SSC15-III-1

The NASA Optical Communication and Sensors Demonstration Program: Preflight Update

Siegfried W. Janson, Richard P. Welle, Todd S. Rose, Darren W. Rowen, David A. Hinkley, Brian S. Hardy, Stephan D. La Lumondiere, Geoffrey A. Maul, and Nicolette I Werner
The Aerospace Corporation
P.O. Box 92957, Los Angeles, CA; (310)-336-7420
Siegfried.w.janson@aero.org

ABSTRACT

Small, inexpensive, satellite platforms offer opportunities for pathfinder experiments, space qualification of components and systems, and enhancement of larger assets. The Optical Communication and Sensor Demonstration (OCSD) has become a three CubeSat flight test funded by NASA's Small Spacecraft Technology Program (SSTP) under the Space Technology Mission Directorate. A 1.5U CubeSat using COTS hardware was designed, fabricated, tested, and delivered for launch. This Pathfinder CubeSat will fly by the fourth quarter of 2015. It will demonstrate proof-of-principle optical communications at a very modest threshold objective data rate of 5 Mb/s from low Earth orbit to a ground station. Two more CubeSats, with potential data rates of up to 500 Mb/s and propulsion, are under construction and will fly in January 2016. These CubeSats will demonstrate improved communications capability and the secondary OCSD goal of demonstrating proximity operations between two identical spacecraft using differential drag, a water vapor thruster, GPS measurements, and a laser rangefinder. The current launch schedule provides one to two months of Pathfinder operation before the final two flight units are delivered. We will attempt to implement lessons learned from the Pathfinder in the final flight units to demonstrate a new "Fly as you fly" paradigm enabled by the significant number of CubeSat launch opportunities available each year.

HISTORY

The Optical Communication and Sensor Demonstration (OCSD) started as a two-CubeSat flight test funded by NASA's Small Spacecraft Technology Program (SSTP) under the Space Technology Mission Directorate. The goals were to demonstrate a satellite-to-ground laser downlink with a data rate of greater than 5 Mb/s, and to demonstrate proximity operations using two 1.5U AeroCube-OCSD spacecraft with on-board propulsion.

The project started in October, 2012, with an anticipated one-year design and R&D phase, a one-year build, test, and integrate phase, a 2-to-6 month long "waiting for launch" phase, and a final six-month flight operations phase. We decided to significantly improve the 5 Mb/s laser downlink data rate during the design and R&D phase by replacing the proposed 300 mW output direct drive laser diode with a two stage 10 W fiber laser. This change enabled a potential 33X improvement in data rate. An additional 7X improvement was made possible by utilizing a newly-available 80 cm diameter telescope for our ground station instead of the proposed 30 cm diameter telescope. These two improvements increased our potential downlink data rates by over two orders-of-magnitude to approach 1 Gb/s. This may be a world's record in mission requirements creep, but we wanted to demonstrate data rates far in excess of any RF rates used in any previous or near-term CubeSat. This, of course, made the build, test, and integration phase much harder than originally planned.

Most of the project resources for this second phase were focused on developing the fiber laser and star trackers. The fiber laser was redesigned several times. The first version worked quite well in the laboratory, but could tolerate only a 10^{o} C change from room temperature. This would not work on orbit since the laser system generated 40 W of heat in a ~230-ml volume, and we didn't have enough thermal mass to keep the temperature rise below 10^{o} C. The second fiber laser design used a different optical pumping scheme that was much more temperature insensitive. Reference 1 documents this configuration. A third design was required to enable potting of the fibers to the mechanical structure for rapid heat transfer, and to ensure sufficient heat capacity of the laser system structure to absorb 40 W over the planned 3 minutes of operation without exceeding 40^{o} C. Reference 2 documents this third laser configuration. Another modification was required to protect the delicate fiber coils from damage during integration of the laser into the satellite body. Design for assembly is very important in CubeSats where internal free space is at a premium. The final revision for the Pathfinder CubeSat was to drop output power from 10 W to 6 W to improve overall reliability.

Multiple system redesigns for the laser downlink and other systems caused a four month schedule delay, and we still wanted additional time to further improve laser transmitter packaging for assembly, and overall reliability. Fortunately, we were offered an additional launch opportunity, and decided to fly our qualification spacecraft as a pathfinder test. "Test as you fly" is one of the tools we use to decrease CubeSat mission risk. We are now adding "Fly as you fly" to the tool kit.

