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FM-DIAL Preliminary Detection Sensitivity Measurements

Appendix E

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5-9-2002
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1. Introduction

This update briefly reports new measurements and analysis that are used to determine the noise equivalent absorbance for the FM-DIAL (frequency modulation – differential absorption light detection and ranging) system. The modeling work that is performed in parallel with the LIDAR experiments provides a useful benchmark to predict the performance of an experimental setup, and a detection sensitivity to strive to realize. Often, the theoretical performance is difficult to obtain experimentally, but with careful design experiments can come close to being limited by fundamental noise sources.

The basic idea behind the experiments in this work consists of directing a laser toward a scattering target, and collecting the scattered photons using a telescope. This is very similar to just having a laser traversing a long path length absorption cell, and the emerging beam imaged onto a detector. In these types of experiments the conversion to concentration is performed using Beer's law. The absorbance is given as:

$$A = -\ln\left(\frac{I - \Delta I}{I}\right). \tag{1}$$

The smallest absorbance that can be measured is related to the smallest ΔI that can be measured. Often, the smallest measurable value of ΔI is equated to the high frequency noise floor of the measurement system. For the FM-DIAL experiment, this would just be the noise observed at the detector when the laser was turned off or blocked. This type of estimation of the absorbance sensitivity provides a useful limit; however, this is an optimistic (and sometimes misleading) way to report the experimental sensitivity. Using this simple approach tends to neglect important noise sources, for instance laser noise, speckle noise, atmospheric effects, as well as other noise sources. A more robust method of determining the detection sensitivity involves performing an actual experiment many times and analyzing the results to determine the true experimental sensitivity. This approach has been used, and the preliminary results provide a statistically significant estimate of experimental detection sensitivity.

2. Experimental

The FM-DIAL system was set up for outdoor field experiments with the emitted laser beam directed toward a 10” diameter tube 24” long, with the far end capped off with a foam scattering surface. The tube was designed to release nitrous oxide (N_2O), and provide partial containment for the ‘plume’ that was released. The distance from the FM-DIAL cart to the gas tube was about 40 meters. The transmitted laser beam was adjusted using a rudimentary transmit beam expanding telescope, such that the power projected into the detection field of view was maximized. The returned power was found to be approximately 1nW.

The laser frequency was ramped at 100 Hz, scanning over approximately 1 cm^{-1}, with a high-speed 100 kHz sinusoidal modulation imposed. The high-frequency modulation was about 0.1 cm^{-1} peak-to-peak (optimized for atmospherically broadened absorption features), and provides the modulation used for lock-in detection. The ramp provides an optical frequency scan to get an actual spectrum over about two N_2O absorption features. Using lock-in detection, the first derivative signal was recorded on a digital oscilloscope and used for estimating the absorbance and detection sensitivity. Data collection consisted of saving ten blocks of 512 individual scans totaling 5120 scans. A second data collection consisted of an actual release of N_2O from the gas tube where a single block of 512 scans was collected. Representative samples from the first and second data collect are presented in Figures 1A and 1B.

