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CUBESAT-SCALE LASER COMMUNICATIONS

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ABSTRACT

We report on the development of an optical space-to-ground communications system scaled for application in 1.5U CubeSats. The AeroCube Optical Communication and Sensor Demonstration (OCSD) has as its primary payload a 10-W laser for a LEO-to-ground communications demonstration. The OCSD laser is hard-mounted to the spacecraft and beam steering is accomplished through precision pointing of the spacecraft as a whole. This capability is enabled through development of an advanced CubeSat-scale attitude-control system capable of pointing the spacecraft to within 0.2 degrees of the target. The OSCD program includes three flight units; a pathfinder that will fly in summer 2015 and two follow-on units that will fly in December 2015. It is anticipated that the program will demonstrate optical communication rates of at least 50 Mb/s, with the possibility of rates up to 200 Mb/s. Although not high in comparison with laser communication systems designed for larger spacecraft, the rates represent a 1 to 2 order-of-magnitude improvement over RF communication rates typical of CubeSats.

INTRODUCTION

The revolution in the development of kg-class spacecraft engendered by the establishment of the CubeSat standard has led to rapid development of a host of new satellite designs and applications. CubeSats are often seen as providing opportunities for pathfinder experiments, space qualification of components and systems, and enhancement of larger assets. However, many CubeSat projects are aimed at providing significant stand-alone mission capability, and these missions often involve downlinking of substantial quantities of data. The data demand of CubeSats can be well beyond the capacity of traditional radio-frequency (RF) communication systems, particularly when these systems are constrained by the power, mass, and volume limits of CubeSats. Optical communication systems present an appealing alternative to traditional RF systems in that they are capable, in principle, of substantially higher data rates than RF systems, while working within much smaller mass and power limits. The Optical Communication and Sensor Demonstration (OCSD) is a CubeSat flight test developed by The Aerospace Corporation and funded by NASA's Small Spacecraft Technology Program (SSTP) under the Space Technology Mission Directorate. The primary mission of OCSD is to demonstrate an optical downlink with a very modest threshold objective data rate of 5 to 50 Mb/s (although significantly higher rates are anticipated). A secondary mission is to demonstrate sensors and methods for proximity operations between two CubeSats.

Why Laser Communications?

Advances in micro/nanoelectronics have enabled unprecedented data collection and storage capabilities in spacecraft of all sizes. A current generation 15-megapixel color imager operating at 30 Hz can generate over 10 gigabits/s (Gb/s) of raw data. Even with low-loss video compression, data rates can easily exceed 200 megabits/s. Recording this compressed video over an entire orbit would require about 132 gigabytes (GB); slightly more than the 128 GB storage capacity of a micro SD flash memory card. A terabyte (TB) of data can be readily stored in a CubeSat, and with a little more effort, over 10 TB is possible.

Sending this amount of data to the ground from a power- and antenna-gain-limited RF system on a small satellite is a challenge. Good S-band CubeSat downlink can handle a data rate of several megabits/s. Downloading a terabyte using a single ground station at a rate of 5 megabits/s (Mb/s) with an average of four 10-minute passes per day (very optimistic) would take almost 2 years. Storing terabytes of information is easy; sending it to the ground is hard. Either an order-of-magnitude or more increase in the number of ground stations, or an equivalent increase in downlink data rates, is required to enable more reasonable data download times.

Laser communications offer Gb/s data rates; a several order-of-magnitude increase in rate compared to radio frequency (RF) communications. NASA's Lunar Laser Communication Demonstration (LLCD), an experiment on the Lunar Atmosphere and Dust Environment Explorer (LADEE), sent data from lunar orbit to the Earth in late 2013 at a record-breaking rate of 622 Mb/s.[1] This was six times faster than previous RF communications from the moon, using a transmitter with half the weight and one quarter the input power of an equivalent RF system. Note that communications from the moon, with a link length of about 400,000 km, is many orders-of-magnitude harder than from low Earth orbit (LEO), with a link length of about 1000 km.

Optical satellite-to-ground data rates in excess of 5-Gb/s have already been demonstrated using LEO spacecraft. Members of The Aerospace Corporation, in collaboration with Tesat-Spacecom, previously demonstrated 5.625-Gb/s bidirectional laser communications between a 6.5-cm diameter ground station at the European Space Agency Optical Ground Station in Izana, Tenerife, and a 12.5-cm diameter terminal mounted on the Near Field Infrared Experiment (NFIRE) satellite in low Earth orbit (LEO).[2] The spacecraft terminal had a mass of 35-kg, a power consumption of 120-W, a 0.5 x 0.5 x 0.6-m size, and transmitted 0.7-W at 1064-nm wavelength.[3] This high-performance system with a ~50-microradian angular beam width and gimbaled pointing system would obviously not fit in a CubeSat.

OCSD FLIGHT DEMONSTRATION

The OCSD flight hardware will consist of three 1.5-unit (1.5U) CubeSats that will be launched as secondary payloads on two rideshare missions. A single pathfinder satellite will be launched in summer 2015, followed by a pair of Block-II satellites in December 2015. The pathfinder satellite will demonstrate all the subsystems required for the primary OCSD mission, and will be used to evaluate the performance of the attitude-control system. The pathfinder satellite is also expected to demonstrate optical downlinking at speeds up to 100 Mb/s.

