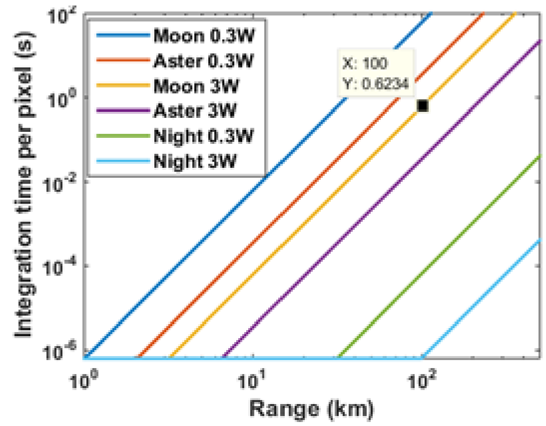


Figure 2: Measurement Time for 2U lidar as a Function of Range and Optical Background Conditions of Range Object

ATMOSPHERIC CLOUD AND AEROSOL LIDAR – EARTH AND PLANETARY BODIES

Aerosol and clouds are fundamental properties of any planetary body with an atmosphere and lidar is compelling technology to measure detailed optical scattering intensities, cloud layers, and densities that are difficult for camera systems. Lidar data does not depend on solar illumination and works in daylight and darkness. The vertical resolution lidar offers is not available from cameras and imagers. In fact, the vertically resolved data that lidar can provide can be quite useful in interpreting and analyzing passive optical and radar remote sensing data for earth weather/science applications and planetary science.

A few examples where aerosol data is important include:

- Earth: The NASA CALIPSO lidar has been measuring atmospheric aerosols for >11 years. Is has become critical to weather and global change research and there is widespread demand for this data.

- Researchers are interested in how clouds and Aerosols impact and effect trace gases around Charon, a moon of Pluto. Charon has more than 20 thin haze layers up to 200 km altitude. The layers are coherent over large horizontal distances. Lidar could be used to quantitatively map out these layers.

- Pluto is geologically active and frequent eruption and cloud plumes have been observed from the

New Horizons mission. An aerosol lidar can provide detailed 3D data to help quantify the volume, transport, and distribution properties.

- Saturn's moon Enceladus has more than 100 water vapor jets emanating from the surface along fissures. An aerosol lidar can measure the intensity and volume of these plumes and impact of the moon's atmosphere.

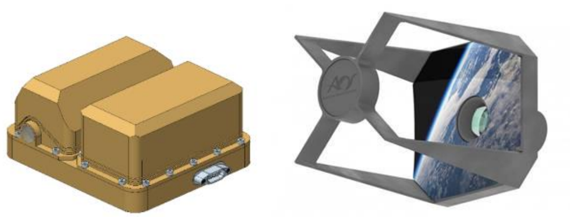
- Europa has an active atmosphere, and future science and lander missions would benefit from cloud, aerosol, and methane measurement of the atmosphere and surface ice.

- The NASA DAWN spacecraft has measured properties in Ceres and Vesta asteroids after its fly-by of Pluto.

Cloud and Aerosol Lidar Concept – Smallsat and Cubesat

Fibertek has been developing lidar technology to support cubesat, smallsat, and large satellite cloud and aerosol lidar. Recent developments in compacting the laser technology into small form factors. High power laser are getting small and more efficient.

New technology enables cloud and aerosol lidars for cubesat and small sat applications as shown in Figure 3. The left side graphic shows a Fibertek designed cubesat-Sized 30 -60 mJ space laser transmitter that can be used for cloud and aerosol lidar. [Size ½ U: 5 cm x 9 cm x 10 cm, low power, < 15 W]. The laser package size includes all optics and electronics. Fibertek has developed a 1U cubesat telescope and the commercial market are also developing them as shown on the right.



Laser in a ½ U size package and Commercial Telescope for 1 U 10cm x 10cm receiver.

The laser as part of a cubesat (6U, 18U, 24U) with an effective 20-cm collection telescope could offer significant capability for earth and planetary missions at a very small fraction of the size and cost compared to typical NASA lidar missions.