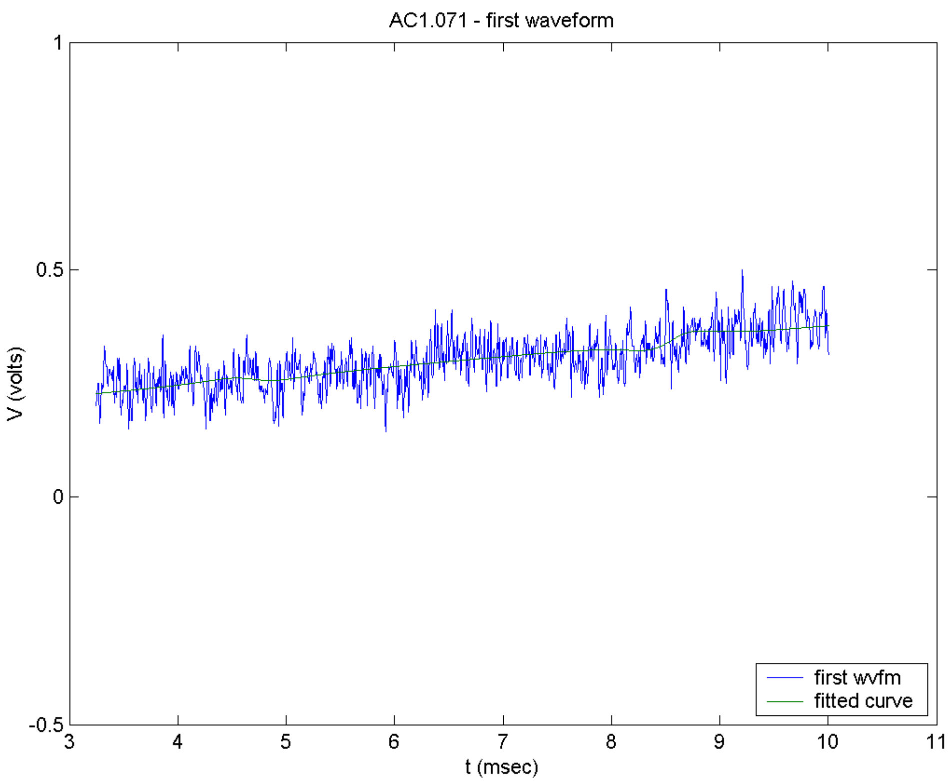

Figure 1A. Representative data trace from the first collect. N_2O was not present for this set of experiments, but a fit was use to determine the amount of possible signal present in the scan.

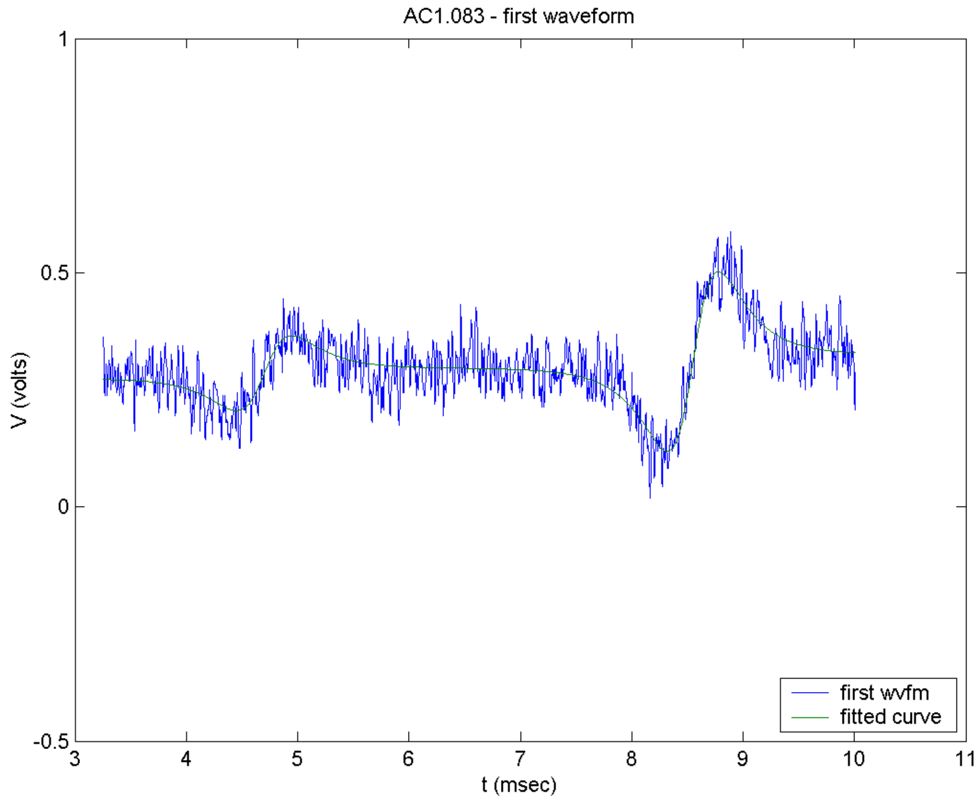

Figure 1B. Representative data trace from the second collect. The gas delivery apparatus was used to flow N_2O into the detection region. Two peaks are easily observed even in this single trace.

3. Analysis

A. Concentration Estimator

Several recent advances have taken place enabling us to estimate the observed absorbance from derivative signals. The absorbance estimator equation that has been derived uses the residual amplitude modulation (RAM) inherent in quantum cascade lasers (QCL). Usually the RAM is regarded as a nuisance for sensor applications; however, in this application it is useful and eliminates the need for a double modulation. The problem is that the calculation of absorbance (equation(1)), requires the ΔI, as well as I to be measured. Using FM, a derivative technique, eliminates the laser dc return signal. Because the QCL has a linear power curve (the slope efficiency), the dc return is proportional to the observed RAM signal. Figure 2 shows the result of the second data collect where gas is released into the atmosphere.

