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Huygens-Fresnel wave-optics simulation of atmospheric optical turbulence and reflective speckle in CO_2 differential absorption LIDAR (DIAL)

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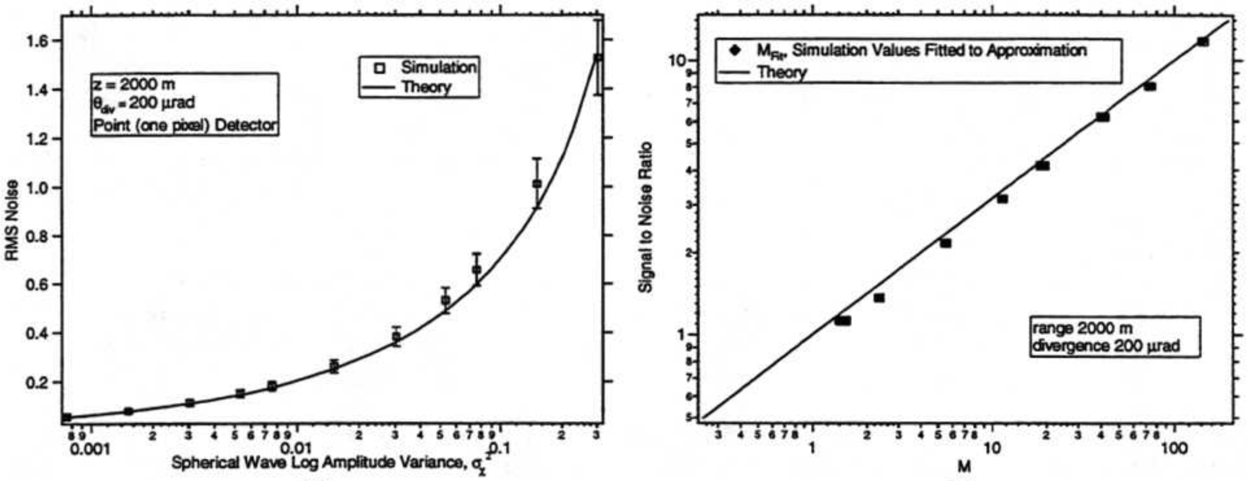
The measurement sensitivity of CO_2 differential absorption LIDAR (DIAL) can be affected by a number of different processes. Two of these processes are atmospheric optical turbulence and reflective speckle. Atmospheric optical turbulence affects the spatial distribution of energy and phase. Measurable effects include beam spreading, beam wander and scintillation which can result in increased shot-to-shot signal noise. In addition, reflective speckle alone has been shown to have a major impact on the sensitivity of CO_2 DIAL. We have developed a Huygens-Fresnel wave optics propagation code to simulate the effects of these two processes. Previously, we compared the ability of our model to predict these separate effects with a combination of theory and experimental observations.[1,2] However, in real DIAL systems it is a combination of these phenomena, the interaction of atmospheric optical turbulence and reflective speckle, which influences the results.[3] We present preliminary results of the comparison of our combined effects simulation with experimental measurements over a finite aperture.

The model employs the Fresnel-Kirchoff Theorem with the Fresnel approximation and assumes paraxial, on-axis propagation.[4,5] The atmospheric optical turbulence effects are approximated by a series of phase screens over several propagation steps.[6,7] Details of our model have been presented earlier.[1,2] This model is applied to a LIDAR geometry in which the beam propagates from the transmitter/receiver through an optically turbulent atmosphere to a diffuse hard target. After scattering from the target, the portion of the beam that reflects back to our receiver propagates along the same optically turbulent path.

We have shown that this model works well predicting separately the effects of atmospheric optical turbulence and reflective speckle.[1,2] The simulation of long-term turbulent beam spreading was in agreement with both experimental data and theoretical predictions. Simulation values for point detector scintillation due to atmospheric optical turbulence showed agreement with theory. This last comparison is provided as an example of our previous work in Figure 1 (a).

We also considered separately the reflective speckle effects in the absence of atmospheric optical turbulence.[1,2] A surface that is rough on the scale of the laser wavelength scatters the coherent LIDAR pulse, which produces a complex interference pattern.[8] This pattern is granular in appearance and is commonly referred to as a speckle pattern. Simulated speckle coherence "sizes" were in excellent agreement with those predicted by theory. The intensity probability distributions predicted by our simulation for circular receiver apertures of varying radii agreed with those observed in experiment and expected from theory. Characterized by the parameter M, which is interpreted as the number of speckle inside the receiver for an average pulse, we compared these probability distributions to geometrical predictions from the ratio of the receiver aperture area to the estimated speckle correlation area. We also compared the *M* value from these probability distributions to the signal to noise ratio obtained from the simulation. This latter comparison is presented in Figure 1 (b) as another example of the resulting excellent agreement between the simulation and theoretical predictions. The simulated intensity probability distributions were consistent with those measured experimentally.[9]



(a) (b)

Figure 1. (a) Scintillation of a laser beam for a point (one pixel ~ 0.0046 m wide) receiver after a 2000 m round trip propagation assuming no reflective speckle generation. (b) Signal to noise ratio versus *M* for 1000 pulse intensity probability distributions and a 2000 m one way propagation with independent speckle realizations. In both simulation scenarios five propagation steps were used for each leg of the round trip with a 512 x 512 grid and a beam divergence of 200 µrad.