Figure 4 shows examples for lidar configuration on cubesat and smallsat spacecraft. The top graphic shows a cubesat lidar configuration utilizing a Fibertek space telescope.

The bottom graphics shows a low-cost small satellite, ESPA ring-launched, lidar with 60-cm telescope. Shown with redundant lasers, detector receiver package, and control electronics package. The lidar is shown mounted on a commercially available small satellite vehicle available in the NASA spacecraft. This configuration is suitable for making range-resolved measurements of planetary clouds, aerosols, and trace gasses.

The ultimate range and cloud/aerosol performance resolution will depend on telescope receiving aperture and laser energy. New laser and detector technology makes it feasible to provide science products formerly only possible by larger and more costly systems.

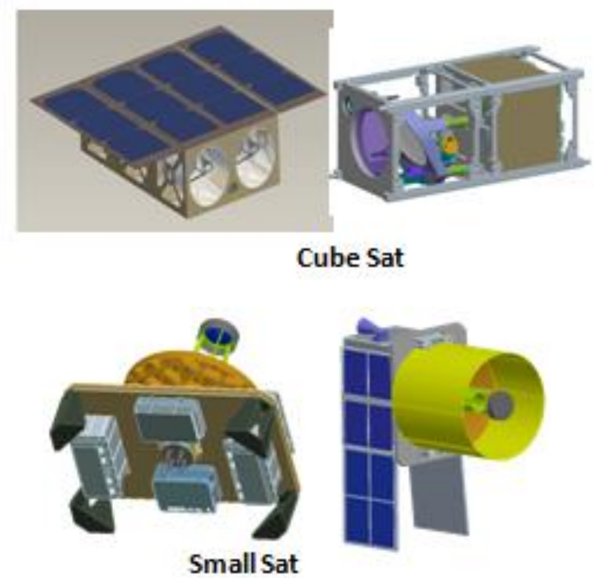


Figure 4: Examples of Possible Aerosol Lidar Configuration for Cubesat and Small Satellite Spacecraft

TRACE GASSES - METHANE, CO2 AND WATER

Fibertek has been developing space laser technology for earth science measurements of CO2, methane, and water vapor. Progress on these lasers indicates they are suitable for earth and planetary missions. As an example, we will describe a 2 um laser transmitter and gas cell locking concept designed for earth to measure CO2 to 1 ppm with a 70-cm telescope from 500 km orbit. Atmospheric and solid surface methane, CO2, and water vapor are primary planetary trace gasses and are fundamentally important to understanding active planetary bodies including earth and almost all NASAsponsored missions. They are greenhouse gasses and often correlated with signs of life.

