Conceptual design of the adaptive optics system for the laser communication relay demonstration ground station at Table Mountain

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ABSTRACT

The Laser Communication Relay Demonstration will feature a geostationary satellite communicating via optical links to multiple ground stations. The first ground station (GS-1) is the 1m OCTL telescope at Table Mountain in California. The optical link will utilize pulse position modulation (PPM) and differential phase shift keying (DPSK) protocols. The DPSK link necessitates that adaptive optics (AO) be used to relay the incoming beam into the single mode fiber that is the input of the modem. The GS-1 AO system will have two MEMS Deformable mirrors to achieve the needed actuator density and stroke limit. The AO system will sense the aberrations with a Shack-Hartmann wavefront sensor using the light from the communication link's 1.55 μm laser to close the loop. The system will operate day and night. The system's software will be based on heritage software from the Palm 3000 AO system, reducing risk and cost. The AO system is being designed to work at r_0 greater than 3.3 cm (measured at 500 nm and zenith) and at elevations greater than 20° above the horizon. In our worst case operating conditions we expect to achieve Strehl ratios of over 70% (at 1.55 μm), which should couple 57% of the light into the single mode DPSK fiber. This paper describes the conceptual design of the AO system, predicted performance and discusses some of the trades that were conducted during the design process.

Keywords: Optical Communication, Adaptive Optics

1. INTRODUCTION

The Laser Communications Relay Demonstration (LCRD) project will demonstrate a high bandwidth DPSK and pulse position modulation (PPM) link from Geostationary Earth Orbit (GEO) as a precursor to the development of a future Advanced Telecommunications and Data Relay Satellite Service (ATDRSS).[1] The DPSK link supports near-Earth links, while the energy-efficient PPM is accepted as the appropriate format for deep space optical communications.

LCRD is led by Goddard Space Flight Center (GSFC) with the participation of Massachusetts Institute of TechnologyLincoln Laboratory (MITLL), Jet Propulsion Laboratory (JPL), and Loral Space Systems. The LCRD payload will be hosted on a commercial communication satellite, and some details of the launch are still being determined. Current plans call for a December 2017 launch on a Loral Space Systems GEO satellite located between 62° W and 162° W longitude; on orbit locations that correspond to minimum elevation angles of 20° from the ground stations GS-1, the JPL Optical Communications Telescope Laboratory (OCTL) ground station at Table Mountain, California, and GS-2, the modified Lunar Laser Communications Ground Terminal (LLGT) at White Sands, New Mexico.

For GS1, an integrated optical system (IOS) at the back end of the OCTL telescope will use adaptive optics (AO) to correct the wavefront distortions on the link. On the downlink, AO will allow the efficient coupling of the aperture-averaged signal into the single mode fiber modem. The uplink will consist of separate beacon and communications lasers. The 1.25 Gb/s coherent DPSK uplink will be a single transmitted beam. Because the 18 μrad point-ahead angle to the geostationary satellite exceeds the isoplanatic angle, it precludes full pre-correction of the uplink beam from the aberration measured on the downlink beam. The measured aberration will be used to partially mitigate tip/tilt beam wander effects on the uplink.

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2. OVERVIEW

The IOS consists of the adaptive optics (AO) system, which compensates for atmospheric turbulence, the transmitter optics, which relay the beam from the laser to the telescope and the receiver optics which couple the downlink beam into the single mode fiber in the modem. The AO system is based on the Palm 3000 AO system[2] at Palomar Observatory on the 5m Hale telescope. This system uses two deformable mirrors (DM); one corrects the high amplitude, low spatial frequency aberrations, while the second corrects the low amplitude, high spatial frequency aberrations. The IOS will reuse the Palm 3000 software architecture[3] reducing cost and risk.

The IOS will sense the incoming wavefront with a Shack-Hartmann sensor in a Fried geometry. We looked at several alternative approaches such as a phase-shifting Zernike sensor,[4] which is very promising, but is at a low technology level. We looked at self referencing inteferometers (SRI),[5] which are immune to scintillation, but require more laser power than is available to LCRD.