The pathfinder satellite has been built, tested, and delivered to the launch integrator. The Block-II satellites are nearly complete; final assembly, testing, and delivery will be completed after results are obtained from the pathfinder satellite. The Block-II satellites will be modified and upgraded as necessary to incorporate any lessons learned in the pathfinder mission, and the laser communication system will be tuned to higher data rates if the results of the pathfinder mission indicate that they can be supported by the attitude-control system. In addition, the Block-II satellites will perform the proximity operations mission by flying relative to one another. Overall, the OCSD effort will demonstrate a number of useful small satellite technologies:

1. Optical downlink communications from a low-earth orbit CubeSat to ground at a rate of 5 to 50 Mb/s (minimum), Modulation format: OOK and 4-PPM (option) with and without Forward Error Correction (FEC).
2. Tracking of a nearby, cooperative spacecraft using a commercial, off-the-shelf (COTS) laser rangefinder,
3. Attitude determination using a sub-cubic-inch star tracker and a number of COTS optical thermometers, COTS MEMS rate gyros, and COTS magnetometers,
4. Orbit rephasing using variable aerodynamic drag, and
5. Orbit control using a safe, non-toxic, easy to flight-qualify, steam thruster.

Figure 1 shows a rendering of an AeroCube-OCSD spacecraft, and figure 2 a photograph of the first OCSD satellite just prior to delivery. Each CubeSat has two deployable wings to provide a wide range (5 to 1) of ballistic coefficient to enable orbit control through variable aerodynamic drag. Variable drag will be used to control inter-spacecraft range when ranges exceed 1 km.

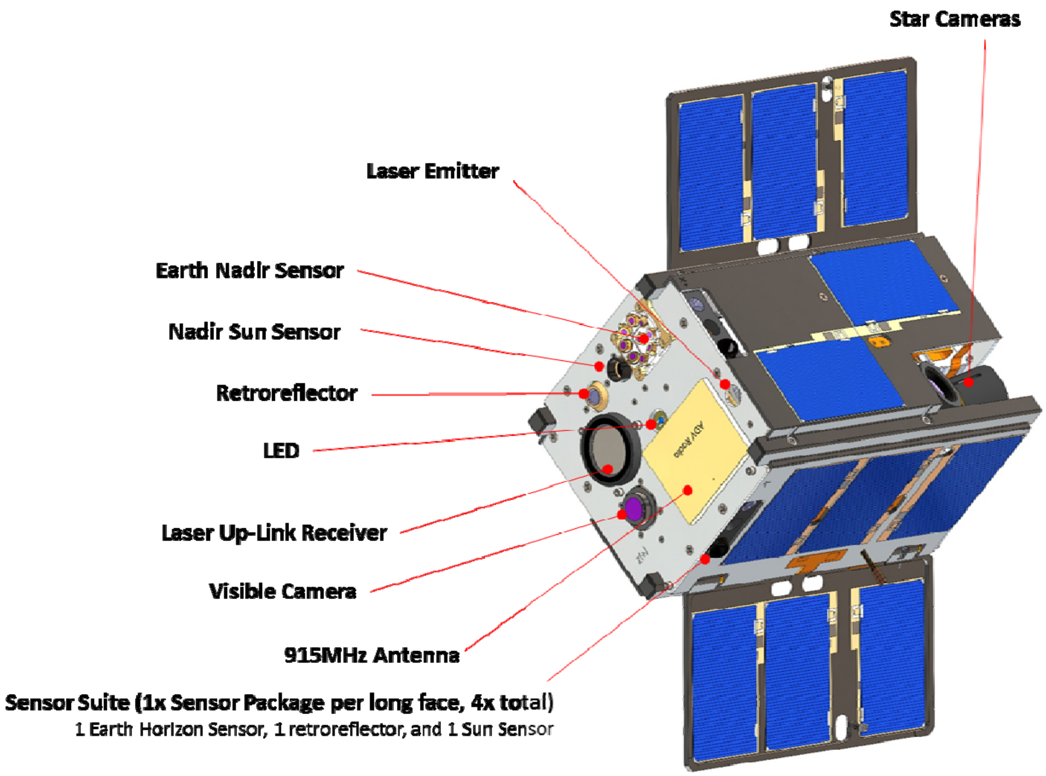

Figure 1: Rendering of the OCSD CubeSat.

