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Recent Developments in Adaptive Optics for the LCRD Optical Ground Station at Table Mountain

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Abstract—The NASA Laser Communications Relay Demonstration project plans to launch an optical payload onboard a satellite destined for a geostationary slot between 60 degrees and 161degrees West latitude. The payload consists of two optical heads with control electronics that relay data between two ground terminals. Current plans call for demonstrating the relay link between ground terminals in Hawaii and the JPL Table Mountain Optical Communications Telescope Laboratory (OCTL) in California. The data formats for the links are pulse position modulation (PPM) and differential phase shift keying (DPSK) at maximum data rates of 311 Mbps and 1.24Gbps DPSK, respectively. The coherent DPSK optical links require implementing Adaptive Optics (AO) to correct wave front aberrations, and enable efficient coupling of the downlink signal into the single-mode receiver fiber. The AO system at OCTL is required to provide wave front correction at 20 degrees elevation, with corresponding Fried coherence parameters of 5.2cm measured at zenith and 500 nm wavelength.

Keywords—Optical communications, Adaptive Optics, OCTL, DPSK, PPM

I. Introduction

The Laser Communications Relay Demonstration (LCRD) project plans to launch an optical communications payload on a commercial satellite positioned in a geostationary slot. The payload consists of a pair of optical heads, control electronics and switching unit, see figure 1, and will support the relay of data between the 1-m optical ground station at Table Mountain CA (GS-1) and a second 40-cm optical ground station, GS-2.[1] One of the key objectives of the project is to evaluate the performance of deep space, PPM (pulse position modulation) and near-Earth, DPSK (differential phase shift keying) optical waveforms as they propagate through the atmosphere. The coherent DPSK links are coupled into a fiber Mach-Zehnder interferometer with a one-bit delay optical path length difference and on to a pair of balanced detectors. While fiber coupling is not required for the 311 Mb/s PPM signaling, it facilitates the design of an integrated modem that can support both waveforms.[2] The GS-1 link is required to operate as low as 5 degrees solar angle, 20-degrees elevation, r_o=5.2-cm, and wind speeds of 2.3-m/s. Coupling the downlink signal into the fiber interferometer under these atmospheric conditions requires adaptive optics (AO) strategies to correct wave front aberrations caused by atmospheric turbulence.

AO techniques to compensate for turbulence-induced aberrations in the wave front were first developed by the US Air Force.[3] It has since been embraced and advanced by the astronomical community with the focus on improving quality and contrast of images such as planets orbiting distant stars.[4] AO's application to ground-to-space optical communications was explored in CEMERLL, an experiment that propagated an atmosphere-compensated optical uplink to the Apollo 15 lunar retro-reflectors to demonstrate scintillation mitigation on the uplink beam.[5] On the downlink, AO supports high data rate links and enables narrowing the ground receiver's field-of-view to enhance the SNR of daytime links and the expansion of the link availability around times of solar conjunction. [6]

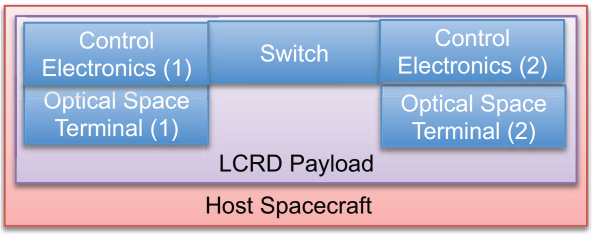

Figure 1. LCRD payload to be on commercial communications satellite

The SWaP (Size Weight and Power), advantages of space-to-ground optical links over RF are well documented, and the low probability of intercept and low probability of detection benefits of the technology recognized. Yet, while the promise of "unlimited" bandwidth of optical links can be readily realized in terrestrial fiber communications, atmospheric turbulence limits the achievable bandwidth in space-to-ground links. By preventing diffraction limited performance, i.e., limiting the focused spot size to the "atmosphere seeing" disk, wave front aberration of the downlink beam prevents realizing the gain of large-area ground telescopes.[7] Realizing 100's Mb/s to 10's Gb/s space-to-ground optical links requires implementation of AO strategies.

