Overview of Optical Ground Station 1 of the NASA Space Communications and Navigation Program

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ABSTRACT

Optical Ground Station 1 (OGS1) is the first of a new breed of dedicated ground terminals to support NASA's developing space-based optical communications infrastructure. It is based at NASA's Optical Communications Telescope Laboratory (OCTL) at the Table Mountain Observatory near Wrightwood, CA. The system will serve as the primary ground station for NASA's Laser Communications Relay Demonstration (LCRD) experiment. This paper presents an overview of the OCTL telescope facility, the OGS1 ground-based optical communications systems, and the networking and control infrastructure currently under development. The OGS1 laser safety systems and atmospheric monitoring systems are also briefly described.

Keywords: Optical Communications, Laser Communications, LCRD, Space-Based Relay, Optical Channel

1. INTRODUCTION

The National Aeronautics and Space Administration (NASA) is working on implementing optical communications in its spacecraft. Currently, NASA spacecraft communicate over Radio Frequency (RF) waves.

The far-field angular beam-width of constant-area paraboloidal antennas and mirrors is proportional to the wavelength of the transmitted signal. Hence, the transmitted signal power of an antenna or lens spreads over a solid angle that is proportional to the square of the wavelength, *i.e.,* the signal power that reaches the receiver is proportional to the square of the frequency. The higher the frequency, the more signal power reaches the receiver, for a given transmit aperture size. The receiver noise also increases with frequency. At optical frequencies, the quantum noise, which is proportional to frequency, dominates. At RF, the quantum noise is insignificant: other sources of noise that do not vary strongly with frequency dominate. Hence, to first order, the receiver noise is proportional to frequency. Since the received signal power is proportional to the square of frequency, the receiver Signal-to-Noise Ratio (SNR) is proportional to frequency. The maximum possible rate of error-free communication increases with received SNR. This is the key benefit of optical communications. The highest downlink RF communications frequency that NASA has used to-date is the deep-space Ka-band downlink frequency of 32 GigaHertz (GHz). The typical downlink optical wavelength is 1550 nanometers (nm), which corresponds to a frequency of 193.5 TeraHertz (THz). The optical to RF frequency ratio is, therefore, 193.5 THz/32 GHz, which is about 6000. All other things being equal, a 1550 nm optical communications' system has the potential to have a receiver SNR that is 6000 times higher than that of a Ka-band system.

RF ground antennas have a cost advantage over optical ground telescopes on a receiver area basis. For example, in 2015, a 34 meter diameter Deep Space Network RF antenna is priced out at less than half the cost of a 12-meter optical station [1]. Therefore, most optical ground systems have smaller apertures than their RF counterparts. Nevertheless, there is plenty of the factor of 6000 in SNR advantage left over, even with a smaller optical spacecraft aperture than that of an RF antenna. The bottom line: optical space communications' systems are capable of higher data rates than RF systems, using smaller apertures on both the spacecraft and the ground, and for the same spacecraft size, mass and power, the key spacecraft "consumables." Recognizing this, NASA is investing in adding optical communications to its arsenal.

On September 6, 2013, NASA launched the Lunar Atmosphere Dust and Environment Explorer (LADEE) spacecraft, built by the NASA Ames Center to explore the environment of the moon. One of the payloads on the LADEE spacecraft was the Lunar Laser Communications Demonstration (LLCD), which comprised the Lunar Laser Space Terminal

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(LLST), an optical communications transceiver [2]. The LLCD mission was managed by the NASA Goddard Space Flight Center (GSFC). The LLST and the primary ground terminal, the Lunar Laser Ground Terminal (LLGT), located in White Sands, NM, were developed and built by the Lincoln Laboratory of the Massachusetts Institute of Technology (MIT/LL). The ground segment also comprised two secondary terminals, NASA/JPL's Optical Communications Telescope Laboratory (OCTL), located at the Table Mountain Facility in California, and the European Space Agency's La Teide Observatory in Tenerife, Spain. LLCD was NASA's first high-rate, two-way, space laser communication demonstration. The LLST was powered up for the first time on September 27, 2013, and its first signal from the moon was received by the OCTL ground terminal on October 18, 2013. Over subsequent months, LLCD demonstrated a data return rate of 622 Mb/s from the moon, until April 17, 2014, when NASA culminated the mission with a planned impact of the LADEE spacecraft on the surface of the moon.

LLCD was an excellent pathfinder/demonstration mission that accomplished all its goals. However, it was designed neither to operate long-term, nor to give NASA the necessary operational experience on day-to-day operations of optical communications. The conditions of Earth's atmosphere impact optical communications drastically. Cloud cover, brightness, turbulence, opacity, precipitation: these conditions make all the difference between being able to communicate and not, and determine the maximum supportable data rate. Atmospheric conditions are not deterministic: they can only be predicted to a limited degree and over a short period of time. Hence, the optimal Concept of Operations (ConOps) for an optical communications' network is far from obvious, as it will depend not only on the topology of the network, the Quality of Service (QOS) and data latency requirements, but also on the availability and local conditions of the atmospheric channel. The Laser Communications Relay Demonstration (LCRD) is the next NASA demonstration mission, designed to investigate these issues [3].

The LCRD mission is a Technology Demonstration Mission selected and awarded by the NASA Space Technology Mission Directorate (STMD) (formerly Office of the Chief Technologist) in 2011 to the Goddard Space Flight Center. Partner organizations in this mission include MIT/LL that is transferring technology to GSFC, and JPL that is developing the primary ground terminal, the OGS1, which is based on necessary upgrades to the OCTL. The LCRD mission will launch two flight laser communications terminals to a geostationary orbit in 2019. It also comprises a second ground terminal, to be located in Hawaii. Thus, with two flight and two ground terminals, the LCRD will be able to sustain dual, simultaneous links and relay links. The mission will provide a long-term space-based technology demonstration of optical communication. The LCRD mission will provide at least two years of continuous high data rate optical communications in an operational environment, demonstrating that optical communications can meet NASA's and other agencies' growing need for higher data rates and enabling lower power, lower mass communications' systems on spacecraft. The dual optical link system will also make LCRD the first step in demonstrating optical communications for the Next Generation Tracking and Data Relay Satellite (TDRS) system. The LCRD mission will advance optical communications' technology toward infusion into both deep space and near-Earth operational systems, while enhancing the capabilities of U.S. industry to provide affordable optical communications systems and components.

To provide continuous communications' coverage to multiple Earth orbiting spacecraft, a network of relay satellites in High Earth Orbit, like the TDRS network, is necessary. The TDRS system comprises the space segment of NASA's Space Network. GSFC manages the development and operations of the TDRS satellites. The current TDRS configuration consists of nine geostationary orbit satellites (four first generation, three second generation and two third generation) distributed to provide near continuous information relay service to Low Earth Orbit (LEO) missions like the Hubble Space Telescope (HST) and the International Space Station (ISS) [4]. To meet the increasing communications' demands of future missions, it is envisioned that a TDRS-like network of satellites that are capable of optical communications will be required. In 2014 and 2015, GSFC conducted a study titled "Earth Regimes Network Evolution Study (ERNEST)," commissioned by the Space Communications and Navigation (SCaN) Office of NASA's Human Exploration and Operations Mission Directorate [5]. Amongst other conclusions, one of the recommendations of the ERNEST study was that TDRS-like communications' relay satellites with optical communications' capabilities be part of the future network of relay satellites in Earth orbit called the Space Mobile Network. These future optical communications relay satellites will require a network of optical ground stations to which they will be able to downlink all the data of their space users, over an optical communications' trunk-line.

NASA's existing OCTL telescope is currently undergoing major upgrades, under SCaN funding, to be ready to serve as the main ground station of the LCRD mission, by the time of its planned launch in 2019. However, the upgrades being implemented at OCTL over the next few years will transform it into OGS1, a capable and versatile, general-purpose

optical communications' ground terminal that will play a significant role in fulfilling NASA's future optical communications' needs.

