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Aperture Averaging of Optical Scintillations in CO_2 DIAL
(Poster Presentation)

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ABSTRACT

Atmospheric turbulence causes several effects on a propagating laser beam. We have previously studied the effects of beam spreading and beam wander, and feel we have a good understanding of their impact on CO_2 DIAL. Another effect is scintillation where atmospheric turbulence causes irradiance fluctuations within the envelope of the beam profile. We believe that scintillation at the target plays an important role in LIDAR return statistics. A Huygens-Fresnel wave optics computer simulation for propagating beams through atmospheric optical turbulence has been previously developed. We modify this simulation to include the effects of reflective speckle and examine its application in comparison with experimental data.

Introduction

CO_2 DIAL (Differential Absorption LIDAR) systems are currently being used at Los Alamos National Laboratory. The system propagates a beam over long distances through the atmosphere. Beam energy is reflected from the earth's surface (or some other target) back to the transmitter/receiver assembly where the signal is detected.

In an earlier paper we detailed a model for the spreading and wander of the beam due to turbulence.[1] Our previous effort was based on well established work in the area of optical beam propagation through atmospheric optical turbulence.[2-7] In that work we discussed C_n^2, the index of refraction structure parameter, C_T^2, the temperature structure parameter and described methods of measuring each using scintillometers and temperature probes. In this paper we make use of data provided by a Scintech Scintillometer which works on the same principle as the Lockheed Scintillometer we discussed previously.

Our model at that time did not account for changes in irradiance fluctuations levels with changing turbulence conditions. In this work we modify an existing model which accounts for transmitter to target as well as target to telescope scintillation and apply it to our system with reflective speckle. The aim is to determine the importance of the effects of scintillation.

Model

The model we will use takes into account how atmospheric turbulence affects the intensity variance of the outgoing and returning beam, including the effects of target induced speckle. We neglect the effects of albedo variations at the target, fluctuations in laser output energy, detector noise and jitter although they may be included later as we improve our model. In this initial approach, we apply a Huygens-Fresnel wave optics computer simulation to model the effects of turbulence.[8] A random phase is added to the optical phase at the target to simulate reflective speckle. This random phase addition is kept constant from shot to shot to simulate an unchanging target. We then propagate this distorted phase front through a return path which includes atmospheric turbulence.

The Huygens-Fresnel wave optics computer simulation uses an N x N array of complex numbers in a plane perpendicular to the propagation axis to represent the electric-field. In order to satisfy the Nyquist criterion, the grid size, Δx, is

$$\Delta x = \sqrt{\frac{\lambda \cdot L}{N}} \tag{1}$$

where λ is the laser wavelength, L is the propagation distance and N is the number of grid points per side. An initial electric-field which is Gaussian in nature (matching, as closely as possible, the characteristics of our real transmitter beam) is the input for the propagation simulation. The simulation propagates this initial electric-field by dividing the path into steps and applying a phase screen (simulating turbulence) at each step. Once at the target, the electric-field is randomized (simulating reflective speckle) through the relation

$$E_{reflected} = E_{target} \cdot e^{i \cdot 2\pi \cdot random(n)} \tag{2}$$

where E_{target} is the complex electric-field incident on the target after propagation through turbulence, $E_{reflected}$ is the electric-field reflected from the target and *random(n)* is a uniformly distributed random number between 0 and 1. This resulting electric-field is then propagated back to the telescope with turbulence effects induced using the same phase screens as the path out. In the telescope plane, irradiance over an area equivalent to that seen by the telescope is summed to simulate the return signal that would be measured. The return signal is then analyzed over a number of realizations of turbulence to determine the normalized standard deviation of the mean.

Following are examples of irradiance patterns simulated by the Huygens-Fresnel computer simulations. These were calculated and plotted using MATLAB[9] with a 512 X 512 array. The propagation distance was 3300 m from transmitter to target taken in 5 steps of 660 m each. As the beam propagation path was horizontal, and about 3 m above ground, a constant C_n^2 value was used. Figure 1 shows the case for zero turbulence with a Gaussian beam incident on target.

