Title: INITIAL AIRBORNE CO₂ DIAL MEASUREMENTS:
DISCUSSION OF RESULTS AND DATA ANALYSIS
CONSIDERATIONS

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Initial Airborne CO, DIAL Measurements: Discussion of Results and Data Analysis Considerations

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A detailed discussion of airborne CO, DIAL measurements obtained from the first joint N-ABLE field campaign at INEL (Idaho National Engineering Laboratory) is presented. System performance characteristics, including return signal strength, averaging statistics, and temporal correlation as well as multi-line DIAL spectral data are discussed. In particular, we review data acquisition and analysis strategies pertinent to chemical detection from a moving platform, such as range determination and correction, and return signal processing (waveform vs. box-car integration, baseline correction). We also report observed effects and variations due to near-field light scattering, pointing and tracking stability, and stack-released plume dynamics.

Introduction

The N-ABLE Lidar project is a joint effort between DOD and DOE that involves mainly three laboratories: US Air Force Phillips Laboratory, US Army ERDEC, and Los Alamos National Laboratory. The primary goal was to demonstrate chemical detection from an airplane using CO, laser differential absorption lidar (DIAL). The main task was to build a state-of-the-art airborne chemical detection system based on currently available “1”-generation CO, DIAL technology leading to the demonstration of an economical operational airborne system by Nov. 1996. This was LANL’s first attempt at operating a CO, DIAL system from an airborne platform and provided an opportunity to learn about relevant airborne operation issues.

The N-ABLE system (see Figure 1 and 2) was designed and built collectively by the three main laboratories with assistance from outside contractors. Each organization was
primarily responsible for one or more of the main subsystems. Briefly, the US Army ERDEC provided the DIAL transmitter which consisted of a normal CO₂ laser, capable of a typical output energy of 150 mJ/pulse and rapid line-to-line tuning up to 200 Hz in a burst mode operation, and a 4X beam expander to reduce the laser divergence to approximately 1 mrad. LANL provided the receiver, and the data acquisition and control systems. The receiver system consisted of a 30-cm diameter telescope, a commercially available 0.5 x 0.5 mm MCT detector, and a custom built relay optical assembly to give an effective f\textsubscript{e} of 0.9 and an approximate FOV of 1.8 mrad. The data acquisition and control system was based on VMX workstations and was custom built to control the transmitter and receiver systems and to acquire DIAL and energy reference signals through waveform digitizers and box-car integrators. The pointing and tracking of the DIAL platform was provided by Phillips Laboratory and was accomplished using the Argus aircraft phase II gimbal system, which was designed to have high locking precision (on the order of 10 μrad). The pointing and tracking of targets could be performed in either of two modes: a combination of GPS (geographical position system) and INU (inertial navigation unit) readings, or an active feedback system using video images from visible cameras aligned with the optical axis of the telescope receiver.

**Lidar System Integrated on to Argus Aircraft, Sept. 1996**

- Slant Range: 7.5 - 15 Km
- Laser: C\textsuperscript{12}O\textsubscript{2}, galvo-tuned FAL
- Pulse Energy: 100 - 150 mJ
- Pulse Width: \sim 1 \mu s
- Repet. Rate: 200 Hz burst mode
- Divergence: 0.8 - 1 mr
- Receiver Aperture: 30.5 cm
- Effective Receiver f\#: 0.9
- Receiver Detector Size: 0.5 mm
- Receiver FOV: 1.8 mr
- Receiver Noise: \sim 1 nW
- Integration Window: 2 μs
- Range Knowledge: +/- 20 m

Figure 1. A picture of N-ABLE platform and system description

The DIAL platform was built and integrated over a period of six months, and was ready for ground tests by July, 1996. Following three months of ground tests, airborne experiments
were performed from 11 October 1996 to 26 November 1996 on the Argus aircraft. The flight tests were conducted at Santa Rosa, NM, and Idaho National Engineering Laboratory.

This paper is intended to provide a technical review and discussion of the N-ABLE airborne measurements and to include mainly field test results that are not being presented in the main N-ABLE technical overview paper. The main focus here is to elaborate on several observations that are pertinent to lidar system performance characterization and to data analysis considerations in airborne experiments.