The laser transmitter is only one part of a laser downlink demonstration. Our laser is hard mounted to the spacecraft body, and spacecraft attitude control is required to point the downlink beam at the ground station. Our laser has a 0.3° full-width at half-maximum (FWHM) angular beam width, so we need spacecraft pointing control to ~0.15° or better. Pointing accuracy for our orbiting AeroCubes is limited to ~1° by the attitude determination accuracy of our current-generation Earth nadir sensor. Our sun sensors provide ~0.2° pointing accuracy, but only about two axes.

We developed cubic-inch (~16 ml volume) size star trackers to provide three-axis attitude determination accuracies better than 0.15°. This was verified using dark sky testing on the ground. We also performed on-orbit testing using reaction wheels and rate gyros on AeroCube-4 to determine that they can control spacecraft attitude to better than 0.1°. Since our pointing accuracy has to improve by about an order of magnitude over what we've flown before, we wanted a test of the entire attitude control system, including star trackers, reaction wheels, torque rods, sun sensors, Earth horizon sensors, control loops, etc., in a relevant environment. The Pathfinder flight provides this opportunity.

The Pathfinder was delivered to the launch provider in March, and should fly by October, 2015. On-orbit testing will focus first on attitude control performance, followed by laser downlink tests. The results from the attitude control tests will be used to fix any remaining hardware and software issues in the two flight units, and to set the divergence angle of the downlink laser. Note that downlink data rate is proportional to the square of the divergence angle, so decreasing this angle provides more bits/s per watt of output power. Our goal for the two flight units is to use only 2 W optical output in order to reduce power consumption and heat dissipation, and to use a one-stage instead of a two stage fiber amplifier. A 2 W one stage design uses significantly less fiber length, requires fewer and smaller components, requires less volume, is much easier to integrate, and is significantly cheaper than the 2 stage design we used in the Pathfinder. A 2 W downlink laser could readily fit in the payload volume of a 1U CubeSat

THE PATHFINDER SPACECRAFT

Figure 1 shows a photograph of the Pathfinder that was delivered to the launch provider. It contains a 6-W output downlink laser, an uplink laser receiver, two independent 915 MHz communications transceivers, a GPS receiver, a 3-axis attitude control system designed for better than 0.15° pointing accuracy, a Jenoptik DLEM-SR laser rangefinder,[3] two star trackers, a color camera with 180° field of view, two deployable solar panels, and a distributed computing system composed of over 20 microprocessors and 3 field-programmable gate arrays (FPGAs). An 8-gigabyte flash RAM memory card is used for data storage. The Earth-pointing face is the top face in Fig. 1; this face contains the uplink laser receiver, the transmitter output window, a medium-gain patch antenna, a sun sensor, a laser retro-reflector, an ultra-wide angle camera, an LED beacon, and our legacy Earth nadir sensor. The locations are shown in the schematic drawing in Figure 2.

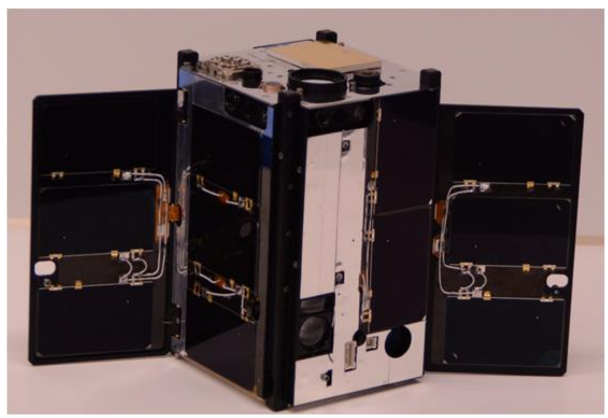

Figure 1. Photograph of the Pathfinder spacecraft with solar wings deployed.

Figure 3 shows the opposite sides of the Pathfinder spacecraft. The top surface now contains the GPS receive antenna, an omnidirectional patch antenna, a sun sensor, a laser retroreflector, an LED beacon, a narrow field of view camera, and a star tracker.

An exploded schematic view of the AeroCube-OCSD spacecraft is shown in Figure 4 below. There are four main subassemblies which are bolted together; the nadir face assembly, the avionics stack (which includes the laser transmitter and batteries), the body, and the zenith face assembly. Electrical interconnections use either rigid male/female sockets, or flexible circuit boards. The Pathfinder contains all of these parts, except for the thruster.

