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Mid-wave infrared DIAL noise phenomenology

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ABSTRACT

LLNL has utilized optical parametric oscillator technology to develop and field a rapidly-tunable mid-wave infrared (MWIR) DIAL system. The system can be tuned at up to 1 KHz over the 3.3-3.8 micron spectral region, where hydrogen-bond stretching modes provide spectroscopic signatures for a wide variety of chemicals. We have fielded the DIAL system on the LLNL site with targets at horizontal ranges of up to 2 km. We have collected data on noise levels and correlations and their dependences on range, turbulence, and receiver aperture size. In this paper we describe some of the implications of this data for MWIR DIAL phenomenology. In particular, the interplay of turbulence and speckle to produce the observed noise fluctuations at short ranges (<500 m) is presented.

Keywords: DIAL, remote sensing, speckle, turbulence

1. INTRODUCTION

Differential absorption LIDAR (DIAL) utilizing laser light backscattered from topographic targets can at best achieve a noise floor often set by the speckle pattern of the reflected light at the receiver aperture. The behavior of the speckle pattern and the resulting noise are influenced by many factors; e.g., pulse-to-pulse beam jitter, target jitter, relative transmitter/target motion, and atmospheric turbulence. Of particular interest for this paper is the interaction between speckle and turbulence. There are many facets to the interaction, some of which have been discussed in previous work,¹⁻⁴ primarily for CO₂ DIAL systems. In the mid-wave infrared (MWIR, $\sim 3\text{-}4\ \mu\text{m}$), the effects should be qualitatively similar to those at CO₂ wavelengths, but with relative importance modified by the larger effects of turbulence and smaller speckle cell sizes found at shorter wavelengths. For example, the observation in Schmitt, et al.³ of a large increase in speckle-produced SNR (signal to noise ratio) for short range and low turbulence, as the speckle pattern at the receiver aperture ceases to be modulated by jitter and turbulence effects, should be much harder to reproduce in the MWIR.

Our experience has shown that at long horizontal range and high turbulence, our system noise is dominated by the modulation of the average return intensity by turbulence on the return path. This noise is characterized by strong correlations between returns that are closely spaced in time ($\sim$ few milliseconds) but widely separated in frequency ($\sim 100\ \text{cm}^{-1}$). In order to avoid the effects of return path turbulence as much as possible, the measurements described here were done at short range (240 and 450 m), but with turbulence levels varying with time of day from $C_n^2 \sim 10^{-14}$ to $5 \times 10^{-13}\ \text{m}^{-2/3}$.

2. SPECKLE AND TURBULENCE INTERACTION

At short range and low turbulence (specifically, when the transverse coherence length ρ_0 is greater than the target spot size D_{targ}), system noise should be dominated by the detector/amplifier contribution and a contribution from speckle produced by laser beam jitter. The latter contribution arises if the outgoing laser beam illuminates different scatterers on the target as it jitters in angle pulse-to-pulse.

As turbulence or range increase, several effects will modify the noise. First, an additional jitter component will be added to the outgoing laser light by turbulence. Second, the speckle pattern returning from the target will be shifted across the receiver aperture by turbulence on the return path. Third, as ρ_0 becomes comparable to D_{targ} , turbulence will modulate the phase of scatterers on the target and produce changing speckle patterns at the receiver. Also, the outgoing beam will spread out because of turbulent scattering: this spread will increase the target spot size and by itself would decrease the speckle cell size (hence decrease speckle noise) at the receiver.

Additionally, as the turbulence increases the outgoing laser light will break up into changing blobs on the target. This scintillation will increase the speckle correlation length (cell size) at the receiver and hence increase speckle noise. Finally, at

long horizontal ranges and high turbulence levels, modulation of the average intensity of the scattered light by turbulence on the return-path will dominate the noise.

