45 Km horizontal path optical link experiment

A. Biswas*, J. Ceniceros, M. Novak, M. Jeganathan, A. Portillo, D. Erickson, J. Depew
B. Sanii, J. R. Lesh

Optical Communications Group
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109

ABSTRACT

Mountain-top to mountain-top optical link experiments have been initiated at JPL, in order to perform a systems level evaluation of optical communications. Progress made so far is reported. The NASA, JPL developed optical communications demonstrator (OCD) is used to transmit a laser signal from Strawberry Peak (SP), located in the San Bernadino mountains of California. This laser beam is received by a 0.6 m aperture telescope at JPL's Table Mountain Facility (TMF), located in Wrightwood, California. The optical link is bi-directional with the TMF telescope transmitting a continuous 4-wave (cw) 780 nm beacon and the OCD sending back a 840 nm, 100-500 Mbps pseudo noise (PN) modulated, laser beam. The optical link path is at an average altitude of 2 Km above sea level, covers a range of 46.8 Km and provides an atmospheric channel equivalent to ~ 4 air masses. Average received power measured at either end fall well within the uncertainties predicted by link analysis. The reduction in normalized intensity variance (σ_I^2) for the 4-beam beacon, compared to each individual beam, at SP, was from ~ 0.68 to 0.22. With some allowance for intra-beam mis-alignment, this is consistent with incoherent averaging. The σ_I^2 measured at TMF ~0.43 +/-0.22 exceeded the expected aperture averaged value of < 0.1, probably because of beam wander. The focused spot sizes of ~162 +/- 6 μm at the TMF Coude and ~ 64 +/- 3 μm on the OCD compare to the predicted size range of 52-172 μm and 57-93 μm, respectively. This is consistent with 4-5 arcsec of atmospheric "seeing". The preliminary evaluation of OCD's fine tracking indicates that the uncompensated tracking error is ~ 3.3 μrad compared to ~ 1.7 μrad observed in the laboratory. Fine tracking performance was intermittent, primarily due to beacon fades on the OCD tracking sensor. The best bit error rates observed while tracking worked were 1E-5 to 1E-6.

Keywords: free-space optical communications, atmospheric scintillation, lasercom, terrestrial optical link

1. INTRODUCTION

The horizontal path optical link experiments were initiated in order to provide a system-level evaluation of optical communications. The NASA, JPL developed OCD[1], served as the lasercom terminal, while a 0.6 m astronomical telescope located 46.8 Km away, was the receiving station. Other horizontal path terrestrial optical link experiments have been recently reported.[2,3,4] Low earth orbiting (LEO) satellite-to-ground optical link experiments, primarily intended to address the impact of atmospheric scintillation on uplink beam propagation, have also been reported[5,6]. Furthermore, an end-to-end optical communications experiment from a geostationary orbit (GEO) satellite to ground has been reported[7]. The experiment to be described utilizes a narrower divergence beam (22 μrad) than has previously been used on horizontal path experiments. This results in a beam foot print at the receiving telescope which is slightly over twice the aperture size. As will be elaborated later in this report this gives rise to rather stringent pointing requirements.

Our long range goals are to assess, develop and validate optical communications technology to support NASA missions[8]. The horizontal terrestrial link experiments we believe will provide an early evaluation of

---

* Correspondence: Email: abhijit.biswas@jpl.nasa.gov; Telephone: 818-354-2415; FAX: 818-393-6142

systems design issues, especially those related to mitigating atmospheric effects, on optical communications links. However, differences in horizontal terrestrial links compared to space to ground links cannot be ignored. The fact that both receiver and transmitter are "immersed" in the atmosphere coupled with the fact that the equivalent of 4 air masses are traversed by the laser beams gives rise to variations in the received beacon focal spot size which would not be encountered if the lasercom terminal were in LEO or higher orbits. On the other hand the static pointing terrestrial link experiment is contrasted by the dynamic, active pointing between spacecraft and ground tracking station. The latter involves slewing across different patches of atmosphere at high angular rates (a few degrees per second for a 400 Km altitude LEO satellite). This we believe will cause a difference in the power spectral density of the intensity fluctuations.

Notwithstanding these important differences the primary objectives for initiating the horizontal path experiments described here, are to: (i) validate uncertainties of optical link analysis at either end; (ii) evaluate the effects of atmospheric turbulence on received signal intensity fluctuations of both the multi-beam beacon and the communications laser beam; (iii) measure and compare the focused spot size at either end of the link to those predicted by atmospheric "seeing" effects; (iv) evaluate the fine steering performance of OCD; and finally, (v) evaluate the end-to-end link performance.