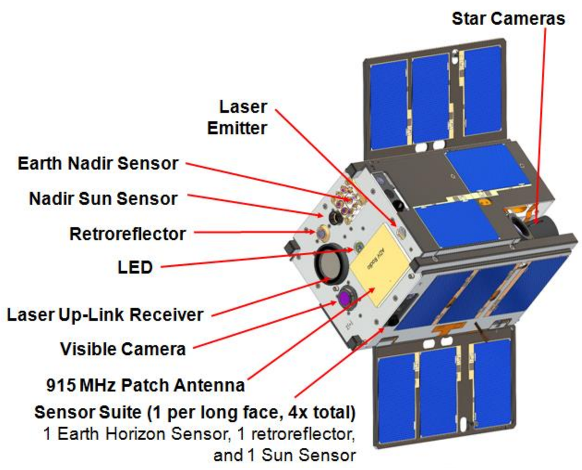

Figure 2. Location of nadir-face components.

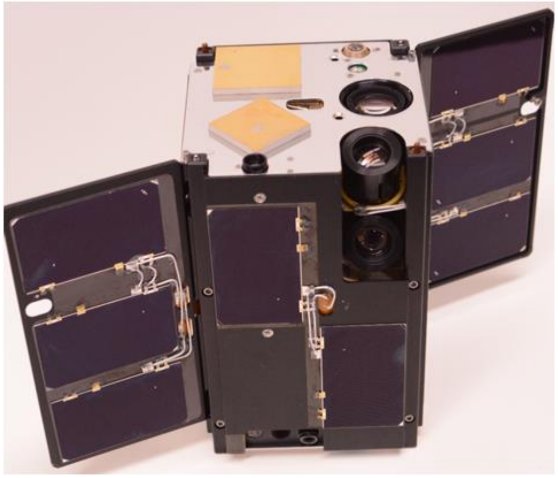

Figure 3. Photograph of the Pathfinder spacecraft with solar wings deployed; alternate view.

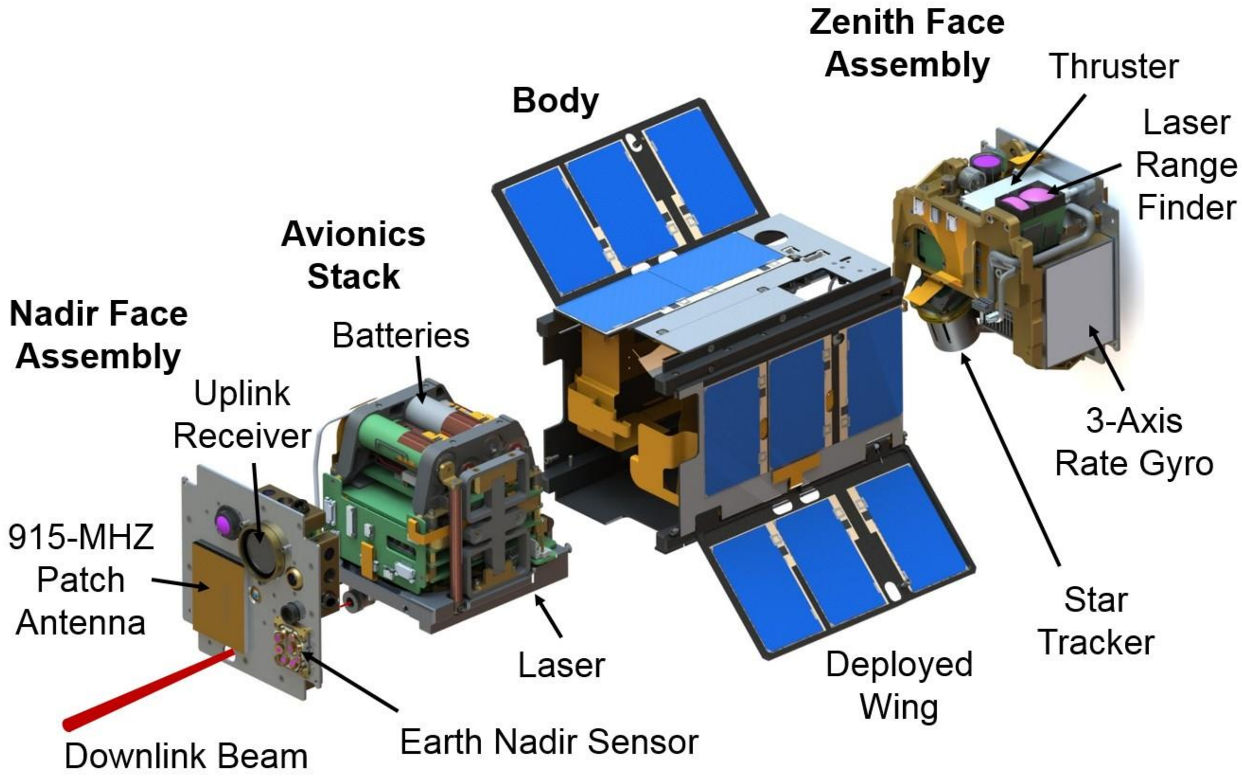

Figure 4. Exploded schematic view of the AeroCube-OCSD CubeSat.