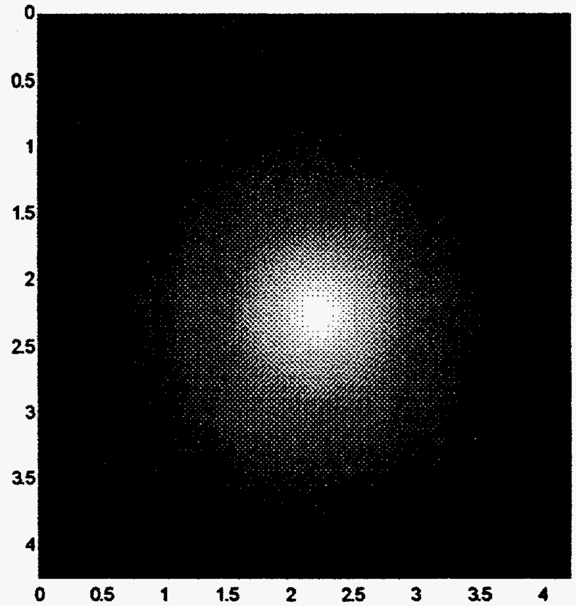


Figure 1. Image of Gaussian beam intensity on target with zero turbulence. The grid dimensions shown in all figures is in meters.

The speckle pattern at the receiver from this Gaussian is depicted in Figure 2. After phase randomization at the target, the beam was propagated in 5 steps of 660 m each for a total distance of 3300 m to the telescope plane. As stated before, in this return propagation we simulated turbulence effects such that the beam propagated through the same turbulence as on the outgoing path.

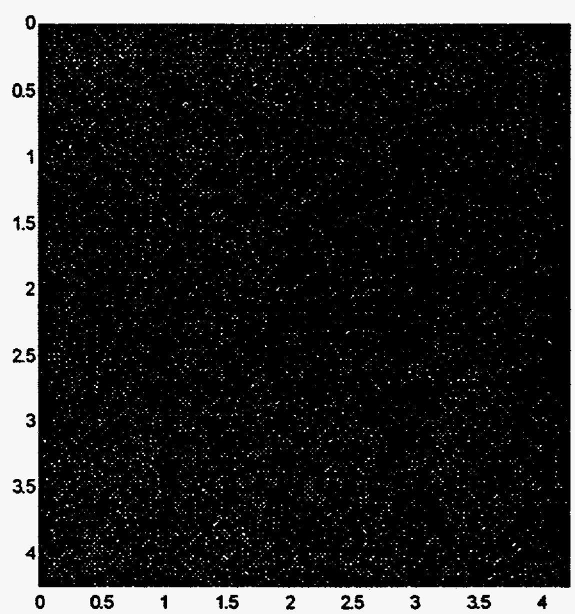


Figure 2. Image of speckle intensity pattern at the telescope with zero turbulence.

Our analysis of the single shot speckle pattern reveals agreement with theory in irradiance distribution (exponential falloff) and correlation size. The theoretical value of the speckle correlation size, D_c, for speckle generated by a Gaussian irradiance pattern on the target is[10]

$$D_c = \frac{2 \cdot \lambda \cdot L}{\pi \cdot w_T} \tag{3}$$

where λ is the wavelength of the LIDAR pulse, L is the propagation distance from the target to the telescope and w_T is the beam spot size on the target. Figure 3 is a comparison of the correlation sizes produced by the simulation for zero turbulence with that predicted by theory. These were calculated by taking the autocorrelation of the single shot speckle pattern. We then estimated the correlation size from the point where the autocorrelation function was down by e^{-1} of the peak value.

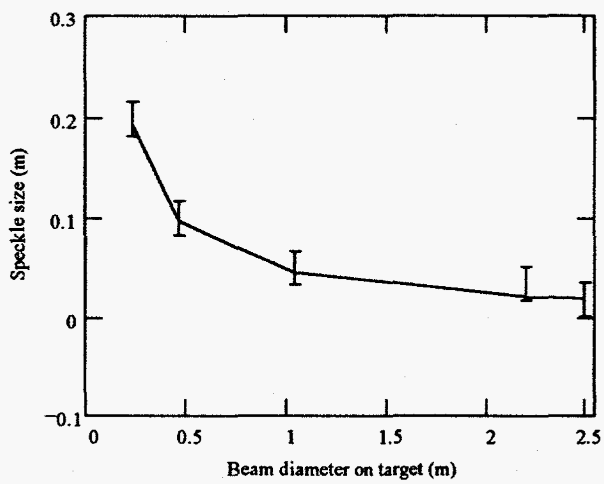


Figure 3. Comparison of simulated speckle size in zero turbulence (error bars) with that predicted by theory (line) as a function of beam diameter on target.