2. EXPERIMENTAL DETAILS

Preliminary results obtained during a week long campaign conducted during June 1998 are reported. Figure 1 shows the 46.8 Km link range with a sectional view of the intervening terrain. As mentioned earlier a 4-beam beacon (780 nm) is transmitted from TMF while pointing the telescope at Strawberry Peak. The OCD located at Strawberry Peak acquires the beacon signal as a focused spot on its focal plane array (FPA) CCD camera. The fine tracking loop of OCD using a two axis fine steering mirror (FSM) points the communications laser beam (840 nm) back to TMF by maintaining a fixed offset between the received
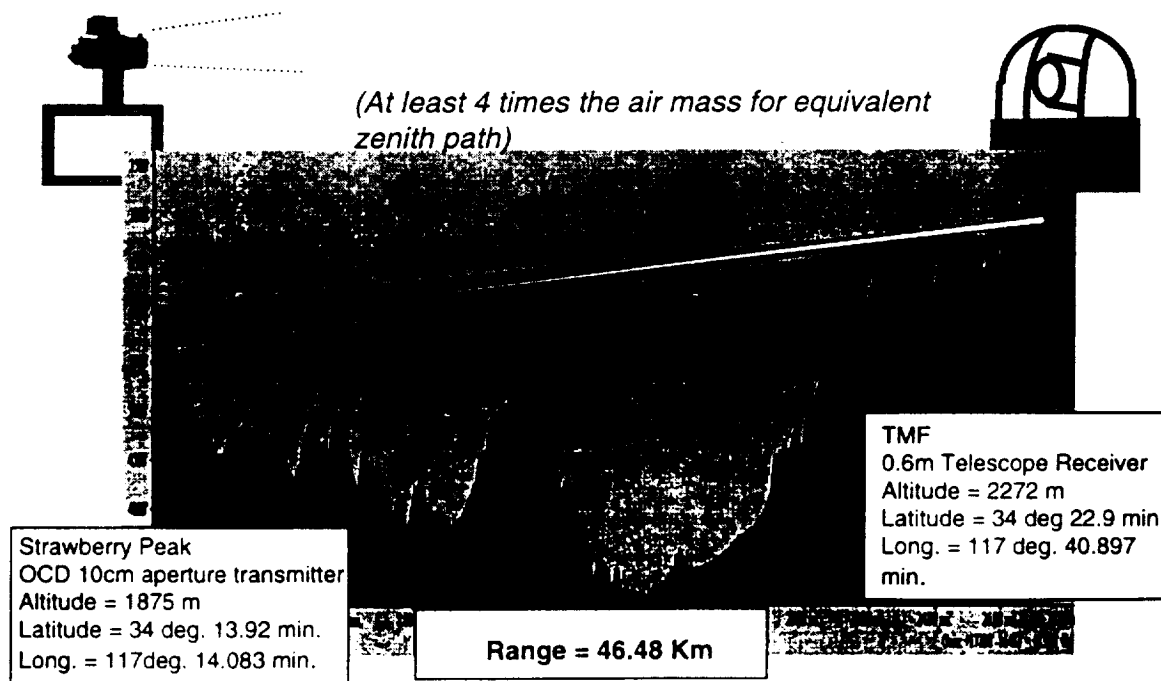

(At least 4 times the air mass for equivalent zenith path)

TMF
0.6m Telescope Receiver
Altitude = 2272 m
Latitude = 34 deg 22.9 min
Long. = 117 deg. 40.897 min.

Strawberry Peak
OCD 10cm aperture transmitter
Altitude = 1875 m
Latitude = 34 deg. 13.92 min.
Long. = 117deg. 14.083 min.

Range = 46.48 Km

Figure 1 Showing a sectional view of the terrain of the intervening optical path used for the horizontal link experiment.

beacon spot and the bore-sighted transmit spot, on the FPA. The beacon spot motion is attributed primarily to atmosphere induced angle of arrival fluctuations at the OCD aperture.

The experimental arrangement, used at either end of the horizontal path, is shown in Figure 2.

2.1 TMF experimental arrangement

The TMF telescope was used in the Coude configuration and Figure 2a shows the setup used in the Coude room. The Coude focus shown in this figure is established with the aid of the focused image of a star at zenith (Vega was used). Ensuring that the receive and transmit focus coincide at this point serves as an aid to achieving transmit- receive co-alignment.

