A Free-Space Optical Terminal for Fading Channels

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ABSTRACT

This paper describes a lasercom terminal using spatial diversity to mitigate fading caused by atmospheric scintillation. Multiple receive apertures are separated sufficiently to capture statistically independent samples of the incoming beam. The received optical signals are tracked individually, photo-detected, and summed electrically, with measured diversity gain. The terminal consists of COTS components. It was used in successful demonstrations over a 5.4km ground-ground link from June through September 2008, during which it experienced a wide temperature range. Design overview and hardware realization are presented.

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1. INTRODUCTION

Terrestrial free-space laser communication links operating at low elevation angles must overcome significant challenges due to atmospheric turbulence. In this paper we describe a terminal designed to be less sensitive to the adverse effects of wavefront distortion and to mitigate instantaneous power loss due to scintillation.

The approach taken in our design was to employ multiple small apertures with no wavefront compensation. There are three reasons for this. First, the use of small apertures virtually eliminates the need for wavefront correction because the small cross-section effectively reduces the wavefront distortion to tilt components only, which can be tracked out with a commercial fast steering mirror. Second, in the presence of scintillation, small apertures increase the likelihood of an ideal or near ideal constant irradiance distribution in the pupil plane, which leads to more efficient coupling into single-mode fiber. Third, by adding the output of several apertures, it is possible to mitigate fading since the likelihood of all apertures experiencing a fade at the same time is decreased.

While air-to-ground applications are assumed to be asymmetric, requiring primarily a high data rate downlink, bidirectional optical signals are required for tracking. For the link experiment described in this report, the terminal representing a ground configuration used spatial diversity while that representing an aircraft terminal did not. A common optical module design was used for all apertures, encompassing the components between fiber and free space and including the pointing mechanisms and spatial tracking sensors. Since air-to-ground applications do not require point ahead between transmit and receive beams a common optical fiber served as both transmitter and receiver, thus simplifying the terminal design by eliminating one pointing mechanism. Fiber elements achieved transmit-receive diplexing.

Simulations of atmospheric channel effects based on our link geometry indicated that apertures smaller than a few centimeters would keep the wavefront distortion low enough to obviate the need for wavefront restoration, thereby simplifying the terminal. After a review of commercially available single-mode fiber collimators we choose to go with apertures of 12 mm diameter, which was sufficient to demonstrate the spatial diversity technique on a relevant horizontal link. Conveniently, this allowed the use of readily available 1” diameter optics throughout the terminal. Beam expanders could be added, if necessary, in future flight designs to provide more optical gain but still consistent with $D < r_0$.

The apertures must be separated by more than the intensity correlation distance in order to realize the potential benefits of spatial diversity introduced by the statistical independence of channel fading. Atmospheric simulation of our link indicated that apertures separated by 10 to 20 cm should be effective in mitigating scintillation. Since there was a lack
of field measurements to validate our simulations, we designed our ground terminal to have four apertures with adjustable separation from 10 to 20 cm. As testing progressed, we determined that a square 10 cm pattern worked well for all conditions that required spatial diversity gain.

Testing of the power delivery system began in June 2008 and continued through September. Communications testing was concentrated in the final two months, and included several 24 hour periods having widely varying climatic conditions.

2. DESIGN OVERVIEW

Figure 1 illustrates the optical designs used for the transmit (aircraft) and receive (ground) terminals, separated into optical modules (OM) and electro-optic modules (EOM). A single optical fiber is used in both transmit and receive EOM designs, with transmit/receive diplexing done in the fiber domain. This approach reduces the complexity of the optical hardware and is enabled by the negligible point-ahead angle in air-to-ground links.

![Diagram of optical designs](image)

In the transmitter (aircraft) EOM, where higher powers would be expected, the T/R diplexer is implemented with a circulator. The receiver diagram illustrates one channel of a four-channel ground receiver. Here a simple fiber Add Drop Multiplexer (ADM) is used as the beacon/receiver diplexer to provide isolation against beacon back-reflection from the fiber collimator. Another ADM also serves as a simple 75 GHz passband filter following the preamplifier, although narrower filtering would provide better performance in an actual flight application. A fiber mechanism to fine tune path length was followed by attenuation of the amplified signal to match the input requirements of the detector-transimpedance amplifier combination. For this demonstration fixed attenuation was used, although dynamic attenuation would be used for flight operation to accommodate dynamic range limitations of the electrical circuitry. Power taps included in both the beacon output fiber and the input fiber monitor respective fiber power levels.

To implement the four-channel diversity ground receiver, the single channel layout is replicated four times. Figure 2 illustrates the overall layout of the diversity receiver. The output signals from the respective transimpedance amplifiers from each channel are summed before driving a common clock and data recovery circuit. Four separate beacon sources on separate wavelengths emit through their respective receiver apertures to serve as tracking beacons for the “aircraft”
terminal. The tracking scheme automatically maintains coalignment of the outgoing beacons. In a flight implementation, the uplink beacons could be modulated to carry low data rate communications.

The optical path difference between the channels up to the summing amplifier had to be maintained to a tolerance of less than 1 cm. To achieve this goal we used both an OTDR for cable matching, and a custom calibrator that simultaneously illuminating all four receiver channels with a large modulated beam that allowed adjustment of the fiber delay modules.