2. OGS1 OVERVIEW

OGS1 facilitates the LCRD objectives of (1) demonstrating a working near-Earth optical communication system, and (2) understanding the limitations imposed by the dynamic atmospheric channel. OGS1 can transmit and receive optical frames to and from the LCRD Payload, using either Pulse Position modulation (PPM) at coded data rates up to 311 Mbps, or Differential Phase Shift Key (DPSK) at rates up to 1.25 Gbps; furthermore, it supports various experimental configurations of the network, and different data services. The data can come from a User's Mission Operations Center (MOC) or be simulated by a ground station subsystem. In support of the second objective, operations will be performed under a wide variety of atmospheric states. Quality-of-signal metrics will be correlated with measurements of the atmosphere along the line of sight, as well as the general state of the air around the ground station, by transmitting various data rates and powers under the different conditions: day/night, clear/cloudy sky or turbulent/quiescent air.

LCRD's mission concept is comprised of relay experiments, single-hop transmissions and loop-back tests. An operational optical communications network is expected to have several space assets sending data to (and receiving commands from) several dedicated Mission Operations Centers via the LCRD relay payload; the traffic would occur at different data rates for the varied Users, and the services may include different data formats. The single-hop cases, in which the data is transferred between the Payload via the Ground Station and on to a MOC, models a direct-to-Earth data flow from an Earth-orbiting instrument or a system outside Earth's orbit; the reverse path, direct-from-Earth communications, can also be demonstrated by LCRD. The loop-back test operation does not model an operational network service; this configuration facilitates correlation of the effects of the optical channel (the paths the uplink and downlink signals take through the atmosphere) with the quality of the link. A ground station sends data to the Payload, which receives the optical frames, demodulates and re-modulates them, and transmits them back to the originating ground station. The ground station will have complete knowledge of the transmitted and received signals, the measurements of the atmosphere and supporting telemetry from the ground station subsystems, facilitating analysis.

OGS1 is based at an existing facility, the Optical Communications Telescope Laboratory (OCTL), with selected upgrades and several novel features: Shack-Hartman wave-front sensor-based adaptive optics (AO), symmetric high-rate downlink and uplink, and multi User/diverse services network. The general structure of the OGS1 system, and its various interfaces, are shown in Figure 1.

Link initiation begins by transmitting a beacon from the ground station to the payload optical subsystem, which allows the payload terminal to point its telescope accurately towards the ground station. The payload then begins to transmit its high-rate optical data to the ground station. The 1-meter-diameter ground telescope collects this light, and using adaptive optics to reduce the atmosphere-induced phase errors across the aperture, couples it into a single-mode optical fiber, which carries the signal to the ground modem. Mere nanowatts (nW) of collected light are sufficient to convert the received modulated optical signal into digital frames, which are then demodulated, and any interleaving and encoding of the User data packets added at the source are reversed. Finally the digital streams are de-multiplexed, and the products of the services are distributed to their separate destinations. In the uplink (or Forward) direction the ground station collects the data units from multiple Users that arrive in any of several formats and rates described below. To make the information robust to atmospheric turbulence losses, the data are encoded and the frames interleaved before being modulated and converted into pulses of light[6]. The optical stream is transmitted continuously at 2.488 Gbps; if no frame is ready to be modulated, an idle frame is injected to maintain a constant physical data rate.
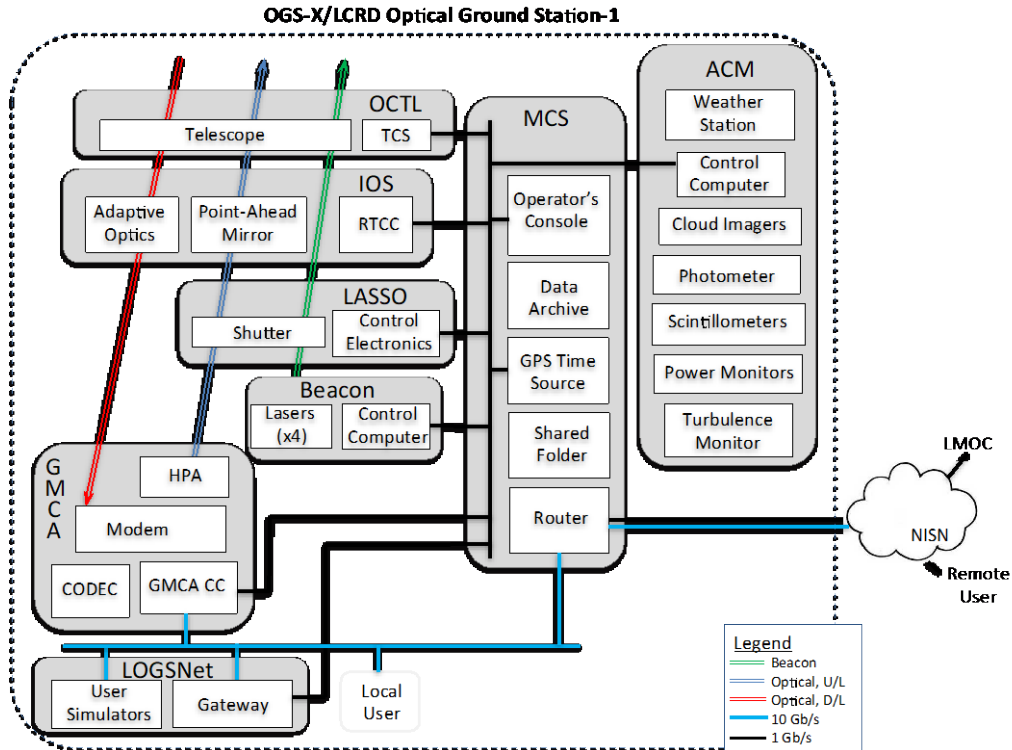
Figure 1. OGS1 Block Diagram.

The Ground Station has two basic external interfaces: optical connections with the LCRD Payload in geo-stationary orbit, and a land-line connection with the LCRD Mission Operations Center (LMOC). In the interface with the Payload, the ground and space terminals exchange up to 1.25 Gbps of user data, as well as in-band commands from the LMOC to the Payload and returning telemetry. This interface also encompasses the aforementioned ground-to-space beacon. Although the rate of transmission of schedules/commands, telemetry, and asynchronous data is less than 20 Mbps, the ingestion and/or distribution of user data totaling several Gbps requires an upgrade of the ground network serving OCTL and the Table Mountain Facility.

OGS1 is one element in the LCRD system. The LMOC generates and distributes unique schedules to each element, so that all elements are properly configured for the coordinated transfer of user data through the system. In order to manage the communications network, the LMOC requires feedback from each element: OGS1 provides its status (telemetry) each second, along with several types of asynchronous data, so that LMOC operators are aware of the state of OGS1 and the data flowing through it.

A typical day of ground station operations will begin with the day's schedule, made up of specific instructions for the ground station, being deposited by the LMOC planners in the OGS1 shared folder. Operators will bring the OGS1 subsystems on line. At scheduled times, the Monitor and Control System (MCS) will command the OGS1 subsystems to execute the planned schedule provided by the LMOC. The MCS will also collect telemetry from the ground station subsystems, archive it and send it on to the LMOC for long-term storage. OGS1 uses its adaptive optics system to maintain the system's fine pointing, and transfer maximum light to the modem. The modems on both the ground and payload side of the link identify synch patterns in the frames to lock the receiver clocks, changing the transmitted header to indicate that temporal and frame synchronization has been completed. At this point the optical link is ready for full duplex transmission of user data. If the link is lost, the acquisition steps are repeated. Whether the optical link is established or not, the MCS will receive new schedules or messages from the LMOC, and to transmit any subsystem telemetry or measurements needed for analysis.