2.1 Opto-mechanical Layout

The IOS requires some modifications to the Palm 3000 system because of the different requirements each system is optimized for. The Palm 3000 system was optimized for high-contrast astronomical imaging, while the IOS is optimized for high peformance performance for near-IR lasers during day and night conditions. The IOS wavefront sensor uses the 1.55 μm downlink beam to measure the wavefront. Wavefront sensor (WFS) speed is critical to enable the AO system to keep up with the quickly changing atmospheric turbulence conditions at the 20° elevation and 3.3 cm r_0 the IOS is required to work at. Our modeling has shown that we will need to have a frame rate of nearly 20 kHz. To achieve our desired level of performance in the specified atmospheric conditions, the IOS requires 28 actuators across the 1m OCTL primary. We will have 2×2 quad cells for each lenslet in the WFS. We selected the Xenics Cheetah InGaAs camera as the basis for our wavefront sensor. This is the fastest frame-rate InGaAs camera on the market today.

We selected the Boston Micromachine MEMS DMs.[6] These DMs have two advantages over conventional DMs. They are much smaller in diameter, which allows all the rest of the optical train to be small. This drastically reduces the cost of the optical train. The second advantage is that the DMs themselves cost less than conventional DMs.

The DM actuator stroke budget is shown in Table 1. The IOS design requires at least 28 actuators across the primary mirror, which caused us to select the Boston Micromachines 32×32 actuator Kilo DM with a continous facesheet. This DM only has an actuator stroke of 1.5 μm, which in turn drives us to use a woofer/tweeter design using the Boston Micromachines 12×12 actuator 3.5 μm stroke Multi-DM in addition to the Kilo DMs. This was the key design decision that indicated it would be wise to base the IOS on the P3K design.

Table 1. The DM actuator stroke budget. The Solar filter will be mounted to the telescope and blocks 99% of the Sun's light, but will cause some aberrations in the beam. The telescope aberrations are from the seven reflective elements of the telescope. The common path aberrations are in the IOS optics before the WFS. We assume each of the 10 optics is built to lambda over 20 quality at 550nm. The dominant term is the atmosphere and is for a r_0 of 3.3 cm at 20° elevation and 1550 μm. The total stroke is the RSS of the individiual terms. This yields a margin of 15%, which is considered adequate for this stage, as contingency on the individual terms is high and it is dominated by the atmosphere, which is well known.

Parameter	Current Best Estimate (nm)	Contingency	Total (nm)
Solar Filter Aberrations	500	25%	625
Telescope Aberrations	200	25%	250
Common Path Aberrations	87	25%	108
Atmospheric Aberrations	2186	15%	2514
Total	2253		2605

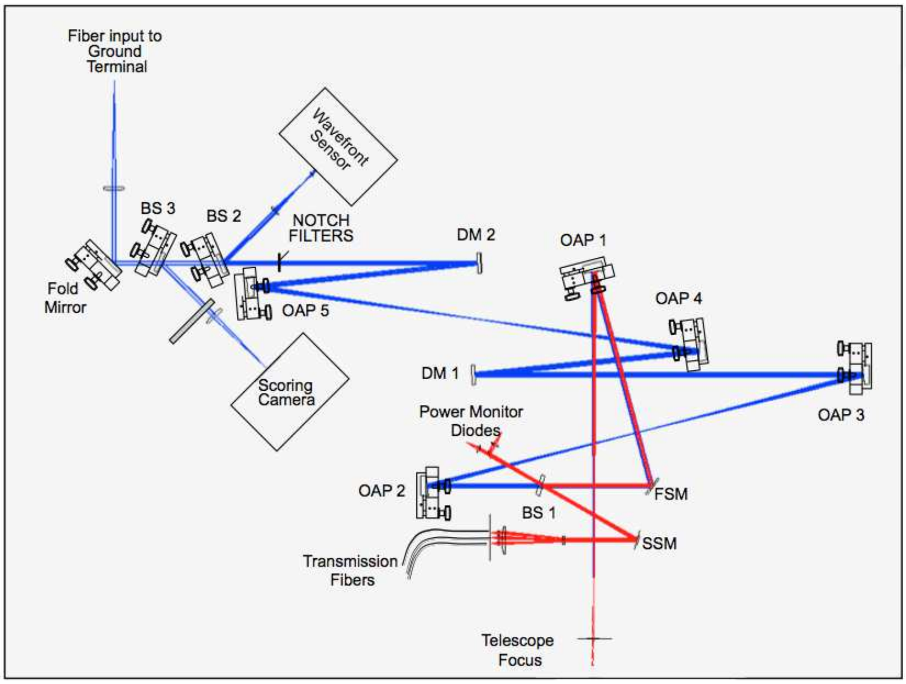

Figure 1. The optical layout of the IOS. See text for description.