3. THE DIAL SYSTEM AND OPERATING CONDITIONS

The laser part of our DIAL system has been described in some detail by Velsko, et al.⁵ For the measurements described here, the system operated with a pulse-repetition-frequency of 125 Hz at $3.66 \mu\text{m}$ (2733 cm^{-1}). The laser light was generated in ~ 10 -ns, $350 \mu\text{J}$ pulses from a LiNbO_3 optical parametric oscillator pumped by Nd:YAG at $1.064 \mu\text{m}$ and injection-seeded at $1.5 \mu\text{m}$.

The targets at 240 m and 450 m were 2×2 ft squares of flame-sprayed aluminum. The targets were rigidly mounted on vertical posts with the intent to mitigate the effects of target motion (jitter) on speckle noise. As the wind conditions were quite high (~ 10 knots on average) during the experiments it is likely all target motion was not eliminated. The targets were aligned off normal to the beam direction to avoid specular glints at the receiver.

By scanning the beam across the target, we were able to obtain good estimates of the average optical beam size. Fig. 1 shows the aligned averages of multiple horizontal scans across the two targets, along with the expected return signal profiles for a Gaussian intensity profile with three different beam sizes – the best fit of $D_{\text{target}} = 30 \text{ cm}$ diameter (at the $1/e^2$ -intensity points) and $D_{\text{target}} \pm 10 \text{ cm}$. The fit can be seen to be both quite good and sensitive to the actual beam size. (The asymmetry in the scan from the 240 m target was caused by a surveying pole that appeared in the middle of the night in the line of sight to the target; the asymmetry was not included in the fit to beam size.) It is apparent from fig. 1 that the transmitted beam is approximately collimated over the target range chosen. The target scans were measured when the turbulence was $\sim 1/2$ of its peak value during the day at $C_n^2 \sim 2 \times 10^{-13} \text{ m}^{-2/3}$. Values of the refractive index structure constant C_n^2 due to atmospheric turbulence were inferred (using the Richardson-number-based expressions for C_n^2 , eq. 6-16 and 6-17, of The Infrared Handbook⁶) from measurements of wind speed and temperature taken at several heights on a weather tower on-site at LLNL. Fig. 2 shows a typical daily profile for the C_n^2 we estimated at the beam propagation height of 3 m.

Figure 1: Measurement of Beam Diameter ($1/e^2$). Left: 240 meter target range; right: 450 meter target range. Both: solid = Gaussian fits, points = measurements.

4. NOISE MEASUREMENT AND ANALYSIS

The transmitter/receiver system allowed scanning to multiple targets with sufficient ease to switch between the 240-m and 450-m targets on a run by run basis during the day if desired. Additionally, the receiver telescope aperture could be varied run by run with a maximum diameter of 35 cm. The noise measurements were accomplished by measuring the return from a target

Figure 2: Calculated C_n^2 dependence on time of day for the results present.

at various apertures for >20,000 pulses/aperture then switching to a different target. This procedure was repeated during the day for turbulence near its peak value (~2 pm) until it approached its minimum value (~8 pm). The C_n^2 plot in fig. 2 is over the day (12 June, 1997) on which the noise measurements were taken. The measurements are shown in fig. 3. Figure 3 presents the average noise for a particular run. The noise is calculated as the normalized deviation of the return signal (scaled by the transmitted energy) over 8-s time slices (1000 pulses) and averaged over a run of ~20,000 - 40,000 pulses. The vertical error bars correspond to the deviation of the noise values over a single run.

Figure 3: Noise dependence on time of day. Left: 240 meter target range; right: 450 meter target range. Both: solid = speckle noise, points = measurements with error bars.