3. OCTL TELESCOPE

The OCTL facility including the 1-m classical Cassegrain telescope has been in operation at the NASA Table Mountain Facility (TMF) since summer 2001. The telescope is designed for precision pointing and tracking (< 2 arcsec rms) of LEO and deep space targets. It has a 1m primary mirror mounted on a fast tracking elevation over azimuth gimbal system with a coudé path that sends the collected light signal into a controlled laboratory area, (Figure 2). An AR-coated fused silica window between final two coudé mirrors prevents exchange of air between the telescope dome and the coudé room, and mitigates any potential chimney effect from degrading the telescope seeing.
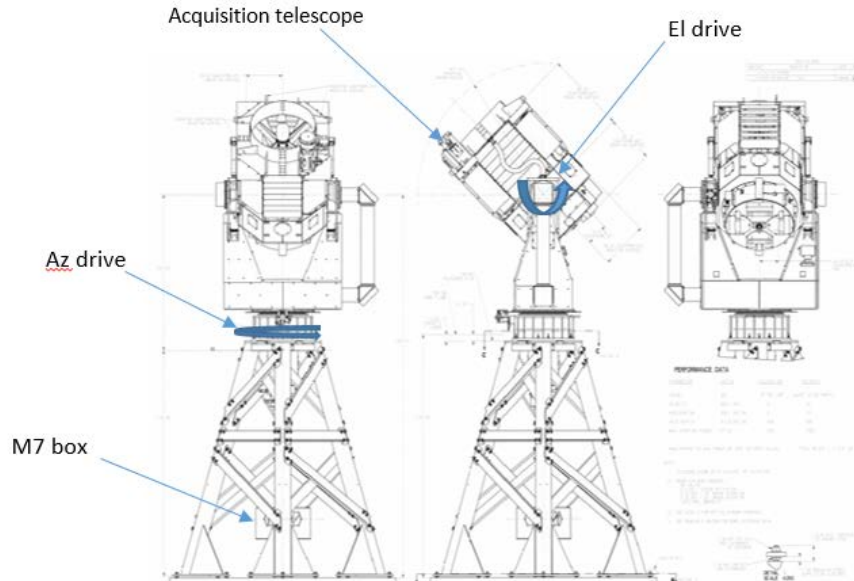

Figure 2. OCTL telescope configuration.

The telescope has a clear view of the sky at all azimuth angles above 0 to 10 degrees of elevation, with the local tree line restricting 0-degree viewing at a few azimuthal angles. The gimbal slew rate is 20 degrees/sec and 10 degrees/sec maximum for azimuth and elevation stages respectively, along with all sky blind pointing error of 17 µrad (1σ). A 20 cm Newtonian finder telescope, co-aligned with the telescope, accommodates auxiliary instrumentation and easily supports acquiring and guiding sources into the main telescope field of view. It provides an unvignetted FOV at its focal plane of 5 mrad. Electrical and fiber optic cables are routed from the telescope and through its service loop to operator control room which can accommodate both day and night operations, with the telescope pointing down to 5 degrees of the sun. The final mirror in the telescope coudé path can point to four different optical benches located inside the coudé room. This allows concurrent development, integration, testing and operations of different optical receive/transmit assemblies.

4. INTEGRATED OPTICAL SYSTEM

The Integrated Optical System (IOS) has three main functions: (1) to relay the uplink beams from the lasers to the telescope with the desired divergence; (2) to provide an acquisition system (separate from the acquisition telescope) so that the telescope can precisely point to the spacecraft; and (3) to efficiently couple the downlink signal into the modem's single mode fiber. To do this, the system must compensate the downlink signal for atmospheric turbulence using an adaptive optics system (AO).

4.1 Hardware design

The transmit system relays four beacon beams from the beacon lasers to the telescope. They form overlapping beams with a divergence of 280 µrad on the sky. This beam width was set to match the spacecraft's location uncertainty. This eliminates the need to scan the sky with the beacon lasers and speeds the acquisition process. The transmit system also

relays the communication beam from the laser amplifier to the telescope with a beam divergence of 20 µrad. The transmit beam is pointed 18 µrad off axis of the optical axis of the telescope to account for the light travel time between the two terminals. The AO system is seeing on-axis light, while the transmitted communication beam is slightly off axis.

The acquisition camera has a field of view of 280 µrad, which is equal to the satellite's location uncertainty projected onto the sky. During the acquisition process, the space terminal will point to the expected location of the ground station and transmit its downlink beam. This will be detected by the acquisition camera and will be used to bring the space terminal's beam to the center of the OGS1 telescope field of view, where it can be detected by the AO system's wavefront sensor (WFS), which can then close the AO loop.

The AO system is a two deformable mirror (DM) design with a Low Order DM (LODM) correcting low spatial frequencies large amplitude aberrations and a High Order DM (HODM) correcting high spatial frequencies small amplitude aberrations. Both DMs have diameters on the order of 1 cm, reducing the size, cost and complexity of the remaining optical train components. The AO system allocates 29 actuators across the diameter of the 1-m OCTL primary to meet the specified atmospheric turbulence correction. A Shack-Hartmann WFS measures atmospheric distortions using 20% of the received power. The speed of the WFS measurement is critical for the AO system to keep up with the rapidly changing atmospheric turbulence conditions at the 20° elevation and nominal 5.2 cm r_0 (referenced at zenith at 500 nm). Our models have shown that we need to have frame rates on the order of 10 kHz to achieve our desired level of performance in the specified atmospheric conditions. The WFS camera is an off the shelf Xenics Cheetah InGaAs camera. Each lenslet in the WFS will illuminate an array of 2×2 detectors on the WFS focal plane array.
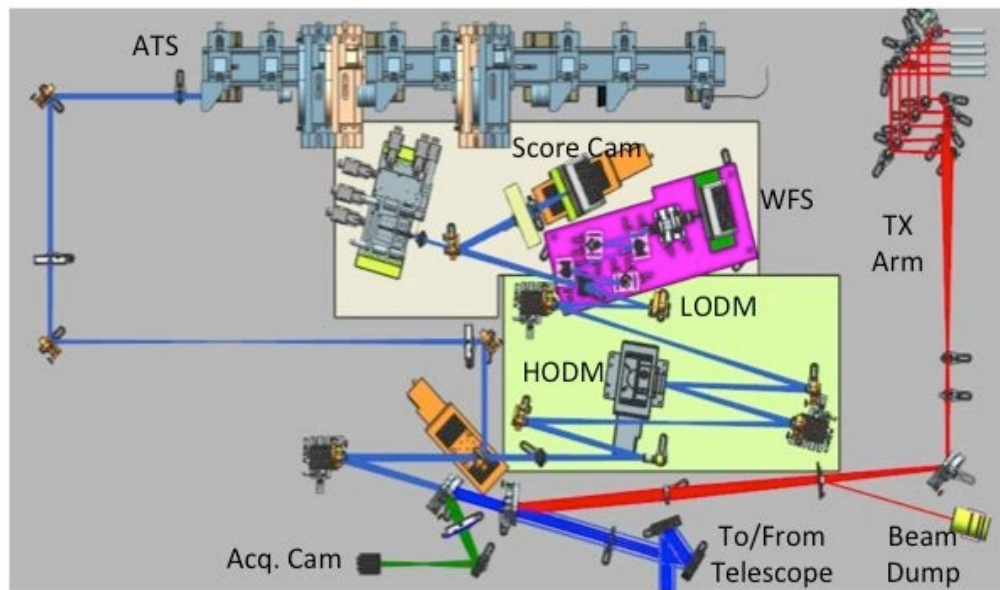

Figure 3. The IOS opto-mechanical layout. The transmit arm is marked in red, the Acquisition arm in green, and the AO arm in blue. The WFS is mounted on the purple breadboard. The remaining components in the AO arm are divided between the tan and green breadboards. The Atmospheric Turbulence Simulator (ATS) is at the top of the layout.

The IOS system will be located on a large optical bench in the coudé room of the OCTL facility. The optical layout in Figure 3 shows the mounting of the optical components on the three separate optical breadboards of the optical bench. The major part of the AO system is mounted on separate breadboards to facilitate moving the system from the development laboratory to the telescope. The WFS mounted on the small breadboard allows the WFS components to be aligned separately. In addition to the WFS pickoff beamsplitter, an additional 10% of the light is diverted from the downlink beam to a scoring camera, which records the point spread function, allowing the measurement of the Strehl ratio, a measurement of the AO system performance during operations. The system also has an atmospheric turbulence simulator (ATS). A mirror can be inserted into the beam path to inject light into the AO system from the ATS. The beam has the same optical properties as the expected downlink from the telescope and forms pupil images at the same locations. The ATS consists of two spinning phase plates with computer controlled rotation rates to simulate a variety of

turbulence conditions [8]. It enables testing of the system in the lab before installation at GS-1 and during set up for operations. The AO system takes up a fairly large optical bench. Long focal length OAPs were used to ease the alignment; for other applications the system could be made much more compact.