Also, the contributions to irradiance fluctuations due only to reflective speckle for this situation are predicted at roughly 4.73% using,

$$SNR^{-1} = \frac{4 \cdot \lambda \cdot L}{\pi \cdot D_T \cdot D_r} \tag{4}$$

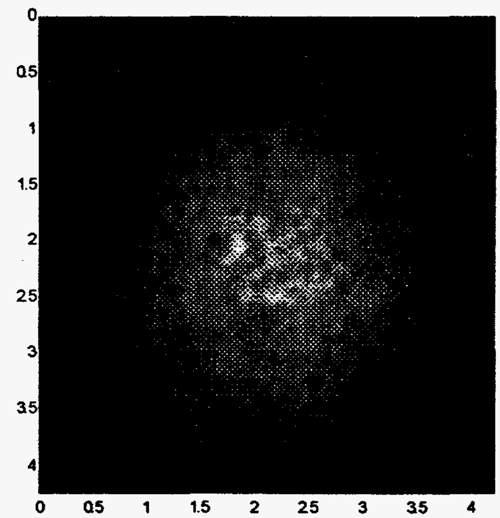
where D_T is the diameter of the Gaussian beam at the target and D_r is the effective diameter at the telescope/receiver. The computer simulation of irradiance fluctuations due only to independent reflective speckle (zero turbulence) yielded 4.51 % $\pm$ 0.40 %. Hence, the simulation yields results within the margin of error of that predicted by theory.

While investigating the speckle generation portion of this model we found an interesting result: the correlation sizes decreased with increasing turbulence indicating a break up of the reflective speckle in the telescope plane. As an example of this effect consider a beam diameter on target of D_T = 0.231 m, the propagation distance $L = 3300$ m and the wavelength λ = 10.6 μm. In zero turbulence, the theoretical speckle coherence diameter is

D_c = 0.193 m. The simulation rendered a value of $D_c = 0.198 \pm 0.016$ m. For a turbulence level of $C_n^2 = 3 \times 10^{-13}\,m^{-2/3}$, the correlation size was found from the simulation to be $D_c = 0.099 \pm 0.016$ m or about half of the zero turbulence value. It should be noted, however, that as turbulence increases, the beam on target is no longer a pristine Gaussian pattern as shall be seen below. Therefore comparison of these correlation sizes with that given by Equation (3) is of decreasing validity with increasing turbulence.

Figure 4 shows the irradiance pattern at the target and the reflective speckle pattern at the telescope plane for $C_n^2 = 1 \times 10^{-14}\,m^{-2/3}$. In Figure 5 we depict the progression from mild to severe distortion of the Gaussian beam on target for increasing levels of turbulence. Figure 6 is comparable to Figure 4 except for $C_n^2 = 5 \times 10^{-13}\,m^{-2/3}$.

a)



b)

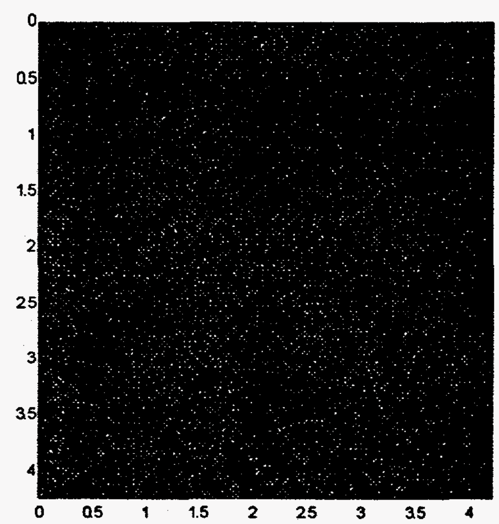
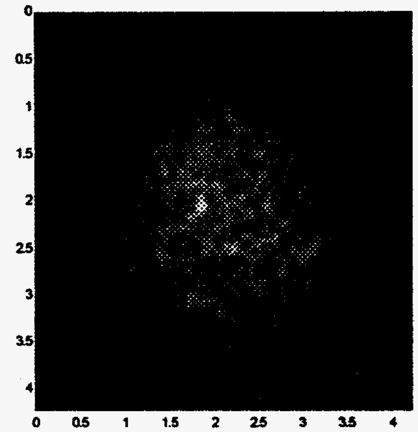