The multi-beam beacon transmit assembly used four separate TE cooled 780 nm diode lasers with a multi-mode fiber coupled to the output. The power emitted at the fiber end was approximately 20 mW for each of these lasers. The output beams from the fiber were first collimated and then guided with the aid of fold mirrors, a combining lens and a dichroic beam splitter, to be output as four co-aligned beams. These co-aligned beams converged to four spots at the Coude focus of the telescope and spread in a manner to provide four sub-aperture spots on the telescope primary mirror. The four beams reflecting outwards from the telescope primary resulted in four co-propagating 100 μrad beams. Based on a 1 mm uncertainty in locating the beam spots at the Coude focus the co-alignment uncertainty is ~ 40 μrad.

As shown in Figure 2a the received signal at the TMF was focused by the telescope and then transmitted by the dichroic beam splitter and collimated using a lens. A portion of the received signal was reflected by a 70/30 beam splitter to allow recording of: (a) intensity fluctuations by a photodiode (4 x 4 mm square and sampled at 1-5 KHz) and (b) pupil images acquired at video frame rates with varying exposure times (30, 20, 10, 5, 1 millisecond) using a CCD camera and frame-grabber. The remaining (transmitted) portion of the receive signal was guided and focused on an avalanche photodiode (APD) with built in transimpedance amplifier. The APD active area was 500 μm with a bandwidth of 450 MHz and a voltage conversion gain of 170 KV/W and a maximum noise equivalent power NEP of 30 fW/√Hz. The effective field of view FOV at the Coude focus was 40 μrad. The APD output is fed to a limiting amplifier which accepts a minimum of 15 mV peak to peak signal. The limiting amplifier signal is fed to a clock and data recovery circuit. A power meter was available for checking power at any desired location of the transmit or receive assembly. A retro-reflector could be used to re-direct the beacon laser spots into the receive assembly pupil imager and focus spot CCD in order to validate receive transmit co-alignment.

The electronic interface diagram also shown in Figure 2a shows how the data acquisition and recording was carried out. The CCD camera outputs were recorded by a PC computer with a frame-grabber card. The APD output was fed to a clock and data recovery assembly. The resulting clock and data outputs could be used for viewing eye-patterns on an oscilloscope or for performing bit-error rate (BER) measurements. The photodiode output was fed directly to a storage digital oscilloscope for recording intensity fluctuations.

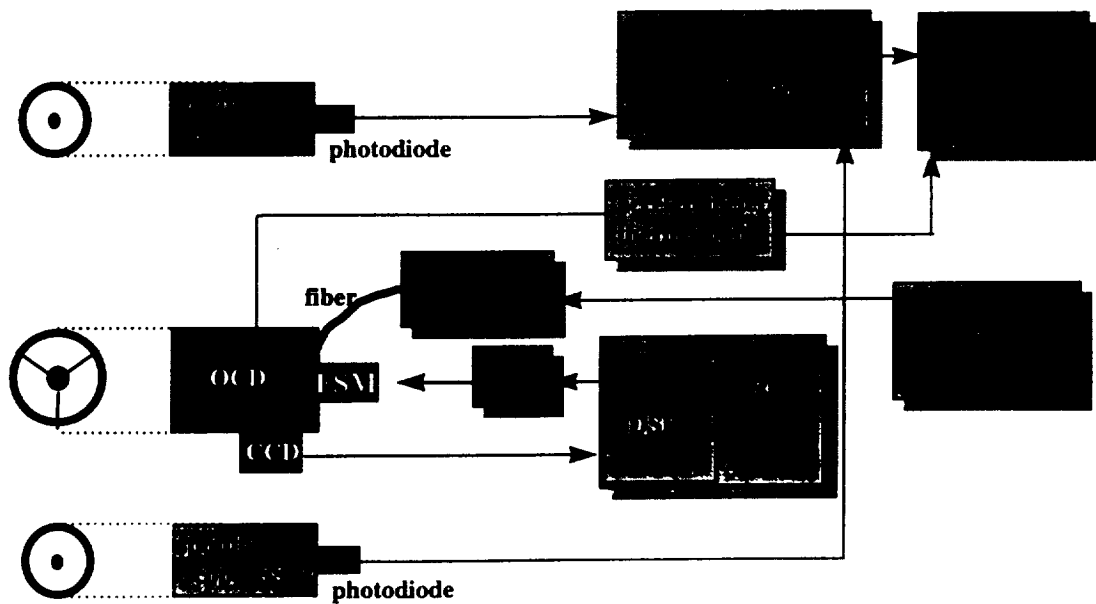## 2.2 Strawberry Peak (SP) experimental arrangement

Figure 2b represents the arrangement used at SP. Shown here are the OCD with the fiber coupled laser assembly and computer interface to control the acquisition and fine tracking functions. The OCD was mounted on a sturdy tripod located on the ground at Strawberry Peak. This arrangement provided a clear line-of-sight to TMF and was preferred over using the tripod on the fire look out tower since the latter arrangement introduced an unknown amount of vibrations and swaying due to wind. Thermocouples and accelerometers were used to independently monitor temperature and vibrations. Two separate spotting telescopes (SS#1 and SS#2 in Fig 2b) were set up on either side of the OCD. SS#1 was approximately 2 m away from the OCD optical axis while SS#2 was 0.5 m on the other side of the OCD. These telescopes were modified to accommodate 4 x 4 mm photodiodes which measured the intensity fluctuations of the beacon beam transmitted from TMF. The spotting scopes were of Maksutov-Cassegrain design with a 90 mm clear aperture and focal ratio of f/13.8.