4.2 Software design

The IOS software is based on the software for the PALM-3000 AO system designed for the Palomar 5-m telescope [8]. Where functionally possible, existing software components are reused. The system design is divided into four main components: a command/automation server, a device driver server, the real-time control component, and the graphical user interface running on a computer in the operator's room. A publish/subscribe communication method is used to transfer messages between components, a particularly effective method for systems with components running in physically separate locations. Where possible, opto-mechanical hardware was chosen so that existing device driver software could be reused. The real-time component uses a Digital Signal Processor (DSP) board with eight on-board DSP chips. Data is moved directly from the frame grabber to the DSP board via direct memory access (DMA), enabling us to achieve the required frame rates. For the IOS, we have implemented a solid-state device in the IOS control computer capable of capturing all data types at the high log rates required for telemetry analysis.
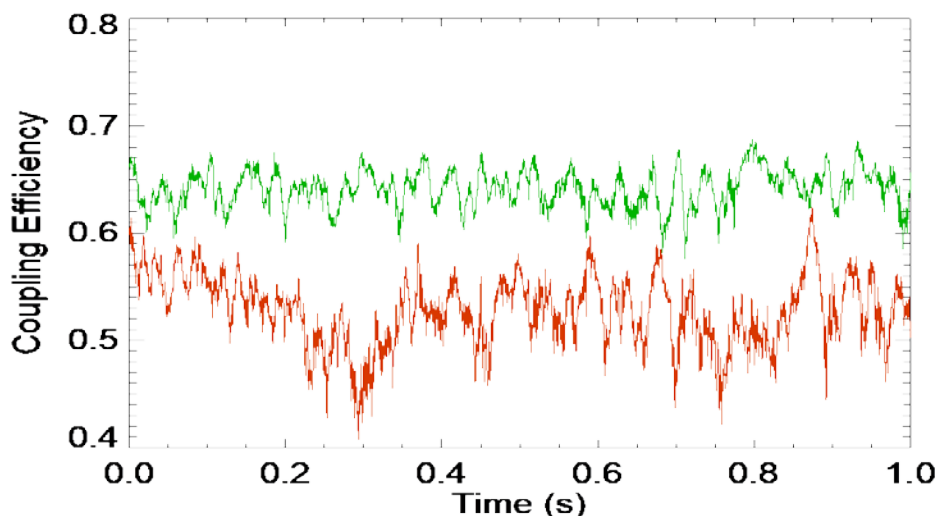

Figure 4. The time series of coupling efficiency. The green curve is the predicted coupling under nominal conditions, while the red curve is for the worst conditions. The nominal conditions have an average value of 0.64 with a standard deviation of 0.0174, while the worst conditions have an average coupling of 0.53 with a standard deviation of 0.0331.

4.3 Simulations

Image quality is the usual metric used to judge AO performance, but for optical communication, what matters is how much light gets coupled into the detector, in our case through a single mode fiber. The metric for that is coupling efficiency and defined as the fraction of the light immediately before the fiber that gets coupled into the fiber. We simulated time series of the coupling efficiency of the system using a wave optics simulation code. Five Kolmogorov turbulence layers were used for the simulations. Long simulation run times are enabled by slowly breaking the frozen flow hypothesis and adding a small component of a new Kolmogorov phase screen at each time step. The simulations were run for two cases. The first case was with the nominal atmospheric conditions for Table Mountain of $r_0 = 5.2$ cm and a ground layer wind speed of 2.3 m/s. The second case was for conditions at the 90th percentile of the cumulative distribution function: $r_0 = 2.7$ cm and a ground layer wind speed of 5.3 m/s. In both cases, the wind profile used was the January San Diego wind profile [9]. This wind profile is the average of decades of twice daily radiosonde launches. It was chosen for the proximity of this launch site to Table Mountain. The wind direction was set to be transverse to the line of sight. The simulation produced 10 runs with a duration of one second each for both conditions at a sampling rate of 10 kHz. The coupling efficiency time series is plotted in Figure 4. The plot includes two consecutive 1 sec runs for the nominal conditions and for the 90th percentile case. At the higher wind speed and lower Fried parameter, the

performance is more variable and produces a lower coupling efficiency. For the nominal case, the coupling efficiency is always above the required 0.55 value, while for the 90th percentile case, the average is just below the required level and sometimes much lower.

5. BEACON LASERS

The purpose of the Beacon Laser subsystem is to provide the uplink acquisition optical reference signal for detection and tracking of the ground station by the wide field of view sensor of the LCRD flight terminal. The acquisition signal is modulated with a specific format to allow the flight terminal to discriminate the beacon waveform from background noise. The LOGS Beacon Laser architecture is based upon the system successfully used at OCTL to support the LLCD project. As such, the Beacon Laser subsystem is comprised of four Master Oscillator Power Amplifier (MOPA) laser transmitters with direct modulation of the amplifier pump diodes, designed for long term operations. The single mode fiber coupled outputs are coupled into the IOS and propagated through the telescope from separate areas of the primary mirror. Besides wavelength, the only difference from the original LLCD beacon lasers is the reduced average output power of 2.5 W per device. The laser parameters are shown in Table 1.

Table 1. Beacon Laser parameters.

Parameter	Value	Comment
Mode	Pulsed	
Wavelength	1550 nm band	
Temp control on wavelength, °C	± 0.1	
Linewidth, nm	< 0.05	
Side Mode Suppression Ratio, dB	> 50	
Average Output Power, W	2.5	10W total, 10–100 % tunability
Modulation, kHz	0.975–1.025	50 % duty cycle
Output power instabilities	< 5 %	
Output beam diameter, mm	3.4	0.64 mrad div. ($1/e^2$)
Beam Quality, M^2	1.0	+0.01, SMF
Modulation Extinction ratio, dB	> 13	20–100% Output
Clock to Average Power Ratio*, dB	$- 2.03$	At full power
Polarization	Unpolarized	

*CAPR $= 10 \log_{10} [0.5(P_{clk}/P_{avg})^2]$

A prototype laser supplied by LeaPhotonics (formerly Manlight) met all the performance requirements outlined above. Another test laser has also demonstrated over 1000 hours of pulsed operation at full power to give confidence in being able to meet the operational lifetime. A selection of test data is shown in Figure 5.
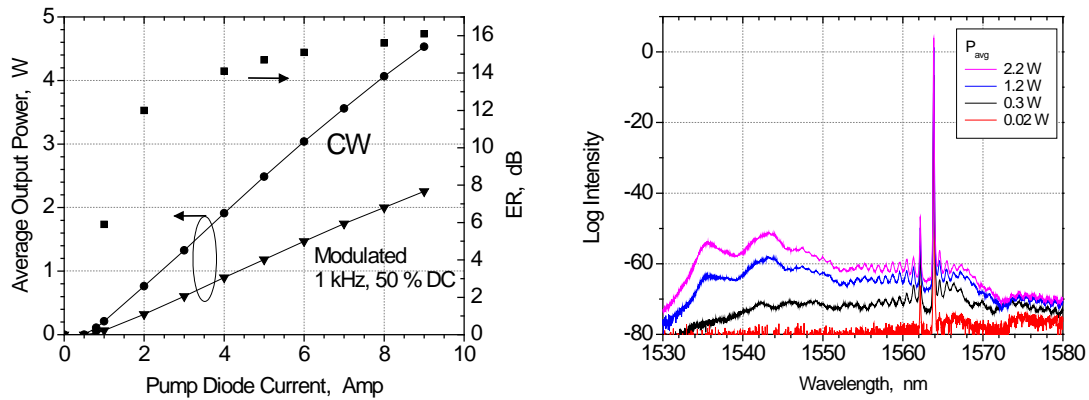
Figure 5. Beacon Laser output power and spectra with seed laser temperature tuning.