The two key optical elements of the adaptive optics system are the wave front sensor and the wave front corrector. Among the sensors considered for the GS-1 are: Shack-Hartmann wave front sensor (S-H WFS) the self-referencing interferometer (SRI), the Zernike WFS, and the curvature WFS. For LCRD the amount of light required for the SRI exceeded the link budget allocation for the WFS, as such it was eliminated from consideration. The deformable mirror sets the sizes of the AO optical train components, and the Boston Micromachines MEMS (micro-electromechanical systems) was selected as the wave front corrector primarily because of its small size.[8] A gradient descent multi-dither adaptive optics (MDAO) approach that does not require a wave front sensor was also considered.[9] The advantage of MDAO was that no light is lost to a wave front sensor arm. Two disadvantages of MDAO were (i) the convergence to a solution becomes intractable as the number of degrees of freedom is increased (i.e., for telescopes with many coherence cells in the aperture, or under conditions of severe turbulence), and (ii) the finite possibility that the servo loop would close around a local minimum rather than a maximum.[10, 11] Results of a trade study that evaluated both the S-H WFS and the MDAO approaches led to the selection of the SH-WFS approach.

In this paper we discuss the LOGS (LCRD Optical Ground Station) Integrated Optical System with an emphasis on the GS-1 adaptive optics receiver system. In Section 2 we discuss the GS-1 Integrated Optical System optical train. In Section 3 we describe the LOGS adaptive optics system its components and its variation on the PALM-3000 System. In Section 4 we present the expected performance of the AO system and the expected coupling efficiency into the receiver fiber under nominal atmospheric conditions. Section 5 is the conclusion and Section 6 the acknowledgements. References are given in Section 7.

II. THE LOGS INTEGRATED OPTICAL SYSTEM

The Integrated Optical System (IOS) consists of three major subsystems: the transmit system, the acquisition system and the adaptive optics system. These systems couple into the 1-m GS-1 telescope and are designed to provide the requisite power flux density at the space terminal and to correct for atmospheric turbulence effects on the downlink.

A. Transmit System

The transmit system relays the uplink communication beam and beacon beams to the telescope. There are four beacon lasers and a single communication laser. Each laser is delivered to the IOS via single mode fiber. The $1/e^2$ full width divergence of the beacon lasers is 280 μrad. The four lasers overlap in the far field and mitigate scintillation effects on the uplink beam. The wide beam divergence avoids the need to implement a point ahead or a search pattern during the acquisition. The $1/e^2$ full width divergence of the communication laser is 20 μrad. A point-ahead mirror in the communications beam optical path allows this narrow uplink beam to lead the received downlink signal by approximately 18 μrad. The uplink beams are transmitted through sub-apertures in the 1-m telescope, but are not tip/tilt compensated. Because the tip/tilt, α, is proportional to the aperture as $D^{-1/6}$, the tip/tilt measured on the downlink through the 1-m aperture will therefore be significantly less than that required to correct tip/tilt on the 10.8-cm $1/e^2$ uplink beam.

To comply with safe laser beam transmission requirements, such as when the US Strategic Command precludes uplink transmission, a safety shutter is incorporated in the transmitter optical train. The shutter is a reflective design that directs the beam, to a water-cooled beam dump. This approach prevents degradation of the lifetime resulting from the continued turning on and off of the laser to meet the safety requirements.

B. Acquisition System

The IOS has the responsibility for the initial acquisition of the target. This is accomplished with an acquisition camera before the AO system. The camera is a Xenics XS InGaAs camera with 320x256 pixels and a 60 Hz frame rate. It is sensitive from 1-1.7μm and will be used to acquire the downlink. A beam-splitter reflects 1% of the light of the downlink beam into the acquisition system. A lens reimages the beam onto the 280μrad field of view of the acquisition camera. The camera's field-of-view is set to be larger than the maximum uncertainty in the satellite location. This dramatically speeds up acquisition by allowing acquisition to be done in a single telescope pointing without having to resort to scanning.

III. LOGS ADAPTIVE OPTICS SYSTEM

The LOGS AO system is the heart of the IOS and is based on the PALM-3000 AO system installed on the 5-m Hale telescope at Palomar Observatory.[12] The two LOGS deformable mirrors (DM) correct the high amplitude, low spatial frequency aberrations, and the low amplitude, high spatial frequency aberrations, separately. The small -less than 1-cm diameter- LOGS MEMS DMs reduce the size, cost and complexity of the remaining optical train components.[13] To comply with the required Technology Readiness Level (TRL-6) of the Technology Demonstration Missions program, the IOS AO system reuses the PALM-3000 software architecture; this also reduces cost and risk.