Laser System

The downlink laser is based on an amplitude-modulated 1064-nm wavelength master oscillator (the seed laser) with a fiber output at ~10 mW average power, followed by two stages of fiber laser amplification. The polarization-maintaining ytterbium-doped fiber amplifier stages take this 10 mW-level seed output power first to 0.3 W, and finally, 6 W. Figure 5 shows a schematic of the transmitter, which is designed to operate over a temperature range of 10-50 ^{o}C.

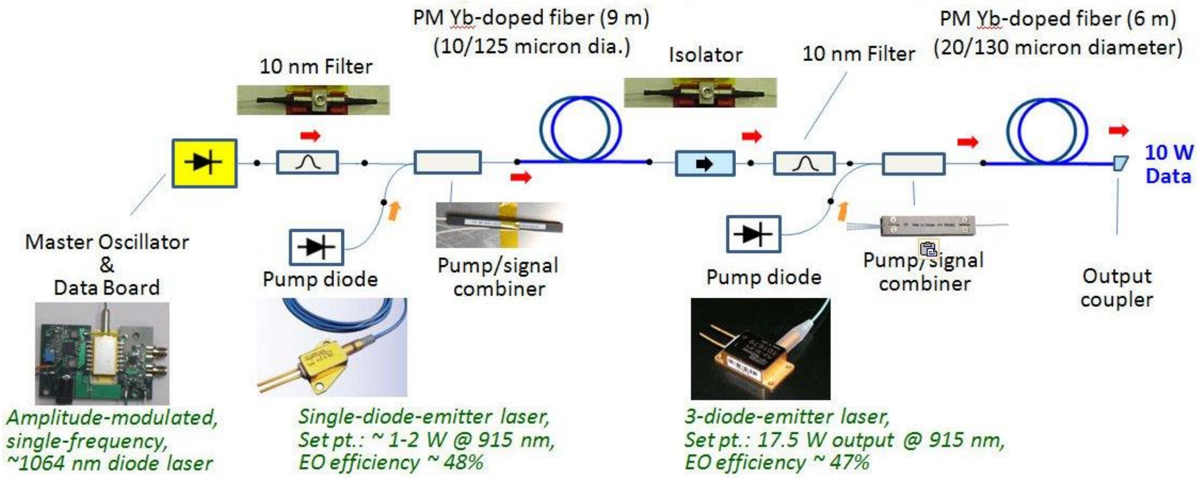

Figure 5. Schematic diagram of the laser transmitter.

Figure 6 shows a photo of two laser transmitters in the clean room awaiting assembly, and Figure 7 shows a photograph of one ~9 x 9 x 2.5 cm laser transmitter during spacecraft fit checks. The star trackers and MEMS gyro shown on the bottom right in Fig. 7 are connected to a different assembly than shown in Fig. 4, but when assembled, reach the relative position shown. This is a dense spacecraft. Laser components are mounted to an anodized aluminum base plate with fiber windings on both sides. Nusil CV-2946 and heat conducting epoxy were used to transfer heat generated in the laser diode pumps and gain fibers, respectively, into the aluminum mounting structure that also serves as a heat sink.[4]

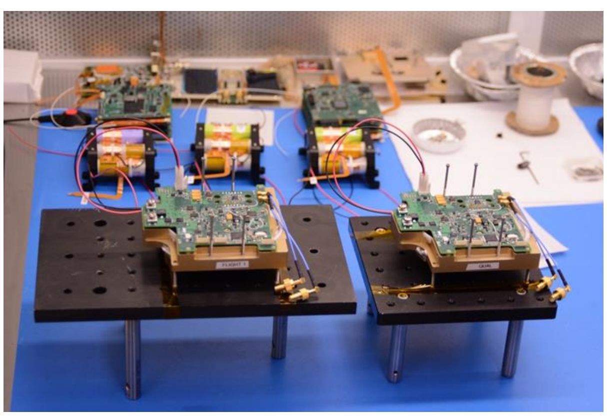

Figure 6. Photograph of two laser transmitters.