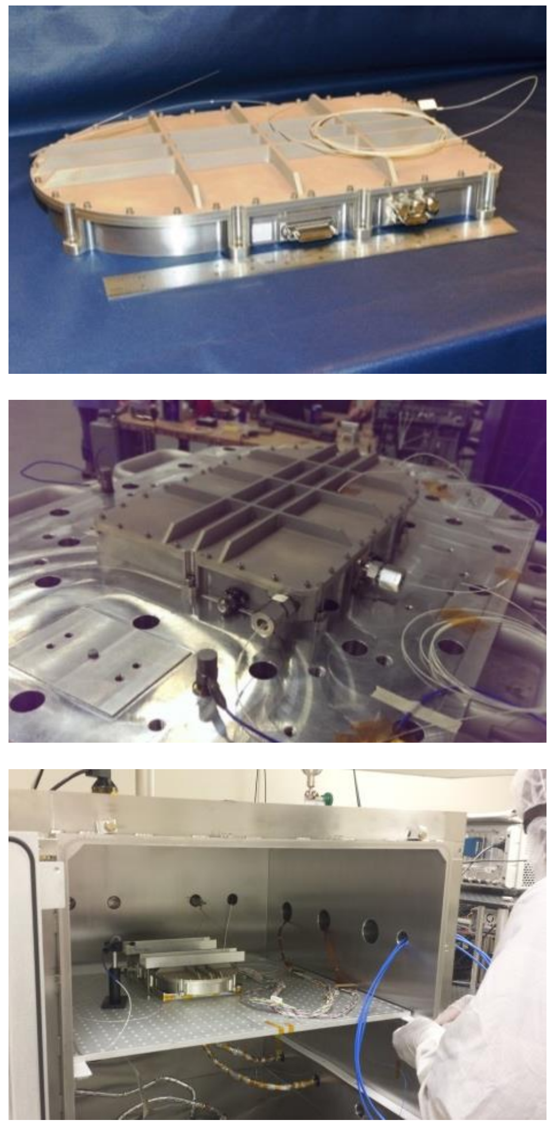
There is significant interest in narrow linewidth 2051 nm laser transmitters for atmospheric CO2 remote sensing. It is generally recognized that 2 um has stronger absorption lines, and trade studies have identified performance benefits at this wavelength compared to 1.57 um.1,2 NASA is interested in maturing the technology readiness of 2051 nm laser transmitters to Technology Readiness Level 6 (TRL-6). NASA has successfully demonstrated a CO2 Integrated Path Differential Absorption (IPDA) lidar system in an airborne platform.3-5 An all-fiber, higher power, and highly efficient version of the transmitter is targeted for a space-based satellite measurement system with global coverage. The fiber transmitter's small form factor and projected very high reliability and long lifetime significantly increase the number of potential uses in NASA pathfinder missions. Potential missions include earth and planetary polar-orbiting missions using COTS small satellites and unmanned aerial vehicles (UAV) where the lidar is flown on a global hawk at 65,000 feet as part of an Earth Venture Suborbital (EVS) mission. Achieving power scaling and compact form factor for the transmitter requires high efficiency and high-gain performance for the transmitter.

Mission Concepts, Packaging, and SWaP – Water Vapor, CO2 Lidar

The 2-um fiber laser's efficiency, reliability, and package size make it an ideal lidar transmitter for earth and planetary science.6,7 While this paper describes operation at 2051 nm for CO2 lidar, the laser can efficiently operate between 1.9 nm and 2.1 um. There are strong water vapor lines in the 1.9 um range and a nice isolated line at 2060 nm that has recently been used for an H2O lidar. For planetary lidar where lower concentration of water is expected the 1.9 um will provide high sensitivity.

The laser can be readily packaged using heritage space TRL-6 design used for the 1.5 um transmitter as discussed below. The efficiency, reliability, and maturity of the underlying optical component technology means these transmitters can be used for near-term space missions and can be built in a number of form factors to support planetary cubesat, smallsat, and large planetary orbiting missions.

Fibertek has previously developed a similar narrow linewidth erbium-based space TRL-6 transmitter8,9 for CO2 lidar3,4 at 1571 nm and for space laser communications. Our transmitter for JPL's Deep Space Optical Communications (DSOC) project is scheduled to fly on the NASA Psyche mission (Figure 5). The DSOC laser provides 6 W average power using pulse position modulation (PPM) with up to 1 kW peak power.10-13 The 20 W TRL-6 transmitter has been tested to NASA vibration General Environmental Verification Standard (GEVS) and has been thermal cycled at survival and operational temperatures (Figure 5). Fibertek has also demonstrated pulsed versions at 1.5 um with ~ 1 mJ/pulse, 1 usec pulsewidth, and 800 W peak power for range-resolved and high signal-to-noise ratio (SNR) lidars.14



Cubesat Lidar Version for Remote Sensing of Carbon Dioxide and Water Vapor

Figure 5: Fibertek Developed 20 W 1.571 Transmitter for CO2 Lidar

Photos show the laser mounted on a vibration table and in a thermal vacuum chamber. The laser was tested to NASA GEVS standards for TRL-6

environmental testing. The all-fiber 2-um transmitter can fit into this same package.

Fibertek has developed a 4U cubesat-sized package for the 2-um fiber transmitter that can be used for water vapor lidar at 2.06 and 1.9 um and for CO2 detection at 2051 nm. The package, shown in Figure 6, includes the 25 W 2 um coherent laser, seed 2-um distributed feedback (DFB) laser and local oscillator, gas cell and locking electronics, and all other laser electronics. The interfaces to the transmitter will be 28V input power, a digital command and control and an output optical fiber to interface with the output telescope, and a local oscillator optical signal. The transmitter at 15-25 W average power supports 500 km planetary orbits.