Figure 4. Images of a) intensity pattern on target and b) its speckle intensity pattern at the telescope plane for $C_n^2 = 1 \times 10^{-14}\,m^{-2/3}$.

a)



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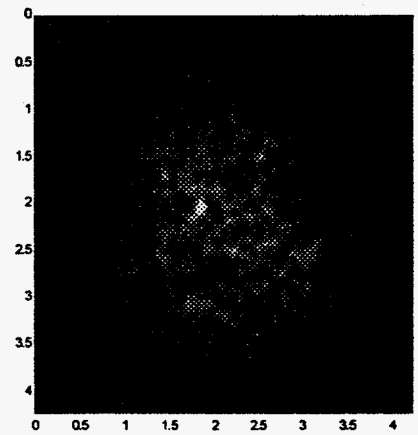


c)

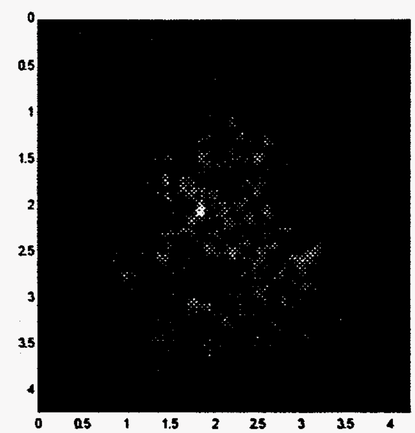
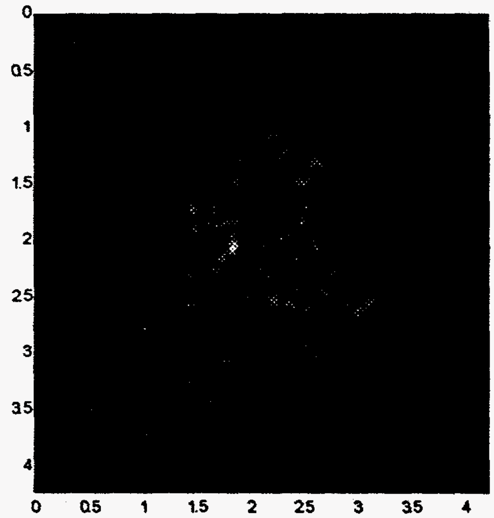


Figure 5. Image of intensity pattern on target with a) $C_n^2 = 5 \times 10^{-14}$ $m^{-2/3}$, b) $C_n^2 = 1 \times 10^{-13}$ $m^{-2/3}$ and c) $C_n^2 = 3 \times 10^{-13}$ $m^{-2/3}$.

a)



b)

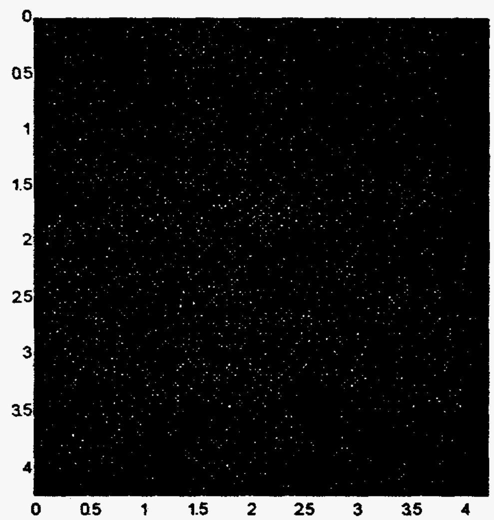


Figure 6. Images of a) intensity pattern on target and b) its speckle intensity pattern at the telescope plane for $C_n^2 = 5 \times 10^{-13}\ m^{-2/3}$.

Figure 7 shows a side by side comparison of the computer simulated fluctuations of irradiance summations at the telescope aperture for two different levels of turbulence. There is a definite increase in these fluctuations for the higher turbulence level. This is reinforced by Figure 8 which shows a general increase in these fluctuations for increasing C_n^2.