**Experimental Configuration**

The aircraft typically flew circular patterns (see Figure 3.) around a target location at slant ranges of 7 to 15 km and slant angles of 20-25° with respect to the ground plane (higher altitudes were flown at longer ranges to keep the angle relatively constant.). The altitude was generally held near 3 to 5 km (10000 - 17000 ft) above the target elevation with the ground level about 1.7 Km (5000 ft) above sea level. Typically, it took between 5 to 6 minutes for the aircraft to make a complete orbit around a target site at a slant distance of 10 km. The CO₂ laser beam was pointed at various ground targets using the Argus gimbal mirror assembly. Pointing and tracking of this mirror was controlled by the Argus flight crew with a dual mode tracker (GPS/INU or visible cameras). Typically, the GPS/INU system provided the rough location of targets of interest. The pointing and tracking was then handed off to visual observation through the cameras. Two cameras (a 2.3° wide FOV and a 0.6° narrow FOV),
aligned collinear to the laser beam axis, were used to acquire and lock onto a target while lidar data were collected. The tracking system was capable of offsetting the track location to a fixed point <150 m from the locked target (limited by camera FOV). This system performed most successfully in night flights using a 500 W light beacon as the tracking target. Daytime operation of the pointing and tracking system was difficult due to, in general, the lack of an appropriate high-contrast target. Extensive meteorological data were recorded near the target location site during the experiments, and also before and after the experiments at altitudes up to a few kilometers. Frequent updates of wind direction were sent to the aircraft so that the tracking location could be changed to keep the laser beam on the released chemical plume.

In all flight experiments, natural terrain which included local vegetation and ground soil near the test sites provided the target spot for the laser beam. The vegetation was typical of arid western topography, with a mixture of sage scrub and native grasses. In some cases, a pre-plowed dirt area was used as a standard target location to provide a more uniform albedo background. Extended measurements were also made on a variety of terrain in the area (e.g. bare dirt, sage/grass, lava rock fields, coniferous trees, cultivated alfalfa fields).
Results and Discussion

One critical factor that separates airborne experiments from ground measurements is the effect of the aircraft motion. Moving platforms create many issues of interest and concern, in particular: pointing and tracking, range determination and correction, atmospheric effect due to changing path and pathlength, ground albedo variations, and speckle effects. The absolute inertial pointing accuracy for the Argus platform was found to be on the order of a few degrees. This was mainly attributed to inadequate star calibrations of the INU due to cloud obscuration. However, using a “good” target, i.e. a point source such as a light beacon operating at night, the Argus gimbal was able to lock on to the target with excellent stability (3.4 to 13.3 μrad RMS) using active feedback from camera beacon images. Narrow FOV camera tracking of a point source or scene tracking just after sunrise was also demonstrated with limited success. Scene tracking capability was affected by sun angle and the contrast of the locking target to scene background. In most cases, it was determined that a high contrast target (such as a tree in a dirt patch or a boulder in a snowy field) was sufficient to allow stable tracking with the cameras. However, as the aircraft orbited, the viewing angle changed and so would the shading of such a target. This eventually caused the gimbal system to lose track at some part of the orbit. In daytime experiments, a “flat” high contrast target (or a point source) is needed to allow continuous operation. Offset tracking (where the lidar system is pointed to a fixed offset distance from the tracking point) was also demonstrated and found to have a few anomalies. Specifically, the vertical offsets appeared to hold well and the horizontal offsets appeared to vary as the aircraft move in a orbit (see discussion in IR camera results below). The offset tracking is an important feature to allow searching or mapping a downwind chemical plume and is currently being investigated to determine the cause of the observed anomalies.

Figure 4. Overlaying of outgoing and return waveforms over a time period of 130 seconds.
Ranging of the DIAL platform was accomplished in three modes: manual, GPS, and waveform. The manual mode was used primarily for manually setting a desired range at the convenience of the operator for benchmark experiments on the ground. It was found to be not very useful in flight due to the constant change in range (typically < 30 m/sec rate of range change). The two auto-ranging modes: GPS (using GPS updates) and waveform (triggering off digitized return signal with a preset threshold value) modes were used mainly in flight with reasonable success. Figure 4 depicts that the accumulated return waveform is broadened by approximately 150 ns. This is indicative that the precision of waveform ranging to be around 20 m at an approximate range of 10 Km and in approximately 130 seconds of flight time. The waveform ranging worked well for the case where return signal had good SNR's (typically > 4). The GPS mode did not perform as well as the waveform mode in this case. Figure 5 shows two examples of GPS range data compared to the lidar range determined by return signal waveform analysis. The differences are attributed to the relatively slow GPS update rate of 1 Hz that could not quite keep up with the aircraft movement (the rate of movement of the aircraft is shown in the bottom part of Fig. 5). Under the designated flight patterns, it was determined that the pilot was routinely able to hold the aircraft slant range change to below 30 m/s. Using the GPS mode, the range setting could be off as much as 30 m for one second. Work is currently underway to improve this deficiency by providing more frequent updates.