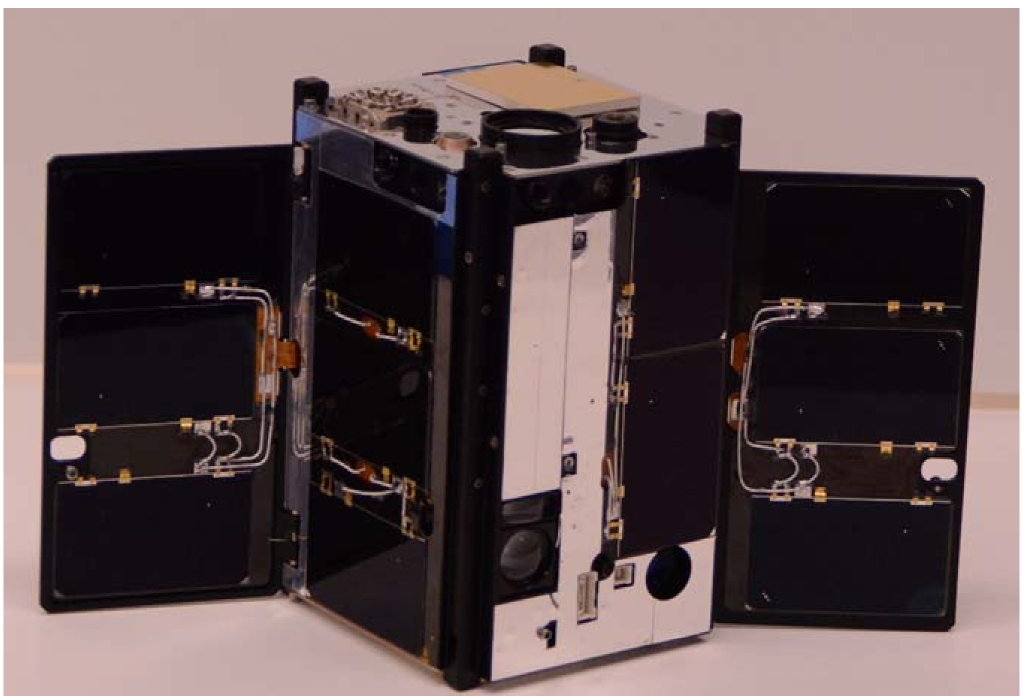

Figure 2: Photograph of the first OCSD CubeSat.

One of the key mass and complexity drivers in traditional space-based laser communication systems is the gimbal system used for fine pointing. In contrast to these systems, the OCSD CubeSat architecture does not include an optical gimbal. Instead, the communications beam is fixed in its orientation relative to the spacecraft body, and is pointed only by steering the spacecraft as a whole. Eliminating the gimbal and increasing the angular beam width to several milliradians to allow spacecraft body-pointing of the laser enables a significantly smaller, lighter optical terminal than typical laser communication systems. This approach takes advantage of the exceptionally low moments-of-inertia of CubeSats, and their ability to perform rapid slew maneuvers. For pointing, we have developed miniaturized sun, Earth-horizon, and Earth-nadir sensors and a cm-scale star tracker that will provide the required attitude references for our attitude-control system. Pointing accuracy and stability are key to any free-space optical communications link. The overall trade-off is size, complexity, and cost for communications bandwidth. While our experiments are not intended to demonstrate ultra-high bandwidth communications, the goal is to test the limits of low-cost, rapidly-deployable, small satellite platforms for optical communications, remote sensing, and other applications.

Laser Transmitter

The 1064-nm-wavelength optical downlink uses a low power amplitude-modulated diode laser followed by two polarization-maintaining ytterbium-doped fiber amplifier stages.[3] Figure 3 shows a schematic drawing of the laser design. Figure 4 shows a photo of the laser transmitter slice (during assembly) that occupies a volume of ~10x10x2.5 cm.

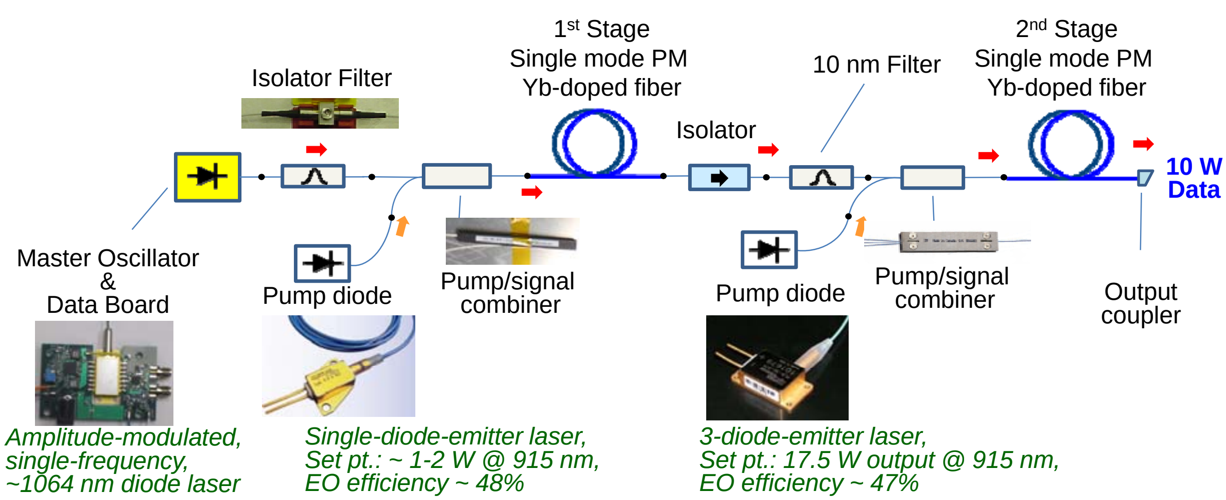

Figure 3: Schematic of the laser downlink transmitter.