2.3 Operational procedure

The optical link is initiated by transmitting the multi-beam beacon to SP using the TMF 0.6 m telescope. Previous experience allowed reliable pointing of the telescope to SP. The output of an intensified CCD
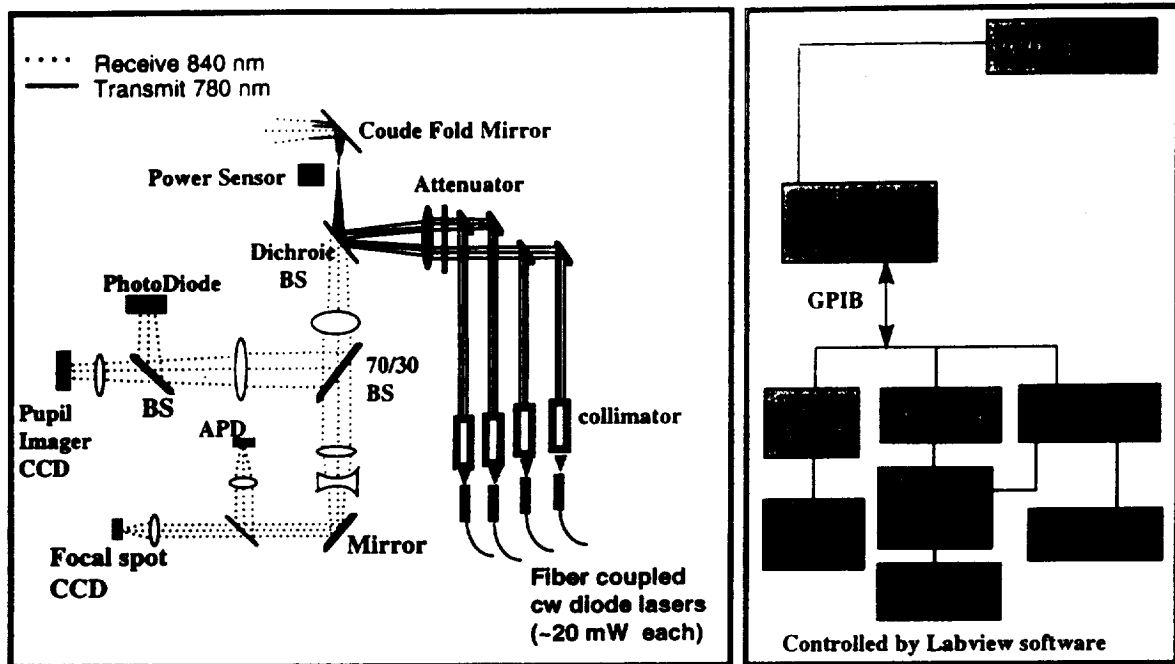
Figure 2 Showing block diagrams for the experimental arrangement used at (a) the TMF Coude room, shown as separate optical and electronic layouts and (b) the Strawberry Peak location. The spotting scope, SS#1 was ~2m on one side of the OCD while SS#2 was ~0.5 m on the other side of the OCD.

camera mounted on a six inch spotting scope co-boresighted to the TMF telescope served as an aid to validate the pointing. Use of the intensified camera was restricted to night time backgrounds. The spotting scopes at SP were manually aligned to acquire the beacon signal. A He:Ne laser beam appropriately

attenuated was first transmitted in order to allow nominal alignment of the spotting scopes while viewing through the eyepiece. Once this was accomplished the eye-piece was replaced with the photodiode assembly and the alignment of the spotting scopes was refined by maximizing the intensity of the beacon laser signal on the photodiodes. The procedure followed for getting the OCD aligned consisted of turning on the OCD transmit laser and blind pointing the OCD toward TMF, while manually adjusting the gimbal azimuth and elevation adjustments. When OCD's transmit laser spot appeared on the TMF spotting scope intensified camera monitor, telephone feedback from TMF to SP allowed finer adjustment. This led to the next stage when the received spot from OCD could be viewed through an IR viewer at the Coude focus. The power sensor was then used to monitor the received power at TMF Coude and once again through telephone feedback this was optimized by electronically stepping the OCD fine steering mirrors. Once nominal alignment was achieved the option of turning on the fine tracking loop of OCD could be invoked and all the measurements to be described initiated. As pointed out our initial alignment procedure relied on night time background conditions, however, once established the link could be maintained past sunrise.