Uncertainties in path and range due to a moving platform did contribute to the observation of variations in return signal strength. Fortunately, with an observed moving rate < 30 m/s, it was estimated that measurements made on a time frame below 0.1 sec would result in an amplitude error on the order of 0.1% (due to 1/R² range and atmospheric spectral corrections assuming the CO₂ laser lines not on a strong water or ozone absorbing lines). This appears to
agree with the analyzed results that when the ratio of signal amplitudes of two laser lines in a burst were taken, most of these variations could be removed from the return signal statistics. Using a galvo-tuner, the laser line-to-line tuning was achieved on every 5 ms. Similarly, the effect due to background albedo could be reduced if multiline spectral measurements were implemented on a fairly fast time frame. Figure 6 illustrates the result of a set of measurements on a variety of natural targets in flight. No particular effort was made to lock the laser beam on to a fixed point (the DIAL system was pointed roughly at a target with jitters of several mrad).

![Graphs of various terrains](image)

**Figure 6.** Multiline spectral scans of various terrains at 10 Km range.

The general spectral shapes were fairly similar and demonstrated qualitatively the reproducibility of spectral features which were dominated by atmospheric absorption, except perhaps the spectrum of trees. Even though each of the overall spectra required a few minutes of averaging to measure, most of the effects due to platform motion were removed because the spectral sampling was accomplished within 0.1 seconds. Thus, high sampling rate and rapid laser line tuning are important factors in reducing variations due to a moving platform. This
holds true only if, in the process of making the laser perform these tasks, one does not introduce other sources of signal variation, such as laser beam profile and steering fluctuations. When comparing to data obtained from a stationary target in ground measurements, speckle de-correlation in the moving platform data sets also appeared to have been partially achieved. However, since most of the N-ABLE measurements were conducted under conditions where the speckle variation was not the dominated noise source (not speckle limited, they were limited by detector noise, albedo change, and range effects), it was difficult to determine the limiting sources of noise in the averaging statistics. Some examples and discussion of these results are presented in the N-ABLE technical overview paper by B. R. Foy, et. al..

Figure 7. A plot of peak return signal predicted vs. atmospheric extinction with 1% or 2% ground albedo. The dotted lines are observed peak signal amplitude at various ranges.

Radiometric calculations of lidar return signal intensities from several slant ranges were performed using known lidar transceiver optical and electrical parameters. This was intended to validate the N-ABLE system performance and capability. One set of results comparing the estimated signal strength to detected signal amplitude for 7.5-, 10-, and 15-km is summarized in Figure 7. The atmospheric extinction values were estimated to be typically between 0.04 to 0.09 km\(^{-1}\) depending on the laser lines used. This was based on one-way path measurements using a detector (monitoring directly the amount of laser light) on the ground. The extinction data were found to be in good agreement with model calculations using rawinsonde data. The results for all three ranges appeared to match the case where the effective target reflectance was on the order of 1% at the approximate slant angle of 20° with an average atmospheric extinction of 0.06 to 0.07 km\(^{-1}\). These atmospheric extinction measurements can be compared to typical values of
0.08 to 0.10 km$^{-1}$ measured on the ground for a horizontal path at Los Alamos, and as much as 0.2 km$^{-1}$ sometimes measured at the Nevada Test Site (NTS) during the summer months.

In an attempt to attain best system performance, special attention was given to the examination of the return signal shot-to-shot fluctuations, particularly, the averaging statistics and the temporal correlation in the data set that may result in poor averaging statistics. Generally, we observed that single line averaging statistics are sometimes significantly improved by taking the ratio to another line. This was particularly true in the case of airborne measurements where the dominant source of variations was due to a common cause, such as albedo changes introduced by platform movement. Several data sets were shown to have the desired $1/(\sqrt{N})$ behavior when the ratio of two line return signals was taken. The opposite effect appeared to be observed in the stationary platform case where the measurements were obtained on the ground with a short-range 1-km target. With the high SNR’s in these ground measurements, it is expected that the return signal statistics were most likely dominated by speckle noise effects. Different spectral lines appeared essentially uncorrelated. Examples of these are presented in Reference 1.

In an attempt to attain best system performance, special attention was given to the

One major concern of relevance to the performance of signal averaging statistics was that the measured signal amplitudes might contain biases due to the way the data was acquired and analyzed. Comparisons were made to investigated the two types of lidar data obtained: digitized waveforms and box-car integrated values. The waveform data were analyzed two ways, either the peak value of the return signal was recorded or the integrated waveform was used. From the
waveform case, an interpolated baseline based on two pre-selected segments before and after the signal pulses was used for analysis. Figure 8 illustrates this procedure. The results indicated that for the cases where good auto-ranging was achieved, i.e. the box-car window was properly set around the return signal, there was essentially no difference between the integrated waveform and the box-car results. The difference appeared to be in the tenths of %, not readily discernible in most of our data set. However, in the case of using the peak value of the waveform, large variations were observed depending on the SNR of the return signal. For low SNR, peak value detection was deemed not to be the data reduction procedure of choice.