As configured, the laser is capable of delivering in excess of 10 W of optical output at 1064 nm at a wallplug efficiency of 25%. For the first flight, we will operate our laser transmitter 6 W of optical output power. The consequent waste heat load in a 1.5U CubeSat is a thermal challenge, and to mitigate this, we limit the duration of each laser transmitter event to 3 minutes. This is the maximum length of time a satellite at 600-km altitude would be more than 30 degrees above the horizon for a favorable link budget. The laser system is mounted on an aluminum tray to transfer heat from the pump diodes, and this tray is thermally connected to the aluminum body. The body becomes a temporary heat sink and long-term thermal radiator. Unlike many CubeSats, our shell, or body, is machined out of a single block of aluminum to provide structure, heat transport, and high skin electrical conductivity for passive rotational damping by Eddy currents. This shell will help to dissipate heat generated during laser events.

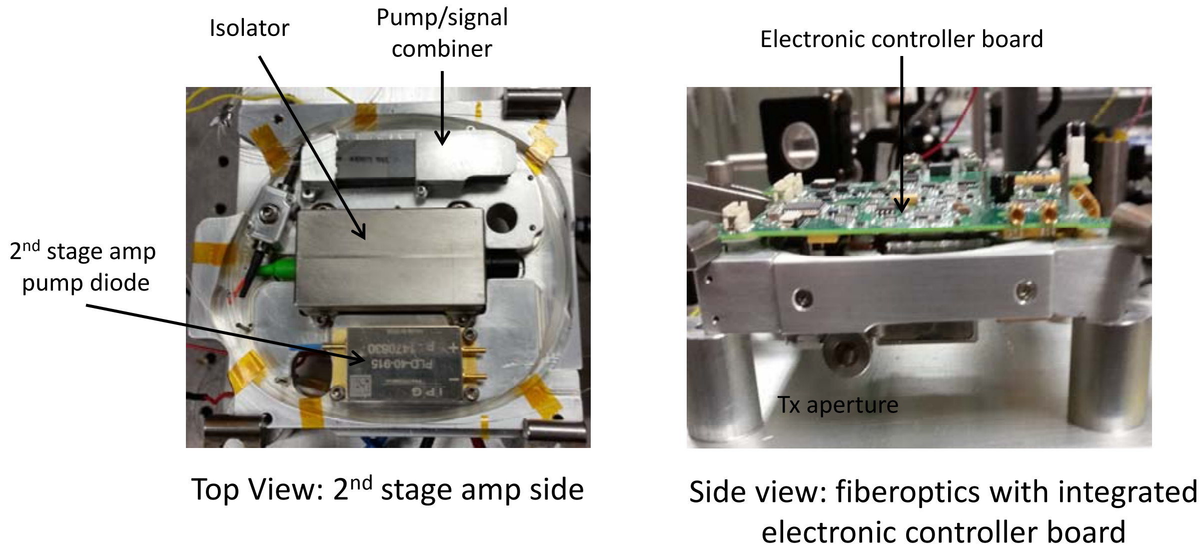

Figure 4: Photographs of laser transmitter.

The downlink laser has a full-width-half-maximum (FWHM) beamwidth of 0.35 degrees. This is the widest beamwidth that yields 50 Mb/s data rates at half-maximum signal levels using our optical ground station located at Mt. Wilson, California. Figure 5 shows the calculated irradiance as a function of radius from the beam centerline at a range of 900 km. Also shown are expected data rates for three angles off of centerline. These rates are based on 10 W output power at the satellite, on/off modulation with an 8:1 signal-to-noise ratio, 32% atmospheric absorption and scintillation loss, and a 30-cm diameter receive telescope with an avalanche photodiode detector with a noise equivalent power of 5 x 10^{-14} W/$Hz^{1/2}$. The intent is to receive data from the satellite at 5 to 50 Mb/s rates with a bit error ratio (BER) of 10^{-4}; one bit error, on average, for every 10,000 bits received. Note that our spacecraft has better than 0.1-degree attitude knowledge using either the star trackers or uplink laser beacon, and 0.1-degree control authority using our heritage 3-axis reaction wheels.