The IOS will be located in the coudé room of the OCTL facility. This room allows for multiple experiments to be set up at the same time, and a flat mirror on a rotation stage directs the optical beam to the specific setup. IOS will be located on a standard optical bench, and will be isolated from the room atmospheric turbulence with an enclosure. This will also minimize stray laser light from leaving the set up.

The optical layout is shown in Figure 1. In the following description, we trace the light coming from the telescope. First the beam hits the first of five off-axis parabola (OAP1) mirrors, which forms a pupil on the fast steering mirror (FSM). The beam then hits a dichroic (BS1) which transmits the downlink beam, but reflects the injected uplink beam back towards the telescope. A portion of the transmitted beam will leak through the dichroic and this is detected by a set of PIN diodes; one senses the uplink communication laser and the other senses the uplink beacon laser. The power will be monitored to ensure the lasers and their transmission system are functioning correctly. After BS1, the downlink beam encounters OAP2 and OAP3, which form a second pupil on the low-order deformable mirror (LODM). The beam then encounters OAP4 and OAP5 which form a third pupil on the high-order deformable mirror (HODM). The next optic is a pair of filters that block any back scattering from the uplink beam from entering the downstream sensors. These filters provide 180 dB of supression for the uplink beam wavelength. The wavefront sensor picks off 10% of the light with BS2. Another 10% of the light is picked off for the scoring camera. A fold mirror keeps the beam on the bread board and sends it into the single mode fiber that goes to the ground terminal.

On the uplink arm, there will be four beacon fibers and a single communication fiber. These will be collimated and then transmitted out of the telescope. A slow steering mirror (SSM) provides the point ahead angle (caused by the light travel time from the ground to the moving satellite) and is expected to be kept stationary during operations. In addition to the optics shown, there will be an aperture stop and possibly a Lyot stop to prevent stray light from the Sun from entering the wavefront sensor.

2.2 Software

The IOS software is based on the Palm 3000 software design.[3,7] 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.

For the IOS, we intend to reuse the Palm 3000 command/automation and device driver servers, although only some of the Palm 3000 automations will be reused by the IOS, and so several new automations will be needed. Where possible, opto-mechanical hardware will be chosen so that device driver software can be reused; otherwise new device driver components and drivers will be required. The real-time component implemented on graphics cards will be reused, although we are currently investigating the feasibility of a GPUDirect optimization upgrade. The Palm 3000 graphical user interface is not suitable for the IOS, and so a new GUI design will be provided.

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.

The real-time IOS components running on GPUs will be written using the CUDA architecture, while all other system codes will use the nesC language operating on the linux PC platform. As was used with Palm 3000, the IOS software will be tightly managed using the GIT version control system.

3. PERFORMANCE EXPECTATIONS

The system is designed to produce a Strehl ratio of 73% for the most stressing atmospheric conditions. This Strehl ratio produces a coupling efficiency into the receiver modems single mode fiber of 57%. The system is designed to work at a telescope elevation of 20° above the horizon. Until the LCRD host spacecraft is selected, we will not know the true elevation. The highest it can be is 54°, if the spacecraft is at the same longitude as OCTL. The system is being designed to work at an r_0 of 3.3 cm measured at zenith and 500 nm. We expect to see these conditions predominantly during the day; at night we expect much better conditions with correspondingly improved coupling efficiency. The expected coupling efficiency is shown as a function of r_0 and elevation angle in Figure 2. It is a plot of the coupling efficiency as a function of r_0, for possible satellite elevation angles. As the figure shows, the larger the value of r_0, and the higher the elevation angle, the better the coupling efficiency. The worse case r_0 of 3.3 cm is only expected during the day; at night we expect much higher r_0 values and correspondingly better performance.

During LCRD operations, the IOS will only be used at the single wavelength of the LCRD downlink laser, but during testing it will be used to observe stars using broad band filters. Figure 3 shows the performance as a function of wavelength. The curves are all for a satellite elevation of 50° and the color curves correspond to r_0 varying from 5-15 cm.

