LOW-ORDER ADAPTIVE OPTICS SYSTEM FOR FREE-SPACE LASERCOM: DESIGN AND PERFORMANCE ANALYSIS

K. H. KUDIELKA, Y. HAYANO, W. KLAUS, K. ARAKI
Communications Research Laboratory, 4-2-1 Nukui-Kitamachi, Koganei, Tokyo 184-8795, Japan

Y. ARIMOTO, J. UCHIDA
National Space Development Agency of Japan, Tsukuba Space Center, 2-1-1 Sengen, Tsukuba, Ibaraki 305-8505, Japan

A laser communications demonstration experiment (LCDE) between the Communications Research Laboratory in Tokyo and the International Space Station is being designed and implemented. To efficiently couple the downlink laser beam into a single-mode Erbium-doped preamplifier and to reduce uplink beam wander and scintillations, we plan to use low-order adaptive optics. The envisaged system dithers the wavefront actuators and evaluates the resulting variations of the received optical power. Simulation shows that, when controlling tilt, focus, and astigmatism, the power penalty due to residual wavefront error amounts to 2.3dB.

1 Introduction

The high bandwidth offered by free-space lightwave communication systems makes them very attractive for future satellite networks requiring intersatellite links of the order of 1Gbit/s. Also, the large amounts of data gathered by Earth-observing satellites or manned spacecraft could be easily downloaded to Earth in a relatively short time.

To demonstrate the advantages of free-space laser communications, the Communications Research Laboratory (CRL) is implementing an experimental link between its optical ground station, situated in a western suburb of Tokyo, and the Japanese Experimental Module (JEM), which is part of the International Space Station.[1] The aims of this project are (1) to realize a compact, light-weight optical terminal, utilizing components and subsystems already developed for terrestrial fiber communications, (2) to demonstrate detection and ranging of space debris, and (3) to demonstrate the feasibility of a space-to-ground link using a ground station equipped with adaptive optics (AO). Table 1 summarizes the key parameters of the communications link. To make maximum use of terrestrial fiber technology, both the uplink and the downlink wavelength have been chosen to lie in the 1.5μm wavelength band. Erbium-doped power- and pre-amplifiers will be employed in both terminals.

Parameter	Downlink	Uplink
Wavelength	1.552μm	1.562μm
Data rate	2.5Gbit/s	1.2Gbit/s
Output power	0.4W	1W
Modulation scheme	intensity modulation	
Transmit telescope diameter	15cm	10cm
Receive telescope diameter	50cm	15cm
Detection scheme	direct detection	
Sensitivity (bit-error rate: 10^{-9})	90photons/bit	

Table 1. Key parameters of the Laser Communications Demonstration Experiment

Also, the modulation scheme is compatible with terrestrial systems.

At the ground station, the optical radiation received from JEM has to be fed to the optical pre-amplifier in a single spatial mode. Hence, diffraction-limited performance of the optical system is required. Measurements of the atmospheric turbulence at $\lambda = 0.8\mu$m revealed Fried's coherence length r_0 to be between 5cm and 9cm.[2] For $\lambda = 1.55\mu$m and a receive telescope diameter of $D_r = 50$cm, one calculates $2.5 \leq D_r/r_0 \leq 4.5$, a range that suggests the use of low-order adaptive optics.

2 Design of adaptive optics system

The block diagram shown in Figure 1 gives an overview of the adaptive optics system to be implemented. The interfaces are CRL's 1.5m telescope on one side and a fiber-coupled transmitter/receiver pair on the other side. Acquisition and coarse pointing will be handled by separate subsystems.

The downlink beam passes through the telescope (used subaperture: 0.5m, magnification: 20) and is reflected by a fast steering mirror and a 13-electrode bimorph mirror (CILAS model BIM-13). A quarter-wave plate converts the circular state of polarization into a linear one. Then the beam passes a polarization splitter, which is used to superimpose the uplink beam. Finally, the beam is truncated to its final diameter (2.5cm) and coupled into a polarization-maintaining single-mode waveguide by a lens.

With the fast steering mirror and the deformable mirror, the adaptive optics system is able to correct five optical aberrations: tilt (2), focus (1), and astigmatism (2). In order to estimate and compensate the current wavefront parameters, we make use of the well-known multidither concept:[3] Each parameter is dithered sinusoidally, and the resulting oscillation of the quantity