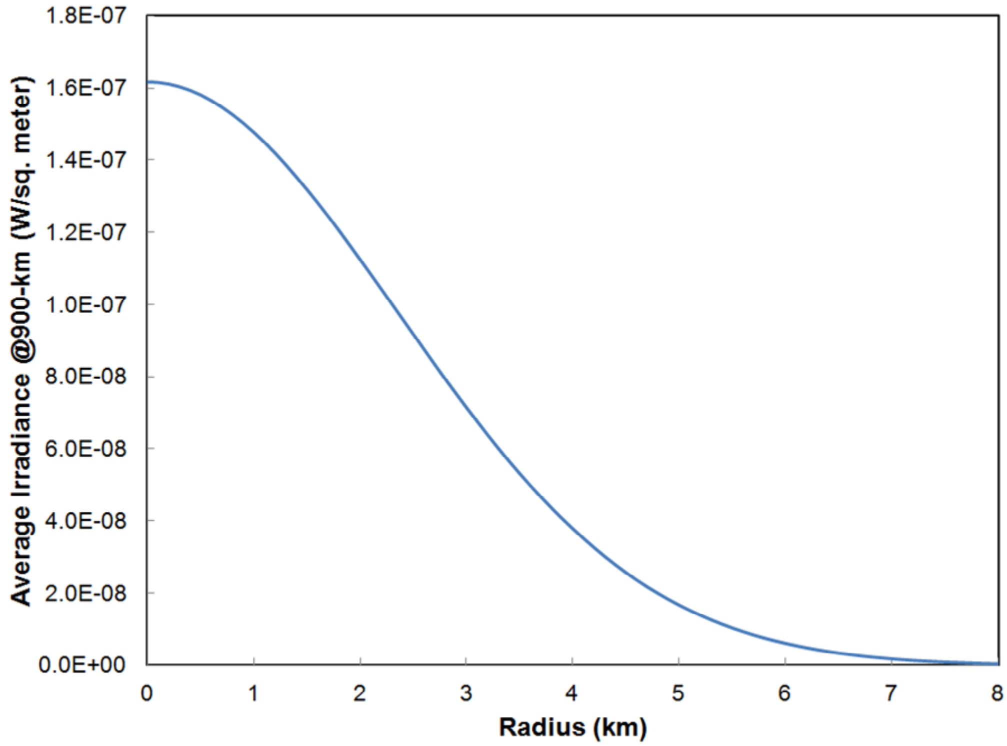

Figure 5: Average irradiance at 900-km range as a function of radius from the beam centerline for a 0.35-degree FHWM beam width.

OCSD Bus Subsystems

The most-challenging bus system needed to support laser communications in a CubeSat is the attitude-control system. Other systems include navigation, power, and communications.

Navigation

Precision pointing of the spacecraft at the ground station requires not only attitude control but also knowledge of the spacecraft position. As a demonstration mission, the pointing direction for each spacecraft is pre-calculated on the ground as a function of time using high-precision orbital elements based on multiple, recent (within 24-hours), GPS fixes over one or more orbits. Our flight-proven GPS receivers have a single point positional accuracy of ~20 meters, resulting in instantaneous in-track and cross-track positional errors less than 10 meters when using multiple GPS fixes over an orbit, along with high-precision orbit fitting software. For OCSD, this calculation will be done on the ground. Future missions will need to incorporate precision orbit determination on the spacecraft to allow autonomous pointing at the optical ground terminal.

Power

As built, each CubeSat weighs 2.5 kg and consumes under 2 W during most of the mission life. During laser communication engagements, which are expected to last no more than 3 minutes, the spacecraft will consume an additional 40 to 50 W for operation of the 10-W optical transmitter. The wing surfaces and two of the rectangular side panels have three, 1-W, triple-junction solar cells, while the remaining two rectangular side panels have two, 1-W triple-junction cells. Maximum solar input power is 9.5 W, and typical orbit-average input power is expected to be 4.5 W. Two COTS 18650 size high-energy lithium ion batteries with a total capacity of 14 W-hr provide spacecraft power during eclipse, and two COTS high-current 18650 size lithium ion batteries provide over 50 W to the laser transmitter during optical downloads. The high-current batteries are a type typically used to power hand-held portable drills and other power tools.

Communications

Although the OCSD spacecraft will have a very-high data capability in the optical system, it is an experimental system and will not be used for command and control. Primary communications will be through two different on-board radios and a set of four RF ground stations. The on-board radios were both developed at Aerospace. The primary radio operating at 915 MHz, is identical to the radios that Aerospace has flown in eight prior spacecraft. The second radio is a newly-developed software-defined radio (SDR), also operating at 915 MHz, that will be flown as an experiment on this mission for possible use on future AeroCube Spacecraft.

Attitude Control

The Attitude Determination and Control System (ADCS) includes sensors to measure attitude and actuators to control it. The sensor system on OCSD includes both coarse and fine attitude sensors.

Coarse Attitude Sensors

Since the spacecraft can and will fly with a wide range of orientations to support both optical downlink and proximity operations, we incorporated six 2-axis sun sensors, four Earth-horizon sensors, a two-axis Earth-nadir sensor, and two sets of 3-axis magnetometers as basic attitude sensors. This highly-redundant combination of sensors allows continuous attitude determination with about 1-degree accuracy even with multiple attitude sensor failures.

Our sun and Earth-nadir sensors, described in previous work, have successfully flown on three different spacecraft missions. [4,5] Once calibrated, our sun sensors have a 0.32-degree root mean square (rms) error, over a 35-degree field of view (FOV), in two axes. Based on flight data from multiple missions, our Earth-nadir sensor has 1-degree accuracy in two axes.