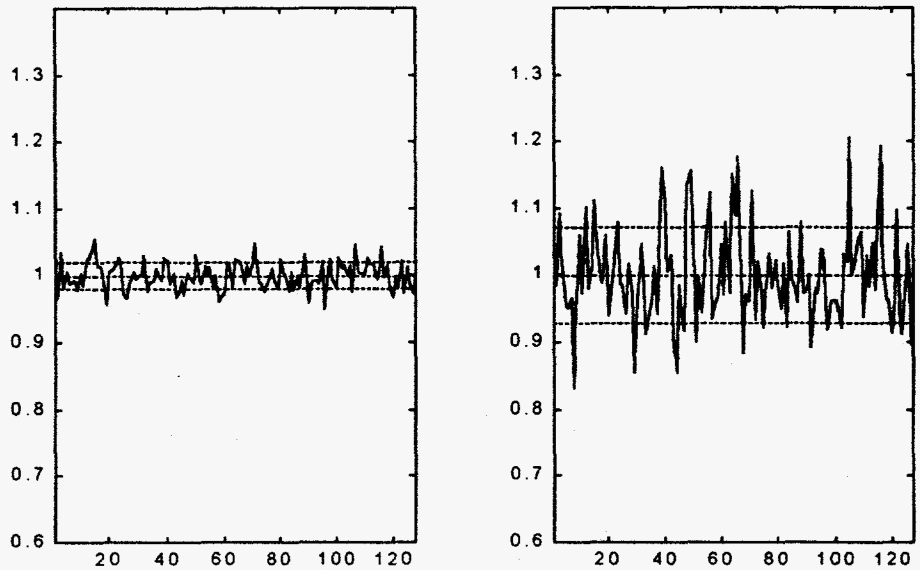


Figure 7. Computer simulation intensity summations (normalized) at aperture for $C_n^2 = 1 \times 10^{-14}$ $m^{-2/3}$ (left) and $C_n^2 = 6 \times 10^{-13}$ $m^{-2/3}$ (right) for the 128 realizations of turbulence. The horizontal lines represent the normalized mean and standard deviation from the mean.

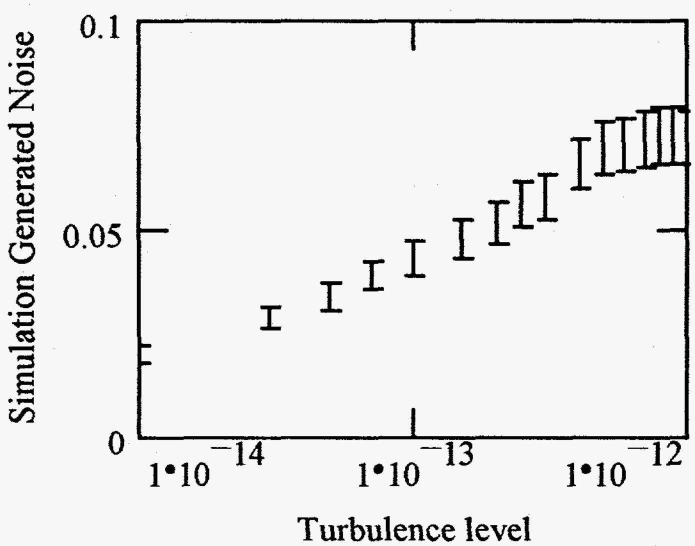


Figure 8. Variation of irradiance fluctuations predicted by computer simulation versus C_n^2.

With recent discussion of the importance of return path turbulence[11], we examined the effect of turbulence on the outgoing path relative to turbulence on the return path with results shown in Figure 9. In both cases the reflective speckle randomization remained constant for all 128 realizations of turbulence thus simulating an unchanging target. For low turbulence, the return path effects are greater. However, as turbulence levels increase, the outgoing path turbulence tends to dominate. This outgoing path effect does appear to saturate at $C_n^2 = 1 \times 10^{-12}$ $m^{-2/3}$ and again equals that of the return path effect at $C_n^2 = 3 \times 10^{-12}$ $m^{-2/3}$. One explanation for this behavior is that before saturation, there is an increasing variation of the intensity pattern on the target. This results in irradiation of different portions of the target (essentially different speckle generators) on each realization of atmospheric turbulence and a corresponding increase in the noise seen at the telescope. Since our target was modeled with a fixed randomization for speckle generation, the intensity variation on target has the effect, with increasing turbulence (before saturation), of illuminating an increasingly different set of speckle generators for each realization of turbulence.