3. RESULTS AND DISCUSSIONS

The results of measurements made together with analysis based on FOCAS[9] and theory[10] are presented and discussed below.

3.1 Link analysis
Nominal, best-case and worst-case predictions of the average power expected at either end of the optical link were obtained by analysis. A comparison between measurements and prediction provides an assessment of the link uncertainties.

Figure 3a shows the comparison between optical power received through the two spotting scopes and the predictions for a single 100 μrad divergence 20 mW beam transmitted from TMF. The system loss consists of the transmit/receive antenna gains, relay optics losses of the transmitting and receiving telescope assemblies *(the latter was verified in the laboratory while the former is based on specified reflectivity and expected performance degradation of the TMF telescope mirrors)* and the space loss. The atmospheric losses are based on FOCAS predictions for varying visibility conditions while the pointing losses account for reasonable mis-pointing limits of the TMF telescope. The measurements agree with nominal predictions. In general, power measured through SS#2 (see Fig 2b) measured ~ 5 dB more power than the SS#1. This observation is consistent with SS#1 being off-axis by ~2m on the foot print at SP, assuming that OCD is nominally on axis.

Figure 3b shows a comparison of the 840 nm optical power received at the Coude focus of the TMF telescope, with predictions. The system loss, atmospheric transmission loss and pointing losses were obtained in a manner identical to that stated above. A beam spread loss term is included since the effect of the atmosphere on the low divergence, near diffraction limited beam exiting the OCD is non-negligible. Night time observations of the beam footprint received at TMF through an IR viewer supported these predictions. In general the measured powers are lower than the nominal predictions. The largest source of uncertainty in this analysis is the TMF telescope receive transmission at 840 nm and the worst-case predictions are probably dominating.