Our chip-scale magnetometers also have roughly 1-degree accuracy in two axes when instantaneous position is known and the local field is interpolated from an up-to-date magnetic field table. Magnetic field bias errors from magnetized batteries, other ferromagnetic parts, and permanent magnets in reaction wheels and other components contribute to this error.

One set of new coarse attitude sensors was developed for this mission. Each spacecraft has four COTS Melexis MLX90620 infrared array sensors as an attitude determination experiment to locate the Earth's warm limb against cold space. These sensors have a 4 x 16 array of thermopile temperature sensors that can optically read temperature with a 0.25 K (rms) temperature difference from -50 C to 300 C at a 4 Hz rate.[6] Each pixel has a 3.75 x 3.75-degree field of view, potentially enabling nadir determination accuracy of 0.3-degrees when all four sensors can see the Earth's limb. These sensors provide a backup to the legacy Earth-nadir sensor and should be less affected by cold, high-altitude clouds.

Fine Attitude Sensors

Precision pointing for laser communications using the 0.35-degree FWHM downlink beam width requires a 0.175-degree spacecraft-to-ground-station pointing accuracy; much tighter than the 1-degree pointing accuracy provided by our legacy attitude sensors. The OCSD, as a demonstration mission, includes two independent fine attitude sensors to allow operation in either a closed-loop mode or an open-loop mode. Either system independently is capable of achieving the mission goals. However, both will be tested to develop an understanding of the systems and their applicability to future missions.

Closed-loop control for tracking the laser ground station is provided by integrating a modulated, 10-W, 1550-nm laser uplink at the ground station, co-aligned with the telescope receiver, and a lensed photodiode receiver on the satellite. This system will provide better than 0.1-degree pointing at the ground station during an overhead pass. The uplink receiver consists of narrow band pass filter followed by an 18-mm diameter lens that focuses incoming light onto a 1.5-mm-diameter InGaAs quad photodiode. Individual currents from each of the four diodes are used to generate error signals for each of two axes, while the summed output provides data. The optical uplink data rate is less than 10 kilobits/s.

Open-loop pointing is enabled through the use of star trackers that were developed based on experience obtained with simple imaging systems on AeroCube 4.[7] Dual star trackers on each OCSD CubeSat use an Aptina MT9V022 monochrome WVGA imager with five times the sensitivity of those on AeroCube 4. These imagers are coupled to f/1.2 lenses, compared to f/2.0 for AeroCube 4, resulting in 3 times the light collection capability. A Spartan-6 FPGA reads an image frame, processes the field, and outputs a collection of star locations. These data are further processed by a 16-bit microcontroller using a star catalog to output pointing direction as a set of quaternions. One star tracker points 20 degrees off the +Z direction (typically zenith), while the other is canted by 70 degrees to provide angular diversity in case stray light from the Earth, moon, or sun, interferes with one tracker. Figure 6 shows an image of the camera assembly on OCSD including two star cameras, one high-resolution flight camera and one proximity-sensor camera. Star fields are imaged about once per second, and quaternion outputs are combined with more rapid rate-gyro data to provide continuous attitude information with less than 0.1-degree error.

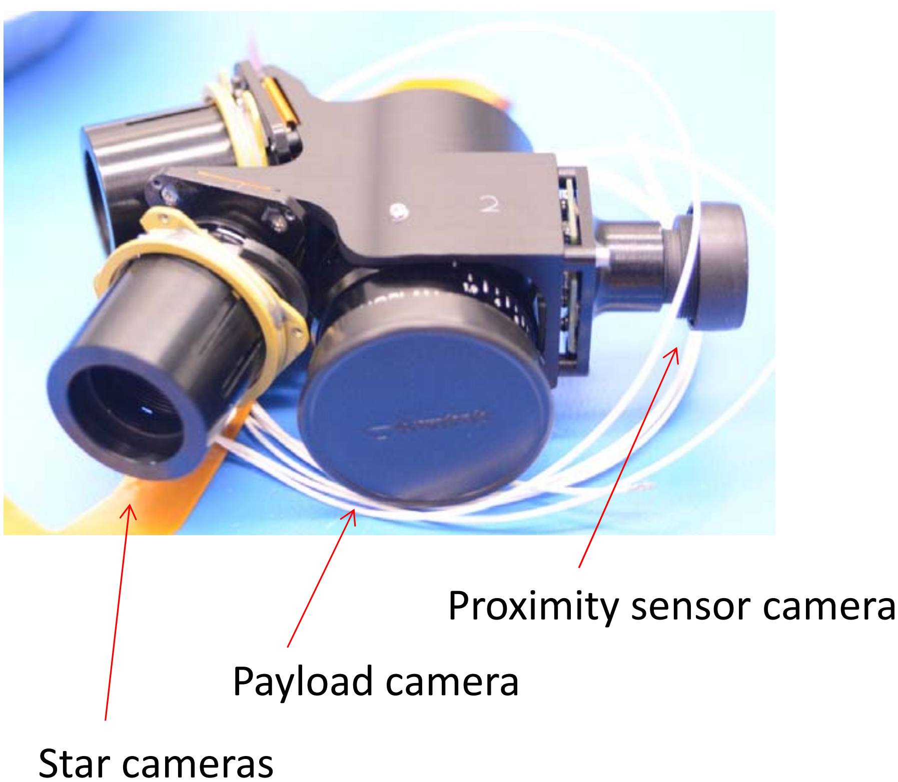

Figure 6: Photograph of the OCSD camera package including two star cameras, one flight camera, and one proximity camera.