A small lens, the output optic placed after the 2nd amplifier stage, was adjusted to yield the desired output divergence. In our case, we used a 0.3º FWHM angular divergence to match the required 0.15º (3σ) spacecraft pointing uncertainty. The laser beam exits to the left in Fig. 7. As configured, our laser is capable of delivering in excess of 10 W of optical output at 1064 nm at a wall plug efficiency of 25%. We de-rated it to 6 W in order to boost reliability for the Pathfinder laser downlink.

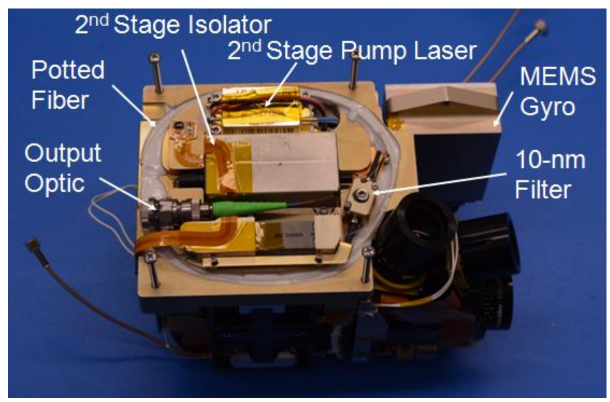

Figure 7. Photograph of the laser transmitter.

The largest component in the laser assembly, other than the aluminum structure/heat sink, is the second stage isolator. Optical isolators use Faraday rotation, and Faraday rotation of plane-polarized electromagnetic waves requires a magnetic field. Unshielded, these fields can add to the magnetic moment of the spacecraft, thus making attitude control harder as the local magnetic field varies over an orbit. Unshielded magnetic fields also disturb the Earth's local field, making on-board magnetometers much less accurate. We therefore encapsulated the optical isolators in mu-metal shields.

The avionics stack and batteries are below the laser shown in Figure 7 (see Fig. 4). The star trackers and MEMS 3-axis gyro are part of the zenith end assembly.

Uplink Beacon Detector

Closed-loop pointing at the optical ground station is accomplished using an uplink laser, bore-sighted with the receive telescope, in the ground station. The uplink receiver, as illustrated in Fig. 4, has a 2.5-cm-diameter port on the nadir face. A 10 nm wide band pass filter passes the 1 to 10 kb/s, on-off keyed, 1550 nm wavelength uplink beacon signal to an 18-mm-diameter lens that focuses incoming light onto a quad photodiode. It can accommodate a 1º off-axis input error which is compatible with attitude control errors when the star trackers are not used. The quad photodiode and associated electronics generate pointing error signals for the on-board attitude control system. The closed-loop pointing system can point within 0.02º; well within our 0.15º required for the Pathfinder.

Uplink data are collected by summing the quad photodiode signals together. When no data are present, the uplink beacon is a square wave with 50% duty cycle. When data are present, the overall duty cycle is still 50%, but the high and low signal periods will constantly vary.

Star Trackers

All three of our OCSD CubeSats (Pathfinder plus two flight units) can operate in either closed-loop or open-loop tracking mode. A star tracker is the only way to obtain the 0.15º or better pointing accuracy we need for the laser downlink using open-loop pointing. In open-loop mode, the ground station becomes simpler because it does not need an uplink laser beacon.

Our star tracker main board, shown in Figure 8, is part of the avionics stack illustrated in Fig. 4. This board is actually an image-processing board that supports star tracker operation using two CMOS monochrome image sensors, and image/video processing of three more color CMOS image sensors. It contains two main processors: a low-power PIC24FJ256 microcontroller and a Spartan-6 LX100 FPGA. The FPGA can also act as a general-purpose camera for both photos and video, storing raw or JPEG-compressed frames to external flash memory. The PIC receives commands from the main flight computer, controls power to other devices on the board, loads the FPGA firmware, and matches the filtered image against a catalog of stars to solve for attitude when required.

When used as a star tracker, the FPGA interfaces with up to five image sensors, captures and timestamps raw image data, and applies the star-tracker image filters. Raw image data is buffered in a 128-MB DDR2 RAM. The FPGA can also act as a general-purpose image processor for both photos and video, storing raw or JPEG-compressed frames to flash memory. Note the silver SD memory card slot in the center of the board, just to left of the Spartan-6 FPGA, for flash memory storage.