6. GMCA

The LCRD Ground Modem Codec and Amplifier (GMCA) serves as the optical communication interface between OGS1 and the LCRD payload. All command/telemetry and user data is transmitted and received through the GMCA. The GMCA structure, and its main interfaces, are shown in 6. As the name suggests, the GMCA is composed of three primary elements: a modem for converting digital information to an optical waveform and back, a codec for applying and decoding forward error correction information, and a high power laser amplifier (HPA) for boosting the transmit power transmitted from the ground to the payload. In addition, a control computer integrated into the codec logic coordinates the components of the GMCA and interfaces with the MCS to exchange data. These components are described in the following subsections.
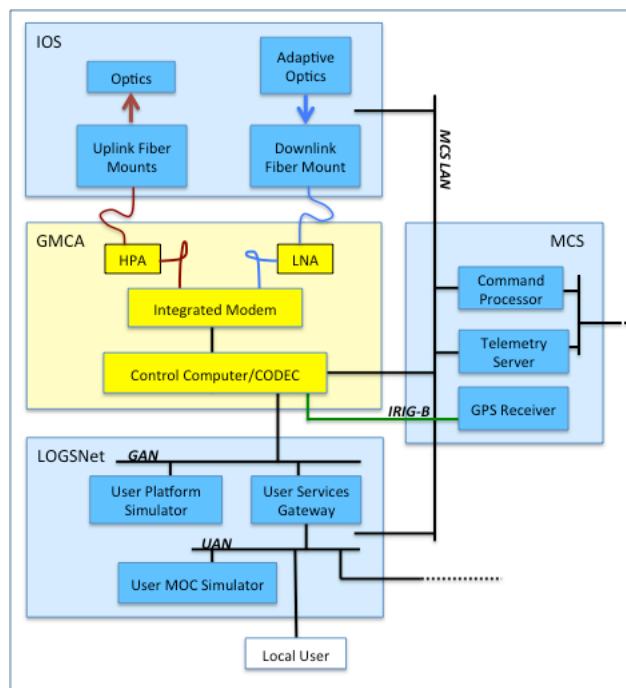

Figure 6. Organization of the GMCA, and major interfaces to external systems.

6.1 Ground modem

The ground modem portion of the GMCA is responsible for modulating digital information from the User MOC Simulator (UMS) onto an optical carrier wave transmitted by the IOS, and demodulating received optical signals into digital information. The modem is being developed at NASA Goddard Space Flight Center based on a design from MIT Lincoln Lab. It will be installed at OGS1 during system Integration and Test (I&T).

User data and command/telemetry information coming from the UMS (via the User Services Gateway) is interleaved and packaged into frames prior to transmission. The interleaving is performed through a convolutional interleaver with 162 branches and a bit-depth parameter between 128 and 96,000 bits, giving an interleaver depth of approximately 1 second. Each frame payload is 64,800 bits in length, of which 32,208 bits are information bits with the remainder from forward error correction. Each frame is prepended with a 1024-bit header containing control channel information (e.g., frame sequence numbers) and quantized channel state information.

There are two modulation formats supported by the modem. The modem supports differential phase shift keying (DPSK), in which a bitstream is encoded using a phase shift of the carrier wave of 180 degrees to indicate a 1, and no phase shift to indicate a zero. DPSK is preferable for its spectral efficiency in near-Earth scenarios, but in deep space applications (operating in the photon-starved regime), the determination of phase shifts is much more challenging. The preferred signaling scheme in the latter case is pulse position modulation (PPM). PPM divides a symbol into M timeslots, and sends a pulse in one of those timeslots to encode a bit sequence of length $\log_2 (M)$. LCRD supports 16-PPM, so each symbol is composed of 16 timeslots, and a single pulse is transmitted in one of those timeslots to convey 4 bits of information.

A wide range of data rates is possible from the modem, ranging from 2 to 2488 Mbps. Since the channel coding scheme is fixed and there are only two modulation formats, the modem changes the data rate by inserting or removing "dead times" between 176-timeslot physical transmission bursts. The nominal (no dead time) transmission rate for DPSK is 2880 Mbps, of which 2488 Mbps is allocated as user data. For DPSK the dead time ranges from 0 to 39 slots, corresponding to a maximum link rate of 2880 Mbps and a minimum link rate of 72 Mbps. For PPM, the dead time is realized as the insertion of between 0 and 3 empty PPM symbols, leading to a link rate of between 240 and 720 Mbps. These rates are further reduced by a factor of two when utilizing forward error correction. Additionally, a symbol repeat method is implemented as a simple approach to increasing data robustness at low decoding complexity. On top of the error correcting code applied by the codec, each symbol can be repeated up to 16 times. The lower end of the data rates are reached when using forward error correction, a dead time of 39, and a repetition factor of 16.

The bandwidth is multiplexed into 6 logical channels, three of which receive forward error correction and three of which bypass the error correction and interleaving. The channels which receive forward error correction can be further classified as Service mode, in which the data is interleaved with other data streams, or Single User mode, in which a single data stream receives the full bandwidth of the transmission.

Once the data from the UMS has been encoded, interleaved, packaged into frames, and modulated to an optical signal, it is sent through an optical fiber to the high power amplifier. The output signal into the high power amplifier and the received payload signal have carrier frequencies in the short-wavelength infrared region.

6.2 Codec/control computer

The codec portion of the GMCA implements a DVB-S2 concatenated-code forward error correction scheme [10]. This concatenated code consists of a rate ½ LDPC inner code taking 32,400 bits as input and producing 64,800 bit length codewords. The outer code is a BCH code with 32,208 information bits encoded to 32,400 bit codewords. The outer code is capable of correcting up to 12 errors, and is intended to clean up the error floor of the LDPC code. This corresponds to a normal length FEC frame from the DVB-S2 standard.

In addition to the channel coding logic, the codec hardware also contains the GMCA Control Computer (CC), which manages the interface between the UMS and the GMCA. The CC connects to the MCS via a 1 Gbps Ethernet LAN, sending the MCS once-per-second telemetry data and performance files to be transferred to the LMOC. Similarly, the MCS sends commands to be executed by the CC that set the modem parameters. Finally, the MCS provides the CC a GPS disciplined timing reference signal via IRIG-B.

6.3 Amplifier

The GMCA amplifier takes the low power (mW range) optical signal output from the modem and amplifies it to between 1 and 10 W average power. The amplifier is a commercial device capable of accommodating a wide range of dead times demanded by the modem output. The counterpart to the HPA is a low noise amplifier, which serves a similar purpose on the receiver end of the modem.

7.   MONITOR AND CONTROL SUBSYSTEM

The Monitor and Control Subsystem (MCS) provides the overall real-time monitoring and control functions for the ground station to coordinate the operations of all the other subsystems within OGS1. It also provides the networking infrastructure for LAN connectivity and inter-process communications among subsystems.

7.1 Approach

The MCS provides the OGS1 operator with control over all ground station subsystems as shown in Figure 7. Specifically, the following capabilities are supported:

1. Configure and control all subsystems
2. Monitor subsystems' health and status
3. Collect, manage, and distribute subsystem telemetry data
4. Support schedule-based experiments to allow for automated or semi-automated operations
5. Provide an operator's graphical user interface (GUI)
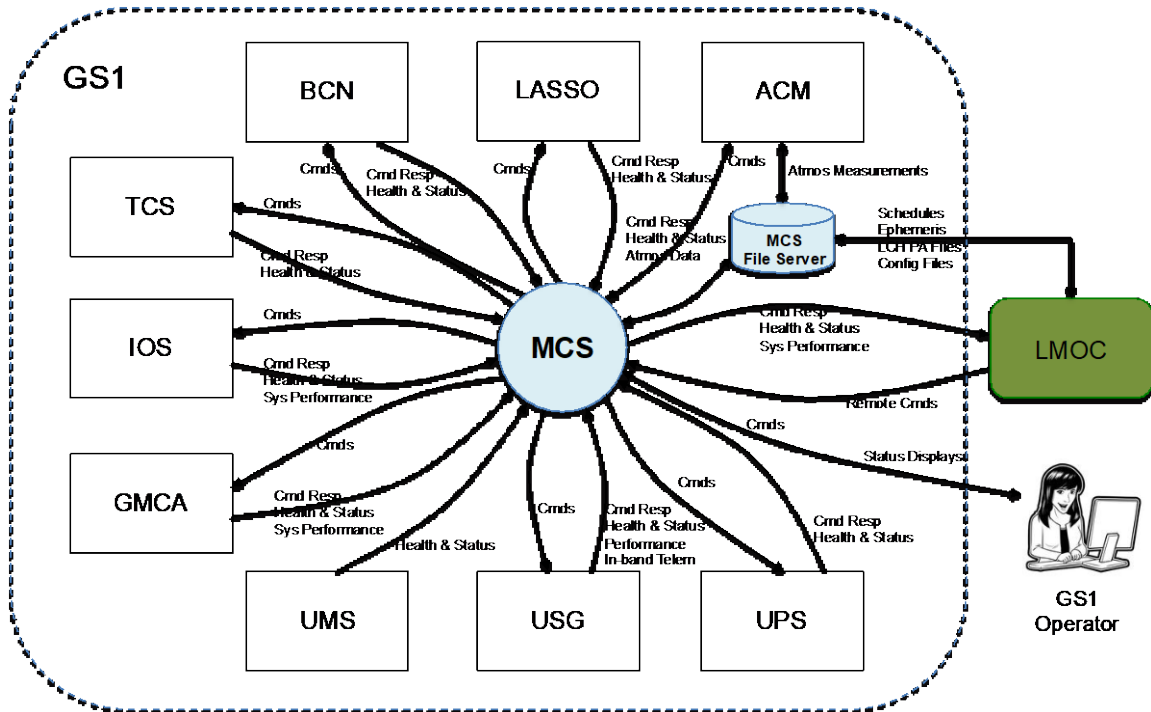6. Provide a time source and network time synchronization service