![Figure 2. Overall layout of the four channel diversity receiver.](image)

The common OM design is shown in Figure 3 along with the implemented control loops. Initial boresight alignment between fiber and FPA utilizes a flip-in hollow core retroreflector. The alignment of the 4% beam splitter is adjusted to position the return signal onto the desired track point on the FPA. In normal operation, three tracking loops are employed in the module to maintain tracking, fiber boresight, and offloading of the fast steering mirror (FSM) bias.

![Figure 3. Block diagram of Optical Module indicating control loop used for alignment and operation.](image)
The primary tracking loop drives the fast steering mirror to hold the incoming optical beam centered on the track point of the focal plane array (FPA) in the tracking camera. The boresight tracking loop adjusts the 4% splitter to keep the incoming beam centered on the fiber, so long as the primary tracking loop is operating. This maintains alignment of the fiber to the FPA. The third loop adjusts the pointing of the output steering mirror to offload any dc bias from the FSM, thus maximizing its dynamic range. The output mirror is a stand-in for wide field of regard gimbal in a fieldable system.

The transmit module, representing the aircraft, used a single optical module, while the four-channel ground receiver used four optical modules of the common design. Two channels are built on a single plate, and are mirror images of one another. The output steering mirrors were mounted on a common rail to allow adjusting the output beam separation to evaluate the intensity coherence length of the channel, as illustrated in Figure 4.

![Schematic Channel Pair Layout](image)

Fig. 4. Schematic Channel Pair Layout

A second such plate is then mounted over the first, inverted so that the components sides of the plates face each other. Mutual spacing of the second set of beams from the first set is controlled by the length of the mounting posts connecting the two plates. For the bulk of the horizontal link testing, the beams were positioned at the corners of a four inch square pattern. This provided adequate decorrelation of the incoming scintillation pattern to demonstrate spatial diversity.

### 3. HARDWARE REALIZATION

Each channel consists of a steering mirror mounted on a rail that allows the aperture separation to be adjusted. The fast steering mirror compensates for variations in beam tilt detected by the tracker. A beamsplitter taps off a small portion of the received light and directs it through a focusing lens and filters to an area camera serving as the tracker. The majority
of incoming light passes through the beam splitter to the fiber collimator, where it is coupled into single mode fiber to terminate in a photo-detector.

Two commercial 18” x 18” breadboards were populated with two channels each. One of these is pictured in Figure 5. All the optics and major components are COTS hardware, as were all of the active mounts. A few static mounts, brackets and spacers were fabricated in-house. Beam paths are indicated in the figure.

![Breadboard with two receiver channels.](image)

The fast steering mirrors and controllers are Newport model FSM-300, the steering mirrors are Newport laser line dielectrics in Newport U-100 mounts driven by picomotor actuators from New Focus, and the collimators are Lightpath PN10265900. Beam splitters are from CVI and are also driven by picomotors. The focus lenses are Newport BK7 plano-convex singlets. Spectral filters are narrow passband telecom filters from BARR Associates. Neutral density filters from Thorlabs are used to attenuate the tracking signal.

Two breadboards were assembled into a four-channel unit by flipping one over and installing it directly on top of the other with posts as shown in Figures 6 and 7. This was done in order to obtain the desired minimum spacing between the channels. Vertical aperture spacing was adjustable by stops along the posts. Figure 6 provides a front view of the OM with the lower right hand aperture shifted in position to facilitate tests of channel decorrelation with aperture spacing. Figure 7 is a side view of the unit in link operation.
Fig. 6. Front view of four channel optical module, showing one aperture displaced for testing.

Fig. 7. Side view of four-channel receiver in link operation.
4. DEMONSTRATION LINK

A nearly horizontal demonstration link of 5.4 km length was formed by placing the 4-aperture receiver in a telescope dome located on MIT property in Westford, MA. A transceiver having a similar design, but which incorporated a single transmitter, was placed in a small room located just below the ranger’s booth in a firetower in Groton, MA. The terrain below the link was suburban and included roads, fields, ponds and forest. The link was first operated in June 2008 and testing was performed periodically through September 2008, thus encompassing late Spring, Summer, and early Fall climatic conditions.

The environment in which the terminals were located was not temperature or humidity controlled and consequently they saw ambient conditions ranging from about 100° F with high humidity in August to some cool, dry nights in September when temperatures dipped to about 40° F.

Link operation was typically during daytime working hours, but also included some evenings and a few 24 hours periods of continuous operation. Terminals were operated with clear skies and direct sunlight background as well as partly cloudy conditions with heavy cloud cover, but never during rain. The receiver field of view (FOV) was pointed nearly directly west and therefore the evening sun would fall in its vicinity. However, the sun was never directly in the receiver’s FOV.

5. SUMMARY

Simple transmit and receive terminals were built to support validation of optical spatial diversity fade mitigation in a quick-reaction, limited-budget horizontal link demonstration. A common optical module approach simplified the system design. Hardware was implemented primarily with COTS telecom parts. A fiber nutation scheme was implemented to maintain high fiber coupling efficiency with COTS parts in an uncontrolled thermal environment. The system performed well, enabling channel characterization and communications performance testing throughout the program.