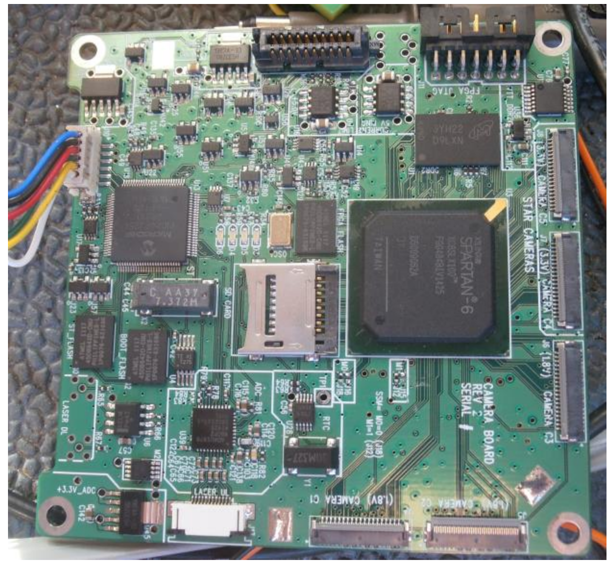

Figure 8. Photograph of our star tracker/ image processing board.

The two star trackers are shown in the CAD rendering in Figure 9 with their light baffles extended. The baffles are deployed using “muscle” wire that allows resetting and hundreds of ground tests using the same hardware; reliability is vastly improved over one-time melt wire approaches. Each camera assembly contains a lens, mounting hardware, and an image sensor daughter card, with multiple designs to serve various mission requirements. Up to five image sensors can be connected to the mainboard using fine-pitch flexible flat cables that provide adequate cable-routing flexibility without the complexity and power consumption of a serializer/deserializer connection.

The star-trackers use Aptina MT9V032 CMOS image sensors (Grayscale, 752×480 pixels). We use two star trackers to provide resilience against image flares due to the sun, Earth, and moon; the one with the darkest background image can be selected at any given time. If both trackers become temporarily blinded, we can use the low-drift rate MEMS gyros that can provide the required ~0.15º attitude determination accuracy for at least 10 minutes. Figure 10 shows a photograph of the camera assembly that includes the two trackers, an Earth imaging camera, and a side-looking camera for proximity operations.

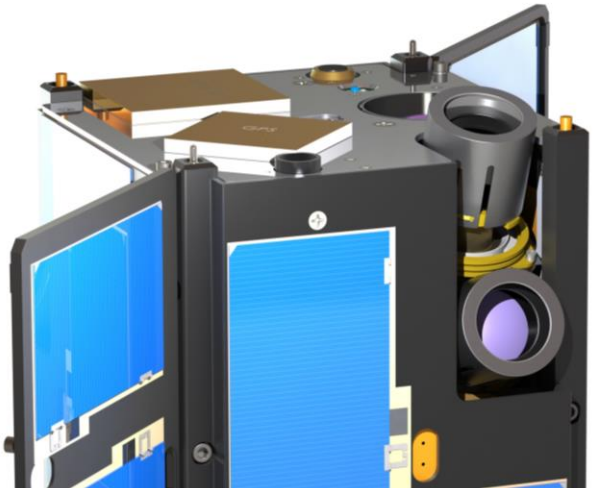

Figure 9. CAD rendering of the zenith-face showing the two star trackers on the right with deployed baffles.

Figure 10. Photograph of the assembled star tracker (left), Earth imaging camera (bottom middle), and side-looking camera (right side) module.

Our star trackers have identified stars down to 5.8th magnitude using a 0.1-s exposure in ground tests. On-board image processing using the FPGA includes "hot" pixel blanking, row-, column-, and global-median filtering, sliding window median filtering, circular mask filtering, and adaptive thresholding.[5] Figure 11 shows the power of these algorithms when applied to a typical, noisy, low-contrast image produced by a CMOS imager. The top image is the raw input image, and the bottom is the output image ready for star centroiding, and star identification. Our star tracker consumes 0.31 W in standby mode, and 0.53 J per "fix." Attitude fixes are obtained once per second with the MEMS gyro providing attitude estimates between attitude fixes.