The solid lines plotted in fig. 3 correspond to the speckle noise given by

$$\sigma_{spk} = \left(1 + 1.088 \frac{D_{rec}^2}{D_{corr}^2} \right)^{-\frac{1}{2}}, \quad (1)$$

where D_{rec} is the receiver diameter and D_{corr} is the speckle correlation diameter in the receiver plane given by

$$D_{corr} = \frac{4\lambda L}{\pi D_{targ}}. \quad (2)$$

Here λ is the laser wavelength, and L is the distance from the target to the receiver. Eq. 1 is derived for a Gaussian beam and a circular aperture using the formalism given in Goodman,⁷ and assumes an ensemble of independent speckle patterns. Two observations can be made from fig. 3. The noise levels are consistently above the fully modulated speckle noise level and the measured noise follows C_n^2 . Both of these observations are reasonable given the calculated turbulence levels during the measurements as will be discussed in the remainder of this paper.

The effect of turbulence during the measurements is related to the transverse coherence length, ρ_0 , given by

$$\rho_0 = (0.55k^2C_n^2L)^{-3/5} \quad (3)$$

and $k \equiv 2\pi/\lambda$ for a spherical wave. ρ_0 is plotted in fig. 4 assuming the C_n^2 profile of fig. 2. During most of the day ρ_0 is less than D_{targ} and becomes comparable to the beam diameter near sunset.

Figure 4: ρ_0 dependence on time of day.

The effect of turbulence on short-term beam spread $\langle \rho_s^2 \rangle$ and beam centroid motion (jitter) $\langle \rho_c^2 \rangle$ can be described^{8,9} by

$$\langle \rho_s^2 \rangle = \frac{4L^2}{k^2 D^2} + \frac{D^2}{4} \left(1 - \frac{L}{f} \right)^2 + \frac{4L^2}{k^2 \rho_0^2} \left[1 - 0.62 \left(\frac{\rho_0}{D} \right)^{1/3} \right]^{6/5}, \quad (4)$$

and

$$\langle \rho_c^2 \rangle \simeq \frac{2.97L^2}{k^2 \rho_0^{5/3} D^{1/3}}, \quad (5)$$

for a beam with an initial diameter D and radius of curvature $-f$. Equations 4 and 5 assume $\rho_0 < D$ and the target is in the near field of the effective coherent aperture, $L \ll k\rho_0^2$. For the target ranges chosen turbulence does not significantly alter the beam size or pointing jitter. However, given $\rho_0 \leq D_{targ}$, the turbulence will modulate the phase of the scatterers on the target and varying speckle patterns are expected on a pulse-to-pulse basis. This argument becomes less valid as ρ_0 becomes on the order of $D_{targ}/2$. This would make the measurements ~ 8 pm fall outside the fully modulated speckle regime. However high wind conditions during the measurements suggest target motion would be sufficient to maintain the full speckle modulation. Additionally, the C_n^2 values are changing rapidly in this time period and errors in their calculation can easily account for the

continued full speckle noise level for the final runs. This leads one to expect the measured noise level to be at least that of the speckle limit shown in fig. 3.

Turbulence can additionally affect the noise level via intensity scintillations and return path turbulence effects. Intensity scintillations can break-up the transmitted beam into beamlets, thereby increasing D_{corr} and increasing the observed speckle noise. Return path turbulence will modulate the intensity of the light scattered by the target observed at the receiver and also increase the noise level. Beam intensity scintillations can be described by the variance in the log-amplitude fluctuations, σ_χ^2 , and the intensity fluctuations, σ_I^2 , using

$$\sigma_\chi^2 = 0.307k^{7/6}L^{11/6}C_n^2, \quad (6)$$

and

$$\sigma_I^2 = \exp(4\sigma_\chi^2) - 1, \quad (7)$$

assuming the beam behaves as a plane wave (reasonable for our nearly collimated beam over the chosen target ranges). For the conditions of the current measurements, $\sigma_\chi^2 \leq 0.3$, and so the above expressions for scintillation are within the range of validity of the Rytov approximation. The calculated standard deviation of the intensity is shown in fig. 5. Estimation of the noise due to return path turbulence involves propagating the electric field at the target with random realizations for the surface roughness through the turbulence in the path to the receiver and integrating over the receiver aperture. This process is tedious but the calculated noise variance can be shown to scale linearly with C_n^2 if C_n^2 (and hence σ_χ^2) is moderate. Additionally, for fixed D_{targ} and L we find the variance scales approximately inversely with receiver diameter for $D_{rec} \geq 5$ cm.