3.2 Atmospheric turbulence effects on the link
Intensity fluctuations arise due to atmospheric perturbations of the propagating laser beam since mechanical jitter is negligible in this static pointing experiment. Thus random phase front perturbations of the propagating wave front cause intensity fluctuations due to constructive and destructive interference at the receiver aperture. Superimposed on these are intensity fluctuations caused by beam wander. The overall intensity fluctuations can be characterized by the scintillation index σ_I^2 defined for received intensity I as:
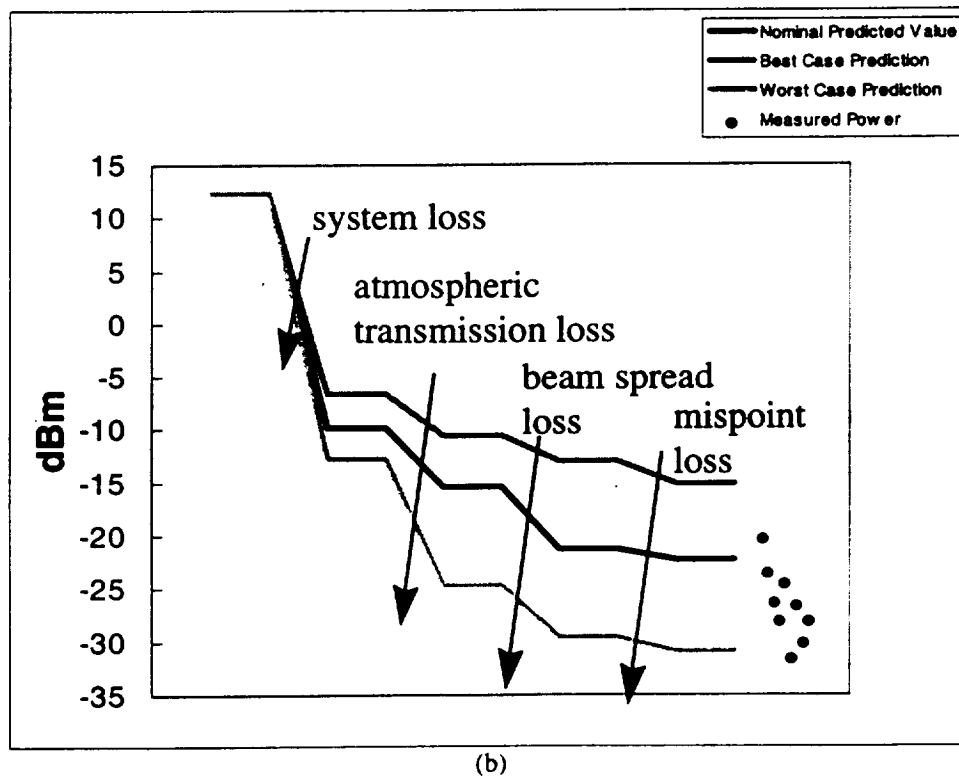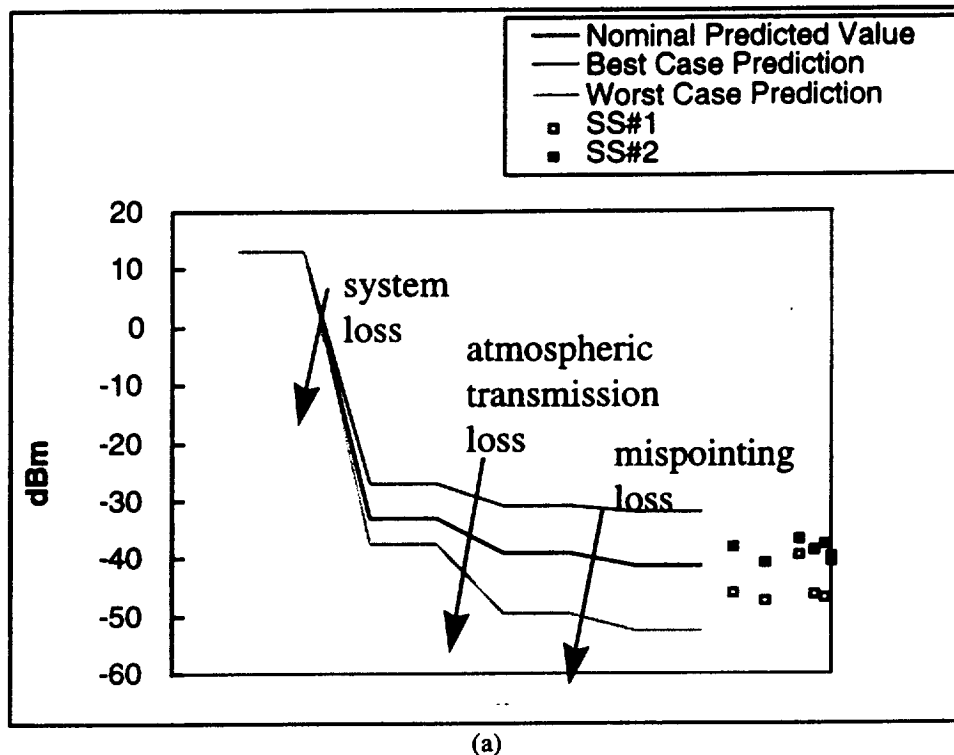
Figure 3 Results of the link analysis compared with (a) measurement for a single 100 µrad, 20 mW, 780 nm laser transmitted through a sub-aperture of the TMF telescope and received through the spotting scopes at SP (b) measurements of the 22 µrad, 17 mW, 840 nm laser transmitted from OCD and received at Coude focus of TMF telescope.

$$\sigma_I^2 = \frac{\langle I^2 \rangle}{\langle I \rangle^2} - 1$$

where the angle brackets denote an ensemble average.

Table 1 shows σ_I^2 for each of the four beacon lasers, as well as, that for the combination of all four co-propagating lasers. The σ_I^2 values were determined for intensities recorded through each of the spotting scopes. These measurements were performed between 10:12 and 10:42 PM on June 18, 1998.

Table 1 Showing σ_I^2 determined from intensity fluctuation measurements performed between 10:12 on and 10:42 PM, June 18, 1998. 1 KHz sampling rate was used.

	Beam 1	Beam 2	Beam 3	Beam 4	Beams 1,2 3 & 4
SS#1	1.04	0.76	0.75	0.85	0.34
SS#2	0.50	0.82	0.68	0.73	0.22

Table 1 shows that 4 beams combined results in a lower value of σ_I^2 as expected. If all four beams had exactly the same irradiance and overlapped perfectly the reduction would have been a factor of 4. In Table 1 the average reduction is 2.35 for SS#1 and 3 for SS#1. The reason why we do not realize the predicted extent of reduction is related to the imperfect overlap as evidenced by the received powers for the individual beams. A second difficulty we experienced with the beacon was a mechanical drift of the beams over time attributed to temperature variations in the Coude room and the standard spring loaded laboratory mounts not being thermo-mechanically stable. The dynamic range of the 4-beam fluctuation reduced to 13-14 dB from the 17-21 dB observed for the single beams

In general the single beam intensity distributions were qualitatively in between a log normal and a Rayleigh distribution as has been shown[11] before. One noteworthy observation was that in general the single beam scintillation indices σ_I^2 obtained for intensity recorded using SS#2 (average 0.66) were less than SS#1 (average 1.04). This observation though in qualitative agreement with Gaussian beam scintillation characteristics shows a larger difference than displacement from the beam axis would theoretically predict. Based on our observations it would appear therefore, that scintillation does get worse with static mis-pointing the quantitative disagreement with theory needs further investigation.