4. SUMMARY

The IOS design is based on the proven design of the Palm 3000 AO system and is a key enabling element of the GS1 system. We are currently engaged in the detailed design of the system and long-lead items are being procured. We expect to get first light of the system in the lab in FY 2014 and first light on the sky in FY 2017.

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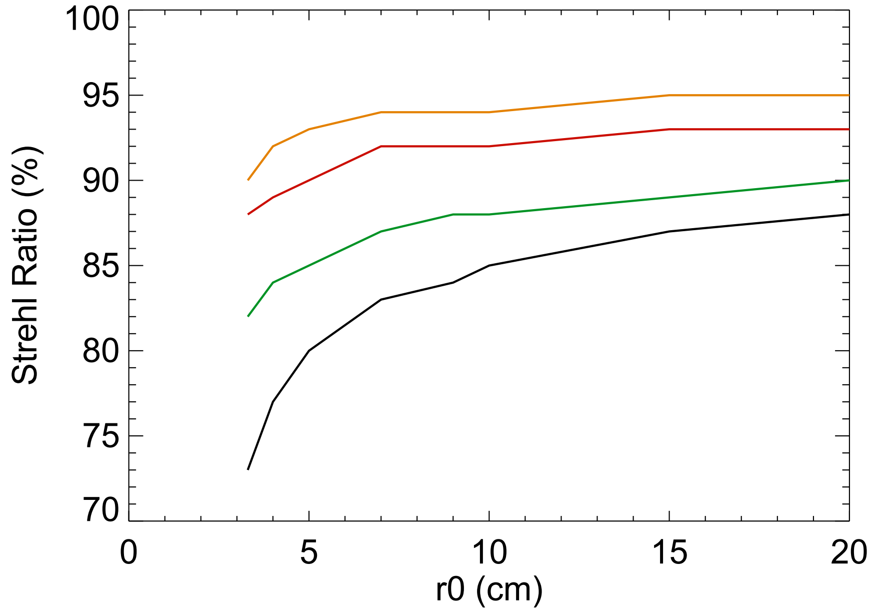

Figure 2. The coupling efficiency of the IOS system as a function of r_0. The four colors lines indicate the elevation angle of the host satellite. The black line is for 20°, the green for 30°, the red line for 40° and the orange line is for 50°.

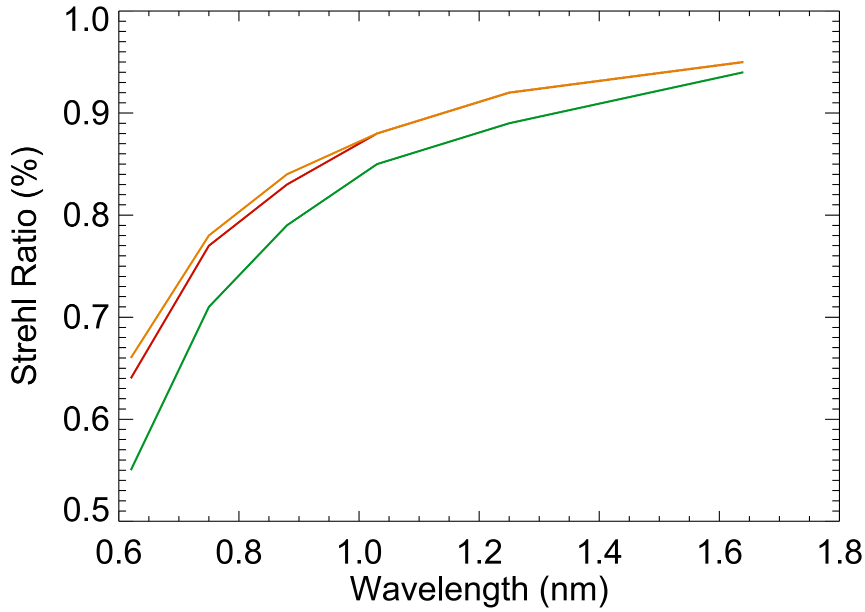

Figure 3. Performance of the IOS as a function of wavelength. The elevation angle for all curves is 50°. The green curve is for r_0 of 5 cm, the red curve for 10 cm and the orange curve for 15 cm.

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