Airborne chemical plume detection measurements were accomplished using line source (20 m in length and about 1 m above ground) and a stack (21 m above ground) releases. In reference 1, the chemical detection limits for three test chemicals, SF₆, ethylene, and TEP, were summarized at several ranges. Because the chemicals were detected several tens of meters (up to 200 m in some cases) downwind from the release point, as one might expected, large variations in plume concentrations were measured. The variations depended to a large extent on the local wind speed and direction, and the overlap between the laser footprint and the plume dimensions (including the plume depth). Figure 9 show one such plot of the estimated relative absorption amplitudes as well as the relative chemical flow rates as a function of time for both SF₆ and ethylene line releases. The absorption amplitudes were calculated using a LANL in-house chemometric analysis package². The observed large fluctuations in absorption were mainly a result of the laser beam being moved on and off plume in several attempts to locate it and variations in the wind direction. With the line releases and typical slow wind speeds (~ 2 m/s

![Figure 9. Time history of chemical releases and CO₂ DIAL measurements](image-url)
with the laser pointed at 10 to 100 m from the release point), the plume spread out reasonably uniformly and plume dynamics played only a minor role in the observed variations. Figure 10 shows an example of plume mapping from a stack release. The variations in absorption were captured in a much shorter time frame. This is indicative of plume break-up

![Plume Mapping](image)

**Figure 10.** The aircraft orbit, the relative wind direction, the relative offset distance to release point, and the observed plume variation for one chemical release test.

expected for a stack release. These plume break-up effects were observed with our IR camera imaging system. One example of each of the line and stack releases is shown in Figure 11. In the near-ground line release, the chemical plume was trapped beneath an inversion layer and remained well-confined, whereas in the above-ground stack releases, the plume varied greatly in location and size.

Additional details of the lidar system performance were investigated by observing the CO₂ laser spot on targets with IR camera. As shown in Fig. 11, the laser footprint on a dirt target 10 km from the aircraft was measured to have a diameter of about 10 m as expected for a 1 mrad divergence beam. On one run, the beam was located very close to the camera's location, allowing us to observe the detailed structure of the ground reflection. In these images, there is a low-level, variable return, presumably caused by speckle; and a number of bright, stable, apparently specular reflections. By further analysis we should be able to determine
whether the return is dominated by speckle or specular effects. We should also be able to examine the detailed variations of the speckle pattern.

During good locking conditions, only a slight movement of the beam spot was detected in the instances in which the beam aim point and the tracking point were the same (i.e. no offsets). It should be informative to compare the observed movement in IR camera images to the movement of the tracking point in the visible camera images to discern possible angular deviations between IR laser transmitter and the visible tracking channel. In the case when “offset” tracking was performed, the beam was found to move in a circular path on the ground as Argus performed its orbit. The beam was supposed to remain targeted on a single point. This is illustrated in Figure 12. One flight exhibited an overshoot and another flight exhibited an undershoot. In addition to the regular circular motion, the beam exhibited smaller irregular motions. This indicated a potential problem with this mode of tracking or in the optical alignment of the lidar system with respect to the pointing and tracking system. We intend to investigate these movements with the aid of the IR camera video in the near future.

Conclusion

Using the N-ABLE system, we have successfully fielded 12 airborne tests for approximately 30 flight hours. We have demonstrated pointing and tracking capabilities of the Argus phase II gimbal system at ranges up to 30 km. We were able to validate the airborne CO₂
DIAL system performance and to characterize atmospheric and background variations. The detection of chemical plumes against natural background was demonstrated at ranges up to 15 km. From the N-ABLE experience, we also have learned that Argus is a proven and workable platform for future airborne experiments. The pointing and tracking functions work well with high contrast targets. Day-time tracking operation needs to be improved with the use of better targets or control electronics and software. Real-time pointing and tracking diagnostics such as the IR camera have proven to be very helpful. Several system design issues that were not discussed here still need to be carefully investigated in order to improve system performance. These include near field light scattering, receiver detector baseline issues, and thermal stability.

Figure 12. Offset tracking resulted in a circular beam path on the ground

- Not all detected laser shots are shown
- Red outlines depict beam image, not actual size/shape of beam

Of the DIAL platform. We have also found RF and EMI interference to several electrical instruments caused by the 400 Hz prime power and high voltage laser discharges. Special care in the grounding, shielding, and layout of these instruments will be required to minimize this problem. In terms of the actual airborne DIAL system performance, we have found real-time target ranging played an crucial role in data collection precision. Proper ranging procedures and return signal analysis routines are required to ensure superior performance. It was determined that natural target albedo and background variations could be significantly reduced through line-to-line spectral normalization. Atmospheric transmission variations could be quantitatively predicted and modeled, if appropriate atmospheric parameters were measured. We have also observed that lidar return signal to noise ratio increases as $N^{1/2}$ (with N # of shots averaged) as predicted under favorable conditions.
Reference

1. “Summary of Results from the N-ABLE Field Experiments,” Bernard R. Foy and et.al., 1996 CALIOPE ITR proceedings.

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