Intensity fluctuations were recorded for the beam received at TMF in a manner identical to that used at SP except for the fact that a much larger (0.6 m) collecting aperture would cause aperture averaging[6] to reduce the observed σ_I^2. A calculation using the Gaussian beam theory predicted $\sigma_I^2 \le 0.1$ compared to plane wave theory which would predict $\sigma_I^2 \sim 0.3$. However, measurements performed between June 16 - 20, at times ranging from 2:00 - 6:00 AM yielded an average value of 0.43 +/- 0.20.

The large discrepancy was attributed to the large extent of beam wander observed. Thus when OCD was blind pointing without tracking the beam wander of the foot print received at TMF was 4 m compared to the predicted maximum peak to peak value of 1m. The measured beam spot size was 1.67 m compared to a 1.2m expected from normal spreading due to beam divergence. This large beam wander induces large intensity fluctuations and they could account for the large σ_I^2 observed.

The focused spot sizes were recorded both for the beacon beam received at SP by the OCD CCD and for the OCD beam transmitted to TMF by the CCD placed in the Coude room (see Fig 2a). These spot sizes can be predicted based on the atmospheric coherence length.

Atmospheric coherence length (r0) predictions for the OCD beam received at TMF can be made assuming Gaussian or plane wave for the limits where r0/2 is much smaller or much larger than the atmospheric inner scale[4]. All these approximations yield r0 values ranging from 3.6 - 12 cm (1 mm atmospheric inner scale

was assumed) with corresponding atmospheric "seeing" from 1.6-5 arcsec. The corresponding focused spot sizes lie in a range from 52 - 172 μm. The actual measured spot size is 162 +/- 6 μm and this would correspond to a "seeing" of 4-5 arcsec (r0~3.5 cm). Considering that TMF night time "seeing" is typically 2-3 arcsec[7] when looking upward this observation seems realistic. The higher range of predicted r0 values where the measurement agrees is satisfied by the plane wave approximation rather than the Gaussian wave approximation.

In addition to the "seeing" effects the angle of arrival fluctuations cause motion of the focal spot. The predicted maximum displacement of the spot center should be contained inside a circle of diameter ~ 70 μm at the TMF focal spot CCD. Our measurements indicate that a blur circle of 200 μm is large enough to contain the observed spot which suggests reasonable agreement with the prediction.

For the spot on the CCD the "seeing" predictions carried out in an identical manner as described above predict a spot size of 57-93 μm, whereas the spot observed on the OCD CCD ~ 64 μm. The angle of arrival fluctuations predicted were ~ 30 μrad but the observed motion of the beacon centroid on the OCD CCD was 60 μrad.

3.3 OCD acquisition and fine tracking performance

The fine tracking mechanism in OCD was used in order to correct the pointing of the transmitted laser beam in order to compensate for the angle of arrival fluctuations of the beacon. The effect of fine tracking on the signal received at TMF was to significantly reduce the frequency of fades as evidenced, for example, by observing the pupil image CCD monitor. However, fine tracking did not completely eliminate fades of the signal received at TMF.

The tracking data logged by OCD indicates that the primary cause for loss of lock during fine tracking was fades in the received beacon intensity. The range over which tracking did work was of the order of 10 dB. Recall that the beacon dynamic range measured independently was ~ 13-14 dB. The standard deviation of the offset between the received beacon and transmitted laser centroid determined while tracking worked was ~3.3 μrad compared to ~1.7 μrad observed in the laboratory.

One of the things not clearly understood as a result of our investigations so far is that even if the beacon fades could be eliminated, for example, by using a larger number of beacon beams, whether tracking would eliminate fades at TMF completely. Though OCD may point the transmit laser beam back at TMF faithfully compensating the beacon beam angle of arrival deviation, subsequent beam wander could cause it to not be centered on the TMF telescope mirror.

3.4 End to end link performance

The output of the APD detector which received the communications signal at TMF was used for clock and data recovery. The recovered signals were used for viewing of eye-patterns on an oscilloscope and bit-error rate testing.