Figure 5: σ_I dependence on time of day.

If the noise due to intensity scintillation on the outgoing beam is assumed to arise from a modification of the speckle noise as viewed by the receiver, a functional dependence similar to return path turbulence would be expected. Additionally, a dependence on target distance consistent with that of intensity scintillation would also be expected. In order to investigate this ad-hoc noise assumption we consider the total noise observed, σ_{total} , to be

$$\sigma_{tot} = \sqrt{\sigma_{spk}^2 + \sigma_{ex}^2}, \quad (8)$$

where σ_{ex} is the noise in excess of the speckle value. The detector noise was experimentally determined to be several orders of magnitude below our typical measured noise. This excess noise is shown in fig. 6 with the error bars in noise as described previously. The solid curves in fig. 6 correspond to the empirical fit given by

$$\sigma_{ex} = \sigma_{ex0} \sqrt{\left(\frac{L}{L_0}\right)^{\frac{11}{6}} \left(\frac{D_0}{D_{rec}}\right) \left(\frac{C_n^2}{C_{n0}^2}\right)}, \quad (9)$$

where σ_{ex0} , L_0 , D_0 , and C_{n0}^2 are constants. The curves in fig. 6 are generated with $\sigma_{ex0} = 0.021$, $L_0 = 450$ m, $D_0 = 0.35$ m, and $C_{n0}^2 = 10^{-13}$ m^{-2/3}. The estimated values for return-path turbulence noise under these conditions are found to be a small component ($\leq 25\%$) of the measured excess noise.

Figure 6: Dependence of the noise in excess of speckle noise on C_n^2 for various receiver apertures. Left: 240 meter target range; right: 450 meter target range. Both: solid = fit, points = measurements with error bars.

5. DISCUSSION

We have experimentally investigated the interaction of speckle and turbulence to produce noise on a MWIR LIDAR return signal. The measurements were obtained with sufficiently short target ranges to produce low to moderate levels of integrated turbulence. In this regime the beam spreading and centroid motion (jitter) due to turbulence were very small and the beam was essentially collimated. However, the turbulence level was adequate – given the relatively large beam diameter – for the transverse coherence length, ρ_0 , to be sufficiently small to produce fully-modulated speckle noise. The variation of the observed noise on C_n^2 also indicates an important noise term dependent on turbulence. The parametric dependence of this additional noise term on C_n^2 , receiver diameter and range suggest it is dependent on the interaction of intensity scintillations and return path

turbulence with the target speckle. As the effects of turbulence on the noise fluctuations are quite apparent in the MWIR even at short target ranges where turbulent beam spread and jitter are negligible, we would expect that most of the effects of speckle-turbulence interaction (e.g., return path turbulence) should also be observable in CO₂ DIAL experiments.

Given the uncertainty in many of the quantities used in determining the noise components (most notably C_n^2) from the current data, isolating the magnitudes of the noise phenomena with certainty is not possible. Several extensions of the current experiments are planned to address this difficulty. First is a direct measurement of C_n^2 . Second is to vary (reduce) the transmitted beam diameter to allow the turbulent regime of $\rho_0 > D_{targ}$ to be investigated. Additionally, the use of multiple wavelengths to investigate the correlation of the fluctuations at different wavelengths is planned (this includes operation at higher pulse repetition rates, i.e. 250-1000 Hz). If return path turbulence is significant then the correlation of noise between wavelengths will be strong, whereas scintillation and speckle effects will produce uncorrelated returns. Additional measurements taken under calm wind conditions are also planned to rule out effects of target motion.

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