Rate Gyros

For robustness and power control, we have two 3-axis rate gyros on each spacecraft. A Sensonor STIM-210 3-axis rate gyro provides a random angular walk of 0.15 deg/(hour)^1/2, but it has a maximum power consumption of 1.5 W and needs a one hour warmup period.[8] These devices are susceptible to helium exposure, which can occur during launch vehicle preparations, so we mount them inside their own hermetically-sealed container.

Another set of rate gyros is in the VectorNav VN-100 inertial measurement unit (IMU), also on each spacecraft.[9] These gyros provide a random angular walk of about 10 deg/(hour)^1/2, but the IMU consumes only 0.33 W. This IMU also contains a 3-axis set of accelerometers, a 3-axis set of magnetometers, and a pressure sensor.

Experiments will be conducted with these two rate gyros to determine the level of accuracy required of the rate gyro to support the laser communication mission.

Attitude actuators

Attitude actuators include a triad of magnetic torque rods and a triad of reaction wheels. The torque rods have a magnetic moment of 0.2-A-m^2. They provide torques for detumbling and reaction wheel unloading. The reaction wheels have flight heritage on multiple spacecraft with 1-mN-m-s of total angular momentum. AeroCube-OCSD slew rates can be in excess of 5-degrees per second using these wheels, and pointing control to within 0.1-degree has been demonstrated on-orbit using these reaction wheels on a similar spacecraft.

Optical Ground Station

In addition to spacecraft systems, successful optical communication requires a compatible optical ground receiving station. Two ground terminals operated by The Aerospace Corporation are located at Mt. Wilson, CA. at an altitude of 1750 m. The Mobile Communications and Atmospheric Measurements (MOCAM) station was completed in 2013 and supports a COTS 30-cm diameter Cassegrain telescope. Initial experiments will be conducted with this system. Future experiments will take advantage of a newer facility, MAFIOT (Mt. Wilson Aerospace Facility for Integrated Optical Tests), which is nearing completion and operates an 80-cm Ritchey-Chrétien telescope. Figure 7 shows the two optical ground stations at Mt. Wilson.

Rough satellite tracking will use high-accuracy ephemerides generated from spacecraft GPS fixes on previous orbits, and a wide field of view (WFOV) tracking camera will provide closed loop feedback to keep the downlink laser photons centered on the avalanche photodiode located at the focus of MOCAM and MAFIOT. This system has been used to track other LEO spacecraft and is fully capable of receiving our optical downlink. The easiest test mode is to download known data patterns and read the BER from the test meter. As we gain experience, we will download spacecraft imagery and videos, and use the FPGA transceiver to process these data.

The uplink laser beacon on the ground station provides the signal for closed loop tracking of the ground station by the satellite. The 10-W, 1550-nm uplink laser is eye safe within 50 meters of the telescope, and meets FAA requirements for operation without an aircraft spotter. We will test this laser uplink mode first, followed by the mechanically-simpler open loop tracking mode based on star tracker data. Long term, this could reduce ground station complexity and cost.