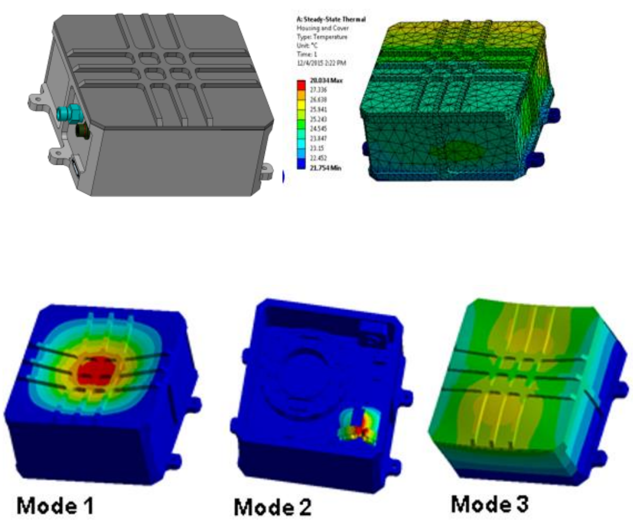


Figure 6. Spaceflight Concept Design for a 4U Cubesat 2 um Fiber Transmitter including precision DFB laser controller and gas cell locking (On, Off, Arbitrary side band). Mass <5 kg. Includes local oscillator. CAD model with Structural and Thermal Finite Element Analysis.

Figure 7 illustrates a possible planetary cubesat configuration for package design and a structural and thermal analysis. The lidar overall power can be reduced to 15 W through operating the lidar at 10% duty cycle, by turning the pump diodes on and off, providing up to 25 W peak power and supporting a range consistent with the optical telescope aperture. For a planetary, 500 km orbit, 70-cm telescope small satellite, the power requirement at 100% duty cycle would be >100 W. The reliability of the systems is expected to be 95% over a 5-year mission.

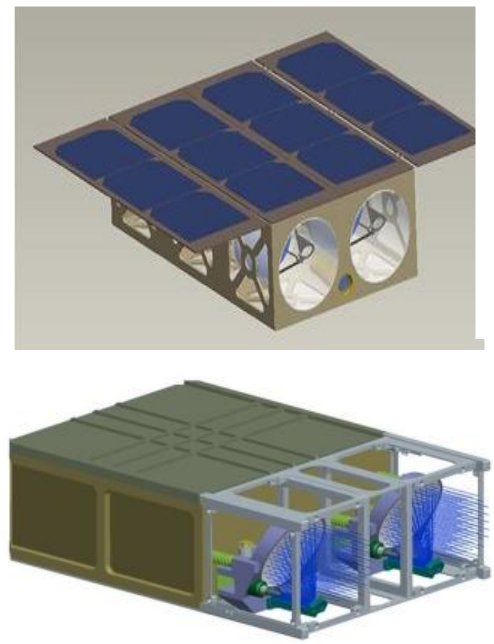


Figure 7. (top) The 2-um Spaceflight Transmitter Enables Viable Cubesat Water Vapor and CO2 Lidar in 6-12U cubesat lidar form factor for planetary science. (bottom) 6U cubesat, shown with Fibertek developed 7-cm telescope transceiver.

The proposed size, weight, and power present a substantial miniaturization of a complex system. The radiation-hard field programmable gate array (FPGA) in the design could be used for the receiver. A receiver detector and transceiver optical telescope would be needed to complete the lidar system.

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REFERENCES

1. G. D. Spiers, R. T. Menzies, J. Jacob, L. E. Christensen, M. W. Phillips, Y. Choi, E. V. Browell, “Atmospheric CO2 measurements with a 2um airborn laser absorption spectrometer employing coherent detection,” Appl. Opt, 50, pp. 2098-2111 (2011).

2. Menzies R. T. and D. M. Tratt, “Differential laser absorption spectrometry for global profiling of tropospheric carbon dioxide: selection of optimum sounding frequencies for high-precision

measurements," Appl. Opt., 42, pp. 6569-6577, 2003.