While the PALM-3000 system is optimized for high-contrast astronomical imaging in nighttime conditions, the IOS is optimized for high performance in the near-IR for both daytime and nighttime operation. The IOS WFS measures the distortion of the 1.55-μm downlink wave front that is induced by atmospheric turbulence. 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 5.2-cm r_0. Our models have shown that we need to have a frame rates on the order of 20 kHz to achieve our desired level of performance in the specified atmospheric conditions. The selected Xenics Cheetah InGaAs camera for the wave front sensor is the fastest frame-rate InGaAs camera on the market today. The IOS requires 29 actuators across the

1-m OCTL primary to meet the specified atmospheric turbulence correction. Each lenslet in the WFS will illuminate an array of 2×2 quad cells.

A. Opto-Mechanical Design

The IOS will be located on a large optical bench in the coudé room of the OCTL facility that can support the simultaneous set up of multiple experiments. A four position rotational mirror flat (M7) allows coudé room experiments access to the telescope. The design calls for enclosing the IOS and the optical beam path to the M7 to mitigate the effects of coudé room turbulence. The enclosure will also isolate the IOS transmitter and receiver arms and minimize stray light entering the IOS receiver arm.

The downlink from the satellite exits the M7 telescope mirror and is folded onto the optical bench through a periscope. It is then collimated and forms pupils on each of three subsequent active mirrors. These are the fast steering mirror that compensates for the bulk tip/tilt motion of the atmosphere, the high-order deformable mirror that corrects for the high spatial frequency aberrations and the low-order deformable mirror that corrects for the lower order spatial frequencies as well as residual tip/tilt error.

The optical layout in Figure 2 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 the green and tan colored breadboards. This separation of components facilitates maneuvering the IOS around the other equipment in the laboratory. The WFS mounted on the small purple breadboard allows the WFS components to be aligned separately. The system also contains a scoring camera, which images the compensated beam. A portion of the light ~10% is sent to the scoring camera to measure the image quality of the post-AO corrected beam. This provides an independent measurement of the AO system performance.

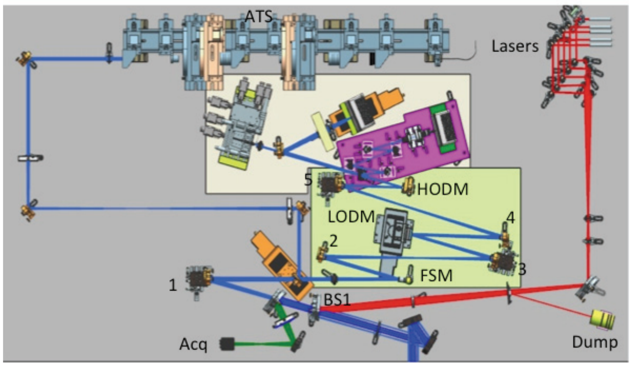

Figure 2: The IOS opto-mechanical layout. The Transmit arm is marked in red the Acquisition arm in green and the AO arm in blue. The WFS is mounted on the purple breadboard. The remaining components in the AO arm are divided between the tan and green breadboards. The Atmospheric Turbulence Simulator is at the top of the layout.

In the following description, we describe the light path from the telescope through the IOS components. First the beam is incident on the dichroic mirror BS1, which transmits the downlink beam, but reflects the injected uplink beam back towards the telescope. After BS1, the downlink beam is incident on OAP(1) and forms a pupil image on the fast steering mirror (FSM). After reflecting from the FSM the beam reflects off OAP(2), and OAP(3) to form a second pupil image on the low-order deformable mirror (LODM). The beam is then reflected from OAP(4) and OAP(5) to form a third pupil image on the high-order deformable mirror (HODM). A pair of narrow band spectral filters after OAP(5) block any backscattered light from the uplink beam from entering the downstream sensors. These filters provide 180 dB of suppression for the uplink beam wavelength[14]. The received downlink is 100 dB less than the uplink, and the large out of band rejection of the filters ensures good SNR at the AO sensors. A beam splitter reflects 20% of the light in the receiver arm to the WFS. An additional 10% is picked off for the scoring camera; a six-axis positioner holds the receiver fiber. This positioner will be adjusted to compensate for slow thermal or mechanical drifts.