Figure 7. Monitor and Control Subsystem

The MCS functions as an OGS operator console through which the operator can issue real-time commands to control, configure or monitor each subsystem. In addition to such primitive commands, high-level functional commands are provided to enable automation of subsystem activities and simplify operations for OGS1 personnel. High-level

commands, for example one to configure and establish an optical link, will generate a number of primitive commands that MCS sends to the appropriate subsystems for execution. The LINK_INIT command is one such command and can take the following form:

```
LINK_INIT SPACECRAFT=<sc_id>, UPLINK_MOD=[PPM|DPSK], UPLINK_RATE=<rate>,
                         DOWNLINK_MOD=[PPM|DPSK], DOWNLINK_RATE=<rate>
```

Upon receipt of the LINK_INIT command, MCS will in-turn generate subsystem commands to command the telescope to track, turn on the beacon, and configure the GMCA for uplink and downlink transmissions. It will then enable LASSO to open the laser shutter and, lastly, command IOS to start its acquisition activities. Such coordinated execution is carried out under the purview of MCS with all interim results and completion or failure status being reported to the operator.

In addition to direct operator input, commands can also be generated or issued via a schedule, an ASCII text file consisting of a list of timed activities, where each activity corresponds to one or, possibly, more high-level commands described above. Such "operational schedule" typically is submitted to OGS1 via a file upload to MCS from the LCRD Mission Operations Center (LMOC) prior to its scheduled execution time. It is the primary mechanism for the LMOC to direct the activities of the OGS to carry out its operations in conjunction with the rest of the LCRD network, with the potential for direct real-time commanding relegated to interrupting schedule execution if necessary (e.g., for safety reasons or due to anomalous conditions). This is known as *schedule-based operations*.

During operations, MCS monitors and reports the health and status of all subsystems collected from so-called *health and status messages,* subsystem performance data, and atmospheric monitoring data. These can be sent periodically by the subsystems during nominal conditions or asynchronously when triggered by errors or anomalous conditions. All OGS1 telemetry data is archived locally at the ground station and stored on the MCS networked file server for post-analysis playback or later retrieval by the LMOC during non-operations hours.

7.2 Inter-process communications

Support of the highly distributed control nature of OGS1 requires a flexible, easy to use, and reliable inter-process communications infrastructure. The MCS Network Communications Services provide a set of network and inter-process communications services for inter-subsystem communications within OGS1. These services allow processes to communicate within a single processor, among different processors, or across networks. They provide subsystems with a simple, socket-based networking facility that uses TCP/IP for reliable, full-duplex, connection-oriented communications between processes (servers and clients, or peer-to-peer). They also support a message-based protocol that preserves message boundaries between senders and receivers, allowing for the exchange of variable-length messages.

One of the design goals is to provide an application programming interface (API) for network I/O that looks similar to that for file I/O. This interface, for example, provides services for communicating processes to open a network connection with a peer, read or write information over the established connection, and close the connection.

Communications among all OGS1 subsystems for sending or receiving commands, command responses, health and status data, and telemetry data are fully supported with the following simple set of Network Services APIs:

- net_init ()   -- *Initialize network connection for a server*
- net_accept ()   -- *Accept connection request from a client*
- net_connect () -- *Initiate connection request to a listening server*
- net_send ()   -- *Send message*
- net_recv ()   -- *Receive message*
- net_close ()   -- *Close connections*

The MCS client-server architecture in relation to a representative subset of OGS1 subsystems is depicted in 8.

OGS-1

LASSO

TCS Position

Health & Status Events

Cmds

MCS Telemetry Server

Health & Status Events

Health & Status Events

Events

OGS-1 Operator

Link Status

Cmd Resp

Health & Status

Cmd Resp

IOS

Cmds

Cmd Resp

Cmds

MCS Command Processor

Cmds

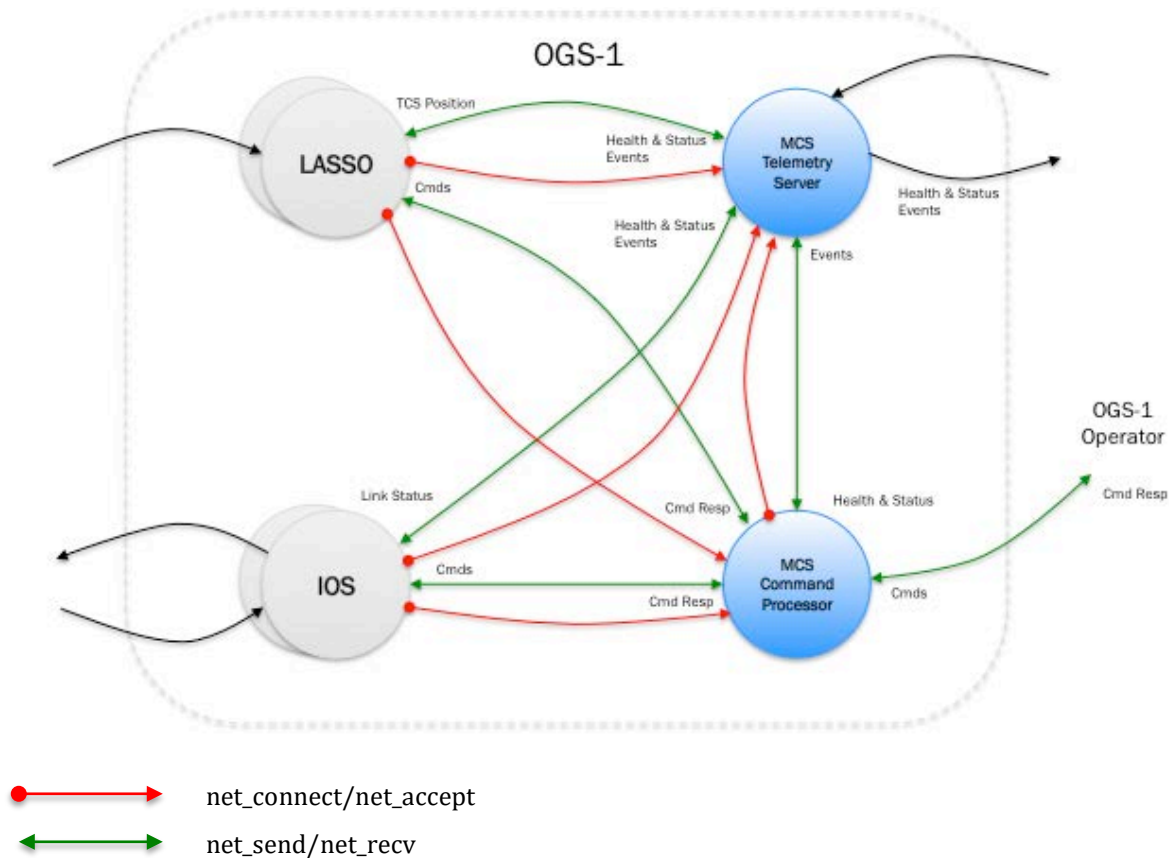● ——→ net_connect/net_accept

——→ net_send/net_recv

Figure 8. MCS Client-Server Architecture.