3. Bing Lin, Amin R. Nehrir, F. Wallace Harrison, Edward V. Browell, Syed Ismail, Michael D. Obland, Joel Campbell, Jeremy Dobler, Byron Meadows, Tai-Fang Fan, and Susan Kooi, "Atmospheric CO2 column measurements in cloudy conditions using intensity-modulated continuous-wave lidar at 1.57 micron," June 2015, Vol. 23, No. 11, DOI:10.1364/OE.23.00A582 | OPTICS EXPRESS A582.

4. Jeremy Dobler, F. Wallace Harrison, Edward Browell, Syed Ismail, "Atmospheric CO2 column measurements with an airborne intensity-modulated continuous wave 157 µm fiber laser lidar," Applied Optics 52(12):2874-92, April 2013, DOI: 10.1364/AO.52.002874.

5. Mahmood Bagheri, Clifford Fez, Ryan Briggs, and Siamak Forouhar, "High-power distributed feedback semiconductor lasers, operating at 2.05 um range," OSA Publishing, https://www.osapublishing.org/ol/upcoming_pdf.cfm?id=278713; https://esto.nasa.gov/forum/estf2014/presentations/B8P4_Bagheri.pdf

6. Doruk Engin, Ti Chuang, and Mark Storm, "Compact, highly efficient, athermal, 25W, 2051nm Tm-fiber based MOPA for CO2 trace-gas laser space transmitter," Proc. SPIE 10083, Fiber Lasers XIV: Technology and Systems, 1008325 (February 22, 2017); DOI:10.1117/12.2250516; http://dx.doi.org/10.1117/12.2250516

7. D. Engin, T. Chuang, M. Storm, "Compact, highly efficient, single-frequency 25 W, 2051 nm Tm fiber–based MOPA for CO2 trace-gas laser space transmitter," SPIE Optics + Photonics Conference, Remote Sensing, San Diego August 6-10, 2017.

8. Mark Storm, Doruk Engin, Brian Mathason, Rich Utano, Shantanu Gupta, "Space-Based Erbium-Doped Fiber Amplifier Transmitters for Coherent Ranging, 3D-Imaging, Altimetry, Topology, and Carbon Dioxide Lidar and Earth and Planetary Optical Laser Communications," The 27th International Laser Radar Conference (ILRC 27), DOI: 10.1051/epjconf/201611902002.

9. Mark Storm and Floyd Hovis, "Space lidar technologies supporting upcoming NASA earth science and laser communications missions," IEEE Aerospace Conference Proceedings, June 2015, DOI: 10.1109/AERO.2015.7119312.

10. Doruk Engin et al., "Highly efficient and athermal 1550 nm fiber-MOPA-based high-power downlink laser transmitter for deep space communication," SPIE 8610, Free-Space Laser Communication and Atmospheric Propagation XXV, 86100G (19 March 2013), DOI:10.1117/12.2005926.

11. D. Engin, S. Litvinovich, F. Kimpel, K. Puffenberger, X. Dang, J.-L. Fouron, N. Martin, M. Storm, S. Gupta, R. Utano, "Highly reliable and efficient 1.5-um fiber-MOPA-based, high-power laser transmitter for space communication," Proc. of SPIE 9081 (June 2014).

12. "Highly-efficient high-energy 1.5 µm pulsed fiber laser with precise linewidth and wavelength control of individual pulses," D. Engin et al., Paper 9834-32, SPIE DSS 2016.

13. S. Gupta, D. Engin et al., "Development, testing, and initial space qualification of 1.5-µm high-power (6W) pulse-position-modulated fiber laser transmitter for deep-space laser communication," Optical Engineering 55(11):111606, August 2016, DOI: 10.1117/1.OE.55.11.111606.

14. D. Engin, B. Mathason, M. Stephan, and M. Storm, "High energy, narrow linewidth 1572nm ErYb-fiber based MOPA for a multi-aperture CO2 trace-gas laser space transmitter," Proc. SPIE 9728, Fiber Lasers XIII: Technology, Systems, and Applications, 97282S (March 11, 2016); DOI:10.1117/12.2212481.