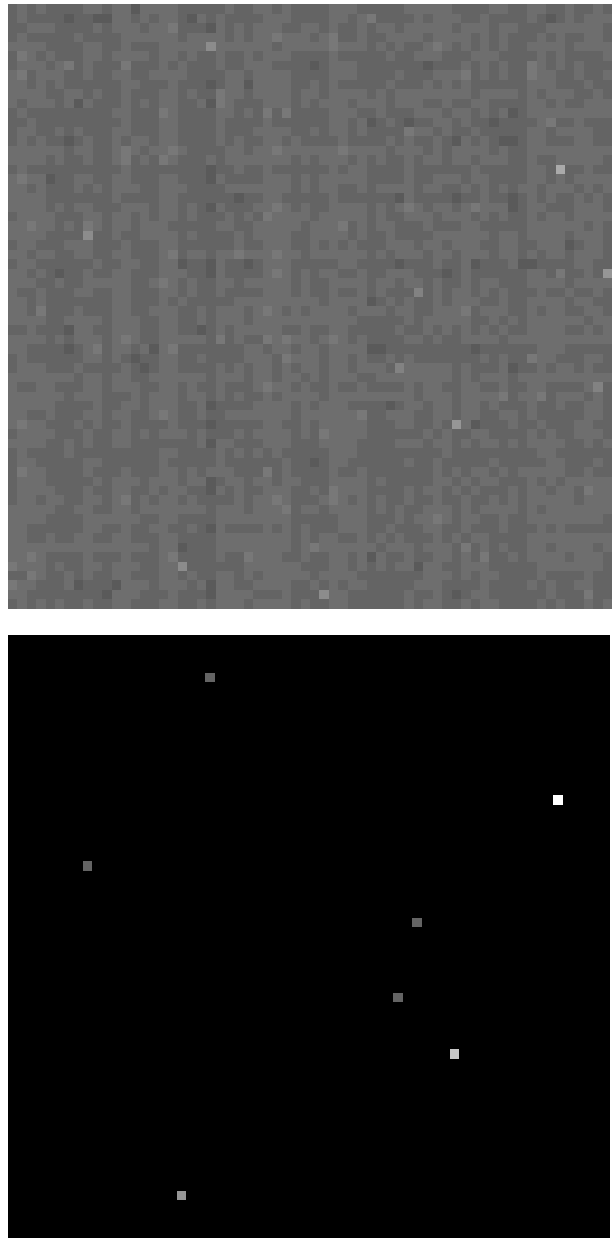

Figure 11. (a) Example input image for our star tracker using dark-sky conditions on Mt. Wilson, CA, and (b) the processed output image.

Another feature integrated into the star tracker processor board is the ability to track stars or other objects of a particular color. This feature will be used to aim a "tracker" OCSD CubeSat at a "target" OCSD CubeSat during proximity operations for the two final flight units. Inter-satellite pointing angles up to 48 hours in advance will be calculated on the ground using downloaded GPS data and high-accuracy ephemerides based on that data. These pointing angles will be uploaded to one or both satellites for crude pointing at each other. On-board color cameras, like the side-pointing camera shown in Figure 10, will take images of the target satellite, which will turn on one or more blue LEDs, and the attitude control system will center that satellite in its field-of-view. One LED is on the nadir face, as shown in Fig. 2, one is on the zenith face, and one is on the face with the rangefinder (top body surface in Fig. 4). These blue LEDs have a 300 mW optical output into roughly one steradian of solid angle, and should be visible out to a range of greater than 10 km using the side-looking color camera.

Once the target is centered within the field-of-view of one of the color cameras, the attitude control system can execute one or more 90º rotations, if needed, to point the laser rangefinder at the target. The laser rangefinder will then be able to determine inter-satellite distance to within 1 meter, out to a range of 2 kilometers. Laser retroreflectors on each spacecraft body surface enable this range using the low-power Jenoptik DLEM SR rangefinder.

THE 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, California, at an altitude of 1750 meters. The Mobile Communications and Atmospheric Measurements (MOCAM) station was completed in 2013 and supports a commercial, off-the-shelf (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 12 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 detector. 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.

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 Federal Aviation Administration (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, open-loop tracking could reduce ground station complexity and cost.

Figure 12. MAFIOT (80 cm. dia.) and MOCAM (30 cm. dia.) optical ground stations at Mt. Wilson.

The optical downlink link budget is given in Table 1 for both ground station apertures for the 6 W laser transmitter on the Pathfinder spacecraft. Link parameters are 900-km range, 1064-nm wavelength, 0.30º FWHM angular beam spread, an angular pointing error of 0.15º, 80% atmospheric transmission, 32% scintillation loss, 50% telescope collection efficiency, and a detector noise equivalent power (NEP) of 5 x 10^{-14} W/$Hz^{1/2}$. MOCAM enables data rates up to 40 Mb/s and MAFIOT enable rates up to 300 Mb/s at this range.