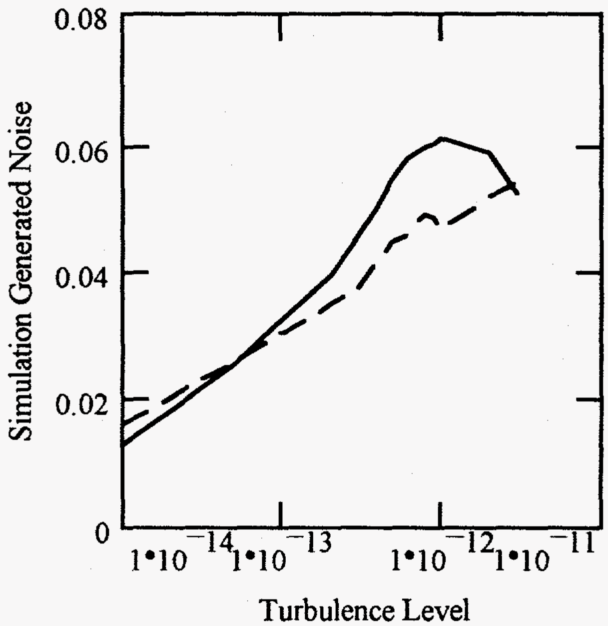


Figure 9. Variation of irradiance fluctuations predicted by computer simulation for: a) turbulence on outgoing path only (solid line) and b) turbulence on return path only (dashed line) versus C_n^2.

Measurements

The LANL Tan Trailer system provided measurements for comparison with the computer simulation. Measurements were taken at the 3300 m (3 km site) and averaged over two minutes (~4000 pulses). The values predicted by the computer simulation used 128 turbulence realizations and were based on one minute averages of C_n^2 from the Scintech Scintillometer. The beam diameter on target was estimated from earlier measurements as ~ 2.5 m.[12] In this case the entire beam was contained within the target area (~ 4 m x 4 m).

Note that the Scintech measured path averaged values at the 3 km site at a height of 1.5 m above the surface. We have converted Scintech values to values at the 3 m beam height using[13],

$$C_n^2(h) = C_n^2(h_o)\cdot\left[\frac{h_o}{h}\right]^{2/3} \tag{5}$$

where h_o is the height of the Scintech measurements (1.5 m), h is the beam height (3 m), $C_n^2(h_o)$ is the value of Scintech index of refraction structure parameter measurements and $C_n^2(h)$ are the adjusted values for the beam height.

Results and Discussion

Figures 10 and 11 compare the shot-to-shot noise on two measured lines to the results of the computer simulation. The two lines shown are typical of the results obtained on most of the 44 lines measured.