Figure 4 shows examples of best and worst case eye-patterns while transmitting data at 325 Mbps. Similar results (not shown) were obtained at data rates up to 500 Mbps. The eye pattern was recorded on a video tape and later viewing showed that every few seconds the clean eye-pattern represented by Figure 4a was interrupted with patterns similar to Figure 4b. When tracking was turned off the eye-pattern degenerated to the Figure 4b like appearance. Evidently the clean eye-pattern of Figure 4a is interrupted due to fades at TMF, whether these are solely due to beacon intensity fades at SP have not been resolved. The best instantaneous bit-error rates recorded with 1 second updates were 1E-6 it generally fluctuated between 1E-5 and 1E-2.

4.0 CONCLUSION

In conclusion a bi-directional link analysis was nominally validated though refining and narrowing the uncertainties would be in order. The multi-beam beacon results confirm the scintillation mitigation.

(a)

... and *data recovery on a 325*
... *The eye-pattern fluctuated*

... the beacon assembly was
... averaging did not eliminate
... compensated beam wander.
... plane wave prediction of
... insistent with predictions
... the prediction by a factor

of 2. An initial evaluation of the OCD fine tracking was conducted revealing a nominal 10 dB intensity range and a 3.3 μrad tracking error standard deviation. An unresolved issue is whether OCD fine tracking would be capable of preventing the beam footprint at TMF from being displaced with respect to the primary to an extent that prevented deep fades.

We need to eliminate beacon fades at the OCD completely by improving the co-alignment and if necessary by increasing the number of beams. Once this is accomplished we will be able to resolve whether a sustained low BER optical link can be achieved along the horizontal path used.

ACKNOWLEDGEMENTS

REFERENCES

1. M. Jeganathan, S. Monacos, "Performance analysis and electronic packaging of the optical communications demonstrator," *Free-Space Laser Communications Technologies X, Proceedings of SPIE*, [Ed. G. Stephen Mecherle], Volume 3266, 33-41, 1998.
2. K.E. Wilson, A. Biswas, S. Bloom, V. Chan,"Effect of Aperture Averaging on a 570 Mbps 42 Km Horizontal Path optical Link," *Atmospheric Propagation and Remote Sensing IV, Proceedings SPIE*, Ed. J. Christopher Dainty, Vol. 2471, 30, April 1995.
3. V. Chan, S. Bloom, "Results of 150 Km, 1 Gbps lasercom validation experiment using aircraft motion simulator," *Free-Space Laser Communications Technologies X, Proceedings of SPIE*, [Ed. G. Stephen Mecherle], Volume 2699, 60-70, 1998.
4. I. I. Kim, E. Woodbridge, V. Chan, B. R. Strickland, "Scintillation measurements performed during the limited-visibility lasercom experiment," *Free-Space Laser Communications Technologies X, Proceedings of SPIE*, [Ed. G. Stephen Mecherle], Volume 3266, 209-220, 1998.
5. P. A. Lightsey, "Scintillation in ground-to-space and retroreflected laser beams," Opt. Engg., 33, 2535, 1994
6. J. D. Shelton, "Turbulence-induced scintillation on Gaussian-beam waves: theoretical and observations from a laser illuminated satellite," J. Opt. Soc. Am. A, 12, 2172-2181, 1995.
7. M. Jeganathan, M. Toyoshima, K. Wilson, J. James, G. Xu and J. Lesh. "Data Analysis Results form the GOLD Experiments," *Free-Space Laser Communications Technologies IX, Proceedings of SPIE*. [Ed. G. Stephen Mecherle], Volume 2990, 70-81, 1997.
8. J. V. Sandusky, M. Jeganathan, G. G. Ortiz, A. Biswas, S. Lee, G. Parker, B. Liu, D. Johnson, J. R. Lesh, "Overview of the preliminary design of the optical communication demonstration and high-rate link facility," *Free-Space Laser Communications Technologies X, Proceedings of SPIE*, [Ed. G. Stephen Mecherle], Volume 3615, (In Press), 1999.
9. M. Jeganathan, "Development of the free-space optical communications analysis software," *Free-Space Laser Communications Technologies X, Proceedings of SPIE*, [Ed. G. Stephen Mecherle], Volume 3266, 90-98, 1998.
10. L. C. Andrews and R. L. Phillips. *Laser Beam Propagation through Random Media*, Chapters 6 and 7, SPIE Optical Engineering Press, Bellingham, Washington USA, 1998.
11. R. L. Phillips, L. C. Andrews, "Measured statistics of laser-light scattering in atmospheric turbulence", J. Opt. Soc. Am., 17, 1440-1445, 1981.