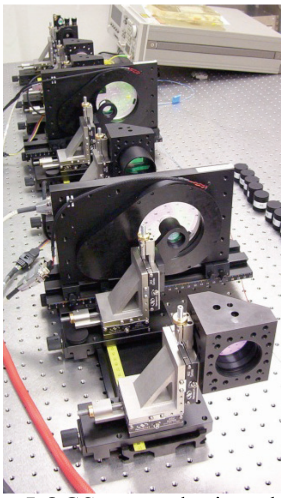

Figure 3. The LOGS atmospheric turbulence simulator built into the IOS optical train allows the simulation of a variety of atmospheric conditions.

Between OAP1 and the FSM mirror, there is a mirror on a translation stage that can be inserted into the beam. When inserted into the beam, it injects light into the receiver optical train from one of three sources (670-nm, 1550-nm, white light) from the atmospheric turbulence simulator (ATS) shown in Figure 3. The beam has the same optical properties as the 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. [15] It enables testing of the system in the lab before installation at GS-1 and during set up for operations.

B. *Software Design*

The IOS software is based on the PALM-3000 software design[16,17]. Where functionally possible, existing PALM-3000 software will be reused for the IOS system. PALM-3000 is a component-based architecture, implementing a structured event-driven execution model and split-phase operations. The system design is divided into four main components: a command/automation server running on the database computer, a device driver server running on a computer located near the instrument hardware, the real-time control component running on graphics cards located on nine computers in a thermally controlled room, and the graphical user interface running on a computer in the operators room. The publish/subscribe communication method coupled with proxy software components are used to transfer messages between components, a particularly effective method for systems with components running in physically separate locations.

The IOS will reuse the architecture of the PALM-3000 command/automation and device driver servers, and automations that are applicable to the IOS. New architectures will be created for the functions that are unique to the IOS. Where possible, we have chosen opto-mechanical hardware that enables us to reuse device driver software. The real-time control system of PALM-3000 was hosted on Graphics Processor Units (GPU). The results of a trade study showed that these did not provide the required frame rate for the IOS. As such they were replaced with a Digital Signal Processor (DSP) board with eight on-board DSP chips. We will use direct memory access (DMA) to get data from the frame-grabber directly to the DSP board enabling us to achieve the required frame rates. The use of a single DSP board also allows the IOS reduce the Palm-3000's nine computers hosting GPUs to a single computer which handles all RTC and hardware control, while a second computer handles the user interfaces.

All published data is written to the database, in the form of commands, status messages, and telemetry data. A separate component acts as the interface to the database; a slightly enhanced version of the Berkeley DB database engine. The PALM-3000 system incorporates one RAID controller. For the IOS, we intend to implement two controllers operating in parallel in order to meet data write requirements at high burst rates.

IV. PERFORMANCE PREDICTIONS

The key metric of AO performance for optical communications is the amount of light coupled into the receiver fiber optic. The factors with the most significant impact on the performance of AO are the severity of the optical turbulence along the propagation path and the amount of light received by the wave front sensor. Optical turbulence increases with decreasing observations elevation angle. The light received at the WFS depends on atmospheric conditions such as haze and clouds. It is also depends on how much light is diverted from the communication beam. As more light is diverted into the WFS, the AO performance improves, which in turn increases the percentage of light that is injected to the fiber. This however is at the cost of reducing the total amount of light able to be injected into the fiber. The performance of AO as a function of WFS input power is non-linear and is shown in Figure 4 for the nominal atmospheric turbulence conditions of a Fried parameter of 5.5-cm measured at 500-nm and zenith; the median atmospheric conditions at OCTL. We have designed the IOS to operate on that section of the curve where the input power to the WFS exceeds -55dBm. At this input power level to the WFS the wave front correction will still maintain the high coupling efficiency into the fiber, even in the presence of a 3dB loss due to attenuation from thin cirrus clouds.

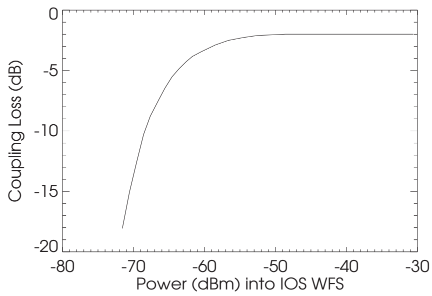

Figure 4: Fiber coupling loss as a function of the downlink power entering the IOS wave front sensor.

V. SUMMARY

We have described the development of the AO system to support the GEO-to-ground optical communications links of the LCRD project. The system will be able to operate under both day and night conditions at target elevations as low as 20 degrees above the horizon. The system is currently being assembled and is expected to achieve first light in the lab 2015. It will then undergo system testing and checkout before being delivered to the OCTL facility.

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