8. LASER SAFETY SYSTEM AT OCTL (LASSO)

Laser beam propagation within the U.S. to space is regulated by various government agencies. OGS1 must fully comply with the Federal Aviation Administration (FAA) ensuring the safety of aircraft pilots and passengers within navigable airspace, and the Laser Clearinghouse of the U.S. Strategic Command (USSTRATCOM) responsible for protecting sensitive space assets. The LAser Safety System at OCTL (LASSO) was developed to address these agency requirements [11]. It is capable of supporting a multi-tiered outdoor laser safety strategy to protect against inadvertent illumination of low aircraft, high altitude aircraft, and spacecraft. The LASSO system in its default state blocks laser transmission with a safety shutter; it then coordinates the inputs from all three tiers and unblocks the laser only when it is deemed safe for transmission.

The precursor to the LASSO system has been in place at OCTL supporting previous optical communication demonstrations for the past decade. Several system hardware and software components are currently being upgraded for integration into the OGS1 system to support long-term LCRD mission operations. A revision to the FAA policy AC70-1 document is anticipated, and is an important factor in the LASSO upgrade design requirements. This revision is the guideline on maximum permissible exposure (MPE) duration for inadvertent laser illumination, which will be based on the SAE AS6029A guidance of 0.25 second rather than ANSI Z136.1 standard of 10 seconds for near-IR wavelengths. Table 2 shows the difference in nominal ocular hazard distances between the two exposure times for the OGS1 transmission lasers. Under the 0.25 second maximum exposure duration, the hazard is dramatically reduced to within the telescope dome and the risk within the Tiers 1 and 2 regions are minimal. These results led to the decision to de-scope the LASSO aircraft detection equipment and focus on updating the remaining components and adding new safety features to the automated shutter control system. Though it is unclear when the new FAA AC70-1 revision will be

published, the OGS1 team has received formal correspondence from the FAA Airspace Policy Group stating their acknowledgement of the SAE AS6029 as appropriate industry guidance for outdoor laser safety system development.

Table 2. Inadvertent illumination hazard distances for OGS1 transmission lasers based on ANSI Z136.1 and SAE AS6029A maximum permission exposure duration guidance.

		Nominal Ocular Hazard Distance [m]	
Laser	Beam Divergence [µrad]	ANSI Z136.1 MPE: 10 sec	SAE AS6029A MPE: 0.25 sec
Comm	20	4732	0.01
Beacon	283	0.01	0.01

9. LOGSNET

A key objective of the LCRD-OGS1 technology demonstration is to evaluate performance and operations for an optical space communications service provider. This will significantly expand NASA Space Communications and Navigation (SCaN) capabilities, in which optical communications resources will be shared across NASA's space flight missions. Advancement of space communications services to both "direct" users and "space relay" users is envisioned. In the "direct" service architecture the user spacecraft communicates directly with the provider's optical ground station, while in the "space relay" service architecture the user spacecraft communicates with the provider's relay satellite via a "feeder" link and the provider's satellite relays the data over an optical trunkline to the provider's ground station. Currently, these two architectures are represented by the radio frequency- (RF-) based SCaN networks of the Near Earth Network and Deep Space Network (both "direct") and the Space Network ("space relay"). While OGS1 will support experiments for both architectures, we concentrate here on the "space relay" case. (In fact, "in-band communications" with the space relay itself as an endpoint is supported, so that the "direct" case is embedded.) The envisioned space relay will have multiple feeder links in which the multiple user data flows are multiplexed to share the optical trunkline. The space relay may also have onboard capability to translate between the optical trunkline and RF feeder links, although user platforms with optical capabilities are increasingly expected. An example space relay is a Mars orbiter with a trunkline to Earth and feeder links to Mars assets. The space relay architecture is illustrated in Figure 9 below, in which two users simultaneously share the system.
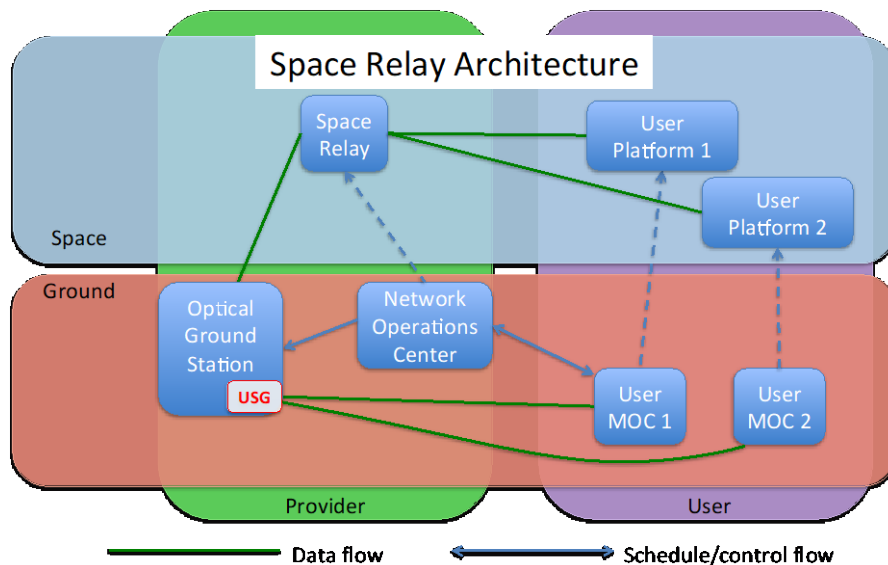
Figure 9. Space Relay Optical Communications Service Provider Architecture.

The LOGS Networking (LOGSNet) subsystem consists of (a) the User Services Gateway (USG) and (b) User Simulators. The LOGS "networking" moniker refers to OGS1 in the context of its operations as a node within the overall LCRD-OGS1 network concept depicted in Figure. The USG is central to the OGS1 capability of providing space/ground communications relay between User Mission Operations Centers (MOCs) and their User Platforms. LOGSNet User Simulators will provide crucial support for LCRD-OGS1 technology experimentation in the absence of actual users, and will evaluate communications performance from a user perspective. Further detail on these component systems follows.

9.1 User services gateway (USG)

The LCRD-OGS1 network architecture prescribes that each User MOC transfers its user data by direct ground connection to OGS1. Specifically, a User MOC connects to the USG for each service instance. The USG relays user data over the optical space link through its internal OGS1 interface to the GMCA. The GMCA handles up to 3 uncoded, plus 3 coded channels for user traffic; signaling among the subsystems ensures data flows are directed according to assigned paths. User data is transferred according to scheduled services. Coordinated schedules are executed for the OGS1 MCS, the User MOC(s), the User Platform(s), and the space relay. The USG is controlled by the MCS, which informs the USG of service start or termination and associated service parameters. A service will proceed according to synchronous execution of the User MOC, MCS, User Platform and space relay schedules, and the USG forms the ground connection with the User MOC enabling user data to flow between space and ground user elements.

The USG performs protocol translation and formatting between space and ground communications. Multiple service types are offered, allowing a broad set of choices to the user. All service types are offered as either "forward" (User MOC to User Platform) or "return" (User Platform to User MOC). At the most primitive level, "Symbolstream" service transfers unstructured user data without channel coding. "Bitstream" service is also unformatted but forward error correction coding with interleaving is provided by the GMCA. These data are "unstructured" in the sense that the provider USG is unaware of any embedded structure in the data stream, although it may exist at the user level.

The next higher layer of service available is the transfer of CCSDS standard Advanced Orbiting System (AOS) data link frames [12]. For return AOS service, the USG tracks the frame sequence numbering to determine whether frames are lost. AOS data transfers between the USG and the User MOC use CCSDS Space Link Extension (SLE) services [13]. The framing protocol used on the OGS1-Relay Satellite link is designed for optical communications efficiency and is not standardized, so the AOS frames are embedded within the optical link frames. This design enables the User MOC to operate using standard, available space communications equipment. A relay satellite with greater capability than LCRD might extract AOS frames for direct radiation onto an RF feeder link to the User Platform, and perform the reverse process for the return direction.