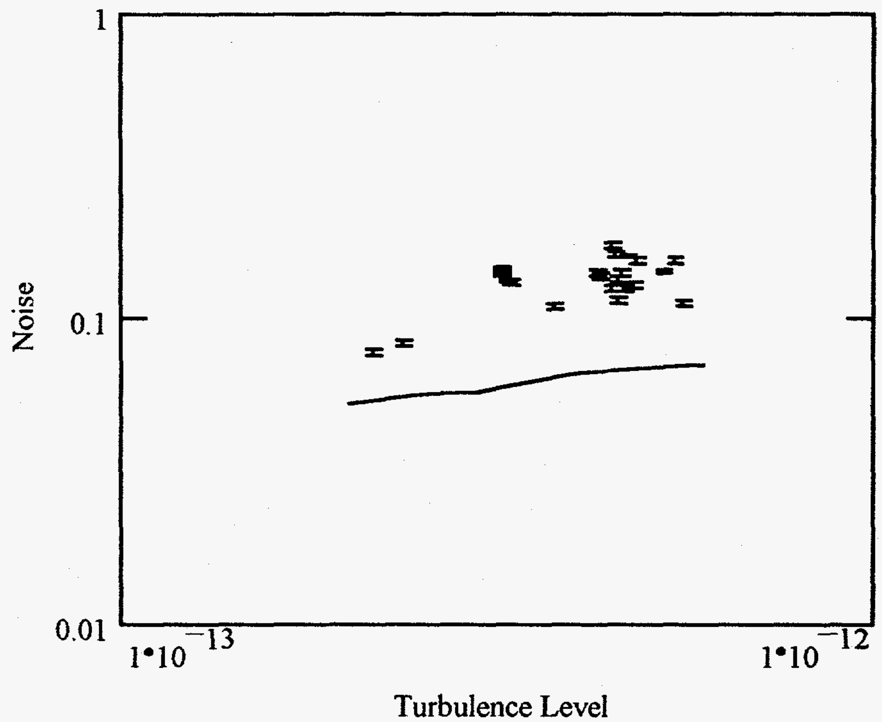


Figure 10. Comparison of the irradiance fluctuations predicted by the computer simulation (solid line) with that measured on a CO_2 wavelength (error bars) versus C_n^2 on 19 June 1996. In this case a propagation distance to the target of 3300 m and a beam diameter on target of 2.5 m were used. Diurnally varying values of C_n^2 as measured by a Scintech scintillometer were used.

The trend of increasing irradiance fluctuations with increasing C_n^2 values seen in computer simulations is in general agreement with measured values. However, the level of irradiance fluctuations does not match. This may be due in part to the fact that other noise sources such as laser noise, detector noise and jitter, at both the transmitter and target, were neglected in the computer simulation.

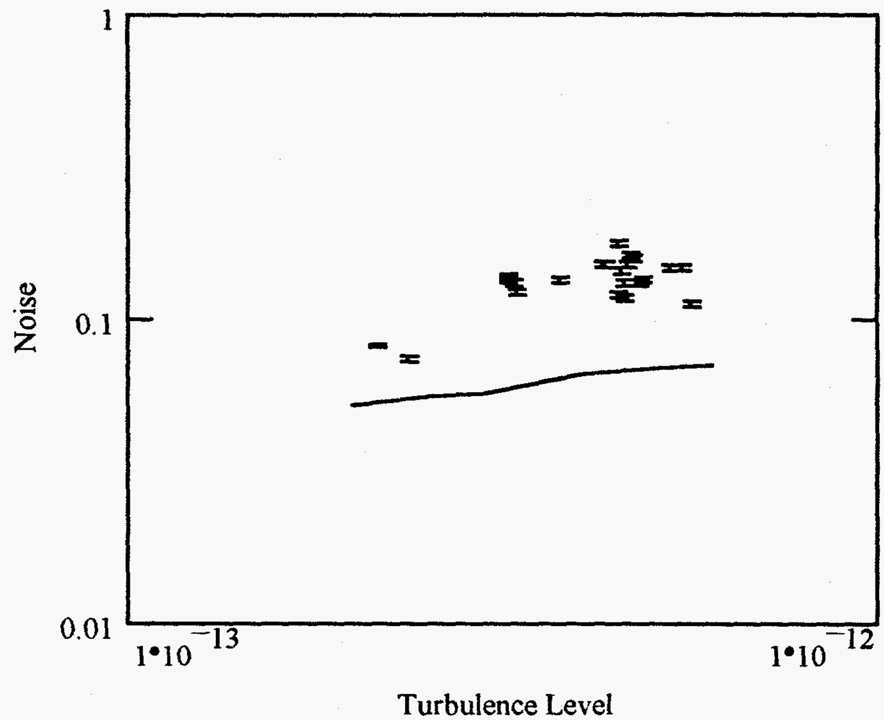


Figure 11. Comparison of the irradiance fluctuations predicted by the computer simulation (solid line) with that measured on a second CO_2 wavelength (error bars) versus C_n^2 on 19 June 1996. Parameters are the same as in the previous figure.

The results seem to indicate that the computer simulation can be reasonably accurate in predicting the trend of measured irradiance fluctuations for our system under the same conditions. Our application of the model does not account for albedo variations, detector noise, jitter and other effects. We intend to improve our model by including these factors. Other improvements may include generating a larger number of phase screens to better simulate turbulence. We may also increase the number of grid elements, N, for better resolution. These last two improvements will, however, have a significant effect on processing time. For each level of turbulence modeled, the 128 realizations of a 512 x 512 grid and 5 phase screens took approximately 6 hours to run on a Pentium 200 MHz with 64 MB of RAM.

Conclusions

These initial results indicate that turbulence plays a measurable role in the irradiance fluctuations of a CO_2 DIAL system. There is, in general, an increase in irradiance fluctuations with increasing C_n^2. Our simulation also found that both paths to and from the target have varying relative importance depending on C_n^2. We also found an indication that turbulence breaks up the target induced speckle into smaller coherence sizes.

Acknowledgments

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