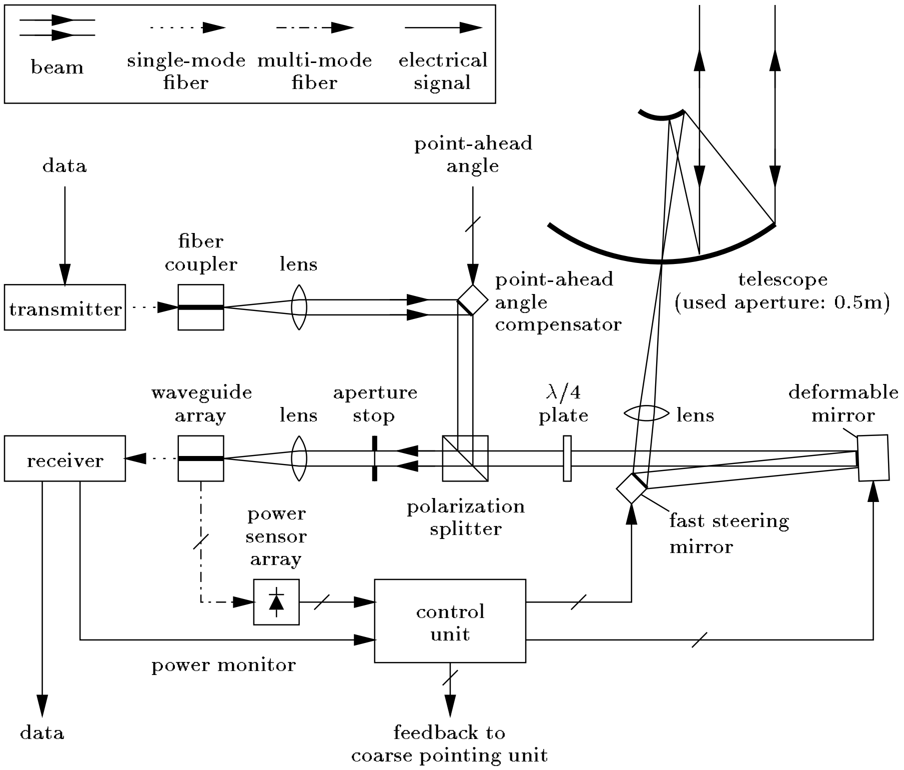

Figure 1. Block diagram of the adaptive optics laser communications system

to be maximized (i.e. the optical power coupled into the receiver) is synchronously demodulated. The such gained error signal is then fed into a loop filter, followed by an integrator. The integrator's output is finally added to the dither signal, and the resulting signal drives the corresponding actuator(s).

For the five control loops to operate independently, the dither signals have to be orthogonal to each other. This is best accomplished by using sine and cosine at three different dither frequencies. Since the bandwidth of the deformable mirror is limited, we plan to assign the highest dither frequency to the fast steering mirror.

For the control loops to lock, the angle of the incident wave has to lie well within the field of view of the telescope, which is about $\lambda/D_r \approx 3.1\mu$rad. Unfortunately, the RMS value of the residual error associated with the telescope's coarse pointing unit, is much larger. Hence, a means for angular acquisition needs to be provided separately.

To this end, a novel device, based on multi-layer polymeric optical waveguides, has been developed:[4] Within the focal plane of the receiving lens, the single-mode waveguide, nominally carrying the communication signal, is surrounded by four closely spaced multi-mode waveguides with rectangle-shaped cores. During initial acquisition, the optical powers coupled into those waveguides are measured by optical power sensors and evaluated by the control unit (see Figure 1). This setup functions as a quadrant detector and requires no additional adjustment.

The control unit, which manages acquisition and tracking of the downlink beam, will be implemented by an off-the-shelf DSP system.

The uplink signal, emerging from the end of a polarization-maintaining single-mode fiber, is collimated by a lens and then deflected by a steerable mirror. This mirror is used for setting the point-ahead angle, i.e. the difference between the direction of the transmitted and the received beam, which is necessary to hit the quickly moving target. At the polarization splitter, downlink and uplink beam are finally superimposed.

3 Downlink performance analysis

In the ideal case, an adaptive optics system would completely eliminate stochastic wavefront aberrations, and the optical receiver would be fed with constant optical power. In reality, however, residual aberrations, i.e. aberrations the system doesn't correct *at all* or doesn't correct *perfectly*, cause a reduction of the received optical power. In case of imperfect correction, the variance of each aberration is influenced by the power sensors' noise, the control loops' finite bandwidth, and the dither signals.