AOS services allow the user to combine and separate multiple streams of data using AOS Virtual Channels (VCs). For example, different instruments onboard the User Platform may be associated with their own VCs. AOS frames are also distinguished by "spacecraft ID" (SCID). The USG is capable of multiplexing AOS service instances associated with different users (having different SCIDs) to share the same optical channel (one of the three encoded paths through the GMCA). For example, referring to Figure, the two User MOCs may transfer forward data over a single optical channel, and the space relay demultiplexes the AOS streams onto the appropriate feeder links. The ability to perform experiments advancing high-speed trunkline sharing strategies is an important OGS1-LCRD mission goal.

The highest layer service offered by the USG is Internet Protocol (IP) service. This is based on the "IP over CCSDS" standard [14]. Variable-length IP packets are embedded in CCSDS Encapsulation Packets [15] that in turn are contained within AOS frames. Multiple IP service instances may be combined on a single optical link channel using AOS multiplexing. The IP service capability lays the foundation for future Disruption Tolerant Networking (DTN) [16] service, which is particularly promising for application to optical links subject to weather outages.

9.2 User simulators

OGS1 will contain a User MOC Simulator (UMS) and a User Platform Simulator (UPS). Both simulators are capable of generating and consuming traffic for any of the service types. They are capable of simulating multiple simultaneous services, as well as multiple users. Each executes its own schedule separately from the MCS schedule execution, thereby enabling accurate representation of scheduled operations of infrastructure-provided optical services to missions. The UMS interacts with the USG using the same connection protocols as would an actual User MOC. The UPS interfaces with the GMCA so that OGS1 mimics a User Platform. Full exercise of data flows may occur using loopback by the space relay and appropriate partitioning of the bidirectional optical link bandwidth.

The User Simulators are designed to evaluate end-to-end performance through the OGS1-LCRD system, including latency and error/erasure performance not obtainable by the USG. In addition, for each service, the traffic source is driven by an experimenter-defined Traffic Profile establishing the piecewise-linear time-dependent offered data rate. This allows performance characterization when the offered rate varies at less than the scheduled service allocated bandwidth, or when gaps in the offered traffic occur, tests proper USG throttling if higher-than-allocated rates are attempted, and permits verification that one user's behavior does not impact another simultaneous user's performance.

10. ATMOSPHERIC CHANNEL MONITORING (ACM)

A primary goal of the LCRD experiment is to augment the practical knowledge of the effects of the atmospheric optical communication channel on a space-to-ground optical (relay) link. The atmospheric optical channel can affect performance of the optical link budget in a number of ways including: (1) cloud opacity that can block or reduce the strength of the optical signal; (2) optical turbulence and wind speed that reduce the coupling of the transmitted signal to the detector; (3) atmospheric propagation loss that reduces the signal strength; and (4) background irradiance, which adds noise to the reception of the transmitted data

To monitor the atmospheric channel for study and correlation with link performance, a number of instruments will be deployed at the OGS1. The ACM will monitor general atmospheric weather conditions at the site, the Fried parameter (r_0) along the line of sight to the spacecraft when the optical communication link is closed, the amount and opacity of cloud coverage, and the downlink communication signal strength.

During the link, r_o will be measured using two different approaches by the IOS subsystem: the IOS' large field of view acquisition camera (Sec. 4.0) will determine atmospheric coherence length based on the measurement of the spread point function at the baseline rate of 1 Hz [17]; at the same time, an independent measurement will be made using slope discrepancy observed at the AO wavefront sensor [18]. The Fried parameter will be extracted at higher rate (than 1 Hz) to properly follow in time the evolution of the optical turbulence.

Cloud coverage will be monitored with long wave infrared range (LWIR) cameras, allowing continuous monitoring (day/night) of the sky. Using carefully-thresholded sky temperature and radiance, it is possible to derive the sky opacity or atmospheric loss due to clouds) [19]. To thoroughly characterize the cloud coverage for the LCRD experiment, two different cloud imagers are used: a narrow field of view system (NFOV) with 20° diagonal field of view that is pointing directly toward the GEO satellite (which monitors the link line of sight) and a wide field of view (WFOV) camera with

110° diagonal field of view pointed to zenith to monitor the total cloud coverage above the optical ground station. Figure 10 describes cloud maps measured by this dual system during a temporary deployment at the JPL in 2015.
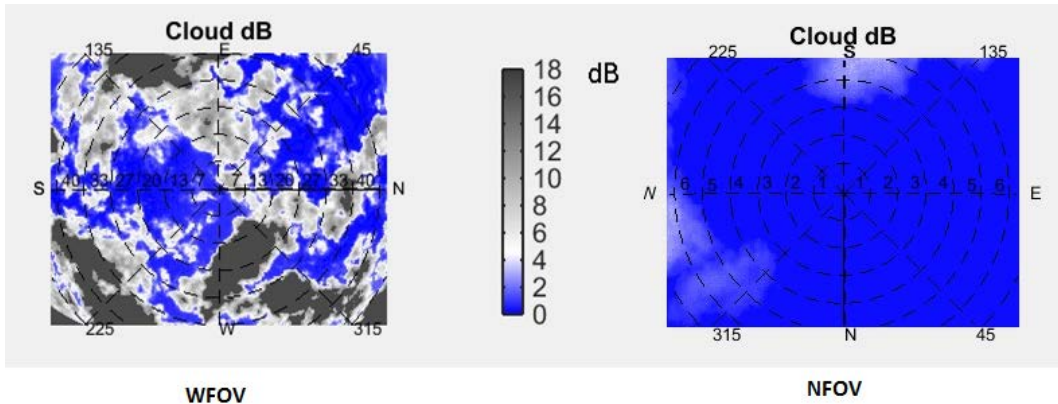

Figure 10. Cloud maps generated by LWIR based cloud imagers during testing at JPL November 9 2015. Left image: Wide Field of View cloud camera shows a spatially rich coverage with clear sky and clouds. Right Image: Narrow Field of View cloud camera showing clear sky at the center of the image. Images are processed in real time and the dB attenuation maps are visualized by a dedicated GUI.

Finally, the downlink signal strength and the sky radiance at the wavelength of operation are monitored using a co-aligned finder telescope of 20cm aperture. This additional sensor monitors the signal at high temporal resolution in order to characterize average signal, signal loss, and fading due to optical turbulence.

All the data regarding the atmospheric optical channel are collected in real time and transferred to the MCS sub-system of OSG1 for storage, and used for correlation with optical link performance.

11. SUMMARY

The conversion of an existing telescope asset, designed for optical communications and precise, all-sky pointing, allows the development team to focus on the research aspects of designing a high-bandwidth optical communications ground station. It also substantially reduces the cost and schedule associated with that development. The selection of a modern, well-designed and frequently-used telescope like the OCTL further reduces the development risk associated with such a complicated endeavor.

While almost all of the sub-systems described in this paper are fairly commonplace from a technology viewpoint, their combination and mutual operation is far from common. To our knowledge, this is the first system that will integrate a large set of various networking services on an optical channel to a space-based asset. It is also one of only a few space-to-ground optical communication systems utilizing an AO system to couple an optical signal from space into a single-mode-fiber-coupled detector, limiting the daytime background light scattered into the system from only a small portion of the sky. Finally, a long operation schedule over multiple conditions, correlated with a wide set of atmospheric and seeing measurements will help to understand the optical channel, its capabilities and limitations.

The OGS1 development effort is progressing toward deployment in support of a mid-2019 launch of the LCRD geo-stationary payload. The OGS1 schedule supports the development of the individual sub-systems outlined above through 2017, with integration and test of the system occurring in 2018. Late 2018 and early 2019 will see the testing of the system with Ground Readiness Tests and Mission Readiness Tests. We anticipate OGS1 will operate for at least two years in support of its mission, with a likely extension to at least five years. We anticipate that this development will mark a major milestone in the development of ground-based infrastructure in support of future NASA space communication efforts.

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