Table 1: Downlink Link Budget

Parameter	MOCAM	MAFIOT
Data Rate	40 Mb/s	300 Mb/s
Photons/pulse onto detector	300	290
Average power on detector	2.3 nW	1.6 nW
Signal/Noise ratio	10 dB	14 dB

PATHFINDER AND FLIGHT UNITS

The goals for the Pathfinder flight are:

1. Test the new attitude control system with dual star trackers and determine spacecraft pointing errors. We need at least 0.15º (3σ) pointing, but expect an order-of-magnitude better.

2. Test the laser downlink using both open- and closed-loop control with data rates up to 40 Mb/s. Anything above 5 Mb/s is a mission success.

The Pathfinder was delivered without a propulsion system since it was not necessary to meet the Pathfinder goals. In addition, the Earth imaging camera and the side-looking camera were disabled; they had last-minute harnessing problems and were left unconnected since they were not required for this first flight.

Our goals for the last two OCSD CubeSats are:

1. Test orbit control using variable drag,
2. Test orbit control using the on-board water vapor thruster,
3. Perform proximity operations,
4. Determine range between the two spacecraft using GPS-derived ephemerides, and/or the laser range-finder, and
5. Test the laser downlink using both open- and closed-loop control with data rates up to 500 Mb/s. This can be accomplished using the 6-W laser downlink with MAFIOT at 700-km or shorter range. For the 2-W downlink, the FWHM angular beam spread has to be reduced to 0.13°, and the attitude control system has to provide 0.065° pointing accuracy. Results from the Pathfinder flight will tell if this is possible.

Meeting goals 1 through 4 with a demonstrated laser downlink data rate in excess of 5 Mb/s would constitute complete OCSD mission success. Goal 5 is two orders-of-magnitude higher than the required 5 Mb/s downlink data rate for mission success. This “super goal” was established internally to set the stage for future laser downlinks with data rates in excess of 1 Gb/s.

SUMMARY

We have built, tested, integrated, and delivered one OCSD CubeSat for launch in late fall, 2015. This Pathfinder spacecraft will be used to test out our star-tracker-enhanced attitude control system and current-generation laser downlink transmitter. OCSD mission success requires a demonstrated optical downlink in excess of 5 Mb/s. We are currently assembling two more CubeSats that will add propulsion and extra imaging capability. Our intent is to get Pathfinder flight data in time to improve the design and/or software for the last two OCSD CubeSats. This “Fly as you Fly” approach is a powerful new tool enabled by the relatively short time, a month or two, between CubeSat launch opportunities.

Acknowledgments

We gratefully acknowledge NASA for providing the funding for this effort, and The Aerospace Corporation for maintaining a world-class CubeSat team and facility.

References

1. Janson, Siegfried W., and Welle, Richard P., “The NASA Optical Communication and Sensor Demonstration Program: An Update,” paper SSC14-VI-1, 28th Annual AIAA/USU Conference on Small Satellites, Logan, Utah, August 2014.
2. Rose, T.S., Janson, S.W., LaLumondiere, S., Werner, N., Hinkley, D.A., Rowen, D.W., Maul, G., Fields, R.A., and Welle, R.P., “LEO to Ground Optical Communications from a Small Satellite Platform,” *Proc. SPIE 9354*, Free Space Laser Communication and Atmospheric Propagation XXVII, 935401, March, 2015.
3. Jenoptik, DLEM-SR Datasheet, Jenoptik Defense and Civil Systems, Jena, Germany, URL: http://www.jenoptik.com/cms/products.nsf/0/645924FE73AE3A1EC125790A0037F7ED/$File/dlem_sr_en_web.pdf?Open , June 2014.
4. Nusil CV-2946 data sheet, Nusil technology LLC, Carpenteria, California, URL: http://nusil.com/products/ProductProfiles/CV-2946/CV-2946P.pdf May, 2014.
5. Rowen, Darren W., Utter, Alexander C., Dolphus, Richard M., and Eddson, Alcid M., “A Miniature, Low-Power, Star Tracker for Precision Pointing Nanosatellites,” paper AAS-15-045, 38th Annual AAS Guidance and Control Conference, Breckenridge, CO, Jan. 30 to Feb. 4, 2015.