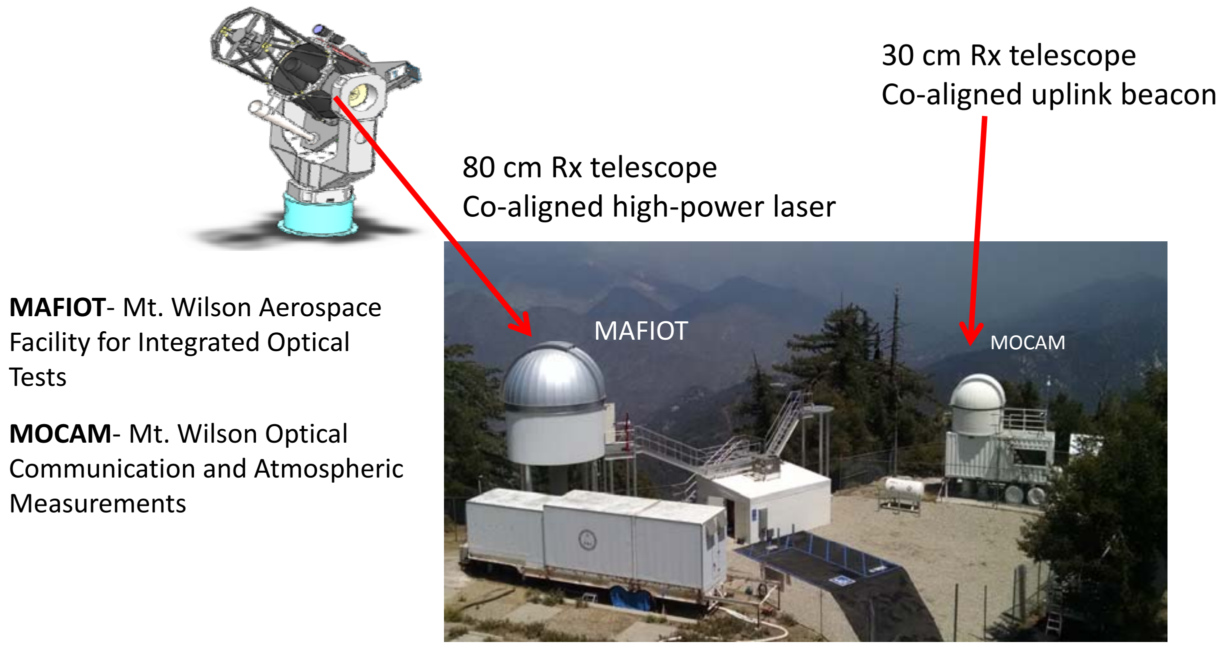

Figure 7: MAFIOT (80 cm) and MOCAM (30 cm) optical ground stations at Mt. Wilson.

SUMMARY

The NASA-funded AeroCube OCSD program is a flight-validation mission designed to evaluate the utility of body-steered laser communication systems for LEO-to-ground applications. The satellite will fly a state-of-the art laser for the downlink, producing a 10-W beam that can be modulated at up to 200 Mb/s. Another key development that enables the anticipated data rates is the attitude-control system. The state of the art in pointing accuracy for CubeSats has been improving from about five degrees in 2008 to about 0.5 degree in 2015.[10] The OCSD spacecraft is expected to push that accuracy to 0.2 degrees, which is sufficient to enable laser communication at 10s of Mb/s from LEO to a 30-cm ground station. Further refinements in the attitude control system, and increases in the collector area on the ground, could easily push data rates well above 100 Mb/s, and rates may approach 1 Gb/s. The first flight unit of OCSD has been delivered, and launch is scheduled for summer 2015. Two additional units have been built, and are scheduled for launch in December 2015. The performance of the attitude-control system will be evaluated during the first flight; if pointing accuracy is better than 0.1 degrees, then the laser-beam collimation optics on the two later flight units will be adjusted to provide tighter beams, allowing for higher data rates.

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REFERENCES

1. Donald M. Cornwell Jr., "NASA's Optical Communications Program for 2015 and Beyond," Proceedings of SPIE Vol. 9354, Presented at Photonics West, February 2015.

2. Fields, R., Kozlowski, D., Yura, H., Wong, R., Wicker, J., Lunde, C., Gregory, M., Wandernoth, B., and Heine, F., "5.625 Gbps Bidirectional Laser Communications Measurements Between the NFIRE Satellite and an Optical

Ground Station," Proc. of the 2011 Int. Conf. on Space Optical Systems and Applications, pp.44-53, Santa Monica, CA, 11-13 May, 2011.

3. Todd S. Rose, Renny A. Fields, Siegfried W. Janson, Darren W. Rowen, David A. Hinkley, Richard P. Welle, "LEO to Ground Optical Communications from a Small Satellite Platform," Proceedings of SPIE Vol. 9354, Presented at Photonics West, February 2015.

4. Siegfried W. Janson, Brian S. Hardy, Andrew Y. Chin, Daniel L. Rumsey, Daniel A. Ehrlich, and David A. Hinkley, "Attitude Control on the PicoSatellite Solar Cell Testbed-2," paper SSC12-II- 1, 26th Annual AIAA/USU Conference on Small Satellites, Logan, Utah, August, 2011.

5. Siegfried W. Janson and David J. Barnhart, "The Next Little Thing: Femtosatellites," paper SSC13-VI-3, 27th Annual AIAA/USU Conference on Small Satellites, Logan, Utah, August, 2013.

6. Melexis Microelectronic Systems, MLX90620 datasheet, URL: http://www.melexis.com/Assets/Datasheet-IR-thermometer-16X4-sensor-array-MLX90620-6099.aspx, Melexis Microelectronic Systems, Ieper, Belgium, May 2013.

7. Darren W. Rowen, Alexander C. Utter, Richard M. Dolphus, Eddson M. Alcid, "A Miniature, Low-Power Star Tracker for Precision Pointing Nanosatellites," AAS 15-045, presented at the American Astronautical Society GN&C Conference, Breckenridge, CO, January 2015.

8. Sensonor AS, Butterfly Gyro STIM210 Multi-Axis Gyro Module datasheet, URL: http://www.sensonor.com/media/90317/datasheet%20stim210%20ts1545.r10.pdf,

9. VectorNavTechnologies, VN-100 web page, URL: http://www.vectornav.com/products/vn100-smt, VectorNavTechnologies.

10. "Small Spacecraft Technology State of the Art," NASA/TP-2014-216648/rev1, Ames Research Center, Moffett Field, CA.