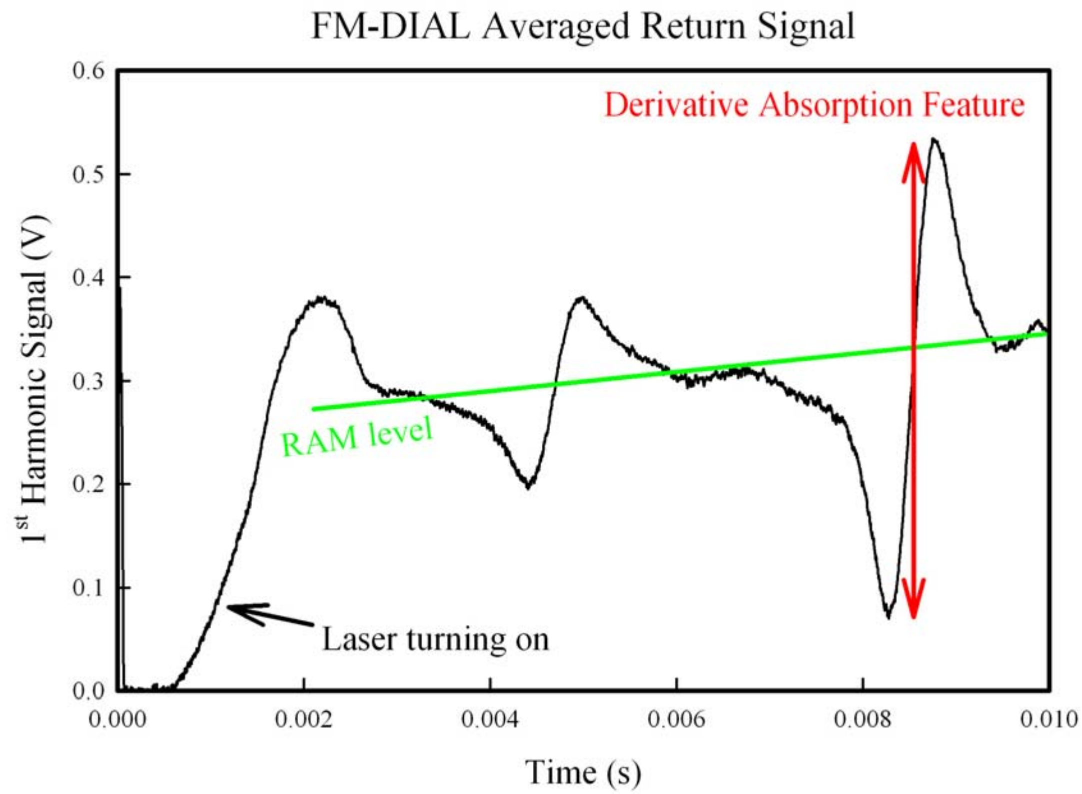

Figure 2. This data consists of the average of a 512-trace block of data where N_2O gas is being released from the release apparatus. The laser is initially off, and the laser is tuned over two N_2O transitions that show up as derivative lineshapes at about 0.0045 s and 0.0085 s. The RAM level is shown as a green line, and the magnitude of the derivative signal from the absorption feature is shown in red.

The data from Figure 2 may be used to estimate the observed absorbance according to the equation:

$$A = \frac{1}{h_1}\left(\frac{I_m}{I_0 - I_T}\right)\left(\frac{V_{1\max} - V_{1\min}}{2 * V_{off}}\right), \quad (2)$$

where h_1 is a constant that may be calculated for a particular modulation pattern, I_m is the laser current modulation, I_0 is laser current at the peak position, I_T is the laser threshold current, V_{1max} is the maximum of the first derivative signal, V_{1min} is the minimum of the first derivative signal, and V_{off} is the RAM level at the peak center. This equation has been simplified using the small absorbance approximation, however the more general equation may be used as well. Using this equation, and the data in Figure 2, the observed absorbance is calculated to be 0.101 and corresponds to a 9.8 torr×m column integrated density, using a line strength for N_2O of 7.02×10^{-22} cm/molecule (cross-section of $\sigma=3.2\times10^{-21}$ cm^2/molecule). Note that the absorption cross-section of some cw agents may be stronger than this cross-section by up to three orders of magnitude, but may require tuning/modulating the laser over a larger optical frequency range. In practice, sections of the data in Figure 2 are fit to a derivative lineshape(s) to determine V_{1max}-

V_{1min}, and the RAM level. The accuracy of the absorbance estimator was quantitatively verified using gas cell experiments in the lab. Quantitative agreement with the known amount of gas in the cell, and with direct absorption experiments, was easily obtained at the 1-2 percent level.