To arrive at a meaningful expression for the AO system's performance, we determine the optical transmit power required to achieve a bit-error rate (BER) of 10^{-9} under the presence of turbulence and AO control, and compare it with the power required in a diffraction-limited system. In a Monte-Carlo analysis, 10000 different stripe-shaped phase screens are moved across the receiver's aperture. The phase screens, corresponding to Kolmogorov statistics, are generated using a method proposed by Winick.[5] While moving each phase screen, a complete time-domain simulation of the multidither control algorithm, described in Section 2, is performed, resulting in a trace of received power versus time. From the trace data, the distribution function of the optical power is easily derived. Finally, by applying the BER formula of an

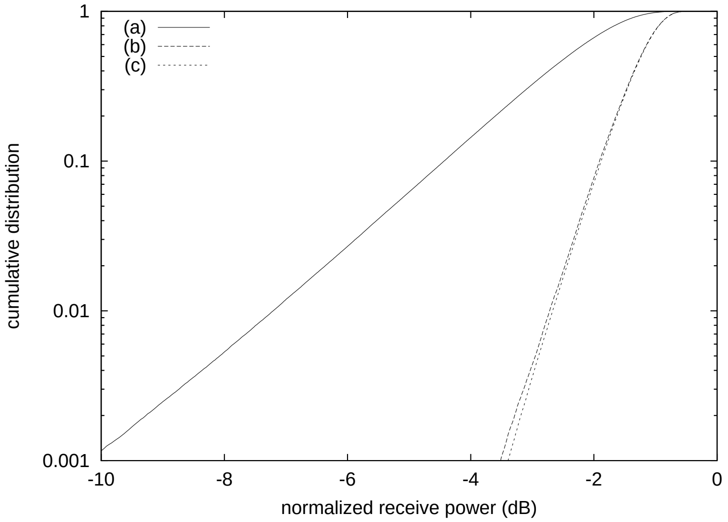

Figure 2. Cumulative distribution of normalized receive power. (a) simple AO system removing only tilt; (b) multidither system; (c) "ideal" second-order AO system.

optically pre-amplified direct detection receiver, the mean BER is determined.

In Figs. 2 and 3 we present the results obtained for $D_r/r_0 = 2.5$ and $f_n D_r/v = 4$ (f_n...natural frequency of control loops, v...effective wind speed). The performance of the multidither system is almost identical to that of an "ideal" second-order AO system which *completely* removes tilt, focus, and astigmatism. The probability, that the received power is reduced by more than 3.5dB, is 10^{-3}. To maintain a BER of 10^{-9} under the presence of turbulence, the transmit power has to be increased only by 2.3dB. For comparison, if only wavefront tilt were compensated, the power would have to be increased by 14.7dB.

4 Conclusion

We have presented a preliminary design study which shows that a simple low-order adaptive-optics system, installed in the optical ground station, will significantly improve the link margin of the JEM demonstration experiment. The proposed system uses a multidither algorithm for wavefront tracking and a focal-plane waveguide array for acquisition.

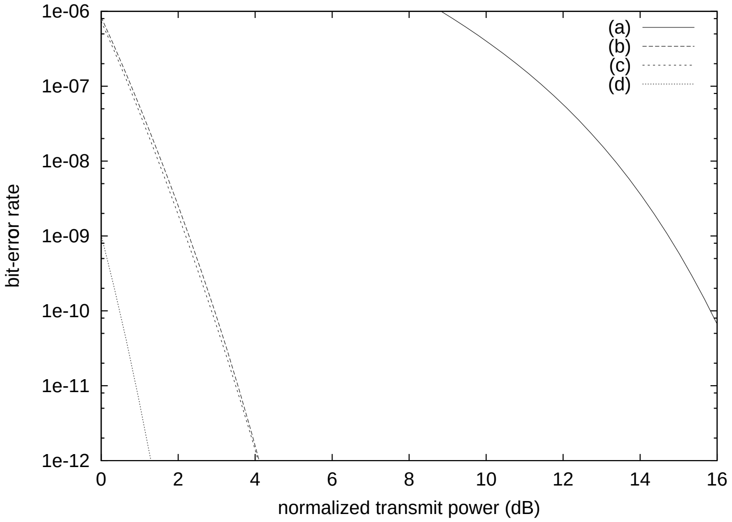

Figure 3. Bit-error rate as a function of normalized transmit power. (a) simple AO system removing only tilt; (b) multidither system; (c) "ideal" second-order AO system; (d) diffraction-limited system.

References

1. Y. Arimoto. Study on high-speed space laser communications using adaptive optics and the demonstration experiment on International Space Station. In *Proc. CRL International Symposium on Optical Communications and Sensing toward the next Century*, pages 72–77, March 1999.
2. Y. Hayano et al. Ground-to-satellite laser communication program at CRL using adaptive optics. In *Proc. SPIE*, volume 3126, pages 208–211, 1997.
3. J. E. Pearson et al. Coherent optical adaptive techniques: design and performance of an 18-element visible multidither COAT system. *Appl. Opt.*, 15(3):611–621, 1976.
4. M. Hikita et al. Fabrication of multi-layer polymeric optical waveguides for space laser communication. In *Proc. IEICE General Conference*, March 1999. Paper C-3-95 (in Japanese).
5. K. A. Winick. Atmospheric turbulence-induced signal fades on optical heterodyne communication links. *Appl. Opt.*, 25(11):1817–1825, 1986.