We conducted experiments during June and July 1998 in the Nevada desert under conditions of varying levels of turbulence (C_n^2) at ranges of ~1340 m and ~2160 m. Our LIDAR consisted of a CO_2 laser with an effective pulse rate per line of ~113 Hz. The receiver configuration was annular with an inner diameter of ~ 4.5" and an outer diameter of ~ 12". We concurrently measured the turbulence level with an incoherent near infrared scintillometer propagating over a path that was approximately a parallel azimuthally to our LIDAR beam but on a slant path at a different height.[10] In determining effective turbulence levels for the experiment, we considered this difference in paths.[11]

The model predictions for the combined effects on single shot RMS noise and comparison to experimental results appear in Figure 2 for the two ranges mentioned above. The two lines we used for this comparison were chosen because of their negligible atmospheric absorption under normal operating conditions. The model, which neglects atmospheric absorption, accurately predicts the level of single shot RMS noise. It also correctly predicts the trend of increasing noise with increasing C_n^2.

For this LIDAR geometry, the single shot RMS noise is 40-50% larger under the higher turbulence conditions. The impact of this trend for LIDAR operations is significant. Even if multi-shot averaging is used to improve the LIDAR measurement, the initial noise level will be markedly higher for conditions of increased turbulence.

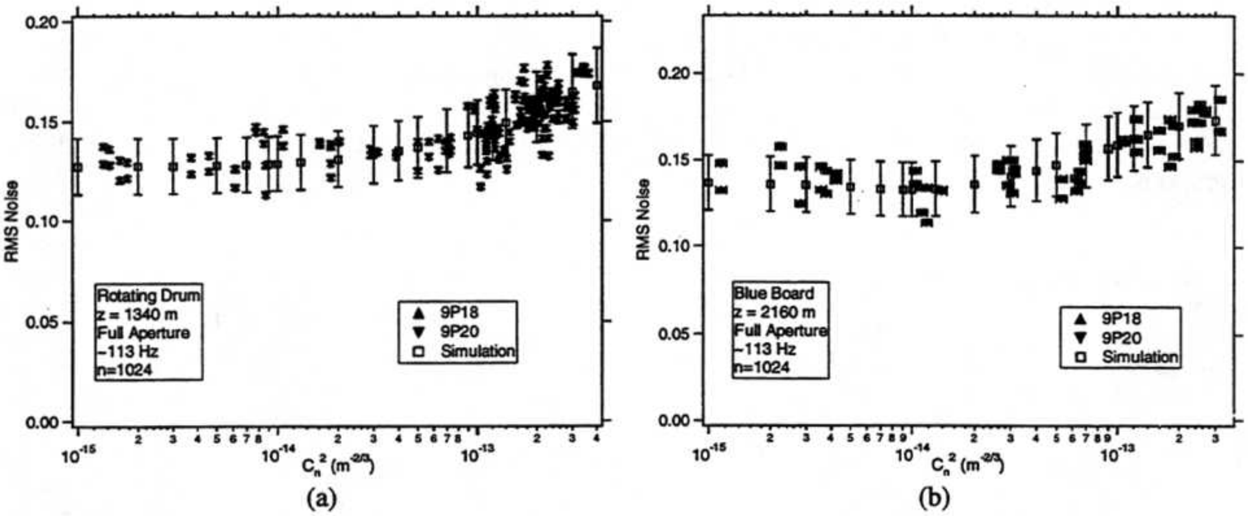


Figure 2. Comparisons of simulation with experiment for targets at (a) ~1340 m and (b) ~2160 m. The beam divergence was approximated as ~340 µrad. Receiver area is ~ 0.06 m^2. The simulation grid was 1024 x 1024. Five propagation steps were used for each leg of the round trip path. The propagation path was assumed horizontal with a uniform turbulence level over the path.

These preliminary results provide experimental verification for our modeling of the combined effects of atmospheric optical turbulence and reflective speckle. The results also emphasize, for this LIDAR geometry, the impact of increased turbulence levels on LIDAR operations and provide motivation for further study.

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