B. Noise Equivalent Absorbance.

The data from the first collect was used to determine the detection sensitivity *experimentally realized* from a preliminary set of experiments. The data consisted of ten groups of 512 individual scans similar to Figure 1A. Each of the 5120 profiles was fit to determine the magnitude of the two derivative lineshapes in the spectrum. Each profile provides information to produce a concentration estimate for both lines in the spectrum. Over the time of the measurement of 5120 profiles, about 100 seconds, the additional noise sources beyond the high frequency noise floor of the detector were observed and analyzed. Figure 3 shows the estimated absorbance in the absence of N_2O for each of the two peaks. The variations in this type of plot allow the construction of realistic noise equivalent absorbances for this type of experiment. For this data set, the predicted (from 512 waveforms) absorbance randomly varied above and below zero, with a standard deviation of 3×10^{-4} absorbance units. A total of ten blocks of similar data were analyzed to produce an average of 3.9×10^{-4} which is the standard deviation for a measurement using a group of 512 waveforms. This noise equivalent absorbance is for a standard deviation, which is 1σ;

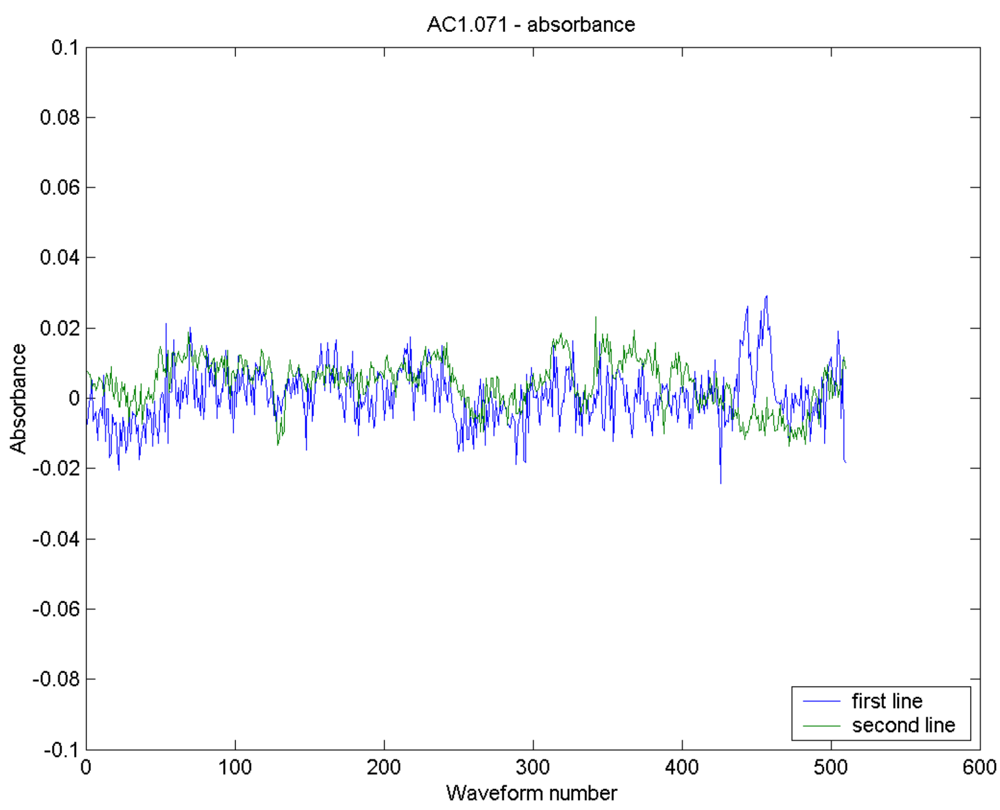

Figure 3. Estimated absorbance for the case of no absorbing species present in the detection region.

however, a more realistic detection limit would be 2σ, corresponding to a confidence of 95% for normally distributed data. While the data is not completely normally distributed, the 2 σ noise equivalent absorbance of 8×10^{-4} represents a useful baseline for the detection sensitivity of the FM-DIAL experiment.

Further work on characterizing the behavior of various backgrounds is in progress. As more is learned about how the backgrounds can vary, this information can potentially be included in a statistical analysis to better extract the detection sensitivity. It is worth pointing out that while the experiment was somewhat optimized, several factor can give signal to noise enhancements over the current experiments. First, a better transmit telescope that is capable of directing all of the laser power into the detection region could provide an enhancement. Because the preliminary results described above appear to be limited by thermal and detector noise rather than speckle, more powerful QC lasers, optimized transmit and receive optics, and optimized, state-of-the-art MWIR detectors will all improve detection sensitivity, even at this range.

The second data collection consisted of an actual atmospheric release of N_2O immediately after the first set of data was collected, using the same apparatus. Representative data was shown in Figure 1b, and the waveforms were analyzed identically to data from the first collection. Each trace was fit to determine the magnitude of two derivative linshapes, the results of the measured absorbance is shown in Figure 4. The variations in absorbance are similar, but larger, to the variations in Figure 3. Part of the variations in Figure 4 are due to the actual concentration of N_2O changing as the plume concentration changes, the rest are due to the statistical fluctuations of the measurement. From this data, the absorbance was calculated to be 0.101 on average, with a signal to noise of about 170 for an average of 512 traces (about 10 seconds of averaging). This data is equivalent to averaging all 512 traces together, and fitting the resulting waveform as presented in Figure 2; however, in this case the statistical fluctuations may actually be monitored as a function of time.

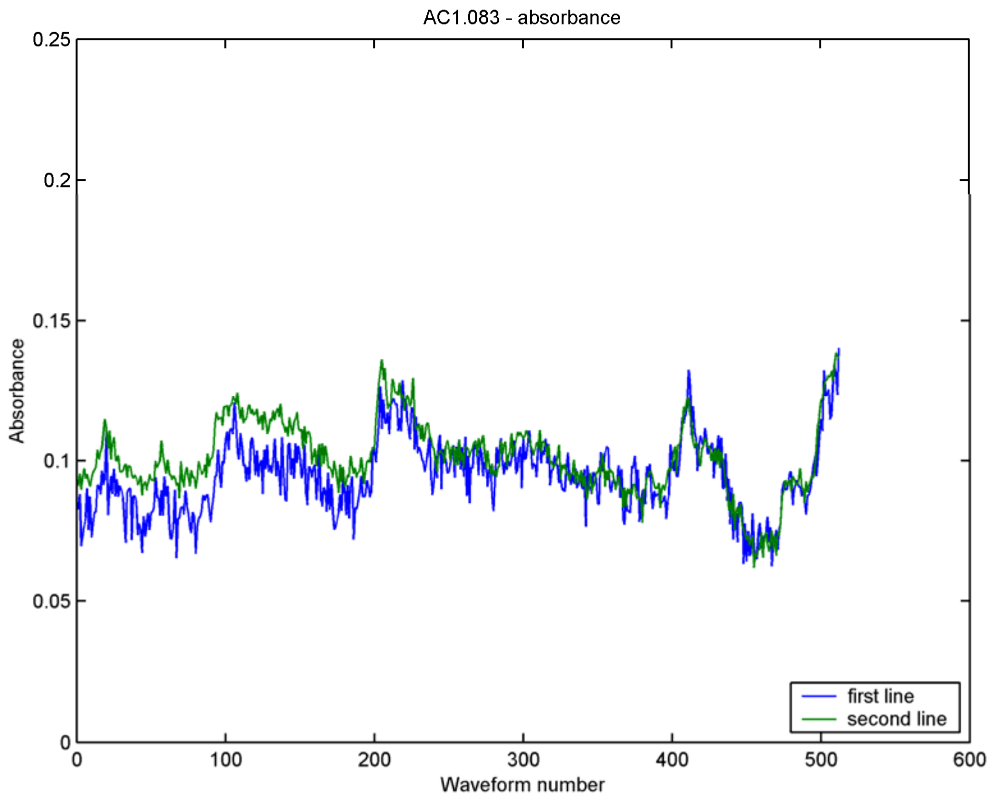

Figure 4. Estimated absorbances for the second data collect.

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